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IntechOpen Series
Civil Engineering, Volume 19

Civil Engineering Annual Volume 2025

*Edited by Amin K. Akhnoukh
and Saúl Antonio Obregón-Biosca*



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Published in London, United Kingdom

Civil Engineering Annual Volume 2025

<http://dx.doi.org/10.5772/intechopen.1014548>

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First published in London, United Kingdom, 2026 by IntechOpen

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For EU product safety concerns: IN TECH d.o.o., Prolaz Marije Krucifikse Kozulić 3, 51000 Rijeka, Croatia, info@intechopen.com or visit our website at intechopen.com.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Civil Engineering Annual Volume 2025

Edited by Amin K. Akhnoukh and Saúl Antonio Obregón-Biosca

p. cm.

This title is part of the Civil Engineering Book Series, Volume 19

Series Editor: Assed Haddad

Print ISBN 978-1-80631-139-2

Online ISBN 978-1-80631-138-5

eBook (PDF) ISBN 978-1-80631-140-8

ISSN 3029-0287

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IntechOpen Book Series

Civil Engineering

Volume 19

Aims and Scope of the Series

Civil engineering is a traditional field of engineering from which most other branches of engineering have evolved. It comprises traditional sub-areas like transportation, structures, construction, geotechnics, water resources, and building materials. It also encompasses sustainability, risk, environment, and other concepts at its core. Historically, developments in civil engineering included traditional aspects of architecture and urban planning as well as practical applications from the construction industry. Most recently, many elements evolved from other fields of knowledge and topics like simulation, optimization, and decision science have been researched and applied to increase and evolve concepts and applications in this field. Civil engineering has evolved in the last years due to the demands of society in terms of the quality of its products, modern applications, official requirements, and cost and schedule restrictions. This series addresses real-life problems and applications of civil engineering and presents recent, cutting-edge research as well as traditional knowledge along with real-world examples of developments in the field.

Meet the Series Editor



Professor Assed N. Haddad is a Civil Engineer with a degree from the Federal University of Rio de Janeiro (UFRJ) earned in 1986, as well as a Juris Doctor degree from the Fluminense University Center earned in 1993, and a Master's degree in Civil Engineering from the Fluminense Federal University (UFF) obtained in 1992. He completed his Ph.D. in Production Engineering from COPPE / Federal University of Rio de Janeiro in 1996. Professor Haddad's academic pursuits have taken him to postdoctoral stays at the University of Florida, USA in 2006; at the Universitat Politècnica de Catalunya, Spain in 2010; and at the University of New South Wales Sydney, Australia in 2019. Currently, he serves as a Full Professor at the Federal University of Rio de Janeiro. He has held visiting professorships at various institutions including the University of Florida, Universitat Politècnica de Catalunya, Universitat Rovira i Virgili, and Western Sydney University. His research expertise encompasses Civil, Environmental, and Production Engineering, with a primary focus on the following topics: Construction Engineering and Management, Risk Management, and Life Cycle Assessment. He has been the recipient of research grants from the State of Rio de Janeiro, Brazil: CNE FAPERJ from 2019 to 2022 and from 2023 to 2025. Additionally, his research grants obtained from the Brazilian Government CNP since 2012 last to this date. Professor Haddad has been involved in several academic endeavors, being the Guest Editor of the International Journal of Construction Management; MDPI's Sustainability, Energies, and Infrastructures; Associate Editor at Frontiers in Built Environment / Sustainable Design and Construction; Guest Editor at Frontiers in Built Environment / Construction Management; and Academic Editor of the Journal of Engineering, Civil Engineering Section of Hindawi. He is currently a Professor of the Environmental Engineering Program at UFRJ and the Civil Engineering Program at UFF.

Meet the Topic Editors



Amin K. Akhnoukh is a Professor in the Construction Management Department at East Carolina University. He earned a B. S. in Civil Engineering from Cairo University, Cairo, Egypt (1997), an M. S. in Civil Engineering from Kansas State University, Manhattan, Kansas (2005), and a Doctorate in Construction Engineering from the University of Nebraska, Lincoln, Nebraska (2008). Dr. Akhnoukh's research interests include the development of high-strength and high-performance concrete mixes for highway construction projects, investigating the short and long-term performance of construction materials, and artificial intelligence applications in infrastructure asset management.



Saúl Antonio Obregón-Biosca is a Civil Engineer from the Autonomous University of Queretaro (AUQ), a Master's in Engineering, and a Ph.D. from the Technical University of Catalonia. He is a Professor-Researcher in the Civil Engineering program at the AUQ Engineering Faculty. He was Queretaro Municipal Minister of Mobility (2018-2021), and obtained the National award "José Carreño Romaní 2016", for a research paper, from the Ministry of Transport and Communications of Mexico and the Mexican Association of Transport Engineering. He is a member of the Mexican National System of Researchers, level 3. He is the author and co-author of more than 50 scientific research papers. His research line focuses on travel behavior and road safety.

Contents

Preface	XIII
Section 1	
Construction Engineering	1
Chapter 1	3
Perspective Chapter: Local Construction Strategies for Climate Adaptation in the Trinational Region of Iguaçu – Brazil, Argentina, and Paraguay <i>by Egon Vettorazzi, Sérgio Lousada and Herlander Mata-Lima</i>	
Chapter 2	25
Exploring openBIM Data Formats Aligned with ISO 19650-4 in Construction <i>by Murat Aydın</i>	
Chapter 3	61
Reevaluating IFC and Comparing USD in the Context of the Built Environment <i>by Murat Aydın</i>	
Chapter 4	83
Applications of Artificial Intelligence (AI) in Infrastructure Asset Management <i>by Amin K. Akhnoukh and Nihal S. Erian</i>	
Section 2	
Transportation Engineering	95
Chapter 5	97
Impact of COVID-19 on Users' Social Perception of Public Transport in Madrid <i>by Alba Gómez-Ortega, Vera Gelashvili and María Luisa Delgado Jalón</i>	
Chapter 6	115
Urban Bus Network Electrification <i>by Dávid Földes, Bálint Csonka and Péter Ákos Szilassy</i>	

Chapter 7

137

The Use of Polymers, Nano-Polymers, and Nano-Modified Emulsion for Gravel Road Maintenance: A Review

by Armand Augustin Fondjo and Elizabeth Theron

Preface

The accelerating pace of technological advancement and the urgent necessity for sustainable solutions have placed the construction and infrastructure sectors at the forefront of global innovation. The “Construction Engineering” section brings together diverse perspectives and cutting-edge research to address the most pressing challenges and opportunities in the built environment today. Each chapter offers a unique lens for examining the intersection of technology, policy, and practice, providing readers with a comprehensive understanding of contemporary trends and strategies.

The opening chapter, “Perspective Chapter: Local Construction Strategies for Climate Adaptation in the Trinational Region of Iguazu – Brazil, Argentina, and Paraguay”, sets the stage by exploring how communities within this strategically significant region are developing localized approaches to climate resilience. Through a detailed examination of cross-border collaboration, this chapter highlights the critical importance of context-specific adaptation strategies in mitigating the impacts of climate change.

The second chapter, “Exploring openBIM Data Formats Aligned with ISO 19650-4 in Construction”, explores the transformative role of digital information management. By aligning openBIM data formats with international standards, the chapter demonstrates how enhanced interoperability and data consistency can improve project outcomes and foster greater collaboration across the construction industry.

In the third chapter, “Reevaluating IFC and Comparing USD in the Context of the Built Environment”, the focus shifts to a comparative analysis of key data exchange formats. This chapter critically examines the strengths and limitations of Industry Foundation Classes (IFC) and Universal Scene Description (USD), offering insights into their respective roles in supporting the evolving needs of digital construction and design.

The final chapter, “Applications of Artificial Intelligence (AI) in Infrastructure Asset Management”, explores the integration of AI-driven solutions in maintaining and optimizing infrastructure assets.

Through real-world case studies and emerging research, this chapter illustrates how AI technologies are enhancing decision-making, predictive maintenance, and long-term asset value.

Collectively, these chapters provide a rich tapestry of knowledge that bridges theory and practice, offering valuable guidance to researchers, practitioners, and policy-makers alike. It is our hope that this book will inspire continued innovation and collaboration, driving progress toward a more resilient, efficient, and sustainable built environment for future generations.

Amin K. Akhnoukh

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Transportation engineering represents one of the most dynamic and strategic areas within civil engineering. Its study involves not only the design techniques and operation of mobility systems, but also a deep understanding of the social, economic, and environmental factors that influence modern transportation planning.

This section is aimed at professors, students, and professionals in transportation engineering. It presents three chapters that address emerging topics, including perceptions of public transportation, sustainable mobility, and the use of polymers for road maintenance. The first chapter, “Impact of COVID-19 on Users’ Social Perception of Public Transport in Madrid”, analyzes how the pandemic influenced the population’s perceptions and mobility decisions in Madrid (Spain). The second chapter, “Urban Bus Network Electrification”, proposes a method for planning charging infrastructure, selecting electric bus types, and estimating costs. The third chapter, “The Use of Polymers, Nano-Polymers, and Nano-Modified Emulsion for Gravel Road Maintenance: A Review”, reviews the application of polymers and nanomaterials to improve gravel road maintenance. This material contributes to the state of knowledge, promoting reflection, research, and practice in two areas of interest to civil engineering.

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Section 1

Construction Engineering

Perspective Chapter: Local Construction Strategies for Climate Adaptation in the Trinational Region of Iguazu – Brazil, Argentina, and Paraguay

Egon Vettorazzi, Sérgio Lousada and Herlander Mata-Lima

Abstract

The Trinational Region of Iguazu presents a climate of high temperatures in summer, low temperatures in winter, and frequent occurrence of extreme climatic phenomena that affect the housing of populations in social vulnerability. In this context, this study explores the architectural solutions for adapting to the climatic conditions of the region, specifically Foz do Iguazu, Ciudad del Este, and Puerto Iguazú. For this, a documentary analysis was first made to know more about the theme and climate of the region. Thereafter, analysis of the riverside dwellings of the three cities in the study was performed, and finally, an analysis of the materials and constructive technologies used to adapt the houses to the local climate was obtained. It was observed that local materials are used in different components of buildings, are of low cost, and have a low environmental impact. Results demonstrate that the residents, even in precarious situations, use creativity to solve the problems of climatic adaptation of buildings using eaves, double wood casement window, wide balconies, landscaping, and elevation of the floor as protection against humidity. The results underscore the significance of close ties and knowledge sharing between academia and communities, acknowledging the value of context-driven architecture.

Keywords: Argentina, Brazil, Paraguay, climate adaptation, social technology, Trinational Region of Iguazu, vernacular architecture

1. Introduction

Climate change is causing significant global warming in a short period of time, negatively impacting health, the economy, and the environment, such as heatwaves present in large cities [1, 2]. Over the past decades, the increasing energy consumption in buildings and industry has reached approximately 40% of global energy consumption [3]. In this context, energy efficiency in the construction sector has been considered a top priority policy among the world's largest economies [4].

International concern about the influence of buildings on natural and energy resources has intensified and is now considered a priority on the global agenda [5].

Official architecture often neglects essential aspects such as materials, energy, context, and society's own needs [6]. It results from the specialization of work and the doctrines of schools and often compromises the harmony between form and context, being more of an invention than a consolidated tradition. In contrast, vernacular architecture follows a path of learning through trial and error, gradual changes, and a self-adaptive process that preserves the integrity between form and context. It is based on tradition and popular knowledge and possesses inherent qualities of passive thermal comfort systems and conservation of natural resources, compared to contemporary "official" architecture [7].

Vernacular architecture typically involves the use of local building materials and techniques that adapt to the particular circumstances of the local climate. It is therefore extremely heterogeneous [8, 9]. Vernacular architecture is characterized by its absence of an architect and design, as defined by academic conception. Generational folk knowledge is applied in the construction of buildings that adapt to the climate without the use of mechanized means to achieve comfort [10].

The term "vernacular architecture" is widely discussed and often referred to, as required, as "anonymous," "spontaneous," "popular," "indigenous," "rural," "informal," "autochthonous," among others. The word "vernacular" comes from the Latin "vernaculus," which originally referred to a slave born in the master's house. The term "vernacular," although not appropriate, is used when Brazilian authors refer to the constructive manifestations of the people [11]. The concept of vernacular architecture has been relatively recent worldwide. Its study began to garner interest in late nineteenth-century England, through architects such as Lutyens, Voysey, and Webb, who recognized its qualities of simplicity, as well as the harmony that this tradition established with the surroundings. However, in the early twentieth century, the subject did not generate widespread interest among architects, which delayed the modern movement's awareness of its importance for a long time [12].

Despite the evident benefits, the distinctive energy characteristics of vernacular architecture gradually lost relevance throughout the twentieth century, especially with the rise of International Style architecture in the postwar period [13]. Over the past century, architecture has progressively distanced itself from traditional culture, knowledge that often evolved over millennia to become perfectly adapted to the surrounding environment, as well as to be highly representative of local cultural identity, and to function correctly according to regional climatic conditions, thus ensuring thermal and luminous comfort [14]. During the 18th and 19th centuries, in the context of the Industrial Revolution, new materials and mass production techniques emerged in architecture. Simultaneously, the development of lighting systems and artificial thermal sources led to the gradual replacement of traditional climate-adapted architecture with standardized and energy-dependent solutions [15, 16]. The energy crisis of the 1970s highlighted the need to reassess architectural design to suit local climatic conditions, aiming to reduce energy dependence and thus mitigate environmental impacts, such as greenhouse gas emissions (GHGs) [14].

Socially vulnerable areas, with limited access to financial resources and industrialized building materials, end up developing intuitive environmental comfort strategies, resorting to low-cost materials readily available locally to adapt housing to the climate.

This chapter addresses buildings located in contexts of social vulnerability, along the banks of the Iguaçú and Paraná rivers, in the Triple Frontier between Brazil,

Paraguay, and Argentina. The Trinational Region of Iguaçu is characterized by high temperatures in summer, low temperatures in winter, and the frequent occurrence of extreme weather phenomena that impact the housing of vulnerable populations. In this scenario, the study investigates popular architectural solutions for adapting to the region's climatic conditions, focusing on the cities of Foz do Iguaçu, Ciudad del Este, and Puerto Iguazú. This topic, although relevant, is still underexplored by academic research. Its importance is highlighted by its connection to Agenda 21 and the Sustainable Development Goals for 2030, especially regarding energy efficiency, reducing resource consumption, and increasing the resilience of vulnerable communities [17].

1.1 Problem statement

Vernacular architecture, as well as architecture aimed at energy efficiency, begins to be revalued from the mid-twentieth century onwards, and with greater intensity after the international oil crisis of the 1970s. Authors such as architect Hassan Fathy, architect Manuel Correia Guedes, and, in the Brazilian context, architect and historian Günter Weimer, present publications of great relevance in the field [11, 18, 19].

One of the main figures responsible for the dissemination of vernacular architecture worldwide was the Egyptian architect Hassan Fathy, who sought to revive ancient Egyptian construction methods using materials available and accessible to the poorer population. Fathy published the book "Building with the People: Architecture for the Poor" in 1969. The work was published in the United States in 1973 and in Brazil in 1980 [18]. The publication had a significant impact on the global academic community, primarily due to growing global energy and environmental concerns (**Figure 1**).

Studies on sustainable architecture and those that value vernacular architecture are developed within the scope of the European project SURE-Africa (Sustainable



Figure 1.
Popular Architecture in Egypt [18].

Urban Renewal: Energy Efficient Buildings for Africa) and coordinated by architect Manuel Correia Guedes. The project aims to deepen and disseminate existing knowledge in four Portuguese-speaking African countries in the field of sustainable architecture—particularly concerning bioclimatic design and energy efficiency in buildings, contributing to improving the habitability conditions of the built environment. The studies encompass, in addition to vernacular architecture, all construction solutions that lead to energy efficiency in buildings. SURE-Africa, which took place between 2007 and 2009, involved academic institutions from Europe and Africa. The main results were published in the form of teaching support materials, as well as manuals of best practices (**Figure 2**) [19].

In Brazil, architect and historian Günter Weimer is one of the main responsible for the most comprehensive studies on the subject in the country. In 2005, he published the book “Brazilian Popular Architecture,” which is currently in its second edition [11]. The work provides a brief national inventory of so-called popular architecture. In 2014, Günter published the book “Afro-Brazilian Interrelations in Architecture,” demonstrating primarily the influence of traditional African architecture on Brazilian architecture (**Figure 3**) [20]. These publications are references for studies aimed at valuing popular architecture as a means of promoting, among other things, traditional construction techniques in search of energy efficiency and thermal comfort.

In recent decades, especially due to the global climate and environmental crisis, various studies have been conducted in different parts of the world to recover passive environmental comfort strategies, especially from vernacular buildings. Research conducted in China demonstrates quantitative evidence of the effectiveness of natural ventilation technologies in vernacular housing and their potential contributions to more sustainable buildings [21]. Qualitative analysis conducted on vernacular buildings in Ecuador reveals that passive strategies used, such as thermal insulation of the envelope, central courtyard, and the shape and orientation in relation to the prevailing wind direction, are effective in dealing with local climatic conditions [22]. Studies on buildings in Mediterranean climates in Spain demonstrate how passive strategies in vernacular buildings help mitigate extreme temperatures [23]. Studies conducted in Indonesia also demonstrate the potential of vernacular architecture



Figure 2.
Vernacular Architecture in Cape Verde [19].



Figure 3.
Architecture in a Brazilian Favela [20].

to maintain internal temperatures within the comfort range [24]. The importance of bioclimatic design, passive cooling and solar heating systems, and vernacular building materials in improving sustainability and thermal comfort is demonstrated in research conducted in Africa [25]. Research conducted in Brazil demonstrates the importance of rescuing traditional elements of architecture, specifically solar control elements, for use in contemporary buildings worldwide to improve internal comfort conditions [14].

1.2 The Trinational Region of Iguaçu and the climate

The tri-border region has continental climatic characteristics, meaning it is far from the ocean. These continental characteristics favor the heating of the territory for long hours, generating thermal discomfort for the population. Another predominant factor is the availability of surface water in the region, which, together with other meteorological factors, contributes to high humidity, increasing discomfort regarding thermal sensation, which is perceived by the local population, especially on days of high and low temperatures.

The study area, known as the Trinational Region of Iguaçu, is composed of the municipalities of Puerto Iguazú in Argentina, Foz do Iguaçu in Brazil, and Ciudad del Este in Paraguay. To the west of Foz do Iguaçu lies the Paraná River, to the south the Iguaçu River, to the north the artificial Itaipu Lake, and to the southeast the Iguaçu River Falls (Iguaçu National Park). In the southwest of Foz do Iguaçu, the Paraná and Iguaçu rivers converge to form the Triple Frontier region. **Figure 4** shows a map of the Trinational Region.

The Trinational Region of Iguaçu has been modernized to primarily cater to tourism demands; it received road infrastructure with the construction of bridges connecting the three countries and experienced a demographic explosion, mainly due to the construction of the Itaipu Hydroelectric Plant and the opportunities provided by cross-border trade. This is why various ethnic groups from different parts of the world have come to join those who had already settled in the area during colonial times.

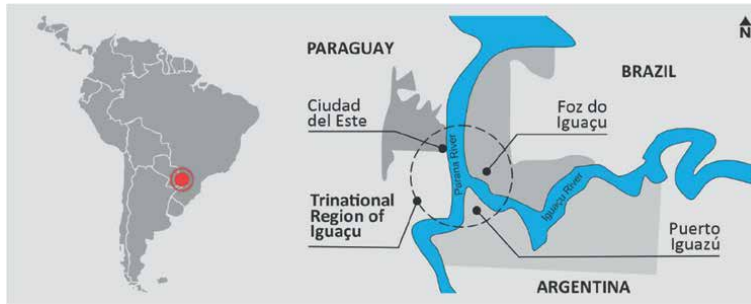


Figure 4.
Location map of the Trinational Region of Iguazu in South America and distribution of the three cities along the banks of the Paraná and Iguazu rivers (Source: Authors).

1.3 Objectives and research question

The objective of the research is to understand the various architectural solutions used by low-income populations to adapt their housing to climatic conditions, with a focus on flood-prone areas in the border region involving Argentina (city of Puerto Iguazú), Brazil (city of Foz do Iguazu), and Paraguay (Ciudad del Este). The study investigates how socially vulnerable populations in the riverbank areas of the Trinational Region of Iguazu have constructed their homes based on local knowledge, using specific building technologies as adaptation strategies to the local climate.

The central research question addressed is as follows: What are the elements of vernacular architecture in the triple border region that promote the construction of resilient and sustainable social housing, taking into account extreme climatic conditions?

2. Methodology

The study was conducted in the three border cities of the Triple Frontier between Brazil, Argentina, and Paraguay. These cities were chosen because they have riverside populations on the banks of the Paraná and Iguazu Rivers, which, despite limited financial resources, employ architectural strategies to mitigate the impacts of the subtropical climate on them.

It is worth noting that, considering the characteristics of the communities in the study area, formal methods such as questionnaires and interviews are not the most suitable for collecting information because they inhibit residents and, consequently, reduce the volume and detail of the collected information.

The summary of the methodology adopted for this study consists of three stages, as illustrated in **Figure 5**. The details of each stage will be presented below, highlighting the procedures used throughout the research.

2.1 Document analysis: Climate and architectural strategies

The first stage of the research involved a literature review and analysis of the climatic conditions of the region, gathering information about the climate of Foz do Iguazu, Puerto Iguazú, and Ciudad del Este. This survey provided an understanding



Figure 5.
Summary of the methodology (Source: Authors).

of the environmental challenges faced by riverside populations and served as a foundation for analyzing the architectural strategies adopted in the region.

Additionally, a study was conducted on the main architectural strategies recommended for the local climate, providing a theoretical framework for interpreting the collected data. To deepen this analysis, a computational simulation was developed using the Climate Consultant 6.0 software, taking Foz do Iguaçu as a representative city, as the three cities share the same climate classification. This simulation was conducted based on the Adaptive Comfort Model, allowing an examination of which characteristics of the dwellings could result in better thermal comfort conditions for the residents.

The parameters adopted in the simulation considered an acceptable comfort range between 80 and 90%. In the case of Foz do Iguaçu, the average monthly minimum outdoor temperature was 14.1°C, while the average monthly maximum reached 26.7°C. The adopted minimum operational temperature was 19.7°C, and the maximum was 28.6°C. These criteria allowed the evaluation of the efficiency of the architectural strategies in mitigating the impacts of the climate on local dwellings.

2.2 Field research and photographic survey

The second stage of the research consisted of a field photographic survey in the border cities of Foz do Iguaçu (Brazil), Ciudad del Este (Paraguay), and Puerto Iguazú (Argentina). The goal was to document riverside dwellings and analyze the construction materials, as well as the strategies adopted by local populations to adapt to the region's climate.

The selection of dwellings followed specific criteria, prioritizing buildings that exhibited typological diversity, variation in the materials used, and different architectural solutions. The choice was made through direct observation in riverside areas with higher socioeconomic vulnerability, considering the visual accessibility of the constructions.

A total of 60 photographs were taken, 20 in each city, covering various aspects of the buildings. The facades were analyzed in relation to the materials used, the position and size of openings, and the types of finishes applied. Roofs were documented considering the materials employed, slope, and the presence of openings for ventilation. Information about the foundations of the buildings was also recorded, identifying strategies for dealing with humidity, floods, and adaptation to the soil.

In addition, ventilation solutions were observed, such as windows, shutters, and strategic openings, as well as shading strategies, including the use of verandas, curtains, and vegetation. The survey also considered the relationship of the buildings with the immediate surroundings, documenting shaded areas by vegetation and other elements that contribute to the thermal comfort of the dwellings. Finally, materials used in the construction of pavements, walls, and fences were documented to understand their impact on climate adaptation and integration with the environment.

All photographs were taken with due care to preserve the privacy of the residents, avoiding direct exposure of the inhabitants and focusing exclusively on the constructive aspects of the buildings.

2.3 Schematic synthesis

In the third stage of the research, the collected data were organized by selecting a representative photograph of a building from each of the studied cities: Foz do Iguaçu, Puerto Iguazú, and Ciudad del Este. This approach allowed for a detailed description of the main construction characteristics and the climate adaptation strategies observed. The analysis of these images enabled the evaluation of the use of locally available materials, predominant construction techniques, and the solutions adopted for ventilation, thermal comfort, and moisture protection.

Finally, a graphic analysis was carried out, in which a schematic synthesis of the characteristics of the riverside buildings in the triple-border region was represented through a drawing containing simplified floor plans and facades. This material provided an objective visualization of the typologies and construction strategies used, consolidating the information gathered throughout the study.

3. Results and discussions

In the following sections, the main results obtained during the research will be presented, providing a detailed analysis of the findings.

3.1 Document analysis: Climate and architectural strategies

3.1.1 Climate analysis of the Trinational Region of Iguaçu based on the Köppen-Geiger climate classification

According to the Köppen classification, the Trinational Region of the Iguaçu River border dominates the climate of the Subtropical Moist Mesothermal type, with relatively warm summers, no dry season annually, and few frosts. It is classified by the abbreviation “Cfa” (humid temperate climate with hot summers), which coincides with the updated classification by [26], also called Cfa (humid subtropical climate, oceanic without a dry season, hot summer), as it is equivalent. The climatic group “C” indicates warm temperate climate, with the average air temperature of the coldest month between -3 and 18°C ; the average temperature of the warmest month is above 10°C , and the summer and winter seasons are well defined. The fundamental region “f” indicates humid climate, with precipitation occurring in all months of the year; absence of a defined dry season, and average precipitation of the driest month should be above 60 mm. The climatic class “a” presents hot summers, and the average air temperature in the warmest month should be above 22°C .

In Foz do Iguaçu, one of the largest annual temperature ranges in the state of Paraná is observed, with an approximate difference of 11°C on average between winter and summer. This occurs due to a lesser influence of maritime conditions compared to other municipalities. For this reason, summers are usually very hot, with average highs around 33°C , reaching over 40°C . Despite being considered mild, winters experience sharp temperature drops that can fall below zero during the passage of cold fronts with polar air masses. Rainfall is typically well distributed

throughout the year, with a slight reduction in winter. The annual precipitation varies around 1800 mm.

In Puerto Iguazú, there is significant rainfall throughout the year, with an average temperature of about 21.2°C and an annual average rainfall close to 1731 mm. The annual average temperature in Ciudad del Este is around 21.6°C, with precipitation of approximately 1721 mm per year.

Naturally, the Trinational Region of the Iguazú possesses geographical characteristics conducive to atmospheric events that affect the local population in some cases. The respective phenomena that act in the region are:

- MCS - Mesoscale Convective Complex: Low-pressure system that generates large storms;
- Chaco Low: Low-pressure system formed over Paraguayan territory, leading to heavy rains;
- Polar Air Masses: High-pressure system that moves from Argentina towards Paraguay and Brazil;
- Equatorial Mass: Equatorial pressure system that transports heat and moisture from the Amazon;
- South Atlantic Anticyclone: High-pressure system that inhibits the formation of rain clouds over the region;
- Frontal Systems: Cold fronts that move from Argentina to the triple border region and in some cases form over the southern regions of Brazilian territory.

In addition to these active events, there are phenomena of planetary character, such as the El Niño and La Niña phenomena, which greatly influence the planet's climate. The Trinational Region of Iguazú is not exempt from these changes, which are accompanied by rising temperatures and increased precipitation, which in some years of activity can triple, as well as a decrease in precipitation and the frequency of intense cold air masses lingering.

All these atmospheric systems play a significant role in the region's climate situation. These events influence high temperatures, river flooding, roof damage to houses, among other factors that bring great harm to the riparian population of the trinational area.

More severe atmospheric events naturally occur in the region due to its geographical characteristics. Considering that human interference affects local climate patterns, the riparian population remains at the mercy of these events. For example, the intensification of storms accompanied by hail, gales, and torrential rains, or even prolonged droughts that occur more frequently, affecting mainly the homes of the population with limited financial resources, such as the riparian population of the triple border region.

In 1982 and 1983, the most intense El Niño events occurred, causing great destruction in South America. In the Trinational Region of Iguazú, the volume of rainfall was exceptional, resulting in over 600 displaced and 170 deaths due to major floods in those years. In 1997 and 1998, El Niño returned with strong intensity, generating heavy rainfall and an abnormal winter with high temperatures for the season [27].

Many researchers attribute human interference in nature as one of the main factors contributing to the alteration of local atmospheric conditions. Most of the riparian population is located along the banks of the Iguaçu and Paraná rivers, where the flow of air masses occurs geographically, leading to the clash of warmer and moister air masses with cooler air from Argentina.

The most recent example of these severe events occurred on the night of September 7, 2015, when the border cities were devastated by a severe hailstorm that struck the region, declaring a state of emergency in several areas. Strong winds and heavy rain fell on the region. Many houses lost their roofs throughout the city, leaving many people homeless. Several areas of Foz do Iguaçu were left without electricity. The Civil Defense set up various tarpaulin distribution points throughout the city to temporarily address the problem [28].

Local climatic adversities affect the homes of populations in situations of social vulnerability more severely, as is the case with the homes under study, which are often built in areas at risk of flooding or landslides and also lack access to construction materials with adequate resistance to the elements.

3.1.2 Recommendation of strategies suitable for the climate of the Trinational Region of Iguaçu

The study did not conduct research on housing occupancy conditions to indicate parameters regarding internal gains, equipment, types of clothing, and metabolic rates, among other factors. The architectural strategies for housing and the Housing and Urban Environment recommended for the regional climate, as well as the results

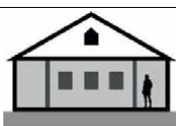
	In well-ventilated humid climates, attics with sloped roofs work well to drain rainwater and can be extended to protect entrances, balconies, and outdoor work areas.
	Position windows in the shade and oriented towards prevailing breezes.
	Traditional passive houses in hot and humid climates should use high and operable (French) roofs and high windows protected by deep eaves and verandas.
	Balconies and screened patios can provide passive comfort through cooling from ventilation on hot days and can prevent issues with insects.
	Use open interior plans to promote natural cross-ventilation or use doors with blinds or ducts if privacy is needed.

Table 1.
Details of Strategies for Housing in the Climates of the Triple Frontier (Source: Authors).

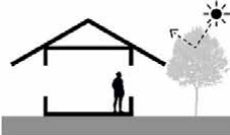
	Use of vegetation (shrubs, trees, ivy-covered walls), especially in the West to minimize heat gain.
	Buildings with long and narrow floor plans can help maximize cross-ventilation in humid and hot-temperate climates.
	Shaded outdoor areas (verandas, patios) oriented towards prevailing breezes can extend areas for hot or humid climates.
	Shade to prevent overheating, openings for breezes in summer, and passive solar gain in winter.
	Horizontal sunshades (designed for this latitude) or other types of solar shading devices can reduce high temperatures.
	To facilitate cross ventilation, position door and window openings on opposite sides, with larger openings facing upward to capture the wind, if possible.
	If the ground is damp, elevate the building above the ground to minimize moisture and maximize natural ventilation underneath the building.

Table 2.
Details of Strategies for Housing and Urban Environment in the Climates of the Triple Frontier (Source: Authors).

of the computational simulation using Climate Consultant 6.0, are detailed in **Tables 1** and **2**, referring to those that work best for housing and the urban environment, respectively.

3.2 Field research and photographic survey

Through the research, it was possible to better understand how the riverside populations of the Trinational Region of the Iguacu construct their homes in a context of limited economic resources, a topic still underexplored. The constructions are based on local knowledge and self-construction. Since the prevailing climate is the humid subtropical mesothermal in the Köppen classification, the thermal discomfort faced by this population in the bordering countries is considerably high, due to the large water content in the region, which, combined with high temperatures, generates a sensation of heat above acceptable values as recorded by official meteorological stations.

It was observed that the solutions adopted by residents of the riverside areas under study use local materials, low-cost, and environmentally friendly to build their homes, seeking to adapt as much as possible to the local climatic reality with what is available in the surrounding environment.

3.2.1 Materials and construction techniques used

In the riverside populations under study, it is observed that the main materials and technologies used are available locally or nearby, are low-cost, and have little environmental impact, such as reclaimed wood from other constructions for closures, windows, and roof structure; stone available in the region itself, mainly used for foundations or the first row of construction; earthen floor; use of ceramic shards in floors and some affordable industrialized materials, such as fiber cement and metal tiles for roofing; ceramic bricks for closures; and cement mortar for bricklaying, and in few cases, for wall coating. However, despite the efforts and local knowledge, most buildings lack materials more resistant to weather and abrupt climatic variations.

In both Puerto Iguazú and Ciudad del Este, as well as in Foz do Iguaçu, it is possible to notice, as shown in **Figure 6**, the extensive use of wood, both for closures and for the roof and the house structure itself. In many situations, the wood used is reclaimed and not repainted.

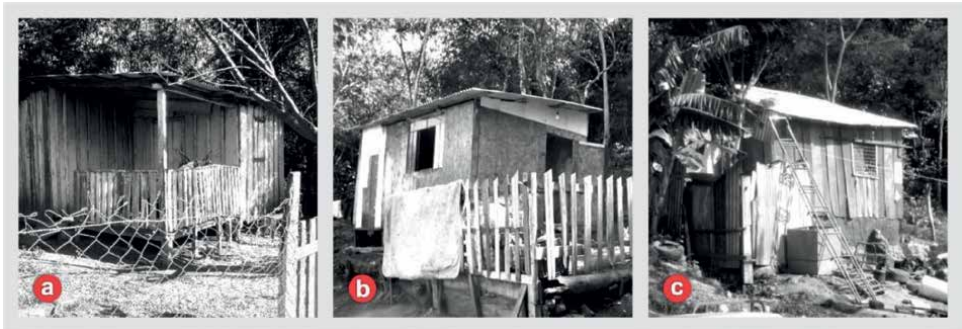


Figure 6.
Use of wood. a. Puerto Iguazú; b. Foz do Iguaçu; c. Ciudad del Este (Source: Authors).

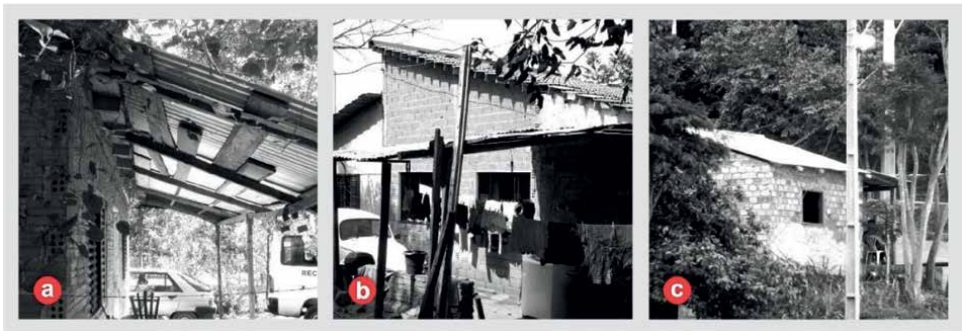


Figure 7.
Use of masonry. a. Puerto Iguazú; b. Foz do Iguaçu; c. Ciudad del Este (Source: Authors).

Regarding the houses with masonry walls, in **Figure 7**, there is a predominance of industrially manufactured ceramic bricks with 6 holes, which most of the time are left exposed, without cement mortar or paint coatings.

Local materials, such as stone, are widely used, mainly for building walls and protecting wooden structures from ground moisture and surface runoff from rain. In addition to reusing wood for closures and roof structures, broken ceramic pieces are also reused to cover both external and internal floors of buildings, promoting the use of material that would otherwise be disposed of in landfills or open dumps. Similarly, other discarded industrialized materials are incorporated into the built environment, such as tires, which are used for fencing due to their abundance, flexibility in adapting to ground settlement, and resistance to alternating periods of heavy rainfall (resulting in flooding) and drought (**Figure 8**).

3.2.2 Strategies for adapting to the local climate

To adapt housing to the local climate, several construction factors influence: the surrounding tree cover, the solar orientation of the building, the location and number of openings, the type of closure used on walls and roofs, and solar protection elements for shading, such as balconies, awnings, eaves, and canopies, among others. Even in a context of limited resources, it is noticeable that, drawing on popular knowledge, residents use creativity to solve the problems of excessive heating and cooling of the building with locally available materials, many of which are reused. Among the main elements used to adapt to the climate of the riverine population of the Trinational Region of the Iguaçu, the following were identified:

- Eaves, for rain protection and shading;
- Windows with external leaves;
- Use of large verandas for rain protection and shading;
- Utilization of local tree cover for rain protection and shading; and finally;
- Elevation of wood from the ground to protect against soil humidity.

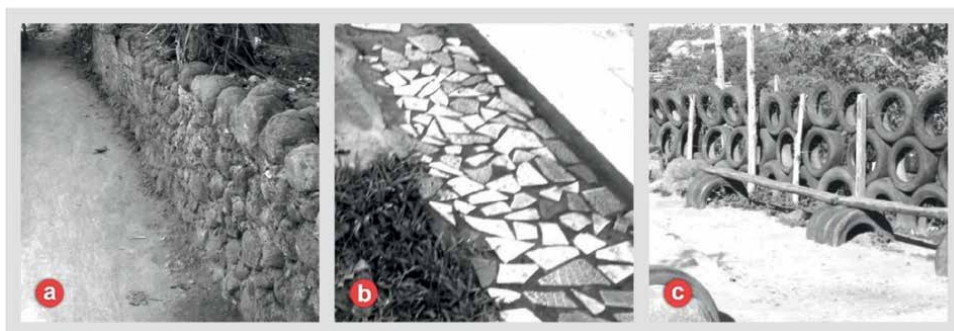


Figure 8.
Use of masonry. a. Use of stone; b. Ceramic fragments; c. Tires (Source: Authors).



Figure 9.
Building elevated from the ground, use of eaves, and vegetation. a and b. Foz do Iguaçu; c. Ciudad del Este
(Source: Authors).

Through the research, it was found that the riverine dwellings surveyed in Foz do Iguaçu, Puerto Iguazú, and to a lesser extent in Ciudad del Este are built in wooded areas, as shown in **Figure 9**. This strategy is interesting because it mitigates direct solar radiation on buildings during hot days, in addition to the fact that vegetation itself is responsible for absorbing much of the solar radiation. At night, when the temperature declines, the tree canopies hold the heat close to the ground, allowing the temperature inside the building to remain cooler. Vegetation also plays a fundamental role in reducing the impact of direct rain on the building, as well as slowing down the time and kinetic energy of the rain when it reaches the ground surface. In some areas of Foz do Iguaçu and Puerto Iguazú, the concentration of vegetation is much more significant, as is the case in areas where most of the poorer dwellings are concentrated.

The relative humidity of the soil and air is high in the Trinational region due to the large number of bodies of water, such as the immense lake created by the Itaipu Dam, the Paraná and Iguaçu rivers. The seasonal fluctuation in water levels is also a concern in the construction of riverine dwellings, as in many situations, buildings constructed with wood are raised from the ground to reduce problems caused by flooding and soil moisture. Another resource used for protection against moisture is the use of stones at the base of the building to prevent direct contact of the wood with the flooded soil.

The abundant use of eaves and verandas is also noted, which help protect the building from direct rain, as well as from direct solar radiation and excessive luminosity. Additionally, the veranda plays an important role in creating a microclimate between the interior and exterior, allowing the external air to be cooled by the shade before entering the building's interior.

Another striking feature of the riverside dwellings under study is the outdoor stoves installed on the exterior side of the houses to prevent an increase in temperature inside the building and minimize the risk of fire. These stoves have a masonry base and are covered by a simple wooden structure topped with fragile fiber cement tiles, positioned only to provide protection from light rain and the sun. Similar structures and arrangements are found in the riverside communities of Foz do Iguaçu and Ciudad del Este.

3.3 Schematic synthesis

3.3.1 Photographic analysis

Below is a representation of a riverside building from each city under study, providing a textual description of the main construction characteristics and adaptation strategies to the observed climate.

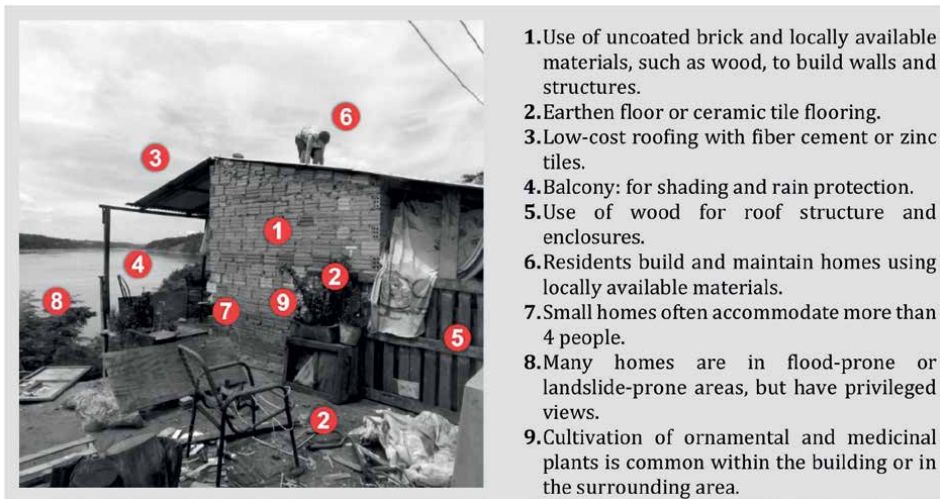


Figure 10.
Example of Construction and Adaptation Strategies to Local Climate, Ciudad del Este, Paraguay (Source: Authors).

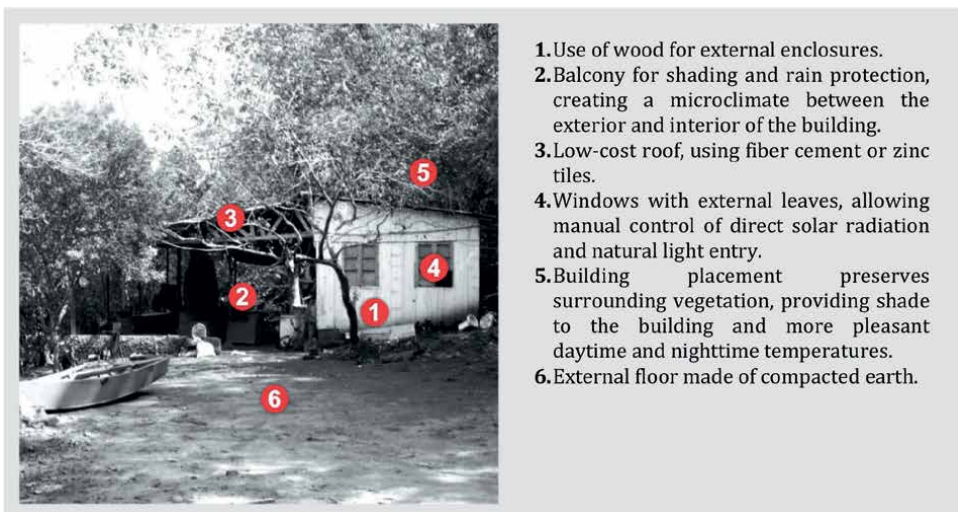


Figure 11.
Example of constructive strategies and adaptation to the local climate, Foz do Iguaçu, Brazil (Source: Authors).

Figure 10 depicts a representative building from Ciudad del Este, **Figure 11** from Foz do Iguacu, and **Figure 12** from Puerto Iguazú.

3.3.2 Graphic analysis

Finally, as the final stage of the research, a graphic scheme of the predominant characteristics of the riverside buildings located in the triple-border region was developed, represented through a technical drawing containing a simplified floor plan and facades (**Figure 13**).

The graphic scheme provided an objective reading of the architectural solutions adopted by the residents, highlighting essential elements for adaptation to the local climate. Among the main strategies identified, extensive eaves and generous verandas were observed, providing shading and aiding in the cooling of the buildings. Additionally, the presence of numerous openings in the facades favors cross-ventilation, contributing to air renewal and maintaining thermal comfort indoors. Another

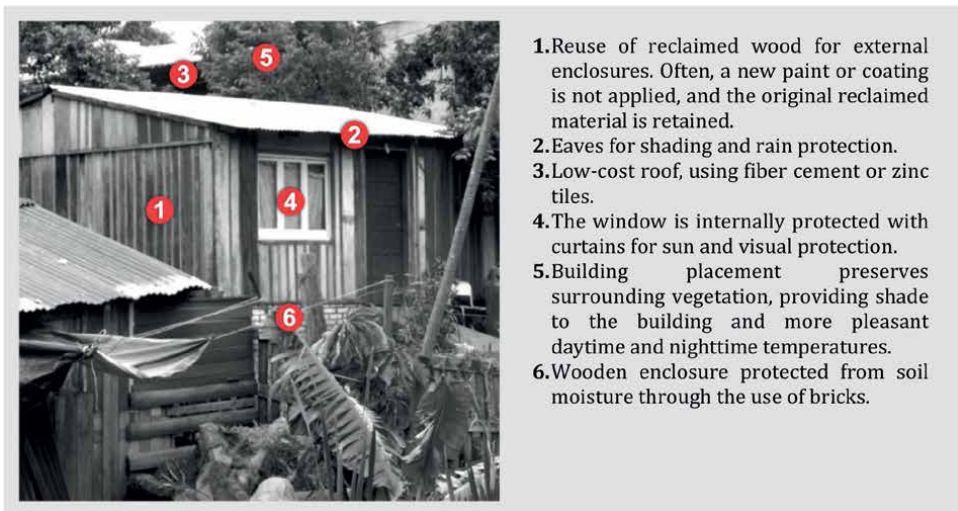


Figure 12.
Example of constructive strategies and adaptation to the local climate, Puerto Iguazú, Argentina (Source: Authors).

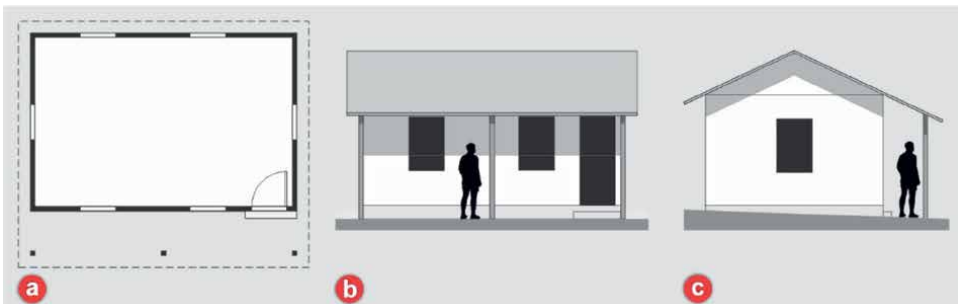


Figure 13.
Schematic plan and facades of riverside buildings. a. Ground floor plan. b. Main facade. c. Side facade. (Source: Authors).

common solution is the elevation of the buildings above the ground, a strategy aimed at minimizing the impacts of humidity, protecting against floods, and improving air circulation at the base of the structures.

4. Final remarks

The work demonstrates that a large portion of the strategies indicated for the climate of the Trinational Region of Iguaçu has been intuitively used in riverside dwellings. This ease of adaptation to the local environment resembles the characteristics of vernacular architecture, which throughout history has shown examples of adaptation to the climatic particularities of different regions of the world, as occurs in the riverside dwellings of the studied region. The analyzed dwellings exhibit common characteristics throughout the region, indicating their authenticity and identity expression. Despite there being aspects to improve, such as the need for flooring and wall covering to ensure greater durability and waterproofing, the characteristics of the dwellings fulfill the function of shelter/protection against the adverse effects of the climate. The solutions found are low-cost and do not entail significant environmental impact. For this, materials found nearby (mainly stone and wood) prevail in the dwellings.

Due to the lack of resources, many buildings are low-rise and use roofing materials that increase internal temperature. Many of the industrialized materials used in buildings, such as asbestos-cement tiles, have inadequate resistance to sudden temperature variations, intense precipitation (rain and hail), and strong winds. It was also found that, in Ciudad del Este and Foz do Iguaçu, some riverside populations build their dwellings in flood-prone areas on the banks of the Paraná River, which is why awareness-raising actions are necessary within the scope of climate change adaptation plans, as well as land occupation and use occurring upstream of riverside communities. Such actions should receive special attention from the public authorities, Itaipu Binacional—whose reservoir management regime and gate control directly impact floods—and other organizations with social responsibility (e.g., Federal University of Latin American Integration).

The results of the study emphasize the need for closer relations and knowledge exchange between the academic community and the populations, recognizing the value of architecture based on spontaneous and intuitive knowledge as an important manifestation of architectural application based on local cultural, environmental, and climatic contexts. Some works with initial studies on bioclimatic strategies for housing intended for the climate of Foz do Iguaçu, based on local climatic characterization, have already been carried out in the Tri-Border Area, such as the case of the “Study of bioclimatic strategies for housing in Foz do Iguaçu” [29]. However, in addition to climate adaptation strategies proposed by regulatory standards, an approach between construction technologies and the socioeconomic reality of each locality is necessary to make them accessible and implementable. Finally, it is emphasized that the Federal, State, and Municipal governments must play an important role in regulation, in order to integrate passive building comfort techniques adequately with climatic, social, and constructional conditions to effectively contribute to housing quality.

Like the works carried out by Fathy [18], Guedes [19], and Weimer [20], the present study seeks to value popular knowledge in architecture, largely self-construction, which even if intuitively, considers local climatic aspects, thus

contributing to energy efficiency and reduction of environmental impacts. The results reinforce this adaptation to local environmental and climatic reality, using available resources, even if precarious.

5. Limitations of the study and future research directions

The study primarily focused on qualitative analyses, examining housing structures through the application of basic passive strategies. However, it is important to emphasize that the research aims to understand the various architectural solutions adopted by low-income communities to adapt their residences to local climatic conditions. This understanding includes an assessment of how the socially vulnerable population in the riparian areas of the tri-border region of Iguaçu built their homes based on traditional knowledge.

Although the study did not employ measurements to assess the thermal performance of the buildings, the investigation contributes to the accumulation of knowledge about riparian housing conditions in the tri-border area. This expands the understanding of local issues, albeit in a limited way, and paves the way for future initiatives to improve the quality of life in these communities.

Acknowledgements

Special thanks are due to Construteam - Engenharia, Lda, Madeira, Portugal, Civil Construction Companies, for the generous financial support granted, which made this study and article publication possible. Their significant contribution was fundamental to the success of this research project. We would like to express our sincere gratitude to Construteam - Engenharia, Lda for their continuous support in advancing scientific knowledge within the field of civil construction. Without their sponsorship, this publication would not have been possible.

Conflict of interest

The authors declare no conflict of interest.

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Exploring openBIM Data Formats Aligned with ISO 19650-4 in Construction

Murat Aydın

Abstract

This study explores the integration of openBIM data formats with the ISO 19650-4 standard to address the ongoing challenges of interoperability, structured data exchange, and lifecycle information management in the AECO industry. The research problem centers on the fragmented adoption of openBIM components and the limited alignment of semantic, technical, and governance mechanisms with ISO-based frameworks. To address this, a dual-method approach was employed. A systematic literature review identified core themes and alignment gaps in current implementations. Complementing this, a conceptual analysis was conducted on 12 openBIM components, such as IFC, bSDD, IDM, MVD, IDS, openCDE, and COBie, with a focus on their semantic structure, validation capacity, and role in information continuity. This dual analysis enabled a horizontal comparison (across components) and a vertical alignment (with ISO 19650-4 requirements), which were synthesized in a structured evaluation matrix. The findings reveal varying levels of maturity, with foundational standards such as IFC and bSDD demonstrating strong semantic and structural alignment, while evolving standards like IDS and openCDE offer precision and operational flexibility. Case studies from major infrastructure projects (e.g., Crossrail, HS2, and Sydney Metro) validate the practical benefits of standardized openBIM implementation in improving coordination and reducing project risk. The study concludes with a call for integrated implementation models that combine semantic clarity, information requirement formalization, and technical validation. The proposed approach contributes to a scalable and ISO-compliant openBIM framework, supporting digital transformation in construction.

Keywords: openBIM, ISO 19650-4, data interoperability, structured data exchange, building information Modeling (BIM), digital collaboration, construction

1. Introduction

The digital transformation of the architecture, engineering, construction, and operations (AECO) industry has brought unprecedented challenges and opportunities for data interoperability, lifecycle information management, and multi-stakeholder collaboration. Within this evolving landscape, openBIM has emerged as a strategic framework for ensuring platform-neutral, standardized, and transparent information

exchange across the built environment. As an initiative developed and maintained by buildingSMART International, openBIM aims to foster seamless integration between technologies, disciplines, and organizations through the use of open, vendor-independent data formats [1–3].

To harness the full potential of openBIM, it is imperative to understand how its key data formats, such as Industry Foundation Classes (IFC), Information Delivery Manual (IDM), Model View Definitions (MVD), and the buildingSMART Data Dictionary (bSDD), align with the structured data exchange protocols prescribed by international standards. Among these, ISO 19650-4 plays a central role by providing a high-level data model for the structured capture, delivery, and verification of information within BIM-enabled processes [4].

Despite growing interest in openBIM, gaps remain in how these formats are practically implemented, validated, and governed across different project contexts. Fragmented adoption, inconsistent interpretation of standards, and insufficient alignment with ISO-based data governance frameworks continue to hinder collaboration and data quality [5, 6]. Therefore, there is a pressing need to critically examine the interaction between openBIM data structures and the semantic, technical, and lifecycle requirements of ISO 19650-4.

This study addresses this need by conducting a detailed investigation into the alignment between openBIM data formats and ISO 19650-4 requirements. It proposes a dual-pronged analytical methodology combining systematic literature review with practical case analysis and presents a high-level integration framework for enhancing data coherence, interoperability, and compliance. By identifying strengths, limitations, and emerging trends in openBIM implementation, the research aims to offer actionable insights for professionals, researchers, and policymakers striving for robust and scalable digital delivery models in the AECO sector.

This paper is structured as follows. Section 2 presents a literature review, exploring prior research on openBIM data formats in alignment with ISO 19650-4. Section 3 outlines the research problem, objectives, and the systematic methodology adopted. Section 4 details the findings from both document analysis and component-level evaluations, while Section 5 synthesizes these findings through a horizontal and vertical alignment matrix. Section 6 discusses the implications of the results and validates them through large-scale industry case studies. Finally, Section 7 concludes the paper by summarizing key insights and reflecting on the future trajectory of openBIM implementation in ISO-compliant digital workflows.

2. Literature review

The progressive digitalization of the construction industry through Building Information Modeling (BIM) has significantly enhanced data interoperability and collaborative workflows. A pivotal component of effective BIM implementation is compliance with international standards, particularly ISO 19650-4, which prescribes a high-level data model and standardized protocols for information exchanges. This literature review examines recent scholarly contributions and frameworks that explore openBIM data formats in alignment with the semantic and technical imperatives outlined in ISO 19650-4 (**Figure 1**).

Early investigations by Kim et al. demonstrated the potential of openBIM technologies in generating construction schedules through automated data extraction, highlighting gains in efficiency stemming from improved interoperability [7].

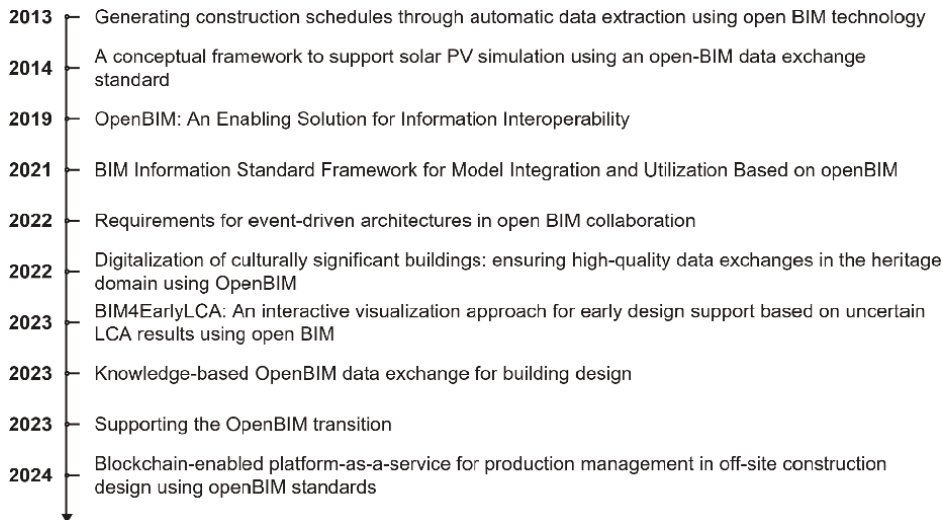


Figure 1.
Overview of selected literature on openBIM and ISO 19650-4.

Similarly, Gupta et al. developed a conceptual framework for solar photovoltaic simulations using openBIM standards, illustrating the importance of standardized data formats in advanced design applications [8]. Jiang et al. emphasized the role of openBIM in harmonizing heterogeneous datasets, reinforcing its compatibility with ISO 19650-4's collaborative data management approach [9].

Building on these foundations, Jo and Choi proposed an openBIM-based information standard aimed at fostering model integration and structured data utilization [10]. Oostwegel et al. expanded the scope by demonstrating the applicability of openBIM in heritage construction, focusing on maintaining data quality and integrity within compliance frameworks [11]. Esser et al. contributed to the discourse by identifying requirements for event-driven architectures, emphasizing the importance of real-time data exchange infrastructure [12].

More recent advancements include Forth et al. (2023), who applied openBIM methodologies to improve early-stage lifecycle assessment (LCA) visualizations, and Khudhair et al. (2023), who introduced a knowledge-based data exchange system that enforces structured information flows for ISO 19650-4 alignment [13, 14]. Further contributions by McGinley et al. (2023) highlighted the strategic relevance of collaborative digital practices, while Liu et al. (2024) introduced a blockchain-enabled openBIM platform for off-site production management [15, 16]. Finally, Yousfi et al. (2024) conducted a case study integrating ISO 19650 and openBIM frameworks, underscoring the practical need for cohesive implementation models [17].

In summary, the literature reveals a clear shift toward aligning openBIM data formats with ISO 19650-4 requirements. This trend signals the increasing maturity of structured, interoperable data environments, which are essential for enhancing information integrity, project efficiency, and strategic collaboration in the built environment.

2.1 ISO 19650-4

While many studies acknowledge the strategic value of BIM in construction, fewer offer in-depth analysis of openBIM data formats or their capacity to enable real-time

data exchange across stakeholders [6, 10, 11, 14, 18–20]. openBIM standards aim to remedy this gap by promoting consistent terminology and predictable data behaviors across project roles, including engineers, designers, contractors, facility managers, and surveyors. The evolution of openBIM formats represents a strategic move toward enhanced software interoperability and lifecycle-centric data management.

Figure 2 presents the six-part ISO 19650 series [4, 21–25]. Of these, ISO 19650-4 specifically outlines procedures for initiating, managing, and verifying information exchanges to ensure the generation of high-quality project and asset information models. As a companion to ISO 19650-1's principles, Part 4 offers guidance adaptable to various asset scales, from individual buildings to complex infrastructure networks, spanning both delivery (ISO 19650-2) and operational (ISO 19650-3) stages.

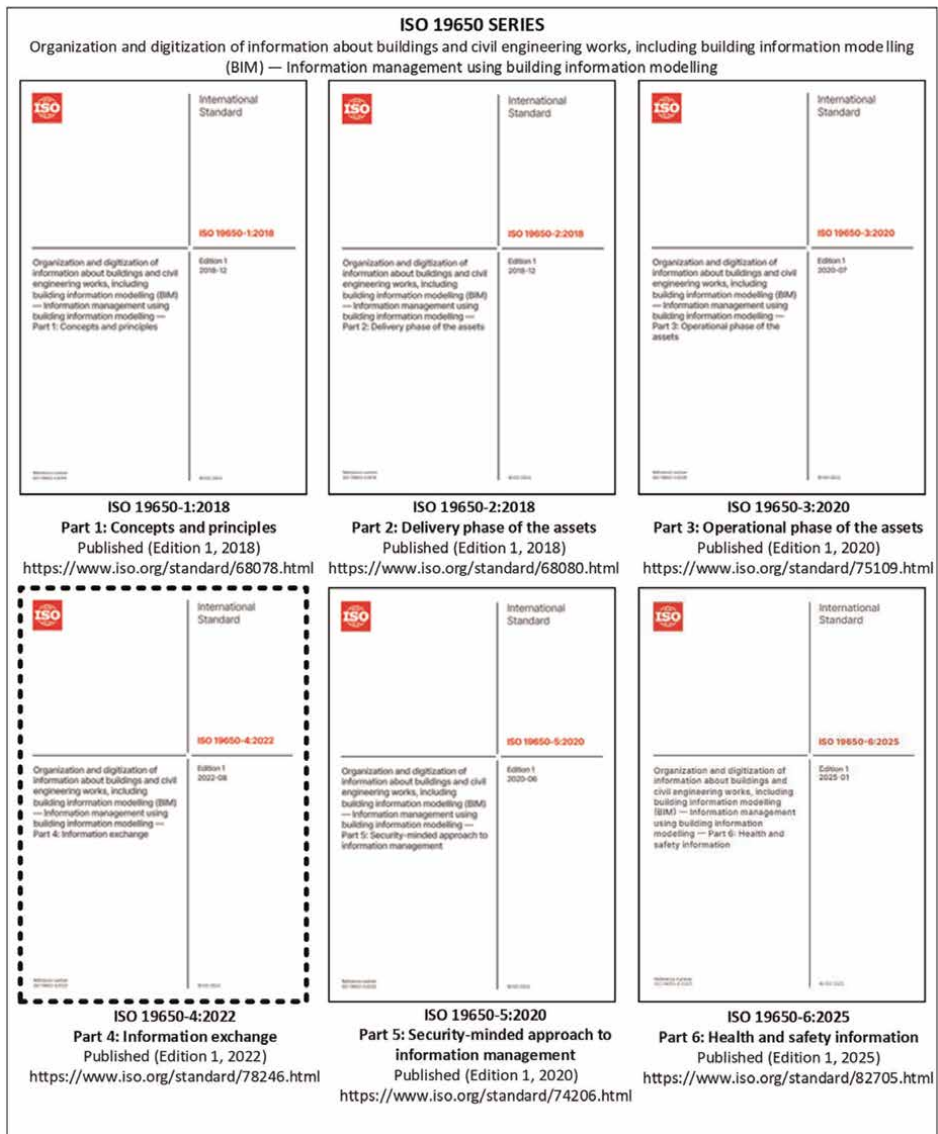


Figure 2.
ISO 19650 series.



Figure 3.
buildingSMART International (bSI) logo [26].



Figure 4.
openBIM logo [28].

2.2 openBIM

buildingSMART International (bSI), shown in **Figure 3**, has played a pivotal role in formalizing openBIM as a vendor-neutral, interoperable solution for the built environment. Since its origins as the Industry Alliance for Interoperability in the 1990s, bSI has advocated for open standards that promote sustainable and inclusive data practices [26, 27]. openBIM enables the creation, management, and exchange of digital building data throughout the project lifecycle in accessible, documented, and platform-agnostic formats.

By prioritizing transparency and long-term accessibility, openBIM establishes a robust foundation for asset-oriented data ecosystems. **Figure 4** illustrates the openBIM logo, symbolizing its commitment to collaborative workflows, risk mitigation, and lifecycle efficiency [10, 14, 29]. openBIM's interoperability breaks vendor lock-in and enables each participant to leverage the most suitable tools without compromising data continuity. Through such alignment, it facilitates integrated workflows, reduces fragmentation, and expands the reach of BIM across disciplines, disciplines, and phases of delivery [11].

3. Method

- *Research Problem*

While the adoption of BIM and openBIM is accelerating across the construction industry, aligning their data formats with the structured exchange principles defined in ISO 19650-4 remains a critical challenge. Fragmented data workflows, non-standardized formats, and interoperability barriers frequently hinder collaboration, data reuse, and information reliability across stakeholders and project phases.

- *Research Aim*

This study aims to assess how openBIM data formats can be effectively integrated within the ISO 19650-4 framework to foster standardized, secure, and

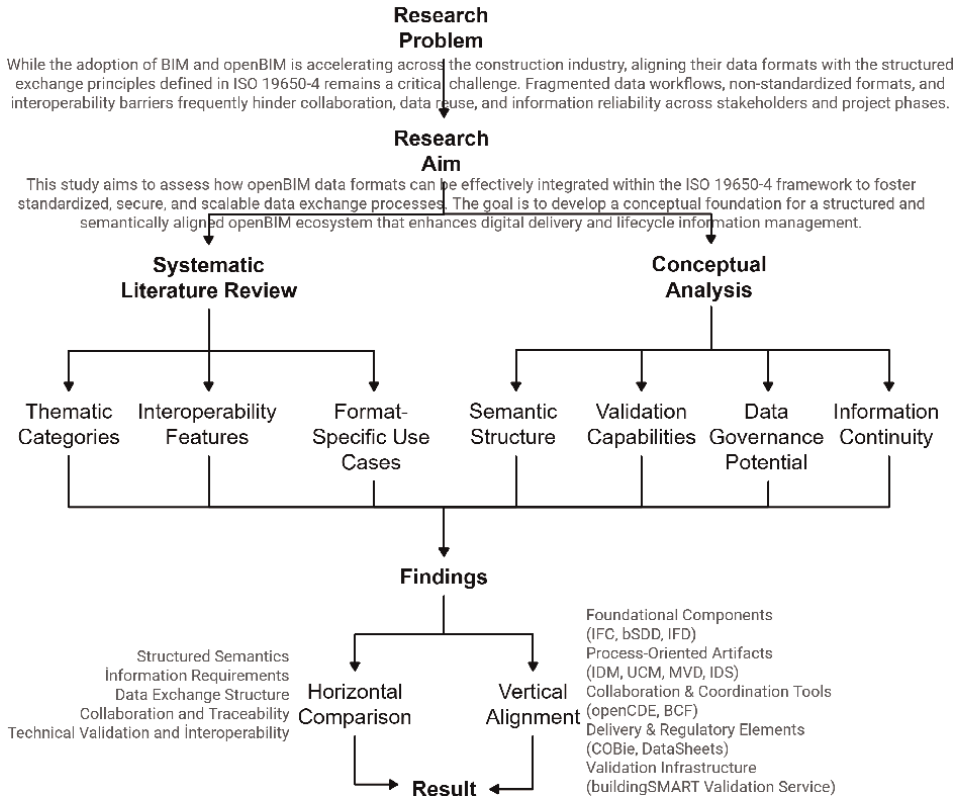


Figure 5.
Method.

scalable data exchange processes. The goal is to develop a conceptual foundation for a structured and semantically aligned openBIM ecosystem that enhances digital delivery and lifecycle information management.

• **Research method**

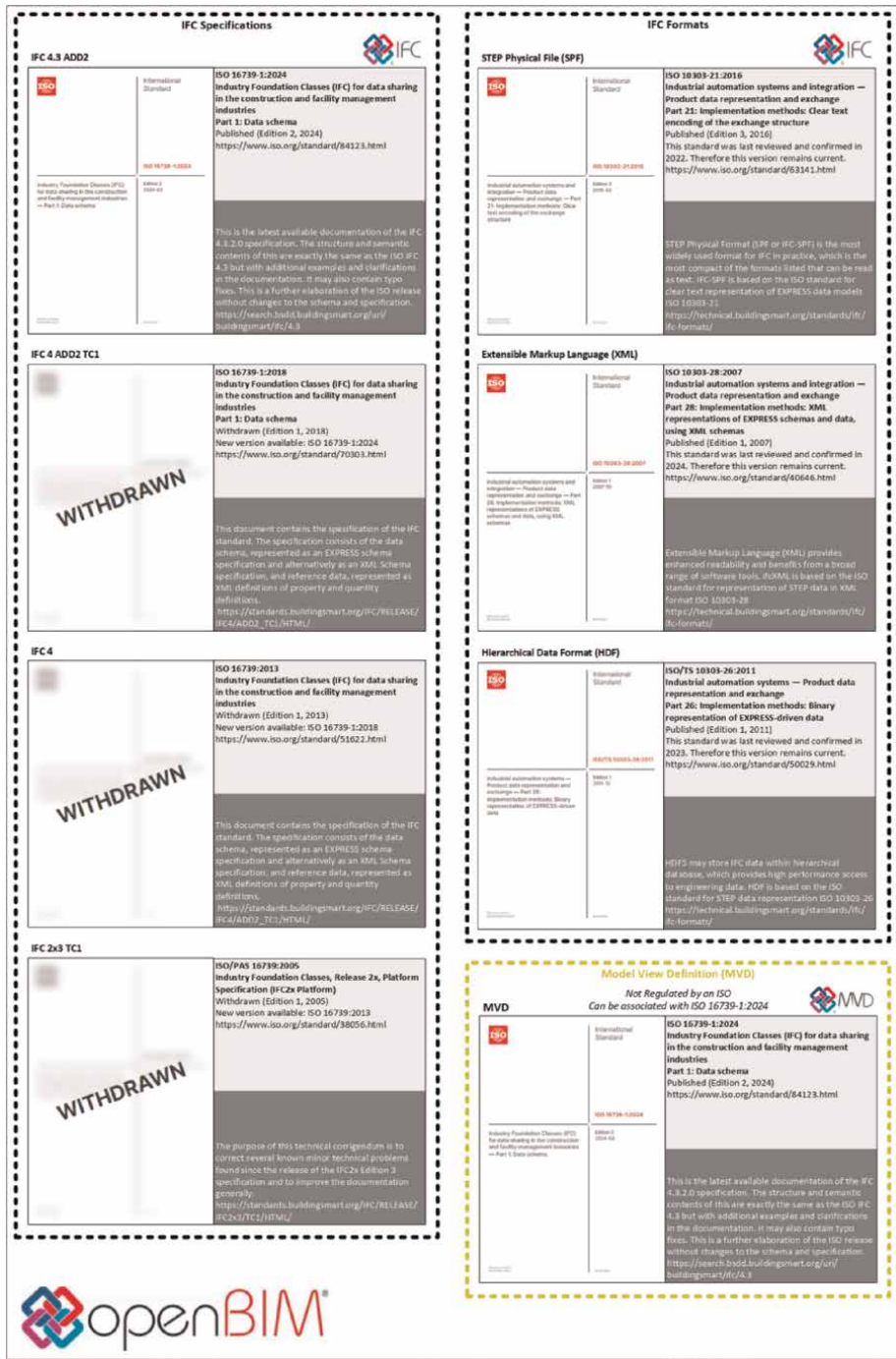
To achieve this aim, as illustrated in **Figure 5**, a systematic literature review was conducted, focusing on peer-reviewed academic sources, industry guidelines, and case-based implementations of openBIM and ISO 19650-4. The review process included defining thematic categories, extracting interoperability features, and classifying format-specific use cases based on their alignment with ISO principles [30, 31].

In parallel, an in-depth conceptual analysis was performed on a curated set of openBIM formats and services, namely IFC, bSDD, MVD, IDM, IDS, BCF, COBie, IFD, openCDE, UCM, and validation mechanisms. These were examined for their semantic structure, validation capabilities, data governance potential, and role in information continuity across project phases.

This dual-pronged methodology enabled both horizontal comparison (across different openBIM components) and vertical alignment (with ISO 19650-4’s hierarchical exchange requirements), laying the groundwork for an integrated data exchange framework tailored to AECO workflows.

4. Findings

This study presents an integrated analysis combining a systematic literature review and conceptual evaluation of openBIM data formats, services, and methodologies in alignment with ISO standards. As illustrated in **Figure 6**, these data formats are



Information Delivery Manual (IDM)



IDM

	International Standard	ISO 29481-1:2016 Building information models — Information delivery manual Part 1: Methodology and format Published (Edition 2, 2016) This standard was last reviewed and confirmed in 2021. Therefore this version remains current. https://www.iso.org/standard/60553.html
	ISO 29481-1:2016	Building information models — Information delivery manual — Part 1: Methodology and format Annex 1 2016-05

ISO 29481-1:2016 is intended to facilitate interoperability between software applications used during all stages of the life cycle of construction works, including briefing, design, documentation, construction, operation and maintenance, and demolition. It promotes digital collaboration between actors in the construction process and provides a basis for accurate, reliable, repeatable and high-quality information exchange.
<https://www.iso.org/standard/60553.html>

buildingSMART Data Dictionary (bSDD)



bSDD & IFD

	International Standard	ISO 12006-3:2022 Building construction — Organization of information about construction works Part 3: Framework for object-oriented information Published (Edition 2, 2022) https://www.iso.org/standard/74932.html
	ISO 12006-3:2022	Building construction — Organization of information about construction works — Part 3: Framework for object-oriented information Annex 1 2022-07

This document specifies a language-independent information model which can be used for the development of dictionaries used to store or provide information about construction works. The model is extended by instantiating content, such as further objects and their relationships, allowing the content to serve as an ontology, taxonomy, nomenclature, lexicon and thesaurus.
<https://www.iso.org/standard/74932.html>

Use Case Management (UCM)



UCM

	International Standard	ISO 29481-1:2016 Building information models — Information delivery manual Part 1: Methodology and format Published (Edition 2, 2016) This standard was last reviewed and confirmed in 2021. Therefore this version remains current. https://www.iso.org/standard/60553.html
	ISO 29481-1:2016	Building information models — Information delivery manual — Part 1: Methodology and format Annex 2 2016-05

ISO 29481-1:2016 is intended to facilitate interoperability between software applications used during all stages of the life cycle of construction works, including briefing, design, documentation, construction, operation and maintenance, and demolition. It promotes digital collaboration between actors in the construction process and provides a basis for accurate, reliable, repeatable and high-quality information exchange.
<https://www.iso.org/standard/60553.html>

Construction to Operations Building Information Exchange (COBie)



COBie

	International Standard	ISO 15686-4:2014 Building Construction — Service Life Planning Part 4: Service Life Planning using Building Information Modelling Published (Edition 1, 2014) This standard was last reviewed and confirmed in 2015. Therefore this version remains current. https://www.iso.org/standard/59150.html
	ISO 15686-4:2014	Building Construction — Service Life Planning — Part 4: Service Life Planning using Building Information Modelling Annex 1 2014-06

ISO 15686-4:2014 provides information and guidance on the use of standards for information exchange for service life planning of buildings and constructed assets and their components as well as the required supporting data.
<https://www.iso.org/standard/59150.html>

Open Common Data Environment (openCDE)



openCDE

	International Standard	ISO 12006-3:2022 Building construction — Organization of information about construction works Part 3: Framework for object-oriented information Published (Edition 2, 2022) https://www.iso.org/standard/74932.html
	ISO 12006-3:2022	Building construction — Organization of information about construction works — Part 3: Framework for object-oriented information Annex 1 2022-07

This document specifies a language-independent information model which can be used for the development of dictionaries used to store or provide information about construction works. The model is extended by instantiating content, such as further objects and their relationships, allowing the content to serve as an ontology, taxonomy, nomenclature, lexicon and thesaurus.
<https://www.iso.org/standard/74932.html>



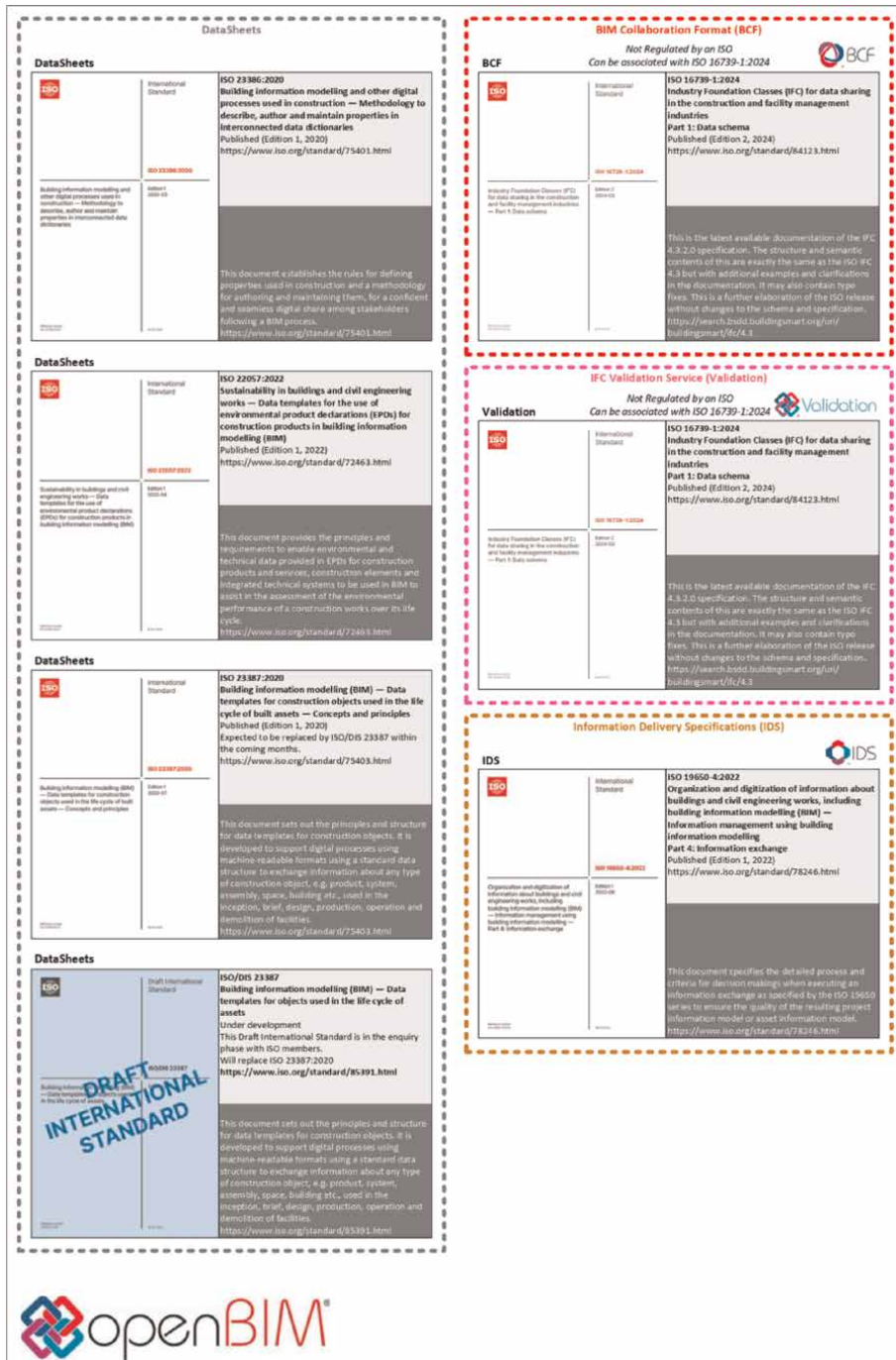


Figure 6.
openBIM data formats as defined by ISO standards.

 Home Standards Services Resources						
Format	Extension	MIME Type	Text	Indexed	Size	Summary
Official						
STEP Physical File (SPF)	.ifc	application/x-step	Yes	No	100%	STEP Physical Format (SPF or IFC-SPF) is the most widely used format for IFC in practice, which is the most compact of the formats listed that can be read as text. IFC-SPF is based on the ISO standard for clear text representation of EXPRESS data models ISO 10303-21
Extensible Markup Language (XML)	.ifcXML	application/xml	Yes	No	113%	Extensible Markup Language (XML) provides enhanced readability and benefits from a broad range of software tools. ifcXML is based on the ISO standard for representation of STEP data in XML format ISO 10303-28
ZIP	.ifcZIP	application/zip	No	No	17%	IFC data may be embedded within a ZIP file. The embedded data may be encoded as either SPF or XML, where the resulting size is typically comparable.
Terse RDF Triple Language (Turtle)	.ttl based on ifcOWL	text/turtle	Yes	No	1372%	More info on: ifcOWL
Resource Description Framework (RDF/XML)	.rdf based on ifcOWL	application/rdf+xml	Yes	No	816%	More info on: ifcOWL
Provisional/Candidate						
JavaScript Object Notation (JSON)	.json	application/json	Yes	No	148%	JSON provides enhanced readability and benefits from a broad range of software tools.
Hierarchical Data Format (HDF)	.hdf	application/x-hdf	No	Yes	n/a	HDF5 may store IFC data within hierarchical database, which provides high performance access to engineering data. HDF is based on the ISO standard for STEP data representation ISO 10303-26
Experimental/Unsupported						
SQLite	.sqlite	application/x-sqlite3	No	Yes	n/a	SQLite may store IFC data within a relational database, which provides indexed access to data within large models and benefits from a broad range of software tools.

Figure 7.
IFC formats of buildingSMART [43].

mapped to their respective ISO references to better understand their roles in enhancing data semantics, interoperability, and management practices within the AECO industry. The following subsections examine each format’s structural components, standardization status, and contribution to standardized data exchange.

- *Industry Foundation Classes (IFC)*

IFC (Industry Foundation Classes) is an open, vendor-neutral data format for representing building information based on the STEP Physical File (SPF) format [32], with additional XML-based alternatives [33, 34]. Since 1995, buildingSMART International has developed IFC as a cornerstone of the openBIM framework, formally recognized in 2013 as an ISO standard with continued updates under ISO 16739-1 [35–42].

Figure 7 depicts common IFC formats used across platforms, while **Figure 8** presents the IFC Specifications Database curated by buildingSMART. The current version, IFC4, supports comprehensive modeling across all primary construction domains, and the anticipated IFC5 release expands coverage to infrastructure assets such as roads, bridges, railways, and tunnels [43].

An IFC file consists of hierarchical object classes with attributes describing semantic and geometric characteristics. As shown in **Figure 9**, its structure comprises three primary levels:

- *General level* (e.g., IfcProject, IfcSite, IfcBuilding, IfcBuildingStorey)
- *Spatial level* (e.g., IfcSpace, representing rooms or zones)
- *Element level* (e.g., IfcRelContainedInSpatialStructure, detailing walls, columns, windows, etc.)

Each element includes a globally unique identifier (GUID), facilitating traceability and consistent referencing. This structured content supports lifecycle-based data delivery, enhancing project coordination and long-term asset management.

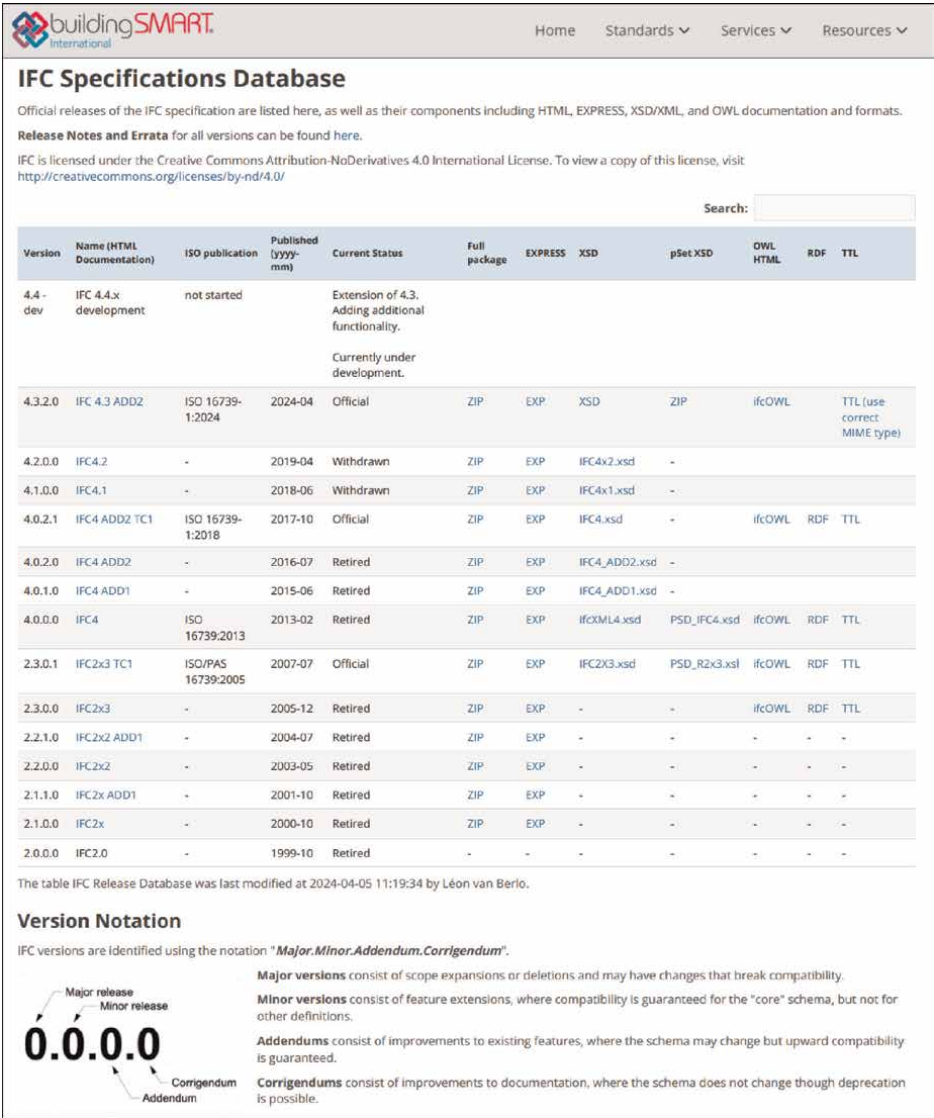


Figure 8.
IFC specification database of buildingSMART [44].

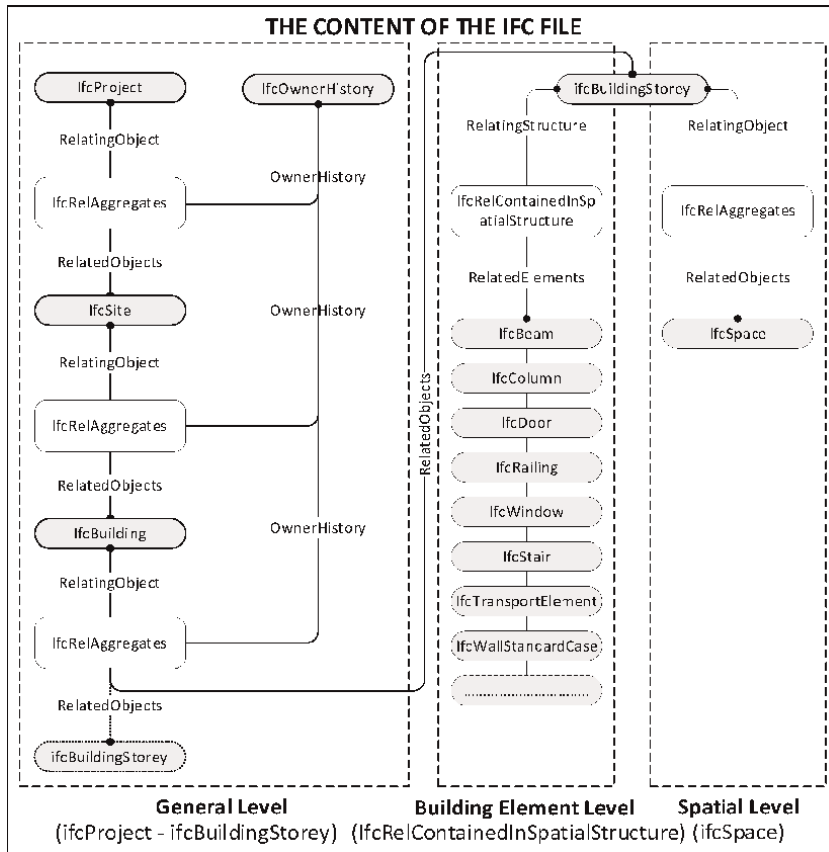


Figure 9.
The structure of the content of the IFC file into three levels.

- *buildingSMART Data Dictionary (bSDD)*

The buildingSMART Data Dictionary (bSDD) is a centralized, web-based platform for developing and managing data dictionaries [45]. It enables semantic modeling by defining terms, their relationships, and structured sets of attributes and values. It supports the creation of classification systems, ontologies, and technical vocabularies.

Figure 10 shows a wall construction schema published via bSDD, illustrating how IFC class definitions, property sets, and hierarchical relations are organized [46]. By serving as a common semantic reference point, bSDD promotes multilingual interoperability and consistent data interpretation across domains and software platforms.

While bSDD itself is not a formal standard, it is maintained by buildingSMART and rooted in ISO 12006-3 (IFD), aligning it with broader semantic integration strategies in the construction sector [47].

- *Information Delivery Manual (IDM)*

The Information Delivery Manual (IDM) defines standardized information requirements and business processes associated with various lifecycle phases [48].

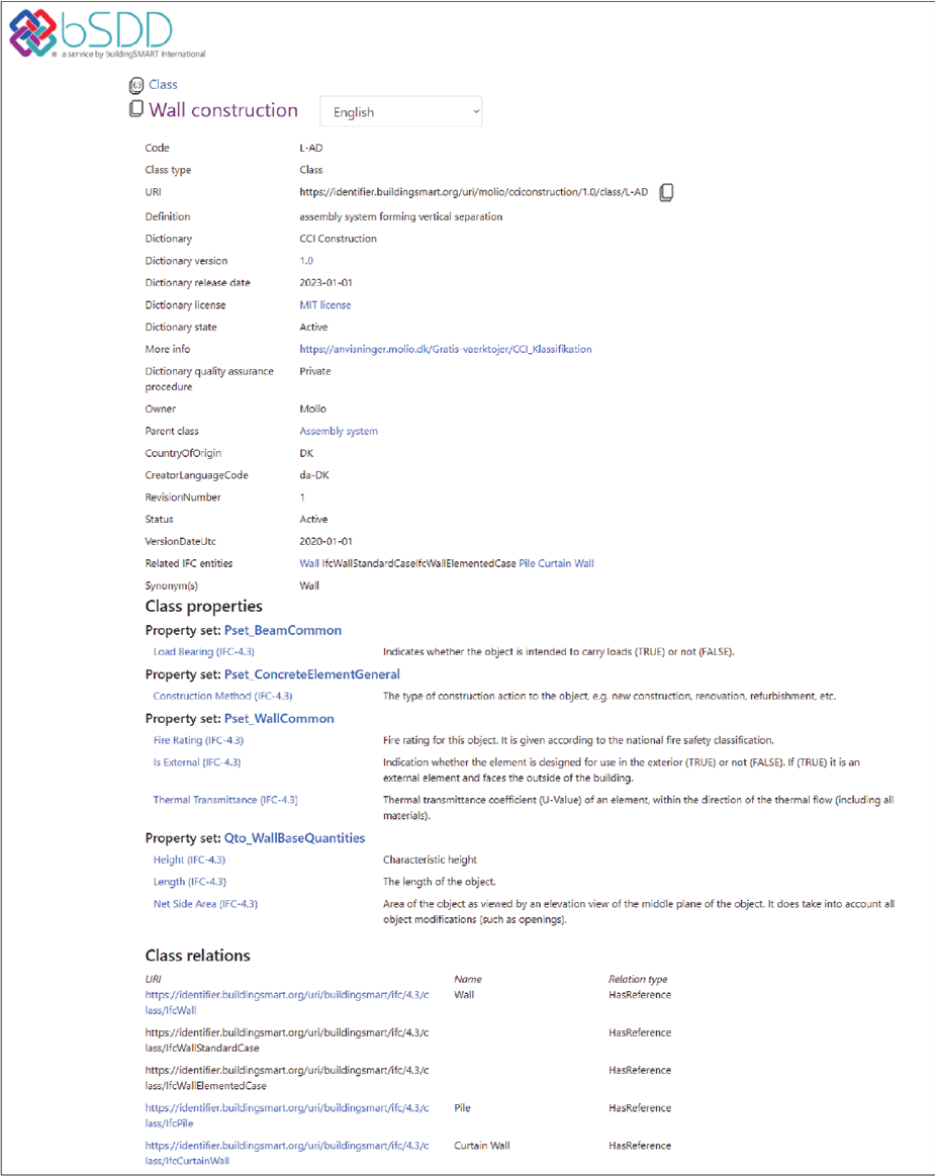


Figure 10.
IFC class definitions of wall construction in the bSDD [46].

Developed by buildingSMART and codified in ISO 29481-1 and ISO 29481-2, IDM supports clear communication across disciplines and facilitates structured data exchanges [49, 50].

IDMs are typically modeled using BPMN (Business Process Model and Notation) and involve three key components:

- *Interaction maps* (defining stakeholders and transaction flows)
- *Process diagrams* (detailing activity sequences)

- *Exchange Information Requirements (EIRs)* (specifying what, when, and how information should be exchanged)

As visualized in **Figure 11**, IDM zones span both user needs and technical solutions. IDM outputs serve as a foundation for defining Model View Definitions (MVDs) and Information Delivery Specifications (IDSs), often in conjunction with bsDD.

Figure 12 summarizes the core elements of IDM: identifying use cases, structuring process logic, and translating information requirements into standardized, technology-neutral documentation. This ensures semantic clarity and machine readability, promoting consistent BIM workflows across the asset lifecycle.

- *Use Case Management (UCM)*

The Use Case Management (UCM) platform, developed by buildingSMART, provides open access to a library of use cases, process maps, and information requirements formulated using the IDM methodology [51]. These use cases represent validated domain-specific practices that can be adopted, adapted, or extended by practitioners to suit their project contexts [49].

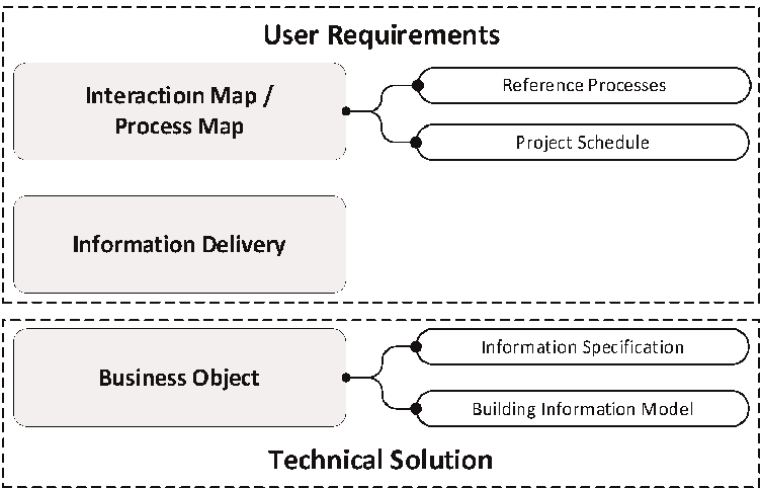


Figure 11.
IDM zones from the perspective of user requirements and technical solution.

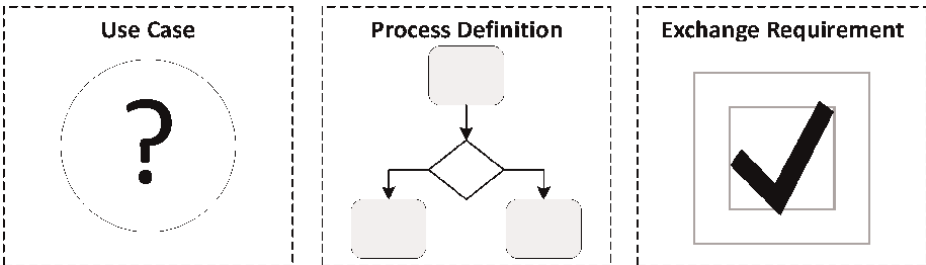


Figure 12.
Three key elements of IDM.

Each UCM entry typically includes a general description, a process map, a process definition, and a corresponding set of information requirements. This structured documentation promotes consistency in the development and communication of use cases, irrespective of the project phase. The defined requirements serve as the foundation for technical implementations in BIM environments and can be translated into Model View Definitions (MVDs) or Information Delivery Specifications (IDSs), depending on the level of detail and formality required.

- *Open Common Data Environment (openCDE)*

Open Common Data Environment (openCDE) is an initiative spearheaded by buildingSMART to enhance data interoperability and stakeholder collaboration through an open integration framework [52]. It provides a vendor-neutral architecture to connect various software applications and streamline data flows within construction projects.

Figure 13 illustrates companies actively supporting and implementing openCDE. Notably, Oracle has demonstrated openCDE’s potential by enabling integration between Solibri and ArchiCAD. Participating members help shape its evolution to meet diverse industry demands. As Liu et al. (2024) suggest, the implementation of openCDE fosters a more transparent, efficient, and collaborative project ecosystem [16].

The framework simplifies platform interconnectivity by removing friction between tools, thereby accelerating design coordination and reducing risk. With seamless integrations, stakeholders can exchange information in real time using standardized protocols. openCDE’s commitment to openness and compliance with industry standards plays a pivotal role in dismantling data silos, increasing user autonomy, and enabling lifecycle-centric workflows [53]. It transforms not only the mechanisms of data sharing but also the culture of cross-party collaboration in the built environment.

- *Construction to Operations Building Information Exchange (COBie)*

The Construction to Operations Building Information Exchange (COBie) is a standardized non-graphic data format that enables digital handover of facility asset information from construction to operations [53–55]. It targets the reduction of time and information loss during the transition from construction to facilities management.



Figure 13.
Companies supporting openCDE.

COBie includes maintainable assets such as HVAC equipment, plumbing fixtures, lighting, and other critical components requiring scheduled servicing [56–58]. Initially launched by the U.S. Army Corps of Engineers in 2007, COBie has since been supported by NASA and the White House Office of Science and Technology. Since 2013, the National Institute of Building Sciences (NIBS) has maintained the COBie standard under a Creative Commons license [59].

Version 2.4 was incorporated into the U.S. National BIM Standard (NBIMS-US) v3 in 2015, and Version 3 is anticipated to be included in NBIMS-US v4 [60]. The success of COBie implementation relies on collective contributions by architects, engineers, contractors, suppliers, tradespeople, commissioning agents, and facility owners. Each party contributes data at predetermined milestones, ensuring completeness at project closeout.

Structurally, COBie is a Model View Definition (MVD) derived from the IFC schema and is delivered in a spreadsheet format composed of interconnected tables. As shown in **Table 1**, the COBie database is organized hierarchically, representing spatial zones, systems, components, and associated information. This structured approach improves information reuse, supports lifecycle operations, and streamlines the transition to facility management.

• *International Framework for Dictionaries (IFD)*

The International Framework for Dictionaries (IFD) is a globally recognized methodology that plays a pivotal role in standardizing information exchange and mitigating language barriers within BIM environments [47]. By offering a comprehensive multilingual object dictionary, IFD facilitates the consolidation of construction and asset data from heterogeneous sources, ensuring semantic clarity across diverse platforms and regions [61].

Employing standardized terminology, covering elements such as building types, space types, and component classifications, IFD enables streamlined e-commerce and automation workflows. Its utility extends to practical operations, including energy monitoring and carbon footprint analysis, offering substantial value to site managers and facilities professionals [62, 63]. Regardless of the source language, IFD’s structured classification system supports model maintenance and consistent data interpretation throughout the asset lifecycle.

As illustrated in **Figure 14**, buildingSMART’s ecosystem integrates IFD alongside other openBIM standards such as IFC and IDM. While IFC provides the core data structure and digital storage layer, IFD establishes the semantic foundation. IDM and MVD further support process definition and technical requirement mapping, ensuring interoperability and cross-domain collaboration in digital construction environments [27].

Overall	Spatial	Asset	Process	Support
Scope	Floor	Type	Package	Document
Company	Zone	Component	Job	Resource
	Space	System	Event	Picklists
	Coordinate	Attribute	Instruction	
			Risk	

Table 1.
The hierarchies in the structure of the tables that form the COBie database.

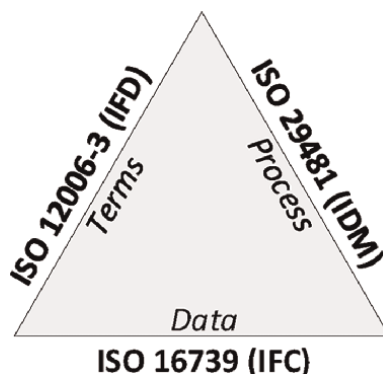


Figure 14.
 openBIM data formats: IFD, IFC, IDM [27].

- *Model View Definition (MVD)*

Model View Definitions (MVDs) translate the process-based requirements defined in Information Delivery Manuals (IDMs) into computer-interpretable technical specifications aligned with the IFC schema [64]. Each MVD defines a targeted subset of IFC classes, attributes, properties, and relationships to support specific use cases or domain workflows [65].

MVDs support varied levels of granularity—from full schema representations to highly specific object types and properties [66, 67]. As illustrated by Lee et al. (2020), each MVD can filter the full IFC schema into a tailored “view” usable by project engineers for coordination, validation, or data transfer [68]. These views can be formalized using mvdXML, a machine-readable format enabling consistent software interpretation [69].

To ensure compatibility, clients are encouraged to apply standardized MVDs referenced in key project documents such as Exchange Information Requirements (EIR) or BIM Execution Plans (BEP). Commonly used MVDs include the following:

Coordination View (CV-IFC2x3): streamlines geometry and spatial elements for multi-disciplinary coordination.

Reference View (RV-IFC4): presents simplified model elements for referencing and visualization.

- *Design Transfer View (DTV-IFC4)*: facilitates a one-directional transfer of rich geometric and attribute data across design applications.

Combined with IDM, bSDD, and IFD, the MVD provides a robust foundation for structured data exchange aligned with ISO 16739-1 [35]. **Figure 15** illustrates officially published MVDs and their corresponding schema versions (e.g., IFC2x3, IFC4), including those approved as international standards or undergoing development via the buildingSMART standards process [36, 37, 39, 41, 71, 72].

- *Information Delivery Specifications (IDS)*

The Information Delivery Specification (IDS) is a new buildingSMART standard that formalizes information requirements in a machine-interpretable XML format [4, 73, 74]. While MVDs support a wide range of technical specifications

IFC Schema	MVD Name	Status	Documentation	Summary
IFC4 ADD2 TC1	IFC4Precast	Final	Full documentation (zip)	Exchange of geometric information between CAD and MES systems for automated production of precast building components.
IFC4.2	Bridge Construction View	Draft	BRIe 2017.10.24	Build and maintain bridges.
IFC4 ADD2 TC1	Reference View	Final	RV 1.2 HTML RV_1-2.mvdxml	Simplified geometric and relational representation of spatial and physical components to reference model information for design coordination between architectural, structural, and building services (MEP) domains
IFC4 ADD2 TC1	Design Transfer View	Draft	DTY 1.1	Advanced geometric and relational representation of spatial and physical components to enable the transfer of model information from one tool to another. Not a "round-trip" transfer, but a higher fidelity one-way transfer of data and responsibility.
IFC4 ADD2 TC1	Quantity Takeoff View	Draft	mvdxML	Estimate and track construction materials and costs.
IFC4 ADD2 TC1	Energy Analysis View	Draft	EV	Estimate and track energy usage and costs.
IFC4 ADD2 TC1	Product Library View	[70]	LV 0.1	Manufacturer product information and configurations.
IFC4	LandXML view		LandXML MVD 1.2	Basic buildingSMART MVD for LandXML v1.2.
IFC2x3 TC1	Coordination View	Final	CV 2.0	Spatial and physical components for design coordination between architectural, structural, and building services (MEP) domains
IFC2x3 TC1	Space Boundary Addon View	Final	SB 1.1	Identification and export of additional Space Boundaries (polygons which define the extents of a space's contact with directly adjacent surfaces [e.g. walls, floors, ceilings] and openings). Can be used for building energy analysis and quantity take-off.
IFC2x3 TC1	Basic FM Handover View	Final	Diagrams – Documentation	Handover of model information from planning and design applications to CAFM and CMMS applications, as well as the handover of model information from construction and commissioning software to CAFM and CMMS applications
IFC2x3 TC1	Structural Analysis View	Final	SA	The structural analysis model, created in a structural design application by a structural engineer to one or many structural analysis applications.

Figure 15.
MVD database [65].

including geometry and relationships, IDS focuses specifically on *alphanumeric requirements*, such as attributes, property values, and units, that define the *Level of Information (LoI)* in a BIM model [75].

Unlike legacy approaches that relied on Excel sheets or PDF documents, IDS allows for direct integration with authoring and checking tools. For instance, an IDS file can:

- Automate the generation of required data structures in authoring environments
- Act as a ruleset for model validation tools to enforce compliance
- Close the feedback loop between specification, implementation, and validation [76, 77]

In essence, IDS offers flexible methods for specifying model expectations, including linking to external classifications, attribute conditions, and custom materials [78–80]. It operates as an XML-based container structured according to the buildingSMART-defined schema and can reference terms stored in bSDD.

As shown in **Figure 16**, an IDS articulates exchange requirements for objects, classifications, properties, values, and measurement units. It plays a vital role in validating model content for clients, authors, and software tools alike, especially in contractual contexts. By ensuring clarity, transparency, and traceability, IDS strengthens the reliability of data exchanges throughout the project lifecycle.

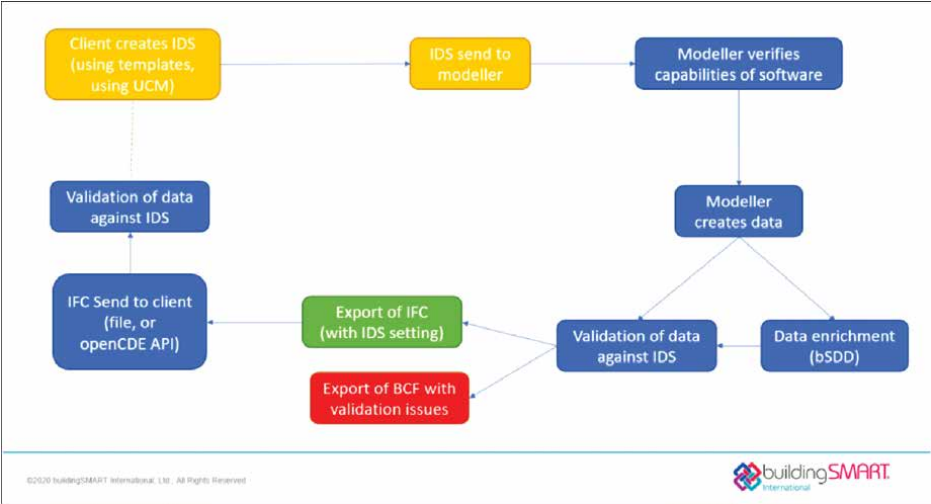


Figure 16.
Computer readable information delivery specification [74].

- *IFC Validation Service (Validation)*

IFC is integrated into all major BIM authoring tools and is subject to certification by buildingSMART International to ensure reliable interoperability and high-quality data exchange. Traditionally, this certification applies to Model View Definitions (MVDs) formally recognized by buildingSMART and is provided as a paid service for software vendors [35, 81].

The buildingSMART Validation Service represents a recent advancement, offering a publicly accessible platform for validating the technical compliance of IFC files [70]. As shown in **Figure 17**, users can upload files to test their syntactic correctness and conformance to the IFC schema. The service also evaluates consistency with

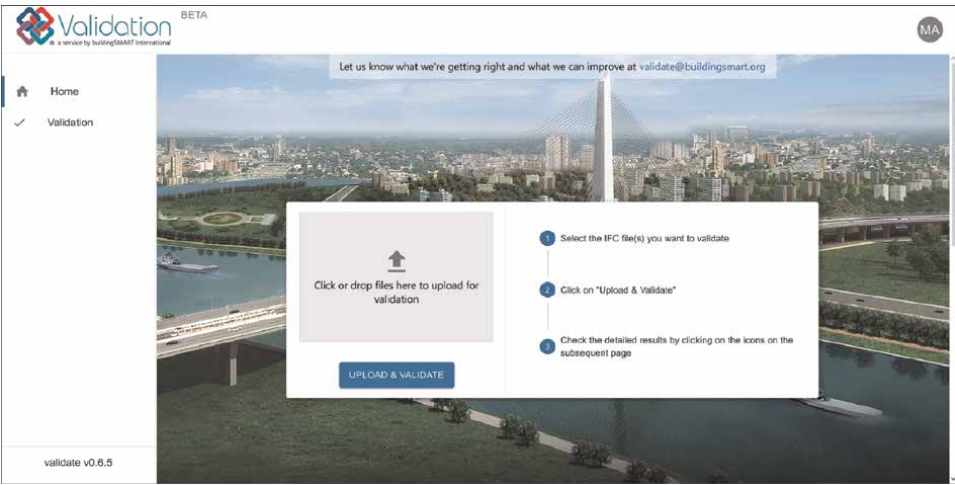


Figure 17.
IFC validation service of the buildingSMART [70].

referenced classifications from the bSDD. However, it does not validate the semantic content of IFC files or verify IDS-based information requirements.

Intended for both software developers and end users, the Validation Service enhances the technical assurance of IFC-based exchanges and supports broader interoperability across tools. While still in beta, it can be accessed by anyone with a free buildingSMART account. Future developments may further integrate this service into formal certification pathways.

- *BIM Collaboration Format (BCF)*

The BIM Collaboration Format (BCF) is an open data format designed to support structured, model-based communication among project stakeholders. Initially developed by Solibri and Tekla in 2009, BCF has since been formalized as part of the openBIM standard under buildingSMART International [35, 82].

BCF enhances interdisciplinary coordination by enabling users to exchange issue-related data, such as comments, affected elements, and viewpoints, without transmitting entire IFC models. The latest release, BCF 3.0, utilizes XML formatting to facilitate interoperability across BIM platforms [83]. As illustrated in **Figure 18**, a web service-based API allows software clients to interface with a centralized BCF server to synchronize issue data.

BCF supports detailed documentation of model issues, including location coordinates, view directions, user annotations, and timestamps [84]. By focusing on relevant context rather than whole-model exchanges, BCF significantly reduces complexity and boosts communication efficiency during clash detection, design review, and construction coordination [85]. The format is widely implemented in mainstream BIM applications.

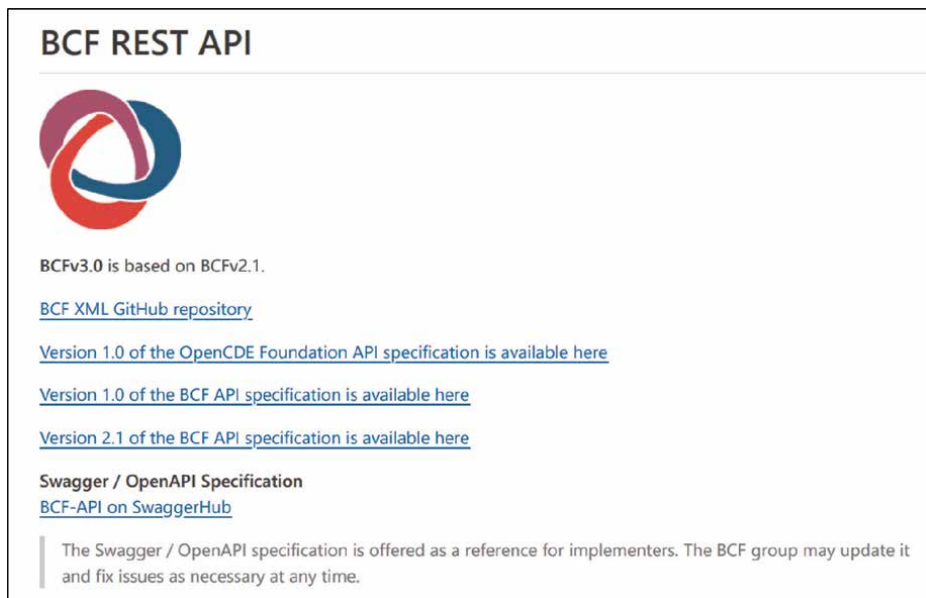


Figure 18.
BCF web service [84].

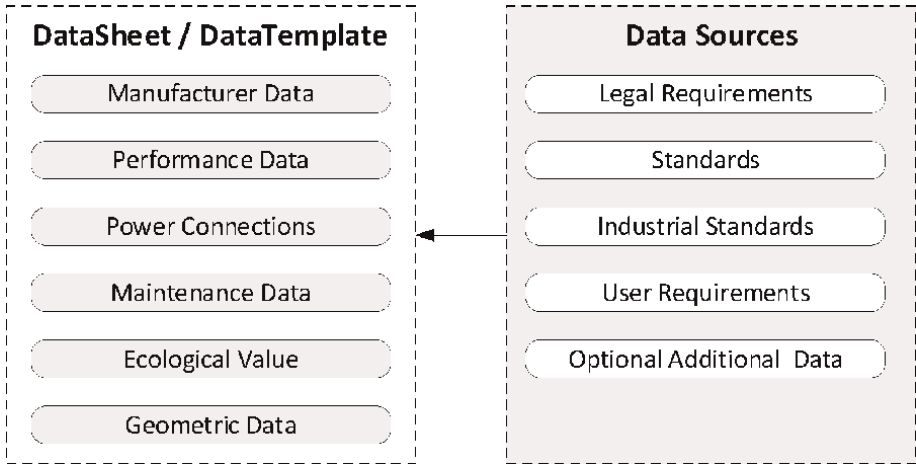


Figure 19.
Data sources in DataSheet/DataTemplate.

- *DataSheets*

DataSheets refer to standardized digital product templates that digitally encode the interplay between harmonized Construction Product Regulation (CPR) specifications and Environmental Product Declarations (EPDs), with their information modeling governed by ISO 23386 since 2020 [86]. These structured templates provide a consistent framework for describing construction product attributes, enabling more reliable integration into digital workflows.

The structure and content of DataSheets are derived from harmonized product standards, ensuring regulatory compliance and alignment with industry approval processes. Recent efforts aim to incorporate sustainability data in line with ISO 22057, further enhancing the ecological transparency of building products [87].

As shown in **Figure 19**, ISO 23387 defines how DataSheets and DataTemplates interface with digital models via characteristics stored in the bSDD. These characteristics can be exchanged using file-based methods (e.g., IFC) or through web services, ensuring compatibility across platforms [88, 89]. Though still in early stages of implementation, these templates represent a crucial step toward consistent, machine-readable product data integration in BIM environments.

5. Results

Building upon the detailed findings in Section 4, this section consolidates the results of the horizontal and vertical alignment analysis of openBIM components with ISO 19650-4 requirements. By mapping each component across semantic, structural, and interoperability dimensions, the study evaluates their collective ability to support structured and scalable data exchange in the AECO industry.

Table 2 presents a synthesis of this alignment in the form of a dual-axis matrix, capturing the extent to which each openBIM standard addresses five core pillars derived from ISO 19650-4:

openBIM component	Structured semantics (bSDD/IFD alignment)	Information requirements (IDM/IDS integration)	Data exchange structure (IFC/MVD coherence)	Collaboration and traceability (CDE/BCF support)	Validation and interoperability (compliance assurance)
IFC	(+) Hierarchical schema with semantic classes	(-) Partial (depends on MVD or IDS support)	(+) Complete model structure with lifecycle coverage	(-) Limited to file-based mechanisms	(+) Validated via buildingSMART certification
bSDD	(+) Centralized multilingual terminology database	(-) Indirect (relies on linkage through IDS/IFD)	(-) Meta-level alignment, not instance-based	(+) Supports consistent term usage across tools	(+) Enables classification validation
IDM	(+) Formal process and role definitions	(+) Captures EIRs and use-case workflows	(-) Requires MVD/IDS for implementation	(-) Not directly tool-integrated	(-) No native technical validation
MVD	(+) Filters IFC schema per use case	(+) Translates IDM into machine-readable views	(+) Enables targeted data views per project phase	(-) No dynamic collaboration features	(+) Essential for software certification
IDS	(+) Specifies object-level alphanumeric content	(+) Defines LoI explicitly in XML format	(-) Complementary to IFC, not geometric	(-) Emerging standard, tool support evolving	(+) Can enforce content rules via validation tools
openCDE	(-) Limited semantic modeling	(-) Emerging linkage with bSDD/IDS	(+) Facilitates multi-app data access	(+) Core platform for traceability and coordination	(-) Depends on vendor implementation
COBie	(+) Tabular structure aligned with IFC MVD	(-) LoI implicit in asset-level data	(+) Non-graphical IFC subset in spreadsheet form	(+) Integrates with CAFM/FM tools	(+) Endorsed by public authorities
IFD	(+) Semantic backbone for object/property mapping	(-) Provides definitions but not requirement logic	(-) Underpins schemas like bSDD	(+) Supports multilingual coordination	(-) Not a standalone validation tool
BCF	(-) Metadata-focused; lacks semantic depth	(-) Communication-centered, not data requirement	(-) No direct data model contribution	(+) Real-time issue tracking and model coordination	(+) API-based interoperability
Validation Service	(-) Technical focus only	(-) Does not assess content/LoI	(+) Tests IFC syntax and structure	(-) No collaboration tracking	(+) Supports automated technical validation
DataSheets	(+) Standardized product data definition	(+) Includes sustainability & regulatory attributes	(+) Connects via IFC & web services	(-) Early-stage adoption	(-) Integration still maturing
UCM	(+) Encapsulates validated use cases	(+) Captures process, inputs, outputs	(-) Requires linkage to MVD/IDS for exchange logic	(-) Passive repository, not an active platform	(-) Validation depends on associated tools

Table 2.
Horizontal and Vertical Alignment of openBIM Components with ISO 19650-4 Requirements.

- Structured semantics,
- Information requirements,
- Data exchange structure,
- Collaboration and traceability, and
- Technical validation and interoperability.

The results reveal significant variation across components in terms of maturity, specificity, and implementation readiness. Key insights include:

- *Foundational Components (IFC, bSDD, and IFD)*: These elements exhibit strong semantic alignment and form the backbone of openBIM's structured data environment. IFC provides a comprehensive, standardized model schema, while bSDD and IFD ensure terminological clarity and multilingual support.
- *Process-Oriented Artifacts (IDM, UCM, MVD, and IDS)*: These components translate conceptual processes into machine-readable specifications. While IDM and MVD are well-established in model and process definition, IDS brings precision to alphanumeric content delivery, addressing Level of Information (LoI) requirements in alignment with ISO 19650-4.
- *Collaboration & Coordination Tools (openCDE and BCF)*: Though not strictly schema-bound, these solutions enhance real-time coordination and transparency across stakeholder platforms. BCF excels in issue tracking, while openCDE provides a platform-neutral environment for data and document exchange.
- *Delivery & Regulatory Elements (COBie and DataSheets)*: These formats enable structured handover and support asset-centric data aggregation, particularly in facilities management and sustainability. COBie's alignment with IFC MVD ensures downstream compatibility, while DataSheets represent emerging capabilities in product-centric modeling.
- *Validation Infrastructure (buildingSMART Validation Service)*: Still maturing, this service offers technical assurance for IFC compliance but lacks content-based validation such as LOI or IDS verification. Nevertheless, it forms a key component in quality assurance pipelines.

Overall, the results confirm that while openBIM offers a rich ecosystem of interoperable components, their integration into a cohesive ISO 19650-4-aligned framework remains partial and uneven. The matrix highlights areas of strength, such as semantic precision, process clarity, and non-graphical data interoperability, as well as gaps in content validation, real-time semantic reasoning, and collaborative data assurance.

This structured analysis underscores the need for a unified implementation model that synthesizes semantic definitions, process modeling, and content verification mechanisms. The foundation laid here provides a roadmap for defining such a model, which is elaborated in the following Discussion section.

6. Discussion

This study, through the integration of a systematic literature review and real-world case analysis, presents a comprehensive evaluation of openBIM data formats within the framework of ISO 19650-4. The dual-pronged methodological design, linking theoretical constructs with empirical observations, has resulted in robust findings that offer substantial value to both academic researchers and industry practitioners.

The horizontal and vertical alignment matrix (**Table 2**) revealed a complex yet interdependent landscape of openBIM tools, each serving different layers of data semantics, process modeling, interoperability assurance, and validation control. While foundational standards such as IFC and bSDD offer strong semantic infrastructure, newer specifications like IDS provide precision in delivering Level of Information (LoI). The emergence of DataSheets and Validation Services highlights the expanding frontier of compliance-driven and product-centric data exchange, yet also exposes gaps in cross-platform integration and stakeholder alignment.

From a broader perspective, the trajectory of openBIM development signals a systemic transformation in how digital data is defined, exchanged, and validated across the AECO industry. With growing pressure to unify on-site and off-site workflows, openBIM has evolved into a decisive factor in software ecosystems, procurement processes, and regulatory frameworks. Its alignment with ISO 19650-4 enhances its relevance as a vehicle for project transparency, interdisciplinary collaboration, and lifecycle resilience [90, 91].

Looking ahead, openBIM is poised to extend into adjacent domains such as facilities management, building performance analytics, and predictive maintenance. The integration of artificial intelligence, machine learning, and service-oriented architectures is expected to bolster semantic reasoning, automate compliance, and support intelligent information routing. The rise of open APIs and web-based validation frameworks further suggests a shift toward decentralized, modular BIM ecosystems. In parallel, immersive technologies and real-time data visualization stand to redefine collaborative practices and decision-making in project environments [92, 93].

6.1 Case studies

To validate and contextualize the study's findings, five large-scale infrastructure projects were selected based on their adoption of openBIM practices in accordance with ISO 19650-4. As illustrated in **Figure 20**, these case studies highlight how different project environments operationalize standard-driven workflows to improve transparency, coordination, and data quality.

- *Crossrail Project (UK)*: By integrating openBIM formats, Crossrail enabled multi-disciplinary data exchange with ISO 19650-4 playing a critical role in structuring information flows. The adoption of a unified Common Data Environment (CDE) reduced project risk and enhanced decision-making efficiency [94, 95].
- *Sydney Metro (Australia)*: openBIM facilitated synchronized collaboration across design, construction, and supply chain teams. Adherence to ISO 19650-4 contributed to early clash detection, reduced rework, and greater interoperability across contractor networks [96].

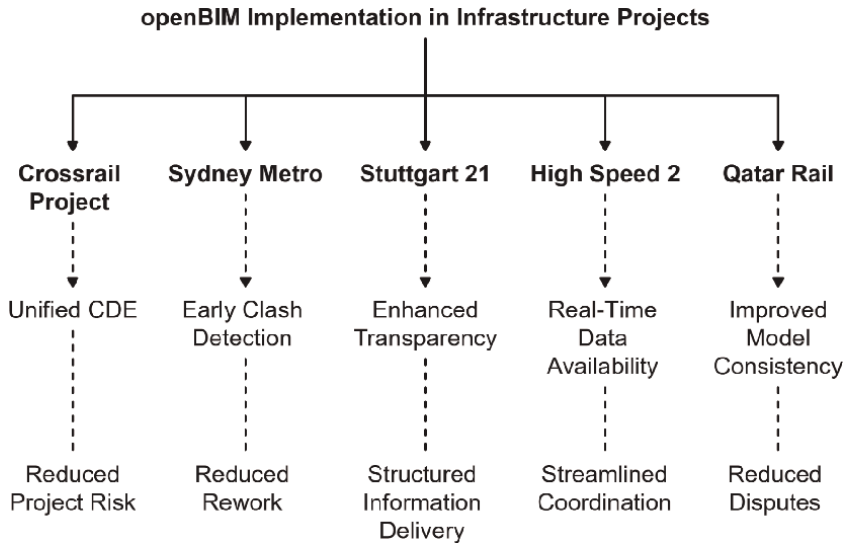


Figure 20.
Real-world examples.

- *Stuttgart 21 (Germany)*: BIM implementation enhanced transparency and structured information delivery. The integration of openBIM standards supported the alignment of spatial, temporal, and stakeholder-specific data exchanges, directly benefiting performance monitoring and stakeholder communication [97].
- *High Speed 2 (UK)*: The HS2 project underscored the importance of real-time data availability and federated information modeling. By aligning with ISO 19650-4, the project team streamlined design and construction coordination, reducing project delays and decision latency [98, 99].
- *Qatar Rail (Qatar)*: openBIM and ISO 19650-4 facilitated coordination across geographically dispersed teams. Centralized information requirements and controlled workflows contributed to improved model consistency and reduced post-construction disputes [100, 101].

These cases exemplify the transformative potential of standard-aligned openBIM implementation. Common themes include improved communication, timely access to validated data, and reduced project uncertainty, highlighting that effective information governance is critical to achieving digital maturity in complex infrastructure delivery.

7. Conclusion

This study has employed a dual-perspective analytical approach, combining systematic literature review and conceptual evaluation, to examine openBIM within the context of ISO 19650-4. It has emphasized the interrelation of data formats, services, and methodologies that form the foundation of a digitally integrated construction

environment. Drawing from both theoretical and empirical insights, the research demonstrates that openBIM represents more than a set of technical tools; it functions as a strategic enabler for digital innovation, collaboration, and lifecycle-driven data management in the AECO industry.

At the center of this integration lies the IFC schema, which enables cross-platform interoperability by establishing a shared data language. Supporting this framework, bSDD centralizes terminology and property structures, while IDM and MVD offer structured pathways for process definition and technical implementation. IDS brings a new level of precision by formalizing alphanumeric requirements in a machine-readable format, supporting the delivery of accurate and accountable data.

Other components such as openCDE, COBie, IFD, BCF, and DataSheets contribute to a holistic ecosystem. They strengthen coordination, standardize asset information, enhance issue tracking, and support product-centric data modeling. The inclusion of validation services and certification mechanisms further ensures data quality, regulatory alignment, and implementation trustworthiness.

As the construction sector moves toward increasingly digital, connected, and intelligent workflows, openBIM is poised to play a foundational role in shaping future project delivery models. Innovations in real-time visualization, immersive platforms, open APIs, and artificial intelligence will continue to deepen openBIM's impact.

To fully harness this potential, it is essential for industry stakeholders to embrace openBIM adoption and build digital competency across all phases of the asset lifecycle. Doing so will reinforce compliance with international standards, foster long-term efficiency, and support the realization of smarter, more resilient built environments equipped to meet tomorrow's challenges.

Acknowledgements

This study complies with national and international research and publication ethics. Ethics Committee approval was not required for the study. AI-assisted language editing tools were used exclusively to enhance clarity and ensure alignment with academic conventions. These tools played no role in the research design, data analysis, or intellectual interpretation. All academic contributions and insights presented in this study are the result of the author's original scholarly work.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

The author received no specific funding for this study.

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Reevaluating IFC and Comparing USD in the Context of the Built Environment

Murat Aydın

Abstract

This study conducts a structured comparative analysis between Industry Foundation Classes (IFC) and Universal Scene Description (USD) to evaluate their respective capacities for supporting next-generation information workflows in the built environment. IFC has long been the cornerstone of open data interoperability in Building Information Modeling (BIM), yet its rigid schema, declarative semantics, and file-based federation model present limitations in addressing emerging needs for dynamic collaboration, granular data extensibility, and AI-integrated operations. In contrast, USD introduces a scenegraph-based architecture with non-destructive composition, layered editing, and schema modularity, originally developed for visual effects pipelines but increasingly recognized for its potential across domains such as robotics, geospatial modeling, and digital twin development. The analysis is framed across five analytical dimensions: data structure and hierarchy, identification and referencing, semantics and extensibility, composition logic and collaboration, and standardization and governance. Findings suggest that while IFC provides foundational stability and regulatory alignment, USD offers transformative capabilities for real-time coordination, semantic fluidity, and multi-author workflows. However, its effective adoption in AECO contexts requires the development of domain-specific schema extensions, quality validation protocols, and integration with existing BIM toolchains. Building on comparative insights between IFC and USD, this study recommends a hybrid strategy in which USD is positioned to complement IFC, enabling more robust interoperability across digital building ecosystems. Future research directions include the institutionalization of schema governance, AI-driven querying over USD-encoded data, and pilot implementations in complex infrastructure environments to assess performance, adaptability, and long-term sustainability.

Keywords: building information modeling (BIM), industry foundation classes (IFC), universal scene description (USD), comparative analysis, built environment, digital twin

1. Introduction

The Architecture, Engineering, Construction, and Operations (AECO) industry is undergoing a major transformation as digitalization reshapes how information is produced, shared, and governed across building lifecycles. The push toward data-centric

collaboration, semantic interoperability, and AI-integrated processes is accelerating the evolution of existing modeling standards. Building Information Modeling (BIM) remains a core methodology within this shift, supported primarily by the Industry Foundation Classes (IFC) schema. Despite its wide adoption and regulatory alignment, IFC faces persistent challenges in areas such as real-time model federation, extensibility, and graph-based data reasoning [1–3].

In parallel, Universal Scene Description (USD), originally developed for the film and animation industries, is being explored as an alternative framework for structured, layered, and scalable model composition [4, 5]. USD's scenegraph structure, non-destructive authoring model, and schema-level modularity introduce capabilities that align closely with emerging AECO needs. Studies in domains such as VFX, biomedical engineering, and robotics demonstrate its versatility in representing complex, semantically rich environments [6–9]. This cross-domain adaptability raises the question of whether USD can also serve as a foundational framework for AECO modeling ecosystems.

While previous works have explored USD's technical features and integration strategies in non-AECO contexts, comparative academic assessments of USD and IFC within AECO-specific workflows remain limited [10, 11]. This research aims to address that gap by investigating the architectural and functional suitability of USD as either a complementary or alternative modeling standard for AECO data environments. The study adopts a comparative analysis method supported by five analytical dimensions: data structure and hierarchy, identification and referencing, semantics and extensibility, composition logic and collaboration, and standardization and governance.

This study is organized into six main sections. Section 1 provides a foundational overview of IFC and USD. Section 2 presents the literature background and prior research. Section 3 outlines the research design and analytical dimensions. Section 4 provides detailed findings from the IFC–USD comparison. Section 5 discusses implications, challenges, and strategic opportunities for adopting USD in AECO workflows. Finally, Section 6 offers conclusions and structured recommendations for future research and practical implementation.

1.1 Industry foundation classes (IFC)

The Industry Foundation Classes (IFC) standard, governed by buildingSMART International, has long stood as the cornerstone of open data interoperability in BIM [3, 12]. Introduced in the mid-1990s, IFC was envisioned as a vendor-neutral specification for representing building and construction data across diverse software environments. As depicted in **Figure 1**, its development has followed a path of incremental enhancements, moving from rigid object classifications to more modular and extensible schemas, as reflected in the ongoing transition toward IFC5 [13–19].

At its core, IFC uses a federated data structure that combines models from different stakeholders using reference mechanisms instead of native compositional inheritance, as shown in **Figure 2**. Its structured, object-oriented inheritance model and large taxonomy of predefined entities and property sets are what make it strong. But these same strengths also show weaknesses: the rigid schema can make it hard to add new features dynamically, and changing existing entities often means changing the schema formally or adding custom property extensions.

Also, IFC's use of Global Unique Identifiers (GUIDs) to keep track of objects can make it harder to keep referential integrity, especially in workflows that have a lot of

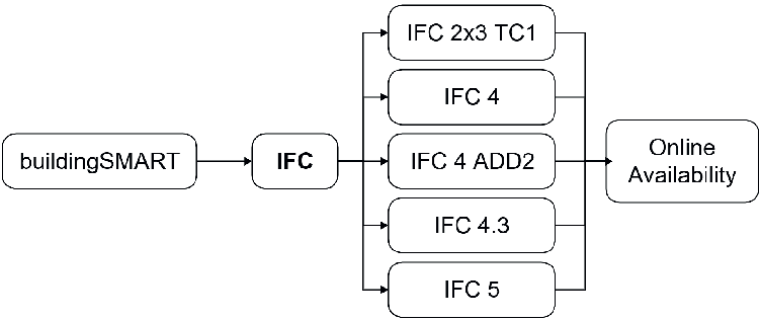


Figure 1.
IFC evolution and availability.

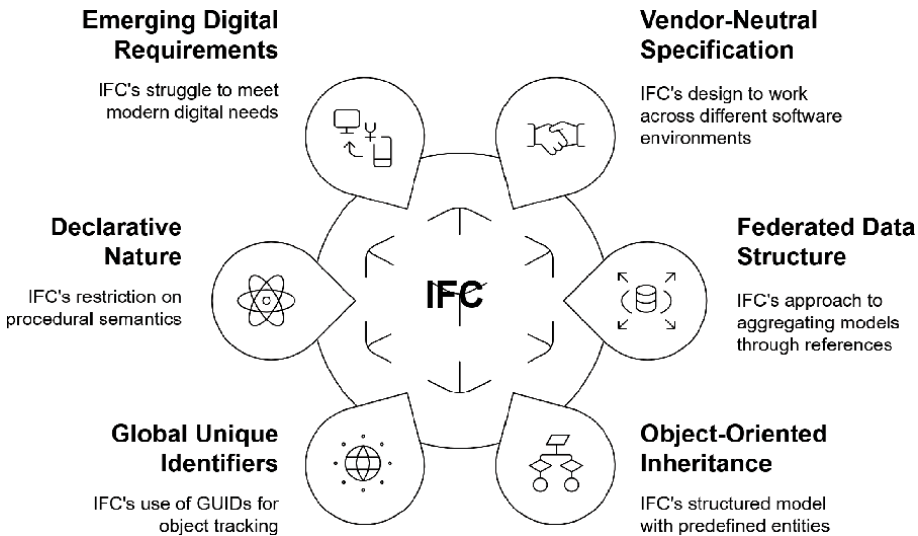


Figure 2.
Factors influencing IFC's evolution and limitations.

partial updates. The schema's declarative nature often makes procedural semantics less useful, which makes it less useful for modeling environments that use parameters or scripts.

IFC has been widely used, but its development has not kept up with new digital needs, especially in areas like real-time collaboration, data composability, and flexible schema overlays. The introduction of modular schema validation and frameworks like the BIM Collaboration Format (BCF) show that people are still trying to fill in these gaps, but the standard is still limited by its old architecture and governance model [20–28].

1.2 Universal scene description (USD)

Originally developed by Pixar to address the complex demands of film production pipelines, Universal Scene Description (USD) has since evolved into a robust framework for structuring, composing, and collaborating on complex 3D data, as shown in **Figure 3**. Its core objective was to allow multiple artists to work non-destructively

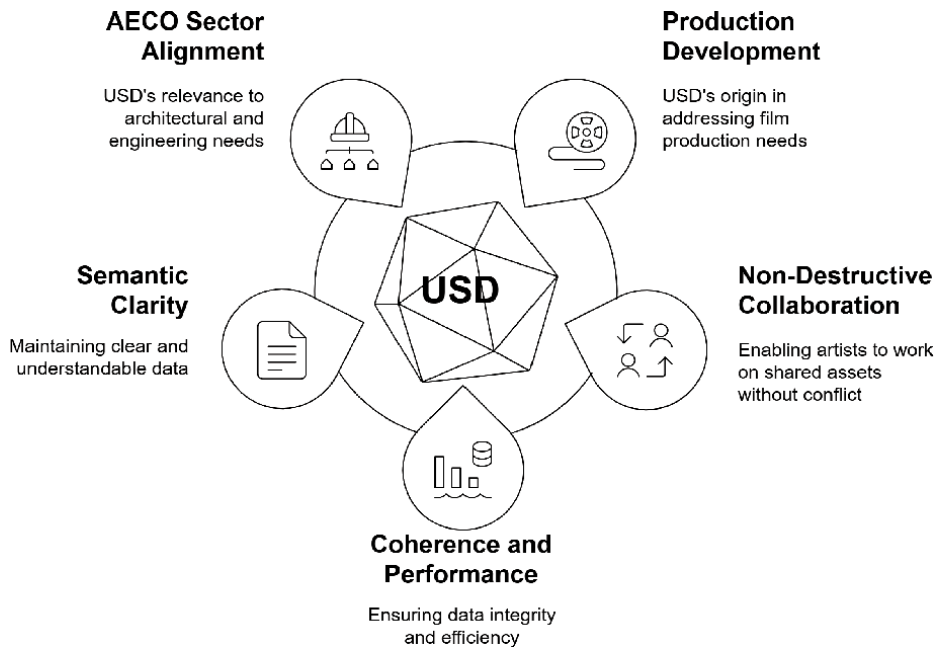


Figure 3.
Factors contributing to USD's robustness.

on shared digital assets across diverse tools and teams, while preserving coherence, performance, and semantic clarity. Although it originated within the entertainment industry, the architectural principles underlying USD closely align with the AECO sector's increasing requirements for model federation, traceability, and data extensibility.

At the core of USD lies the Stage-Prim-Layer hierarchy, as illustrated in **Figure 4**. The Stage functions as the runtime composition engine, aggregating multiple layers and references into a coherent model. Prims (primitive elements) are the fundamental

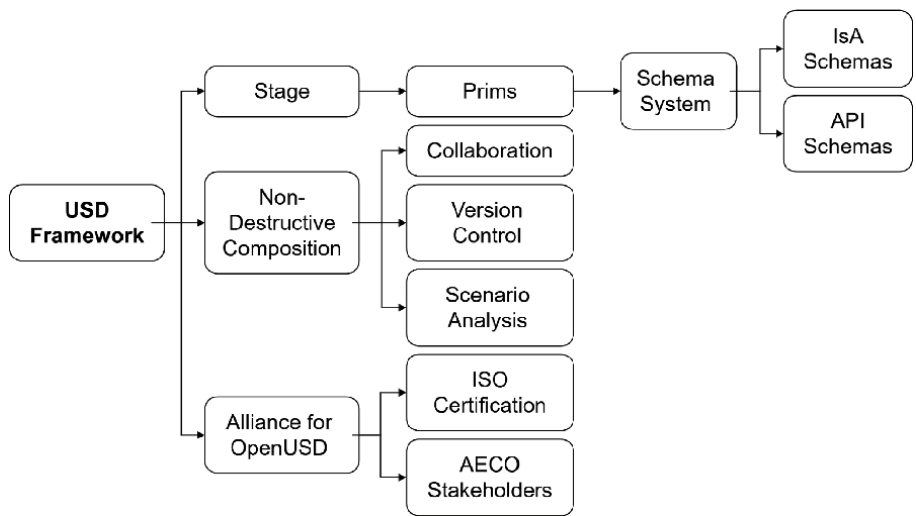


Figure 4.
USD framework and AECO integration.

units of content within a stage, analogous to objects or entities in BIM parlance. Unlike IFC's reliance on GUIDs, USD identifies these elements via namespace-based paths (e.g., Project/Site/Building/Room001/ExteriorWall003) favoring human readability and compositional clarity over strict identifier traceability.

As shown in **Figure 4**, USD's schema system offers two distinct approaches: IsA schemas define an object's type (e.g., UsdGeomMesh), whereas API schemas enrich objects with additional behaviors or metadata (e.g., UsdShadeMaterialBindingAPI). This distinction allows high degrees of modularity and domain specialization, which is critical for adapting a core framework to varied sectors like AECO, VFX, robotics, or gaming. Perhaps USD's most transformative feature is its non-destructive composition model. Using composition arcs such as reference, payload, variantset, and sublayer, users can layer modifications over base datasets without altering the underlying source. This model facilitates granular collaboration, version control, and scenario analysis, which directly align with BIM's emerging demands for partial model sharing, atomic transactions, and auditability.

Recognizing its cross-industry applicability, the Alliance for OpenUSD (AOUSD) was established in 2023 to oversee its governance, extension, and standardization [29]. The initiative is currently advancing toward ISO certification, and the inclusion of AECO stakeholders within AOUSD demonstrates a growing commitment to aligning USD's foundational capabilities with the specific needs of construction, operations, and facility management.

2. Literature review

The comparative analysis between IFC and USD within the AECO domain is an emergent area of inquiry. While IFC has a long-standing presence in BIM workflows, literature directly addressing USD's applicability in AECO remains limited but rapidly expanding, particularly through cross-domain insights. **Figure 5** presents a chronological distribution of key peer-reviewed publications. These works collectively explore core themes related to USD, including its architectural design, scene composition logic, and expanding relevance to AECO-oriented applications. As depicted in **Figure 6**, this review synthesizes key contributions grouped into three primary categories:

1. Core USD structure and workflows,
2. USD's potential in AECO-related digital ecosystems, and
3. Challenges and enablers for domain-specific adaptation.

2.1 Core USD structure and scene composition logic

Most of the early work on USD came from the digital content creation (DCC) and visual effects (VFX) fields. Bloom [10] gives a full picture of how USD is used in animation pipelines, with a focus on stage composition, schema layering, and non-destructive editing [10]. Bolstad [4] also looks at how USD can be used to manage large-scale cinematic visualizations, focusing on how hierarchical scene graphs work best when there are a lot of data [4]. Collins et al. [30] look into how well USD can scale up for use in large businesses, which shows how strong its architecture is [30].

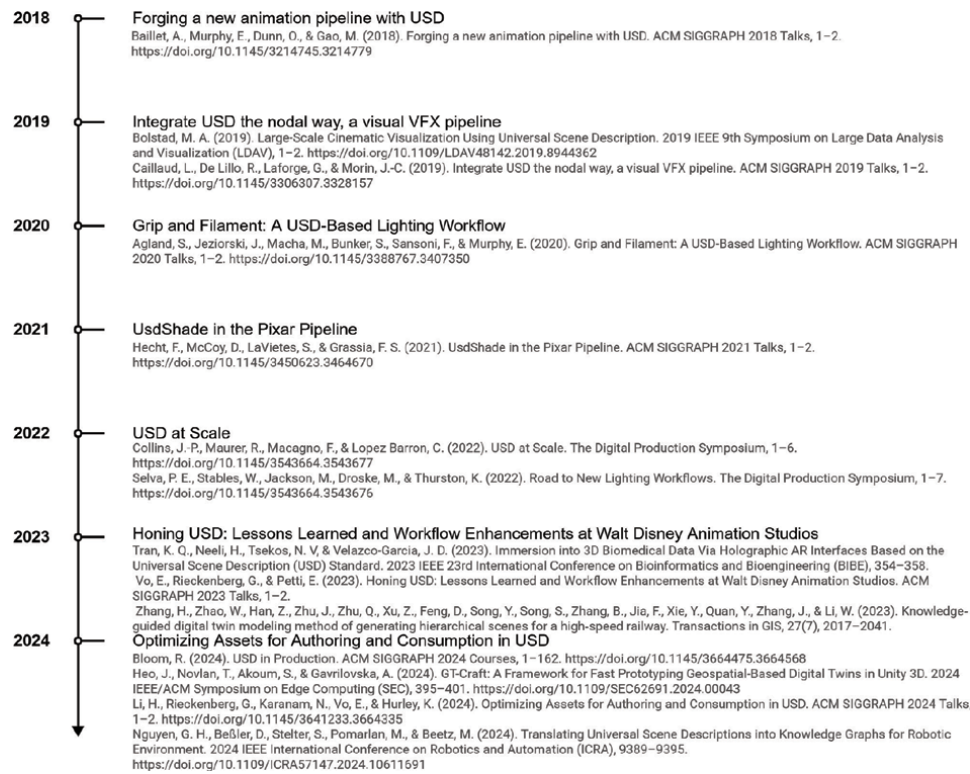


Figure 5.
Timeline of academic literature.

Characteristic	IFC	USD
 Core structure	Long-standing presence in BIM workflows	Hierarchical scene graphs, schema layering
 AECO-related digital ecosystems	Limited direct studies	Growing momentum through interdisciplinary research
 Workflow integration	Transition to USD requires toolchain maturity	Lightweight asset referencing, scenegraph-based thinking

Figure 6.
IFC and USD comparison in AECO domain.

Caillaud et al. [31] look at graph-based nodal workflows, which gives us even more information about how flexible USD is for creating complex digital assets [31]. Vo et al. [5] and Li et al. [32] talk about how major studios improve and optimize their production processes. They show how USD makes it possible to create modular content with very little duplication [5, 32]. Hecht et al. [33] talk about the UsdShade schema and how it helps manage material definitions. They do this by showing how shader graph traversal works with USD’s layered semantics [33]. When combined, these studies show how USD composition and schema management work on the inside. They also give us useful examples for how to structure AECO models.

2.2 USD in AECO-relevant digital ecosystems

There are not many studies that directly look at USD in the AECO field, but more and more research from different fields suggests that it could be useful. Zhang et al. [2] talk about a digital twin modeling method that is based on knowledge and uses hierarchical scene structures. These structures are very similar to USD's Stage-Prim organizational model [2]. Heo et al. [34] also introduce GT-Craft, a geospatial digital twin prototyping framework built in Unity 3D. It uses principles of modularity and composability that are very similar to USD's core architecture [34].

Nguyen et al. [9] make one of the most important contributions to AECO by turning USD structures into knowledge graphs that machines can understand [9]. This translation directly helps meet new needs for incorporating artificial intelligence (AI) and large language models (LLMs) into AECO model governance. Tran et al. [8] show how USD makes it possible to see biomedical models in 3D, which gives useful information for using spatialized representations in BIM workflows [8].

These studies show that USD originated in the entertainment industry, but its architectural features such as non-destructive layering, semantic schema extension, and namespace-based organization could prove highly beneficial for digital construction, operations, and infrastructure management.

2.3 Workflow integration, tooling, and adoption barriers

When moving from IFC-centric to USD-enhanced workflows, it is important to think about both the maturity of the toolchain and the best practices in the field. Baillet et al. [7], Agland et al. [35], and Selva et al. [11] all give real-life examples of how to integrate USD into production pipelines. They show the benefits of lightweight asset referencing and the problems that scenegraph-based authoring paradigms can cause [7, 11, 35]. These experiences give AECO professionals who are moving away from traditional federated modeling approaches useful information.

Kalyuzhnyy et al. [36] also show off an extensible DCC platform called "Wizart," which shows how USD-based tools can be made to work in specific fields [36]. Even though the focus is still on things other than construction, the technical foundation makes it possible for AECO-centric authoring environments.

3. Method

This study adopts a comparative analysis to examine the potential of Universal Scene Description (USD) as an alternative or complementary framework to Industry Foundation Classes (IFC) within the AECO sector as illustrated in **Figure 7**. The growing demands of digital construction, including composability, semantic governance, and AI-integrated workflows, highlight the need for a structured comparison that identifies how each modeling standard can address these challenges.

3.1 Research problem

IFC has long served as a foundational standard for data interoperability in BIM. However, its legacy structure has increasingly struggled to support newer demands such as real-time collaboration, graph-based composition, and flexible data overlays. On the other hand, USD, originally developed for the visual effects industry, offers

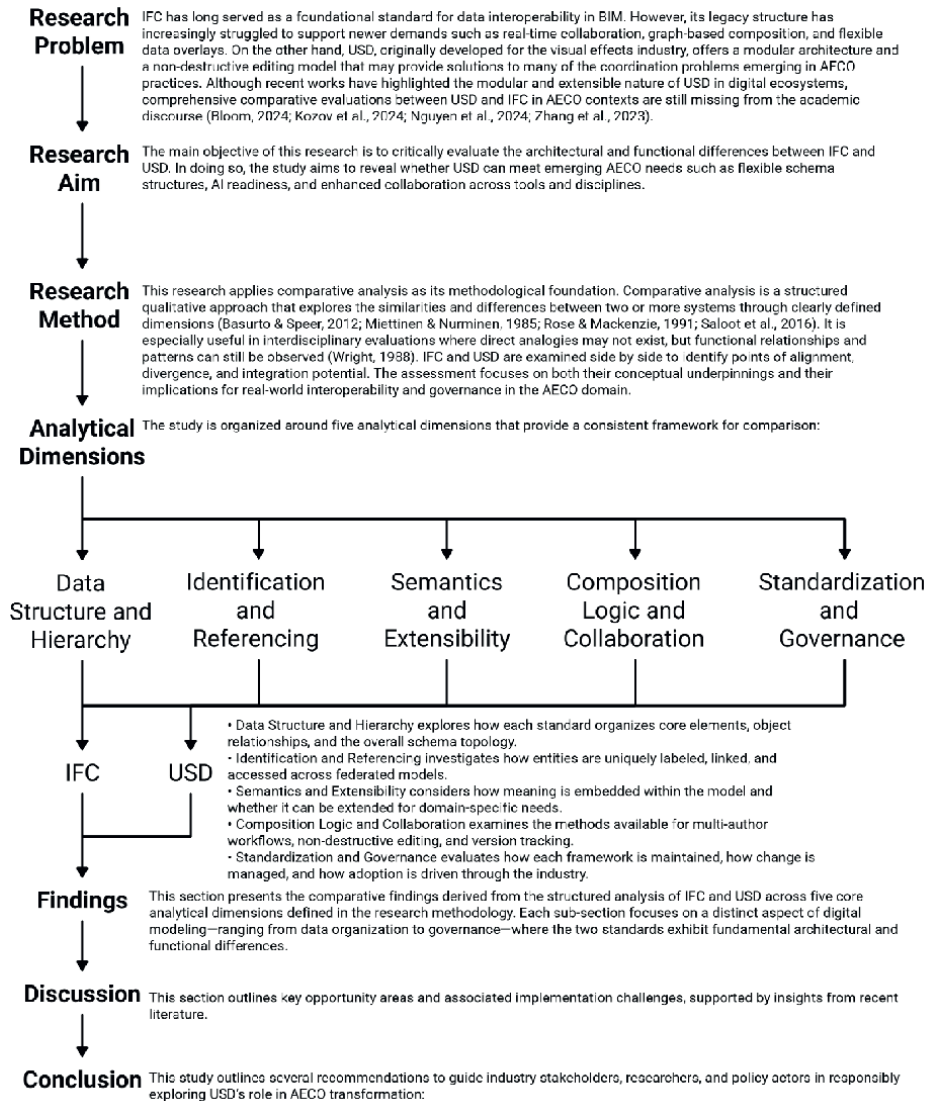


Figure 7.
Methodological framework for comparative analysis of IFC and USD.

a modular architecture and a non-destructive editing model that may provide solutions to many of the coordination problems emerging in AECO practices. Although recent works have highlighted the modular and extensible nature of USD in digital ecosystems, comprehensive comparative evaluations between USD and IFC in AECO contexts are still missing from the academic discourse [1, 2, 9, 10].

3.2 Research aim

The main objective of this research is to critically evaluate the architectural and functional differences between IFC and USD. In doing so, the study aims to reveal whether USD can meet emerging AECO needs such as flexible schema structures, AI readiness, and enhanced collaboration across tools and disciplines.

3.3 Research method

This research applies comparative analysis as its methodological foundation. Comparative analysis is a structured qualitative approach that explores the similarities and differences between two or more systems through clearly defined dimensions [37–40]. It is especially useful in interdisciplinary evaluations where direct analogies may not exist, but functional relationships and patterns can still be observed [41]. IFC and USD are examined side by side to identify points of alignment, divergence, and integration potential. The assessment focuses on both their conceptual underpinnings and their implications for real-world interoperability and governance in the AECO domain.

3.4 Research analytical dimensions

The study is organized around five analytical dimensions that provide a consistent framework for comparison:

- *Data structure and hierarchy* explores how each standard organizes core elements, object relationships, and the overall schema topology.
- *Identification and referencing* investigates how entities are uniquely labeled, linked, and accessed across federated models.
- *Semantics and extensibility* considers how meaning is embedded within the model and whether it can be extended for domain-specific needs.
- *Composition logic and collaboration* examines the methods available for multi-author workflows, non-destructive editing, and version tracking.
- *Standardization and governance* evaluates how each framework is maintained, how change is managed, and how adoption is driven through the industry.

These dimensions were selected based on their relevance to the practical concerns of AECO stakeholders and their significance in broader digital transformation goals.

4. Findings

This section presents the comparative findings derived from the structured analysis of IFC and USD across five core analytical dimensions defined in the research methodology. Each sub-section focuses on a distinct aspect of digital modeling, ranging from data organization to governance, in which the two standards exhibit fundamental architectural and functional differences. The analysis brings together both theoretical differences and real-world effects that are important for AECO workflows. It does this by using technical specifications, schema logic, and authoring models. **Table 1** gives a summary of these differences and explains what they mean for the AECO sector in different situations.

4.1 Data structure and hierarchy

Figure 8 shows how IFC organizes its data using a predefined schema made up of entities, relationships, and property sets that follow a strict inheritance-based

Analytical dimension	IFC (Industry Foundation Classes)	USD (Universal Scene Description)	Implication for AEEO
1. Data structure and hierarchy	Rigid, inheritance-based schema with federated file structures. Object types are pre-defined and grouped via Property Sets. Models from different disciplines are externally referenced.	Flexible Stage-Prim-Layer architecture. Objects (<i>Prims</i>) are structured hierarchically and composed non-destructively across layers.	USD's flexible composition model could support more agile project phasing, partial updates, and better lifecycle integration in AEEO workflows.
Example	<i>IfcWall</i> inherits from <i>IfcBuildingElement</i> ; separate discipline models are merged manually.	<i>UsdGeomXform</i> exists in a stage, influenced by multiple authored or override layers.	Enables fine-grained object management and concurrent updates by different AEEO stakeholders.
2. Identification and referencing	Uses globally unique identifiers (GUIDs) to track elements. Effective for long-term traceability but complicates incremental revisions and collaboration.	Identifies scene elements via hierarchical namespace paths (e.g., <i>/Building/Floor2/RoomA/Wall03</i>), allowing more readable references.	USD's approach promotes better human readability and object traversal, especially in visual tools, though collision avoidance mechanisms would be needed.
Example	GUID: 3D02f9fb... assigned at creation; changes require regeneration and synchronization.	Path: <i>/ProjectA/Site/BuildingA/Floor2/Window1</i> provides intuitive localization within the scene.	Hierarchical referencing could simplify facilities management systems or FM handover models based on spatial logic.
3. Semantics and extensibility	Semantics embedded in core schema; extension via Property Sets (PSets) is loosely governed and tool-dependent.	Separation of structural (<i>IsA</i>) and behavioral (<i>API</i>) schemas allows modular, scalable extensions. Localized behaviors can be added without modifying base definitions.	USD provides more sustainable extensibility, enabling AEEO actors to introduce custom behaviors (e.g., fire rating, maintenance strategy) while preserving interoperability.
Example	<i>IfcDoor</i> can be extended with "Pset_DoorCommon," but validation consistency varies across tools.	A <i>UsdGeomMesh</i> can be augmented with <i>MaterialBindingAPI</i> , <i>VisibilityAPI</i> , or custom metadata schemas.	Enhances semantic clarity and adaptability for complex use cases like smart infrastructure or digital twin integration.
4. Composition and collaboration	Composition is file-based and external; disciplines author in silos and models are coordinated post-facto. Real-time collaboration is limited.	Layered, rule-driven composition supports non-destructive overrides, dynamic scenario testing, and simultaneous contributions across teams.	USD enables parallel, multi-disciplinary authoring and real-time what-if simulations, advancing AEEO workflows toward digital twin maturity.
Example	Architects, MEP, and structural engineers submit separate models for coordination; integration is linear.	Designers can overlay energy analysis, code compliance, or simulation-specific layers without disrupting base geometry.	Supports more interactive design evaluation, sustainability assessment, and LOD-based phase planning.

Analytical dimension	IFC (Industry Foundation Classes)	USD (Universal Scene Description)	Implication for AECO
5. Standardization and governance	Long-established under buildingSMART with international recognition. Update cycles are formal but infrequent; adaptation to emerging tech like AI is slow.	Governed by AOUSD with a fast-moving open collaboration model. Actively evolving toward ISO certification and supports community-driven schema extensions.	AECO stakeholders can proactively shape USD standards to reflect sector-specific needs, ensuring earlier alignment with data governance and automation paradigms.
Example	IFC4.3 added infrastructure entities after years of consultation.	AOUSD announced domain working groups for manufacturing, VFX, and AECO, signaling intent for broader applicability.	Offers early engagement opportunities for AECO professionals to co-develop schema extensions aligned with digital construction goals.

Table 1.
Comparative analysis of IFC and USD across key analytical dimensions with AECO implications.

hierarchy. This structure helps with semantic clarity by allowing for type specialization and consistent classification across fields. But it also limits flexibility, especially when you need to change things at runtime, reuse parts of a model, or restructure things on the fly. The federated structure of IFC models encourages writing in a specific field and organizing files into modules by linking to them from other places. This method, on the other hand, can make it hard to integrate and coordinate data because it can cause problems with version updates or cross-disciplinary alignment.

USD, on the other hand, uses a Stage-Prim-Layer architecture, which is also shown in **Figure 8**. A Stage is like a scene graph that has Prims, which are the smallest parts of model content, organized in a hierarchy. Layers are used to write and change these Prims. Layers define both the original content and the contexts that override it. This architecture allows for high modularity and granular, non-destructive composition workflows. It also makes it possible to update things in real time and write things at the same time, which lets model changes spread dynamically without changing the base geometry or structure. In the AECO sector, where design changes, operational updates, and coordination between teams are becoming more common, these kinds of features are especially useful.

4.2 Identification and referencing

Figure 9 shows how IFC uses GUIDs to find and keep track of model elements. GUIDs are permanent references that work in distributed or federated BIM environments. This method helps keep data accurate and easy to check throughout the life of a project. However, it has some problems during iterative design revisions or collaborative authoring cycles, when updating models can cause GUIDs to change, which can make it harder to keep track of versions and break continuity. Also, the GUIDs themselves are not human-readable, which makes it harder to navigate scenes and refer to things in context.

USD, by contrast, utilizes a hierarchical namespace path system for object identification (e.g., Project/Site01/BuildingA/Floor2/StructuralWall03), also represented in **Figure 9**. This approach reflects the scene graph's structure and allows for direct traversal, semantic grouping, and visual interpretation of model hierarchies. Namespace paths are inherently more readable and align well with user interface

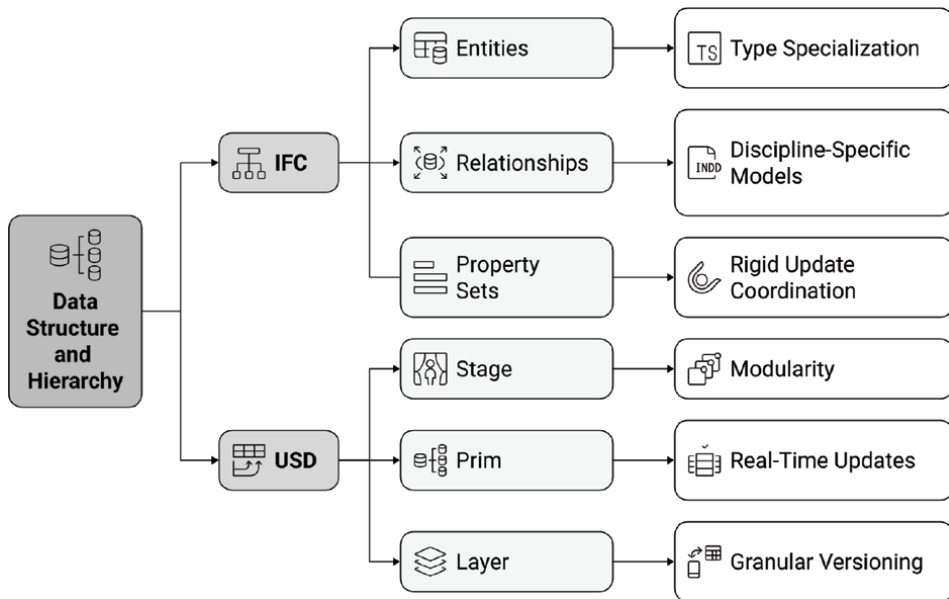


Figure 8.
Data structure and hierarchy comparison.

representations, particularly in environments that support tree-based navigation. Nonetheless, this flexibility introduces new challenges in large-scale, multi-author projects, where inconsistent naming or lack of namespace governance may result in collision risks or unintended overrides. These concerns highlight the importance of establishing clear authoring conventions and conflict-resolution mechanisms within collaborative AECO workflows.

4.3 Semantics and extensibility

In IFC, semantic meaning is embedded directly within its ontology-style schema, where entities encapsulate both structural definitions and domain-specific logic. This approach enriches information fidelity and consistency across disciplines. However, extensibility is primarily achieved through the use of custom Property Sets (PSets), which are loosely governed and inconsistently implemented across software platforms. As a result, interoperability and automated validation are often hindered, particularly when custom attributes lack schema-enforced definitions or standardized interpretation, as depicted in **Figure 10**.

USD adopts a more modular and granular approach by distinguishing between IsA schemas, which define the structural type of a primitive (e.g., `UsdGeomMesh`), and API schemas, which add optional behaviors or metadata (e.g., `UsdShadeMaterialBindingAPI`), as shown in **Figure 10**. This separation promotes composability and allows localized semantics to be layered onto base objects without requiring modifications to the core schema. The ability to incrementally extend functionality in this way supports diverse domain-specific requirements while maintaining consistency with the global data structure. For AECO applications, where models must balance compliance with standards and flexibility for project-specific constraints, USD's extensibility model offers a more sustainable and adaptable semantic framework.

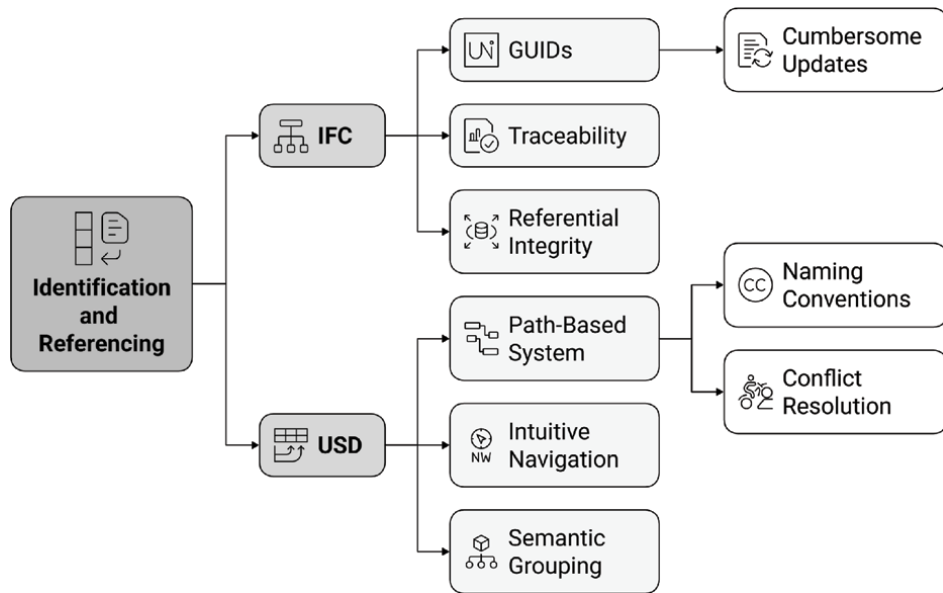


Figure 9.
Identification and referencing comparison.

4.4 Composition logic and collaboration

In IFC, model composition is achieved through a file-based federation approach in which discipline-specific models are authored independently and externally referenced before being aggregated during coordination. This sequential workflow supports formal design validation and clear responsibility separation. However, it introduces rigidity when managing iterative design changes, especially in projects that require frequent synchronization across teams or continuous integration of updates. The coordination model must be manually refreshed and reintegrated, which can become cumbersome in large-scale, fast-moving AECO projects. These limitations are conceptually illustrated in **Figure 11**.

USD employs a fundamentally different strategy based on layered, non-destructive composition. A scene can be constructed by referencing, overriding, or specializing content subsets using mechanisms such as reference, payload, and variantset. These composition arcs allow multiple contributors to work simultaneously on different aspects of the model without interfering with one another's content. Changes can be introduced through override layers that preserve the original structure, enabling seamless branching, rollback, and comparative evaluations. As depicted in **Figure 11**, this model supports scenario-based exploration, “what-if” simulations, and incremental authoring workflows. These capabilities align closely with digital twin development, integrated project delivery, and Level 3 BIM maturity targets.

4.5 Standardization and governance

IFC is maintained by buildingSMART International, a globally recognized standards organization that ensures consistency in documentation, version control, and cross-platform integration across the AECO industry. This institutional maturity provides long-term stability and broad adoption. However, its formal revision process

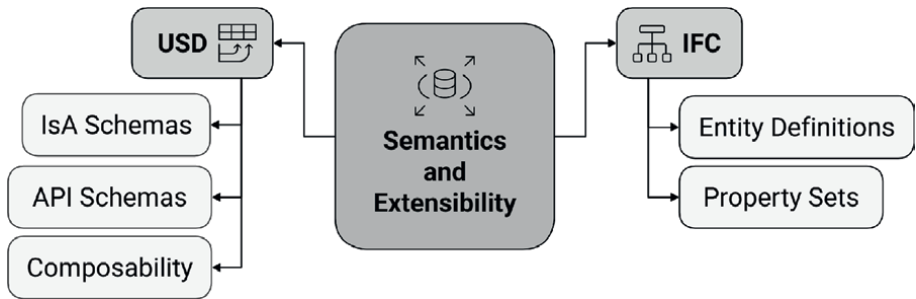


Figure 10.
Semantics and extensibility comparison.

tends to be slow, which can create challenges when adapting to emerging paradigms such as graph-oriented data modeling, semantic ontologies, or AI-driven information querying. These characteristics are illustrated in **Figure 12**.

USD, while relatively new, is governed by the Alliance for OpenUSD (AOUSD). This consortium includes a broad range of stakeholders in digital content creation and industrial technology who actively collaborate to evolve the standard. Its governance promotes transparent development and encourages domain-specific schema extensions. Ongoing efforts toward ISO certification and open tool alignment reflect this commitment. Although AECO-specific implementations and tooling are still developing, the growing participation of architects, engineers, and facility managers suggests that USD could be shaped to address the sector’s operational, semantic, and lifecycle data needs. The governance approach and standardization pathway are visualized in **Figure 12**.

5. Discussion

The comparative findings presented in the previous section highlight that USD’s foundational capabilities, including modular composition, semantic extensibility, and non-destructive collaboration, are closely aligned with AECO’s shifting expectations

 Composition Logic and Collaboration	 IFC	 USD
 Composition Approach	File-based federation	Layered and non-destructive
 Authoring Workflow	Sequential authoring	Concurrent collaboration
 Change Management	Rigid	Fine-grained control
 Best Use Case	Formal coordination workflows	Digital twin environments

Figure 11.
Composition logic and collaboration comparison.

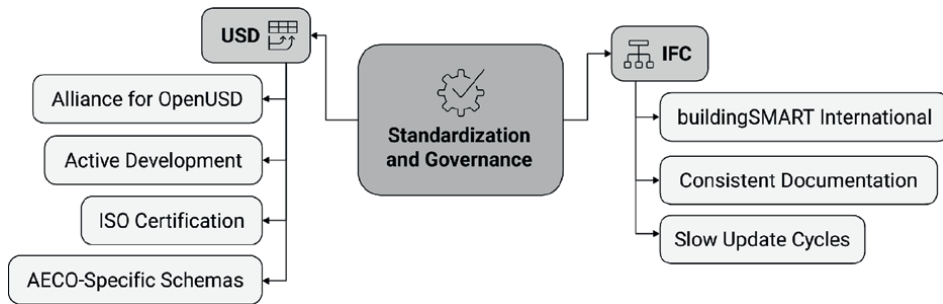


Figure 12.
Standardization and governance comparison.

in digital modeling and coordination. These attributes are particularly relevant in contexts requiring real-time authoring, federated model management, and adaptable data structures. However, realizing USD's full value in the AECO domain depends not only on technical potential but also on domain-specific adaptation, ecosystem maturity, and cultural readiness across stakeholders. As depicted in **Figure 13**, this section outlines key opportunity areas and associated implementation challenges, supported by insights from recent literature.

5.1 Domain adaptation and semantic localization

IFC embeds domain-specific semantics directly into its schema, enabling standardized classification across AECO workflows [3]. In contrast, USD offers a generic schema framework that remains agnostic of any single industry [10]. This structural neutrality allows AECO stakeholders to define localized schema packages, such as UsdAEC, which could encode architectural elements, construction sequences, and facility attributes in a way that aligns with project-specific semantics. Ongoing research emphasizes the value of schema-level localization to support modularity and reuse in AECO contexts [9].

5.2 LLM integration and graph-based reasoning

The scenegraph architecture of USD is a natural fit for a graph-based data structure made up of primitives and relationship arcs. This design fits well with recent improvements in large language models (LLMs) and graph neural networks that can understand how structured relationships work in design data [32]. Being able to show and move through spatial hierarchies, semantic groupings, and linked behaviors in a structured way opens up new possibilities for AI-assisted design intelligence, compliance checking, and automated coordination [9]. But these abilities will depend a lot on the creation of AECO-aligned vocabularies, graph grammars, and promptable ontologies that LLMs can understand in a meaningful way.

5.3 Validation, governance, and data assurance

IFC requires validation through XSD schemas and Model View Definitions (MVDs) to make sure that all regions are consistent and follow the rules. USD, on the other hand, uses a more decentralized approach [2]. Validation in USD is often defined through project-specific test scripts or custom grammars, offering

	Opportunities	Challenges
 Domain Adaptation	Localized schema packages for AECO semantics	Requires domain-specific adaptation of generic schema
 LLM Integration	AI-assisted design intelligence and automation	Development of AECO-aligned vocabularies needed
 Validation & Governance	Flexibility through project-specific validation scripts	Risk of interpretive inconsistencies without shared protocols
 Tooling & Ecosystem	Potential for domain-specific authoring tools	Lacks direct support for critical AECO functions
 Cultural & Contractual	Distributed authoring and collaboration potential	Requires revision of contractual arrangements

Figure 13.
Opportunities and challenges for USD in AECO.

flexibility but requiring discipline to avoid interpretive inconsistencies [10]. To make sure that all teams and platforms follow the same rules and can work together, AECO stakeholders may need to set up shared validation protocols and reference implementations.

5.4 Tooling, training, and ecosystem maturity

USD’s current tooling ecosystem, which grew out of animation and visual effects, does not directly support important AECO tasks like making 2D drawings, finding clashes, taking off quantities, and checking for code compliance [4]. To fill this gap, we need to make domain-specific authoring tools, visual editors, and integration platforms that work with BIM and CDE environments. Additionally, effective adoption will rely on training programs and professional development efforts that familiarize practitioners with the logic of scenegraphs, layering, and composition arcs [9, 10].

5.5 Cultural and contractual considerations

USD’s support for layered authoring and decentralized collaboration creates a new way of thinking about model ownership and coordination. This method is different from the more linear and file-based methods that are common in current BIM standards. Because of this, current contracts may need to be changed to allow for the assignment of duties across overlapping layers, set access control rules, and keep track of who wrote what. Standards like ISO 19650 provide a basis for structured information delivery and responsibility matrices. These could be changed to show how USD can be used for distributed authoring [1].

6. Conclusion

This study conducted a structured comparative analysis to evaluate the suitability of USD as an alternative or complementary framework to IFC within AECO workflows. The research emerged from the limitations of existing standards in supporting

real-time coordination, semantic extensibility, and data-centric collaboration. To address this, the study used a qualitative comparison based on five analytical dimensions: data structure and hierarchy, identification and referencing, semantics and extensibility, composition and collaboration, and standardization and governance.

Findings demonstrated that USD’s scenegraph-oriented architecture and layered composition model provide enhanced flexibility in authoring, federation, and semantic localization. Unlike IFC’s rigid schema and file-based federation, USD enables non-destructive overrides, variant management, and domain-specific schema augmentation without altering the global structure. Moreover, USD’s namespace-driven referencing system and dual-schema design (IsA and API schemas) align well with emerging applications involving AI-assisted modeling, data integration, and digital twin development.

Nevertheless, USD lacks a mature AECO-specific schema, standardized validation mechanisms, and integrated tooling support that reflect current industry workflows. While USD exhibits potential for interoperability and collaboration, its effective deployment in AECO requires intentional adaptation, stakeholder coordination, and cultural acceptance within established regulatory and contractual frameworks.

6.1 Recommendations for future research

As illustrated in **Figure 14**, and based on the synthesis of technical and organizational findings, this study outlines several recommendations to guide industry stakeholders, researchers, and policy actors in responsibly exploring USD’s role in AECO transformation:

- *Pilot projects and prototyping*: Encourage cross-sector initiatives that prototype USD-based workflows in areas such as federated modeling, component authoring, and AI-enhanced compliance checking. Pilot studies will help validate USD’s applicability, performance, and integration challenges under real-world constraints.
- *Development of AECO-specific schemas*: Promote collaborative efforts to establish domain-aligned USD schema packages, such as a modular UsdAEC extension.

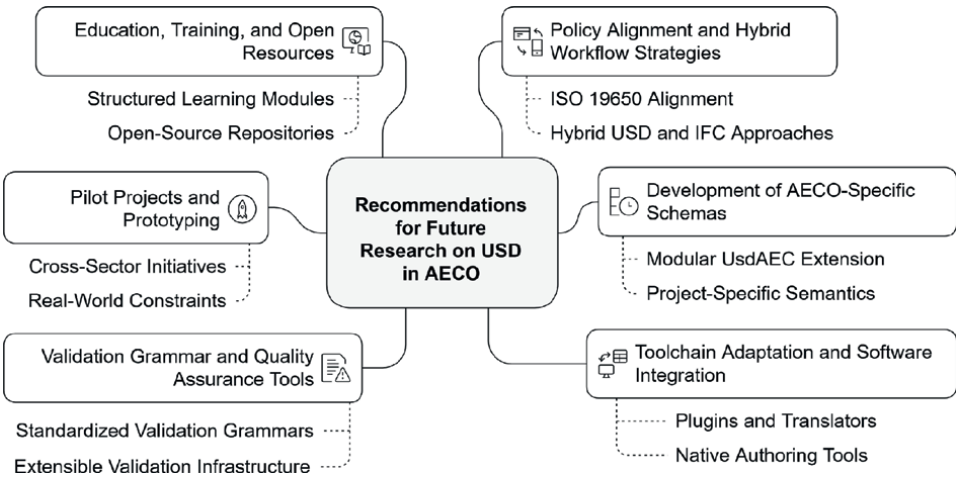


Figure 14.
Recommendations for future research on USD in AECO.

These efforts should capture architectural concepts, building systems, construction phases, and lifecycle attributes, fostering interoperability while preserving project-specific semantics.

- *Validation grammar and quality assurance tools:* Create standardized validation grammars and test suite templates to support regulatory and contract-driven conformance checking. These tools should reflect AECO requirements while leveraging USD's extensible validation infrastructure.
- *Toolchain adaptation and software integration:* Support the development of plugins, translators, and native authoring tools that bridge the gap between USD and common AECO platforms, including BIM authoring tools, CDEs, and Geographic Information System (GIS) systems.
- *Education, training, and open resources:* Design structured learning modules and open-source repositories to disseminate USD knowledge across disciplines. Educational initiatives should target architects, engineers, contractors, and data scientists to facilitate ecosystem-wide capacity building.
- *Policy alignment and hybrid workflow strategies:* Explore frameworks to align USD workflows with existing information management protocols such as ISO 19650 and the Common Data Environment (CDE). Hybrid approaches that blend USD and IFC may support incremental adoption and comparative evaluation of performance across domains.

In parallel with these recommendations, future research could focus on comparative simulations of IFC and USD in design coordination scenarios, the construction of USD-based knowledge graphs for semantic reasoning, and the assessment of long-term maintainability of graph-based models in facilities management. Longitudinal case studies involving public infrastructure or large-scale commercial projects would also help determine the operational feasibility and scalability of USD adoption within regulated AECO contexts.

By positioning USD not as a replacement but as a complementary modeling paradigm, this study advocates for a more flexible, intelligent, and collaborative foundation for next-generation AECO information management.

Acknowledgements

This study complies with national and international research and publication ethics. Ethics Committee approval was not required for the study. AI-assisted language editing tools were used exclusively to enhance clarity and ensure alignment with academic conventions. These tools played no role in the research design, data analysis, or intellectual interpretation. All academic contributions and insights presented in this study are the result of the author's original scholarly work.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

The author received no specific funding for this study.

Acronyms and abbreviations

AECO	architecture, engineering, construction, and operations
AI	artificial intelligence
AOUSD	alliance for OpenUSD
BCF	BIM collaboration format
BIM	building information modeling
CDE	common data environment
DCC	digital content creation
GIS	geographic information system
GUIDs	global unique identifiers
IFC	industry foundation classes
LLM	large language model
MVDs	model view definitions
PSets	property sets
USD	universal scene description
VFX	visual effects

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Applications of Artificial Intelligence (AI) in Infrastructure Asset Management

Amin K. Akhnoukh and Nihal S. Erian

Abstract

Artificial intelligence (AI) is transforming the construction industry in general, and asset management applications in particular, enabling new levels of efficiency, cost and time savings, safety, seamless flow of construction, maintenance, repair, and replacement activities (MR&R). The integration of AI in asset management through decision-making, prediction of future preservation and maintenance needs, and optimization of network-level MR&R activities under budget restrictions hold particular promise. This white paper investigates the current status of AI applications in construction industry, with special emphasis on asset management applications, and explores possible opportunities for future AI contribution. The research findings indicate that AI-driven asset management improves operational efficiency, enhances predictive maintenance, and allows for substantial cost savings due to reduced life cycle cost of infrastructure assets. The successful application of AI in asset management is dependent upon big data collection and selection of appropriate machine learning algorithms. Several impediments to AI applications in infrastructure asset management include possible data privacy breaching, lack of trained workforce, and platform integration complexity. Recommendations include data governance prioritization, investing in workforce development and training, and pursuing pilot projects to build organizational and institutional AI literacy and maturity.

Keywords: artificial intelligence (AI), machine learning (ML), algorithms, asset management, predictive maintenance, preservation, infrastructure projects, life-cycle cost analysis (LCCA)

1. Introduction

The construction industry is a major contributor to the global economy with an approximate market valuation of \$12 trillion. In the United States, the construction market is valued at approximately \$2 trillion (8%) of the national gross domestic product. The European Union's market is valued at over \$2 trillion, with significant contributions from Germany and France. In Asia-Pacific region, China's construction – being the largest on the world – is valued at \$3.5 trillion. In Latin America, the

construction sector is experiencing a steady growth, with significant contributions from Brazil and Argentina. Finally, the Middle East and Africa represent a dynamic segment of the global construction sector driven by large-scale construction and infrastructure projects in countries like Egypt, Saudi Arabia, and United Arab Emirates. Several key trends contribute towards the reshaping of the construction industry including technological advancement, urbanization, and infrastructure development. This research paper presents current infrastructure conditions and significant challenges resulting in growing concerns regarding infrastructure deterioration. Types of AI are presented with emphasis on weak AI applications tailored to asset management and asset preservation. Possible uses of AI in asset management including data collection, data interpretation, prediction of future conditions, and implementation of predictive maintenance to improve asset conditions without violating budgetary violations are presented. Finally, a list of attained advantages and possible challenges are shown. Recommendations for successful AI implementation include data governance prioritization, investing in workforce development and training, and pursuing pilot projects to build organizational and institutional AI literacy and maturity.

2. Overview of transportation infrastructure conditions

The transportation infrastructure market size is estimated at \$690 billion in 2024. The transportation infrastructure annual market is expected to grow at approximately 6.17% to reach \$1256 billion by 2034, as shown in **Figure 1**.

Transportation infrastructure assets including roadways, bridges, and tunnels are faced with significant challenges including budget constraints, global environmental changes, increased population and higher demands posed by larger number of vehicles and heavier cargo transport, and increased rate of natural disasters as seismic activities, high speed wind, hurricanes, tornadoes, acid rain, and wildlife fires. Traditional approaches for transportation infrastructure asset management includes the use of innovative construction materials with increased strength and durability, implementation of asset management systems, early detection of deterioration through continued inspection and remote sensing techniques, implementation of

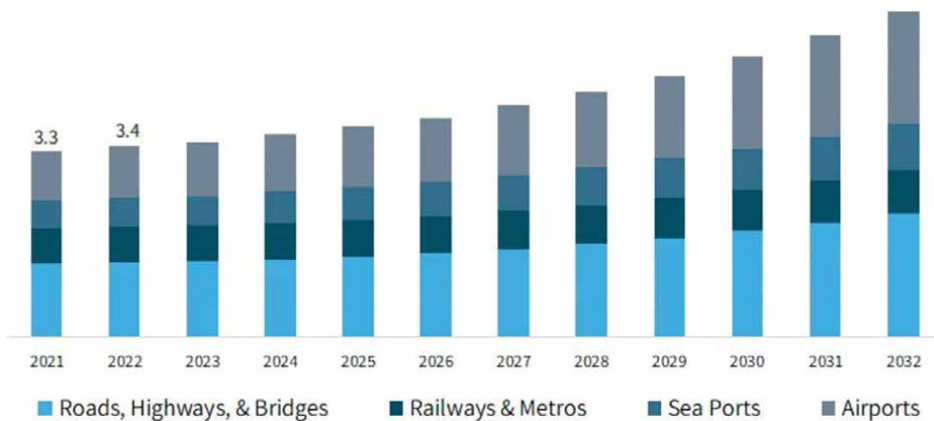


Figure 1.
Transportation infrastructure market growth projection.

nanotechnology in improved projects durability, and using advanced construction techniques with enhanced safety, reduced cost, and minimized material waste as additive construction including 3-D printing of concrete projects [1–3]. In recent years, artificial intelligence (AI) has been incorporated into asset management applications to increase the efficiency of asset management operations and improve/maintain infrastructure asset conditions under significant budgetary constraints. AI is initially applied to project planning, safety monitoring, quality control, and resource allocation [4]. Current trends indicate a rising adoption rate of AI, with market research projecting the global AI in construction market to grow from \$407 million in 2019 to over \$2.1 billion by 2026.

3. History of artificial intelligence (AI) in construction industry

AI encompasses a range of technologies – including machine learning (ML), deep learning (DL), and generative AI, as shown in **Figure 2**.

Current AI applications in construction industry and asset management refer to a set of technologies that allow computers or robotic systems to process information in a way similar to humans. These AI technologies are considered weak or narrow AI. Weak AI applications include self-driven cars (autonomous vehicles), detection of infrastructure distressed like concrete cracks, steel corrosion, and/or pavement distresses as cracks, ruts, and/or raveling. Construction industry is still far from strong AI applications, which refers to the ability of the machines to make decisions without previous observations.

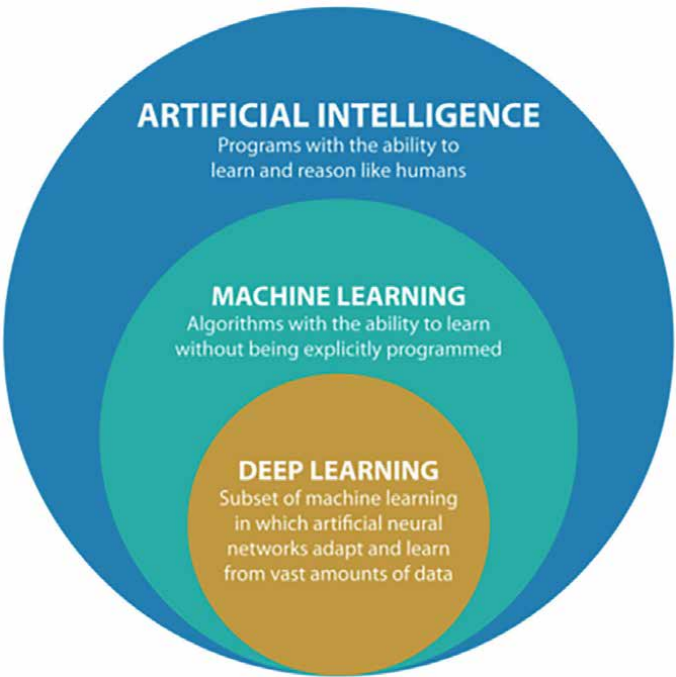


Figure 2.
Artificial intelligence components/range of technology.

The key building block of narrow AI systems is the ability to learn from historical data. This process is defined as machine learning (ML), where practitioners use a combination of computer programming and statistical techniques to generate machine learning algorithms to make predictions in new data. Common ML algorithms included used in transportation infrastructure applications include linear regression, K-means clustering, decision tree, and random forest algorithms. Deep learning (DL) is a subset of machine learning where sophisticated algorithms as artificial neural networks (ANN) and convolutional neural networks (CNN) are used for efficient processing of large volumes of unstructured data through multiple layers of mathematical computation on data in order to make future predictions. DL is characterized by efficient handling of larger datasets as compared to conventional/traditional ML techniques, as shown in **Figure 3**.

On early 2000s, computerized maintenance management systems (CMMS) were introduced. CMMS enabled authorities to identify patterns in asset deterioration, thus reinforcing the case of utilizing predictive maintenance in transportation infrastructure maintenance [5]. Around 2010, AI and ML became integrated into enterprise asset management (EAM) platforms, enabling predictive analytics, risk assessment, and automated decision support. The proliferation of sensors and Internet of Things (IoT) devices provided real-time data streams, which, when coupled with AI, enabled proactive and condition-based maintenance strategies [6]. Today, advances in DL and generative AI are driving the next wave of innovation, including automated inspections using computer vision, digital twins, and comprehensive life cycle management approaches.

3.1 Types of AI

AI can be categorized in several ways, including capability and functionality.

- *Narrow AI*: Also known as weak AI, it specializes in single tasks (e.g., speech recognition and image classification). Nearly all current industry applications use narrow AI.
- *General AI*: Known as strong AI, this theoretical form can understand, learn, and apply intelligence across a broad range of tasks. It remains largely conceptual.

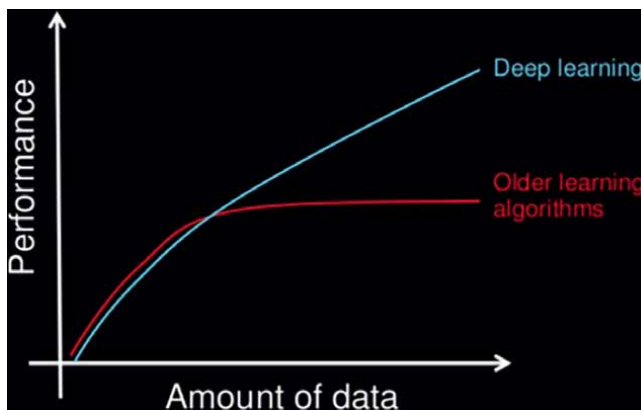


Figure 3.
Advantages of DL vs. ML for large data sets.

- *Superintelligence*: Refers to intelligence surpassing the brightest human minds. It exists only in hypothetical discussions and future projections.

Another classification is by functionality:

- *Reactive machines*: Basic AI systems that react to specific inputs without memory (e.g., rule-based inspection bots).
- *Limited memory*: Systems that use past data for current decision-making (e.g., predictive maintenance tools).
- *Theory of mind*: Still in development, aims to understand human emotions and intentions.
- *Self-aware AI*: A futuristic vision where AI possesses consciousness.

4. AI applications in infrastructure asset management

Current AI applications in infrastructure asset management are utilizing weak (or narrow) AI. It is also classified as limited memory AI, where systems can use past data for current decision-making (as in predictive maintenance applications). Current AI applications include the following:

- *Predictive maintenance*:

Predictive maintenance is one of the most impactful AI applications in asset management. Traditional maintenance relies on fixed schedules or reactive approaches—often resulting in unnecessary costs and unplanned downtime. AI-powered predictive maintenance systems analyze historical and real-time data from sensors (vibration, temperature, acoustic, etc.) to predict when an asset is likely to fail and recommend optimal maintenance intervals [7].

ML models, such as regression analysis, decision trees, and neural networks, can detect early signs of wear and degradation, reduce failure rates, and extend asset life. For example, AI-enabled systems now monitor railway tracks and bridges for anomalies, alerting engineers only when intervention is truly needed [8].

The successful use of AI in predictive maintenance is highly dependent on the amount and the accuracy of the data used in training and validating the machine learning model. Thus, the use of advanced technological in inspection and data collection is detrimental to the AI success.

- *Automated inspection*:

Manual inspections of infrastructure assets are time-consuming, costly, and sometimes hazardous. AI-driven automated inspection leverages computer vision, drones, and robotic platforms to analyze images and video feeds of structures. Deep learning models identify cracks, corrosion, and other defects with greater accuracy and consistency than human inspectors [9].

Drones equipped with high-resolution cameras and AI can survey large areas, creating 3D models of bridges, roadways, tunnels, or buildings for detailed analysis. This approach not only improves safety but also reduces inspection times



Figure 4.
Automated road analyzer – ARAN (Courtesy of Alaska DOT).

and costs, allowing for more frequent monitoring. Currently, state DOTs use LiDAR, drones, thermal photography, and automated road analyzers (ARANs) for roadway and bridge network inspection and data collection. ARANs, shown on **Figure 4**, can collect data at a speed of 50 miles per hour. Thus, it can be used to scan a 300-mile section of the road per day.

- *Enhanced decision making:*

AI augments human decision-making by synthesizing vast amounts of data from diverse sources, historical records, weather forecasts, and more. Advanced analytics platforms combine ML algorithms with optimization models to recommend asset intervention strategies, budget allocations, and long-term investment planning [10].

For instance, AI can help municipalities prioritize repair projects based on risk, cost, and impact, ensuring resources are allocated efficiently. Decision support systems powered by AI also enable scenario analysis, helping managers assess the consequences of different maintenance and investment choices.

- *Digital twins:*

A digital twin is a virtual representation of a physical asset or system, updated in real time with sensor and operational data. AI enhances digital twins by enabling continuous learning and simulation. These models allow engineers to test maintenance scenarios, simulate asset behavior under different conditions, and predict future performance [11].

Digital twins are transforming infrastructure management by providing a holistic view of asset conditions, supporting proactive interventions, and reducing risks associated with unexpected failures.

- *Life cycle management:*

Life cycle management is a comprehensive strategy that spans planning, design, construction, operation, maintenance, and decommissioning of assets.

AI streamlines lifecycle management by integrating diverse data sets and applying predictive analytics to optimize each phase. For example, AI can forecast future maintenance needs, estimate asset depreciation, and guide decisions on asset replacement [12]. Generative AI also plays a role by automating the creation of maintenance plans, generating synthetic training data, and designing optimized asset management workflows.

Additional applications of AI include fields such as healthcare, finance, manufacturing, and education, as follows:

- *Healthcare*: AI assists in drug discovery, personalized medicine, and disease diagnosis [13].
- *Finance*: AI algorithms detect fraud, automate trading, and manage risk [14].
- *Transportation*: Self-driving vehicles use AI for navigation and safety [15].
- *Manufacturing*: Predictive maintenance and quality control are enhanced by AI [16].
- *Education*: Personalized learning platforms adapt to individual student needs using AI analytics [17].

5. Advantages of AI in asset management applications

The integration of AI and computer vision in transportation asset management represents a milestone that reflects a historical shift in how transportation authorities and infrastructure organizations monitor, maintain, and optimize infrastructure projects including road and bridge networks. AI advantages are attained by leveraging advanced machine learning and deep learning algorithms, real-time data analytics, and high-resolution imaging technologies, thus enabling authorities and different project stakeholders to precisely detect deficiencies, propose predictive maintenance, and efficiently allocate resources for job completion. Detailed list of AI advantages is shown in the following section:

- *Operational efficiency*: AI streamlines asset monitoring and maintenance, reducing manual effort and errors. Successful monitoring of transportation assets significantly reduces the time required for maintenance activities, eliminates the need for extended capacity restriction of assets due to lane closures, and/or minimize the need to lengthy detours.
- *Predictive maintenance*: as ML algorithms can analyze historical and real-time data to predict future asset performance. This allows for proactive maintenance before further asset deterioration. In addition, ML can be used to estimate the remaining useful life of assets (RUL), thus providing clear insights into scheduling maintenance at optimized durations, instead of fixed time-based schedules [18–19].
- *Cost savings*: By optimizing maintenance schedules and resource allocation, AI can lower maintenance costs by 10–20%.

- *Improved safety standards:* Automated monitoring and risk detection reduce the likelihood of accidents and hazardous conditions. AI algorithms can analyze historical data to forecast potential safety risks and allow companies to take proactive measures to avoid accidents. AI can be used in worker health and behavior monitoring: real-time monitoring using drones and sensors to provide continuous oversight of construction sites and detect possible safety breaches like not wearing PPEs or operating in close proximity to dangerous equipment. AI and RFID technology are used to alert workers and machine operators when they are in danger of collision.

6. Challenges and limitations facing AI incorporation in asset management

Technical challenges:

- *System reliability and robustness:* AI systems deployed in critical infrastructure must operate reliably under a wide variety of conditions, including adverse weather, unpredictable traffic patterns, and system faults. Ensuring consistent performance in real-world environments remains a significant technical hurdle [15].
- *Data availability and quality:* High-quality, representative data are essential for training and validating AI models, yet many infrastructure settings face challenges in sensor coverage, data sparsity, and noise, which can degrade AI performance and lead to unsafe outcomes [14].
- *Integration with legacy systems:* Many roads, bridges, and tunnels operate on legacy technology. Integrating advanced AI solutions with outdated hardware and control systems is complex and can result in compatibility issues, increased costs, and system vulnerabilities [16].
- *Cybersecurity risks:* As infrastructure becomes more digital and connected, the attack surface for malicious actors expands. AI systems, particularly those connected to critical infrastructure, are susceptible to adversarial attacks and data breaches, potentially compromising public safety [20].

Ethical and societal challenges:

- *Transparency and explainability:* Many AI models, especially those based on deep learning, function as “black boxes,” making it difficult for humans to interpret decision-making processes. Lack of transparency can erode public trust, especially in safety-critical domains [21, 22].
- *Accountability and liability:* Determining responsibility when AI-driven systems malfunction or cause accidents is a complex legal and ethical issue. Clear frameworks for accountability and redress are still evolving, raising questions about liability for operators, manufacturers, and software developers [23].
- *Inclusion and equity:* The deployment of AI in public infrastructure should benefit all societal groups. Risks such as biased data, algorithmic discrimination,

or uneven access to improved services must be carefully managed to prevent exacerbating social inequalities [22].

- *Public trust and acceptance:* Adoption of AI in roads, bridges, and tunnels requires societal buy-in. Concerns over surveillance, data privacy, and perceived loss of human oversight can hinder public acceptance unless addressed by robust governance frameworks [22].

Operational and implementation challenges

- *Cost and resource constraints:* The financial burden of upgrading legacy infrastructure, installing new sensors, and maintaining AI systems can be significant, particularly for municipalities with limited budgets [16].
- *Standardization and interoperability:* The lack of universal standards for AI systems in infrastructure can result in fragmented solutions that do not communicate effectively, limiting system-wide benefits and scalability [24].
- *Continuous monitoring and maintenance:* AI systems require ongoing monitoring, updates, and maintenance to adapt to evolving circumstances and threats. Establishing sustainable models for long-term support is essential for dependable operation [16].

7. Ethical considerations and future trends

With AI's growing role in infrastructure, ethical and governance concerns have come to the fore, elucidating the global landscape of AI ethics guidelines and emphasizing transparency, accountability, and public welfare. As AI systems make critical decisions—from traffic flow to structural safety, the need for robust ethical frameworks is paramount.

Future directions for AI in infrastructure include the following:

- Integration of artificial general intelligence (AGI) to achieve truly adaptive and holistic management systems.
- Expansion of autonomous construction, monitoring, and maintenance, reducing human risk exposure.
- Enhanced collaboration between AI, robotics, and the Internet of Things (IoT) for real-time data fusion and intelligent response.
- Continuous refinement of ethical standards, ensuring AI serves public interests and safeguards privacy.

The convergence of AI with infrastructure technology is not merely an incremental advance—it is a paradigm shift, envisioning roads, bridges, and tunnels as dynamic, self-aware entities capable of learning and evolving in tandem with societal needs.

8. Conclusions

Artificial intelligence is reshaping the construction industry's approach to asset management. AI technologies deliver measurable improvements in efficiency, cost savings, and asset reliability. While challenges related to adoption, data privacy, and integration persist, the benefits of AI-driven asset management are substantial. The future outlook is positive, with continued advancements in AI, IoT, and digital twins expected to drive further innovation. Industry leaders are encouraged to invest in skill development, pilot AI initiatives, and foster a culture of digital transformation to remain competitive.

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Section 2

Transportation Engineering

Impact of COVID-19 on Users' Social Perception of Public Transport in Madrid

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Abstract

The aim of this present study is to analyze how the health crisis caused by pandemic has impacted on public transport users' social perception, on their mobility decisions and whether the policies implemented have generated a greater safety for them. In order to achieve the objective, 1159 public transport users have been surveyed in Madrid. For the methodology, Bitner's Servicescape Model has been used, because through this model, it is possible to analyze the physical environment in which a service is provided. This directly affects the assessment, perception, and user's satisfaction, since the service is produced and consumed simultaneously. To complete the study, a regression model has been carried out. This study is an important contribution to academic literature, as it is the first to examine how the health crisis caused by COVID-19 has impacted on mobility decisions in the biggest city of Spain.

Keywords: COVID-19, pandemic, social perceptions, public transport users, Servicescape model

1. Introduction

Public transport plays an important role in people's lives, being the most ecological and healthy alternative for travel in the city [1]. It underlined the great importance of public transport especially in metropolitan cities to avoid congestion and pollution, promote trade development, competitiveness, and economic activity, as well as promoting social and territorial equity [2, 3]. Another important aspect of an efficient public transport system is the accessibility for everyone [4]. That means that not just the performance of public transportation but also its impact on other social aspects (such as employment rates, public health, and social exclusion) must be taken into account while planning the public transport facilities.

For all the above, when analyzing the public transport system, it is important to analyze how the service is perceived by the users [5, 6]. Several studies on the users' perception of public transport have concluded that service quality is one of the most important factors for users to decide whether or not to use public transport [7, 8]. Factors such as on-board cleanliness, comfort, safety, punctuality, and frequency of

service are main factors in gaining the satisfaction and loyalty of public transport users [9]. However, the current situation caused by the COVID-19 pandemic [10–12] has affected all types of services worldwide, including the public transport system [13, 14]. For fear of not infecting, many people have opted for private transport instead of public, which has changed mobility habits of the users [15, 16]. Moreover, maximum capacity of travelers in the public transport has been reduced, and national and international tourism mobility has been limited [17, 18].

The aim of this research is to analyze how the health crisis caused by COVID-19 has impacted on social perception of public transport users in Madrid, on their mobility decisions and whether the policies implemented have generated a greater safety for them. To achieve this objective, Bitner's Serviescape Model [19] has been applied to analyze social perceptions and to see the effect of COVID-19 on users. A sample of public transport users in Madrid has been used, and the study can serve as a basis for analysis in other cities around the world.

This paper contributes to the existing literature on COVID-19 impact studies in the transport sector, offering a specific view from the users, their perceptions, first impressions, feelings, and behavioral reactions to the situation manifested by the pandemic. This contributes to complete the study of the impact of COVID-19, which is being approached from different perspectives and disciplines.

2. Literature background

COVID-19 spread rapidly almost everywhere, affecting many countries around the world and causing a significant mortality rate [20, 21]. To prevent the spread of the virus, several countries had to declare mandatory quarantine for their populations, thus trying to reduce the number of infected people [22, 23]. Like most countries, in Spain, many companies that were able to change their face-to-face work into online work started to opt for teleworking [24], since the government's recommendation was to facilitate teleworking as much as possible. Because of this, the world of work changed completely from one day to the next [11].

In Spain, after people started working from home and companies closed, almost 19% drop in gross domestic product (GDP) in the second quarter of the year 2020 was recorded [25]. One of the sectors directly affected by the lockdown and pandemic was the public transport sector [15, 16, 26, 27]. Significant increase in teleworking, temporary or permanent loss of job, or changes in labor mobility habits are the factors that decreased significantly the use of public transport in Spain [15, 16]. Other factors also affecting the use of public transport were: the reduction of maximum capacity of travelers in the public transport, service reduction, and decrease of national or international tourist activities [17, 18]. In addition to this, many public transport users refuse to use it to avoid social contact, thus reducing the risk of infection. Therefore, it is important to evaluate the users' perception of public transport safety.

All of the above has caused Spanish public transport to experience a drastic reduction in demand for the system.

2.1 Hypothesis development

The literature review has shown the importance of public transport for society [1, 4, 15]. Although, the situation caused by COVID-19 has put many things to the test, including the policy and image of public transport for its users. The economic

viability of the entire public transport system has been affected, and in the future, public administrations will need to increase subsidies paid to guarantee the correct and effective work of public transportation system. Another piece of information to consider is that after lockdown, public transport has not recovered the percentage of users that it had before the pandemic [16, 18]. Reasons for this may include: fear of infection, permission to work from home, or not having the job because of the pandemic.

In Spain, the biggest city is Madrid, having integrated and high-quality public transport system [28, 29]. Madrid public transport is equipped with a wide range of possibilities when it comes to moving around, has discounts and bonuses for its users, and has a system adapted for the mobility for everyone. However, there is currently no literature on the impact of the pandemic on public transport in Madrid. In view of the above conclusions, the aim of this study is to analyze the perception of public transport users following the policies implemented on the health crisis marked by the COVID-19. According to Rincon-Novoa et al. [30], analyzing consumer behavior from the user's perspective is a topic of interest for public policy, in a context where consumers try to avoid agglomerations. Therefore, the following hypotheses and research question are raised:

RQ1: How the health crisis caused by pandemic has impacted public transport users' social perception?

H1: Policies by COVID-19, which have been adopted specifically in the metro and bus services, affect the perception of safety of both modes of public transport.

H2: Public reporting of increases in cases and outbreaks of COVID-19 has affected users' public transport decisions.

In order to respond to these hypotheses and research question, the city of Madrid has been taken as a pilot test, a city with a high degree of development of public transport networks, considered to be modern and efficient, where urban and suburban transport coexist. This will allow us to obtain a first approximation of the impact that this health crisis is generating on the public transport sector and then to carry out an analysis in other Spanish cities and other capitals of the world.

3. Sample, methodology and questionnaire

3.1 Sample and data collection

First, it is necessary to estimate the sampling error, and we can use the following Random Sampling Error Formula, where:

$$K = 2\sqrt{[(p(1-p))/n]} \quad (1)$$

The size of the sample, n , is determined, 1159 surveys. For p , we assume maximum dispersion, where all elements in the questions have the same probability of being chosen: $p = q = 0.5$. Therefore:

$$p(1-p) = \text{dispersion} = 0.25 \quad (2)$$

So, we get that K for the questionnaire is 2.94%. On balance, the results obtained in our sample of 1159 surveys will fluctuate by $\pm 2.94\%$ at a 95% confidence level in the total population. Responses were collected during the months of July–September 2020.

In order to analyze the extent to which the sample represents the population of Madrid, we compared the main characteristics of this city (with data updated to January 1, 2022, according to the Spanish National Institute of Statistics) with those of the sample. In relation to gender, 48% of the population is male and 52% female. In the sample, the gender distribution was somewhat higher for male respondents (55%). In relation to age, 33% of the population is between 16 and 30 years old, which coincides exactly with the percentage of respondents of this age in the sample. We obtained a higher percentage of respondents between 31 and 50 years of age (50%); however, in the population, this age range represents 31%. In terms of geographic distribution, approximately 50% of the population lives in the capital city of Madrid and 50% in other municipalities. In the sample, 51% of the respondents live in Madrid, 44% in other municipalities, and the rest in other communities in Spain. Finally, if we compare the employment rate, we find that around 60% of the population of Madrid is employed, and in the sample, 70% of those surveyed stated that they were actively working.

For all of the above reasons, the sample is considered to represent the population of Madrid in a significant way.

3.2 Methodology

Firstly, the Bitner's Servicescape Model [19] is used to assess the social perceptions of public transport users. In this way, we will answer the research question 1 raised in this study. This model considers elements that conform to the environment in which the service is produced in order to understand consumers' behavior and observe how it influences certain changes in their purchase decisions. The justification for this model lies in the idea that the physical environment in which a service is provided directly affects the assessment, perception, and satisfaction of the user, since the service is produced and consumed simultaneously. Gao et al. [31] support the idea that certain environmental characteristics influence consumer behavior. The model contemplates three clearly differentiated parts that lead to understanding the social perception of a service:

1. Environmental dimension: understood as the physical and functional space where the service is provided. It generates in the user what the model defines as "first impressions" of the service.
2. Internal responses: more internalized sensations of the user, such as cognitive, emotional, and physiological responses, which arise from the interaction with the service and its environment.
3. Behaviors: after the experience with the service, the user may manifest approaching and avoiding behaviors, which, in turn, have an impact on social interactions.

These concepts related to the Servicescape model have been applied by numerous authors in their research studies [32–36].

The second part of the analysis is based on linear regression and the correlation table to answer the hypotheses raised in this work. Two different models of regression have been elaborated, one with the dependent variable Sec-Cov Bus and another with Sec-Cov Metro (for explanation of variables see annex).

3.3 Research questionnaire

The questionnaire consisted of three blocks based on the Servicescape model. Apart from these three blocks, the questionnaire includes basic questions (e.g., age and gender). The distribution of the questions according to the Servicescape model is explained as follows (Annex shows all questionnaire and its codification used in this study).

In the first block (questions 7–13) about users' first impressions, questions are asked regarding the quality of the environment where the service is provided (air, temperature, noise, smell, space, etc.), about the feeling of safety in the context of COVID-19, among other.

Respect to the “feelings” block (14–19), the questions are more focused on internal user responses, such as whether they reduce the use of public transport if they feel sick, whether it is affected by the number of infected cases reported in the news or where they perceive greater risk of contagion.

Finally, in the behavior block (20–25), questions were included about the reasons for using public transport, the importance of certain service objectives and the services cost increase for user.

The first question of the questionnaire generates a very important distinction between the frequent user and the non-user citizen. If the respondent claims not to be a frequent user, the only valid answers will be those with (**) in the questionnaire (see Annex).

The questionnaire was validated by means of the KMO index and Bartlett's test of sphericity test. The result confirmed the reliability of the questionnaire (KMO = 0.827). After this, Cronbach's alpha was made, where the result was 0.744. Based on this, we can say that the questionnaire was reliable [37].

4. Results and discussion

First, the socioeconomic profile of the respondents is described briefly. In terms of gender, 45% of the respondents are women and 55% men. The 50% of the respondents are aged between 31 and 50, with the second largest group, at 33%, being aged between 16 and 30. The predominant employment situation, with 72%, is full-time work, followed by students with 17%. Likewise, 51% of surveyed people live in the Madrid, while 44% claim to live in other municipalities in the Community of Madrid, a minority from another Spanish community and from abroad.

Other important result in this study is that 73% claim to be frequent users of public transport, which indicates a mobility behavior where the use of the bus and the metro instead of the private transport. However, 60% of the respondents said that they had reduced their use of public transport because of the COVID-19.

4.1 Servicescape model

Based on user responses, the Bitner's Servicescape Model on social perception of public transport in COVID-19 context is analyzed. This will provide an answer to the research question 1.

4.1.1 Block 1: “first impressions”

In terms of air quality, temperature, noise, cleanliness, smell, and space, bus transport environment is better valued than metro transport. With respect to the feeling of security in the COVID-19 context, there is no positive response in none of the modes of transport. Although, in case of the metro, users reflect a clearer trend due to feeling of bad security.

On the other hand, it seems that the indications on safety measures by COVID-19 are indifferent in both modes of transport, although in the case of busses, they are somewhat better-valued. Likewise, the treatment of employees in general seems to be well appreciated by users.

4.1.2 Block 2: “feelings”

The users clearly state that they avoid using public transport if they feel sick. In COVID-19 context, it may indicate that the user takes precautions to avoid contagion and actively participates in preventing its spread.

In general terms, the younger is the age of users, the greater is the reduction in the use of public transport. Also, there is a clear trend to state that the use of transport is reduced when the number of reported cases of contagion increases. The user is indifferent when it comes to evaluation of public transport in Madrid as efficient, modern, and prepared for the pandemic.

Users perceive, in 57% of cases, that the bus has a lower risk of contagion, in 33% of cases they consider that the risk is the same in both cases, and in the remaining 10%, they consider that it is the metro that has a lower risk.

Regarding the open question, about the image with which public transport is associated in the city of Madrid, we have typified the answers obtained based on a common denominator. **Figure 1** shows the percentages recorded:

The most received answers are related to the poor quality of the service, specifically to the image of agglomerations of citizens using transport. Some of the most recorded responses are those related to COVID-19. Specifically, respondents indicated

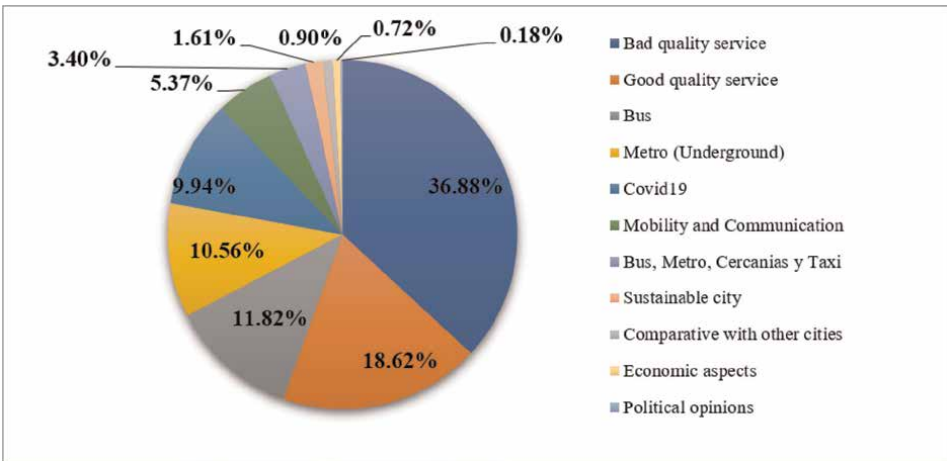


Figure 1.
Typified answers about the image of public transport in the city of Madrid. Source: own elaboration.

issues such as “risk,” “contagion,” “masks,” “safe distance,” and “COVID-19” as indicators that the public transport service is now strongly associated with the pandemic.

4.1.3 Block 3: “behavior”

The results obtained have shown a mandatory reason for using public transport, mainly due to financial savings and lack of a private car. High volume of answers reported that the users using public transport mainly for work purposes and not for leisure activities.

In relation with the service’s objectives, **Figure 2** shows a ranking. This ranking allows to obtain the value or importance that users attach to the following service objectives:

- Waiting times or frequency of service [Tobjet-freq]
- Safety feeling [Tobjet-safety]
- Level of technological development [Tobjet-ICT]
- Speed or travel time [Tobjet-speed]
- Universal accessibility to the service for all users [Tobjet-Univaccess]
- Comfort sensation, quality of space, temperature.... [Tobjet-space]
- Contribution to environmental sustainability [Tobjet-sustainab]

In none of them is the average rating below 4 (“important”), so they are all considered essential for public transport. However, two objectives stand out from the others, frequency and safety. Therefore, in current situation affected by the pandemic, greater security, which may be related to possible contagion, is a key objective for the user. Frequency, on the other hand, can also lead to greater safety, since it contributes to a lower volume of “crowded” passengers on each train at peak times and can reduce the risk of contagion.

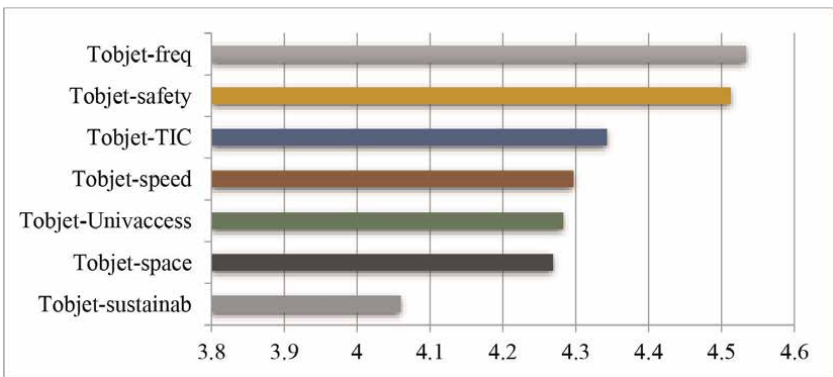


Figure 2.
Objectives' ranking in public transport by users (sorted by average rating). Source: Own elaboration.

Finally, the responses on cost increase of the service for users to have a greater safety by COVID-19 reflect quite a dispersion. However, the tendency toward conformity is a little clearer if the respondent is asked about sharing this cost over all citizens, not just users, as it results in greater safety for all.

4.2 Correlation and linear regression

In this section, we will answer the hypotheses raised above. The dependent variables for testing the hypotheses were users' perceived safety during the pandemic in metro (Sec-Cov Metro) and bus (Sec-Cov Bus). The following variables have been used for explaining the dependent variables: EQ Bus, EQ Metro, Safe-Signal Metro, Safe-Signal Bus, BvsM riskCov, TP-COV, and Tuse-CI (see Annex for more details).

Therefore, the correlation matrix was made (see **Table 1**) where the link between dependent variables and independent variables was shown. There is a strong relationship between dependent variables and explanatory variables as the perceived quality of services and the indications on safety measures during the pandemic. There is an interesting correlation between dependent variables and the news reports about increase in COVID-19-infected cases. As the relationship is negative, this result suggests that when the reports about number of COVID-19-infected cases were going down, users' feelings about the safety to use the public transport were increasing.

However, it should be noted that the correlation results are not conclusive. For this reason, a linear regression analysis has been carried out to confirm the previous

Sec-Cov Bus	1								
Sec-Cov Metro	0.6136*	1							
	0.0000								
EQ Bus	0.7144*	0.4305*	1						
	0.0000	0.0000							
EQ Metro	0.4096*	0.6407*	0.5187*	1					
	0.0000	0.0000	0.0000						
Safe-Signal Bus	0.7137*	0.5191*	0.6382*	0.3980*	1				
	0.0000	0.0000	0.0000	0.0000					
Safe-Signal Metro	0.4948*	0.6551*	0.4470*	0.5338*	0.7406*	1			
	0.0000	0.0000	0.0000	0.0000	0.0000				
BvsM riskCov	-0.2402*	0.0588*	-0.2422*	0.0443	-0.2058*	-0.0393	1		
	0.0000	0.0452	0.0000	0.1319	0.0000	0.1812			
TP-COV	0.5520*	0.5491*	0.4651*	0.4180*	0.5008*	0.4603*	-0.0845*	1	
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040		
Tuse Tuse-CI	-0.2034*	-0.1763*	-0.1324*	-0.0716*	-0.1536*	-0.1224*	0.0602*	-0.1038*	1
	0.0000	0.0000	0.0000	0.0148	0.0000	0.0000	0.0406	0.0004	

*P < 0.05.

Table 1.
Correlation matrix.

Variables	Sec-Cov Bus		Sec-Cov Metro	
	Coef.	P > t	Coef.	P > t
Sec-Cov Metro / Sec-Cov Bus	.4294593	0.000	.4907204	0.000
EQ Metro	-.1396575	0.000	.3563101	0.000
EQ Bus	.4264429	0.000	-.2300399	0.000
Safe-Signal Bus	.4538899	0.000	-.2030143	0.000
Safe-Signal Metro	-.2423583	0.000	.3945092	0.000
BvsM riskCov	-.1114827	0.000	.1407047	0.000
TP-COV	.0849451	0.000	.1374505	0.000
Tuse-CI	-.0361566	0.012	-.0461876	0.003
_cons	.266723	0.013	-.3311515	0.004

Table 2.
Results of the linear regression.

results. Two regression models have been made with each of the dependent variables (see **Table 2**). The result has shown that the explanatory variables justify an overall 73% (r^2) of the proposed model for the variable Sec-Cov Bus and 69% (r^2) for the dependent variable Sec-Cov Metro. Furthermore, the p-value was 0.00 for both models.

The Durbin-Watson statistic has shown the result of 2.01 for the model Sec-Cov Bus and 1.97 for the model Sec-Cov Metro. Through this statistic, the independence of the residuals is detected when it is between 1.5 and 2.5 [38]. In this model, we can assume that the residuals are independent.

In model one, the dependent variable is Sec-Cov Bus, and the Sec-Cov Metro variable is an independent variable. In model two, the dependent variable is Sec-Cov Metro, and the Sec-Cov Bus variable is an independent variable. In both models, we can see that when the user's feeling of safety increases in one mode of transport, it also increases in the other.

In model one, if the perceived quality of service (in terms of air quality, temperature, noise, cleanliness, smell, and space) and the safety signs on bus are well rated, the feeling of safety increases on bus. The same is true for metro in model two. On the contrary, there is an inverse relationship between two modes of transport: if the perceived quality of service and the safety indications on metro decrease, this causes the feeling of safety on bus to increase. This is probably, because the user sees bus as safer than metro. Otherwise, the same is true for metro.

On the other hand, we can see how if users associate metro and bus with efficiency and transport prepared for the pandemic situation, the safety feeling is enhanced when using bus and when using metro. Finally, in relation with the variable Tuse-CI, we can see that when the public transport users' see that the number of infected people drops in, the feeling of safety on bus and metro improves.

5. Conclusions

The results obtained show that in Madrid, there is a high use of public transport. However, because of the health crisis caused by COVID-19, users are trying to reduce

their use as much as possible. This may be due to different reasons. On the one hand, it could be the increase in teleworking, which makes travel for work purposes less necessary. On the other hand, users are increasingly trying to avoid contagion and avoid using this service for non-obligatory travel.

Through the Servicescape Model, we have obtained the following social perceptions on the use of the service in COVID-19 context, answering the research question posed:

1. Users do not value public transport in Madrid as a service prepared for COVID-19. It seems that the policies adopted, or the lack of them, do not contribute to a perception of safety for citizens. In this sense, there is a greater perception of risk of contagion in the metro than in the bus, so policies should be aimed at providing a safer service in the metro and give greater confidence and reliability to the user. The citizens are also willing to bear the increased cost as a burden that results in greater safety for all.
2. User takes precautions to avoid contagion and actively participates in preventing its spread, so reduces the use of public transport as much as possible. The younger is the age of users, the greater is the reduction in the use of public transport. In colleges and universities, part of the teaching is done online, and the policies adopted are aimed at reducing the mobility of these groups. In this sense, we could confirm that the policies are fulfilling their objective.
3. The public transport service is strongly associated with the pandemic. Then, users give a higher priority and assessment to the frequency of the service, for greater control of capacity and the security of the environment where the service is offered.
4. Those users who use public transport for work purposes cannot so easily reduce the use of this service. This fact, together with the use of the service for reasons of economic savings and lack of a private car, reflects obligatory mobility patterns [39, 40]. It could therefore be said that the decision to reduce the use of public transport will mainly affect leisure travel, with the consequent impact on consumption and the economy.

With respect to the first hypothesis, we can confirm that the data recorded show that the policies adopted specifically for the bus and metro service affect the perception of safety of both services together. The model also identifies the key issues on which policies need to take action to increase confidence in public transport safety and avoid COVID-19 risk. Specifically, the quality of the service provided, in terms of air quality, temperature, noise, cleanliness, smell, and space, the indications of safety measures, and the way in which cases of contagion and their evolution are reported. The second hypothesis is confirmed since the increase in reported cases affects mobility patterns and contributes to the reduction in the use of public transport. This statement supports the need to ensure that the information that is transferred about contagion is reliable and comparable over time, since it can affect citizens' mobility patterns.

A. ANNEX. Questionnaire for public transport user perception in the context of COVID-19

Question/Variable name	Possible answers/Code					
1. Are you a frequent user of public transport in the city of Madrid? / Freq-user TM	YES 1			NO 0		
2. Gender / GEN (**) 	Female 1	Male 2		I do not want to answer 0		
3. Age / AGE (**) 	Between 16 and 20 1	Between 31 and 50 2		Between 51 and 65 3	Over 65 4	
4. Situación laboral / EMP-SIT (**) 	Student 1	Part-time worker 2	Full-time worker 3	Unemployed 4	Retired 5	In a situation of ERTE 6
5. Live in / PL-RES (**) 	Madrid City 1	Another municipality in the Community of Madrid 2		In another Spanish community 3	Abroad 4	
6. Have you reduced the use of public transport as a result of COVID19? / T-USE Covid19	YES 1			NO 0		
7. How do you perceive the quality of service in EMT busses in Madrid, in terms of air quality, temperature, noise, cleanliness, smell, and space / EQ Bus	1 (very bad)	2 (bad)	3 (neutral)	4 (good)	5 (very good)	
8. How do you perceive the quality of the service in Metro of Madrid, in terms of air quality, temperature, noise, cleanliness, smell, and space / EQ Metro						
9. How do you assess the feeling of safety in the context of COVID-19 in EMT busses in Madrid? / Sec-Cov Bus						
10. How do you assess the feeling of safety in the context of COVID-19 in Metro of Madrid? / Sec-Cov Metro						

Question/Variable name	Possible answers/Code				
11. The indications on safety measures for COVID 19, in EMT busses in Madrid are considered to be... / Safe-Signal Bus					
12. The indications on safety measures for COVID 19, in Metro de Madrid consider that they are... / Safe-Signal Metro					
13. The treatment of employees is considered to be (driver, ticket agents, security guards...) / Employ-relat					
14. If you feel sick, try to avoid using public transport / Tuse sick (**) Tuse sick (strongly disagree)	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
15. When the news reports an increase in cases and regrowth, affects you to decide use public transport / Tuse-CI (**) Tuse-CI (strongly disagree)					
16. Do you associate Madrid's bus and metro transport with modernity, efficiency, and transport prepared for the COVID-19 situation / TP-COV (**) TP-COV (strongly disagree)					
17. Have you replaced public transport with private transport or other modes of transport (cycling, walking...) as a result of the COVID-19 / TS-COV TS-COV (strongly disagree)					
18. Which of the two transports do you consider to have the least risk against COVID-19, bus or metro? / BvsM riskCov (**) BvsM riskCov (strongly disagree)	BUS (EMT of Madrid) 1	METRO 2	Both equally 3		
19. If you hear about public transport in the city of Madrid, what image/ideas comes to mind / Timage (**) Timage (strongly disagree)	Open answer (see typified answer in Figure 1)				

Question/Variable name	Possible answers/Code				
20. You use public transport mainly for / Tuse reason	For time saving 1	For social awareness 2	For economic saving 3	For lack of a private car 4	Other 5
21. Use public transport for work purposes / Tuse-JOB	1 (not at all)	2 (a little)	3 (sometimes)	4 (often)	5 (very often)
22. Use public transport for leisure purposes / Tuse entertainm					
23. Graduate the importance of the following objectives in public transport: Waiting times/frequency Tobjet-freq Speed/travel time Tobjet-speed Comfort, space, temperature... Tobjet-space Security Tobjet-safety Universal Accessibility Tobjet-Univaccess Technological development Tobjet-TIC Environmental sustainability Tobjet-sustainab	1 (very unimportant)	2 (unimportant)	3 (neutral)	4 (important)	5 (very important)
24. Agree with the increased cost of the service to provide greater security by COVID-19 / Cost-inc safeCov (**)	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
25. The increase in costs must be cover by all citizens as it is in the interest of greater security for all / Cover cost citizens (**)					

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Urban Bus Network Electrification

Dávid Földes, Bálint Csonka and Péter Ákos Szilassy

Abstract

Electric busses are spreading in cities in hope of mitigating local air pollution. Currently, battery electric busses are more expensive and require novel operational methods to optimize their use (e.g., applying daytime charging, and operating trolleybuses). Despite these, the electrification of urban busses is usually ad-hoc, preliminary planning is superficial, and does not consider the relationships among bus lines. This chapter introduces a method regarding charging infrastructure planning, electric bus type selection, and cost estimation. Based on the characteristics of the vehicle, charging infrastructure, bus service (lines, timetable, etc.), and energy consumption, a line-group optimization is introduced, which is the main novelty. The method was applied in a case study considering static terminal and dynamic catenary charging. The results help operators to boost the electrification of the urban bus network.

Keywords: bus network, electrification, electric bus, trolleybus, static charging, dynamic charging, catenary network

1. Introduction

Electric buses help reducing local air and noise pollution, especially in cities [1, 2]. As the consequence of technological developments, especially in the battery industries, electric buses with high range are available in the market. Different bus types are used from high-capacity battery electric buses to trolleybuses without autonomous running capacity. The bigger the battery capacity is, the longer the distance covered autonomously is (**Figure 1**).

Static (in the depot, at the terminus, or bus stops) and dynamic in motion (catenary) charging solutions are applied in the urban bus network. The exclusive use of depot charging results in higher battery requirements. To reduce battery capacity, buses are charged during daytime with static chargers at common terminals (**Figure 2a**) or in movement with dynamic chargers along common sections of bus lines (**Figure 2b**).

In practice, the bus network is more complex, including common sections, and terminals. Furthermore, there is a strong relationship between the number of electric buses and charging units, battery capacity, and charging power. The research questions are how big battery capacity is needed and how big charging power in static chargers or how long dynamic chargers is needed.

More than 100,000 electric buses are running in the world, mostly in China. According to the expectations, the market size will grow fast, and at the end of 2027 almost 700,000 battery electric buses will be on the roads [3].

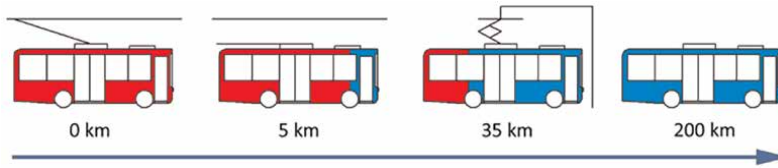


Figure 1.
Flexibility based on the autonomous range of electric buses.

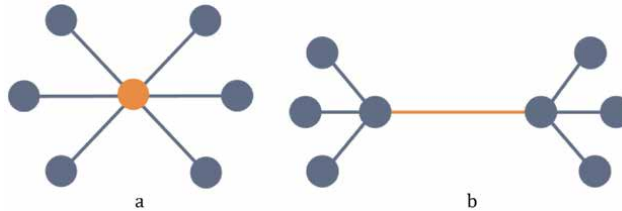


Figure 2.
Bus network characteristics: Asterisk (a), common section (b).

Therefore, a charging infrastructure and electric bus fleet determination methodology were developed to minimize the total cost of deployment and the procurement costs of the charging infrastructure and buses. The novelty of the method is that the optimization is performed for the network and not for only one bus line. Practically, cost minimization can be performed for lines with the same terminus or with significant common section(s).

The remainder of this chapter is structured as follows. In Section 2, the literature is reviewed. The electrification methodology is described in Section 3. The application of the method in Budapest, as a case study, is summarized in Section 4. Finally, conclusions are drawn.

2. Literature review

Several researchers deal with electric buses, developing methods for infrastructure planning or elaborating operational methods to overcome the drawbacks of electric buses such as range limitation and longer charging time.

Baumeister et al. [4] dealt with the optimal design of the catenary system for trolleybuses considering the energy demand of vehicles and mileage. The method minimizes overhead line extension and development costs. In addition, Paternost et al. [5] investigated the power supply of the catenary network using a data-driven approach, in which the current and power of each traction substation are measured. A power supply estimating method was developed to evaluate future development; the energy consumption at sections can be estimated with an error of 7%.

For e-buses with static chargers, the location and charging capacity determination are the most studied areas. Lin et al. [6] dealt with evaluating and fitting the connections between transport and energy networks. It has been established that in order to minimize maintenance costs in terms of time and space, the construction of charging infrastructure, considering the attributes of the electric network, should be optimized. Wang et al. [7] gives an example of simultaneous optimization of charging power and

battery capacity, while Wang et al. [8] dealt with static fast-charging systems. It was proved that pantograph charging could be used to minimize the capacity of the battery. They found that a 13% cost reduction can be achieved with the use of a fast-charging system instead of static, slow charging.

A location planning method for the terminal charger was developed [9], considering the distribution network but not considering other charging opportunities. Clustering algorithms and swarm optimization was used. It was stated that battery electric buses should be operated mostly in an urban environment because of the range limitation. However, e-buses can also be used in intercity and long-distance transport [10]. Though, it was found that 26–60 minutes break for charging should be applied, which can extend the travel time significantly.

The state of charge of the battery and the use of the battery highly influence the availability of the vehicle. Charging scheduling [11] and timetable redesign [12, 13] are widely accepted approaches in electric bus operation. Well-scheduled terminal charging helps e-buses to achieve similar availability to diesel buses [14]. Due to the fixed route and predictable passenger traffic, there is a huge advantage in the charging schedule of public transport vehicles. Therefore, the charging demand of vehicles can be estimated more easily than in the case of passenger cars. In this regard, Wang et al. [15] developed a charging strategy considering energy consumption and electric price alteration to ensure accurate and cost-optimal charging scheduling. Knowing these issues, Leou et al. [16] bring a niche in the research with the minimization of charging costs by shifting charging to off-peak periods. To manage the high grid load caused by charging, a stationary energy storage system can be installed. Using a state of charge (SoC) control strategy for a battery with a 40 kWh stationary energy storage, the momentary power demand from the electric grid can be reduced by more than 70% [17].

Based on the literature review, a timetable redesign is a used approach; however, it may reduce the service quality. Furthermore, usually, one type of charging infrastructure (static or dynamic) is investigated without considering the mixture of them.

In this research, our previous results will be used as a base. With the analysis of static and dynamic chargers, Csonka [18] found that either static or dynamic chargers are preferred for each line out of the equilibrium point, considering the charging infrastructure cost. However, the consumption of buses during a route and the vehicle scheduling were considered with a rough estimation. In this research, the energy consumption calculation was improved based on Szilassy and Földes' study [19] to get more comprehensive results.

3. Methodology

As a basic principle, we considered the current bus lines and timetables. Static terminus charging and dynamic catenary charging were analyzed. Static chargers at intermediate stops were neglected as their use may require travel time alteration. To store the daily energy demand in buses, a high battery capacity is needed in each vehicle, that is expensive and heavy. Furthermore, one charging unit is needed for each bus at the depot that is not efficient in the case of a huge fleet. Therefore, static charging in the depot was only considered as supplementary charging, and buses were considered to have a smaller battery capacity to minimize the vehicle mass. Thus, the vehicles must be charged several times a day.

The same steps were identified in the application of electric buses with static chargers, and trolleybuses with dynamic catenary chargers. However, the calculation method can be different. The steps are as follows:

1. Modeling (physical and energy model)
2. Scenario building
3. Energy consumption calculation
4. Possible charging time determination
5. Charged energy estimation
6. Energy balance calculation
7. Calculating the number of vehicles needed
8. Determining the charging vehicles at the same time
9. Determining the charging devices (number of static chargers, sections of dynamic chargers)
10. Procurement cost estimation

3.1 Physical and energy model building

The energy model is presented in **Figure 3**, summarizing the energy losses from the energy grid to the drivetrain. The energy losses are expressed with efficiency rate

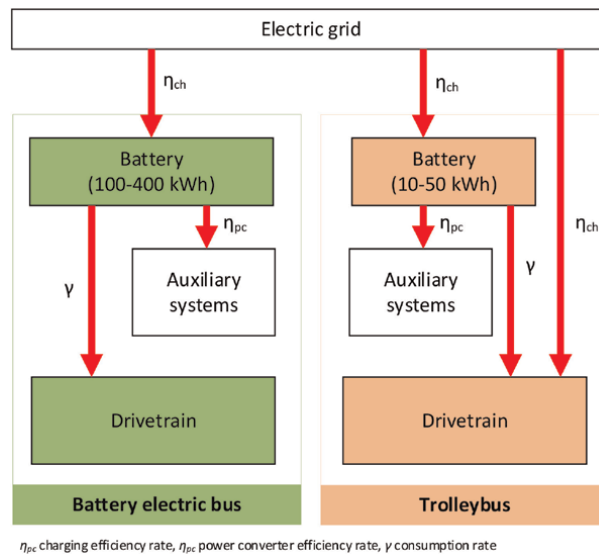


Figure 3.
Energy model.

in the case of energy loss during charging and during the power conversion to operate the auxiliary systems. In addition, the consumption rate expresses the loss from the battery to the drivetrain.

Every bus stops ($i, j \in 1 \dots n$, where n is the total number of stops) are considered as a node. Each section has a direction and connects two nodes. Each section is indicated by its origin and destination node, e.g., section ij . The smallest section is between two stops; the biggest section is between the two terminals. The more detailed the section division is, the more accurate the estimation is.

3.2 Scenario building

Different scenarios can be built by varying the applied vehicles and charging units. In the case of dynamic chargers, scenarios can be built by forming different catenary networks. The scenarios can be compared based on the cost.

3.3 Energy consumption calculation

The $E_{DEMAND,ij}$ energy consumption is estimated between two charging points on a line; namely between terminus in the case of battery electric bus application and between two stops in the case of trolleybus application.

The energy consumption in a section can be estimated by calculating the running dynamics considering the acceleration force and speed on a route, and by calculating the auxiliary system consumptions [19]. Based on the two energy categories - E_{DRIVE} driving dynamic energy consumption and E_{AUX} auxiliary energy consumption -, the E_{DEMAND} total energy demand in kWh can be determined for each ij section (Eq. (1)).

$$E_{DEMAND,ij} = E_{DRIVE,ij} + E_{AUX,ij} \quad (1)$$

The E_{DRIVE} driving dynamic energy consumption in a section is calculated by Eq. (2).

$$E_{DRIVE,ij} = (\gamma + b_{ij} + e_{ij}) \cdot l_{ij} \quad (2)$$

where γ is the consumption rate [kWh/km], which depends on the drivetrain (η_{drive}), and recuperation efficiency (η_{recup}); b is the braking loss [kWh/km]; e is the elevation loss [kWh/km], l is the length of the ij section [km]. The c consumption is a generalized correction value expressing the difference according to bus type and categories (e.g., single or articulated buses). The b breaking loss is estimated from the kinetic energy considering the number of stops in an ij section (Eq. (3)).

$$b_{ij} = \frac{s_{ij} \cdot m_{ij} \cdot v_{max,ij}^2}{2 \cdot l_{ij}} \quad (3)$$

where s is the number of stops on the section, m is the mass of the vehicle on a section which may fluctuating due to the passenger load, and v_{max} is the maximum speed available on the section. The mass of the vehicle may alter in sections expressing the general passenger load. The e_{ij} elevation loss in a section is calculated from the potential energy (Eq. (4)).

$$e_{ij} = \frac{m_{ij} \cdot g \cdot \Delta h_{ij}}{l_{ij}} \quad (4)$$

where g is the acceleration of gravity [m/s^2], Δh is the height difference on a section [m].

According to the previous study [19], the E_{AUX} auxiliary energy consumption can be calculated based on the power and their usage time by Eq. (5). The power demand for cooling/heating the passenger compartment and tempering the vehicle battery is influenced by the temperature as well. For instance, the following consumers can be considered: HVAC (Heating, Ventilation and Air Conditioning) system, BTMS (Battery Thermal Management System), electric power steering, air compressor, doors, parking brake, and wiper system.

$$E_{AUX} = \frac{P_{AUX}}{\eta_{pc} \cdot t_{ij}} \quad (5)$$

where t_{ij} is the travel time in a section; η_{pc} is the power converter efficiency rate; P_{AUX} is the power demand of the auxiliary systems calculated by summing the power demand of the auxiliary systems.

3.4 Possible charging time determination

For electric buses with static charger: The t_{ch} periods spent a bus at a terminal are determined. Periods spent at the terminals are considered if the arrival or departure times are within the analyzed time interval, or the driver starts or ends the resting time within the time interval. Note that technology time for charging should be considered (e.g., approaching the charging station, connection time) thus, the possible charging time is shorter than the actual time spent at a terminal. Moreover, no need to analyze the whole day; rush hours may provide a good estimation as the charging demand is expected to be the highest. The longer the considered time interval is, the higher the reliability of the method is. **Figure 4** depicts the running and possible charging intervals of different buses running on different lines. Terminal A is a common terminal; all the buses may charge there. Bus 1 must be charged at terminal A, bus 2 can be charged at terminal B and bus k can be charged at terminal 3.

For trolleybuses with dynamic catenary chargers: The t_{ch} exact time interval spent at in a section according to the timetable is determined.

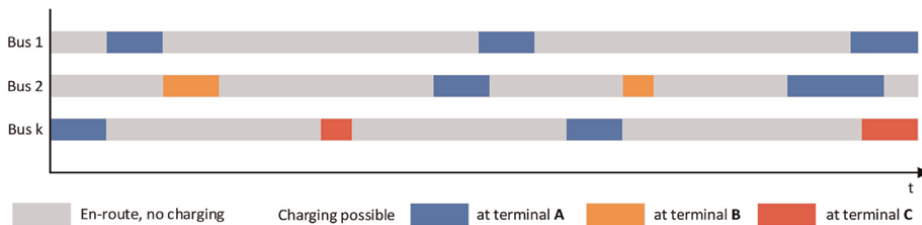


Figure 4.
Possible charging intervals of buses.

3.5 Charged energy estimation

The charged energy by bus k at a charging facility (static charging station or dynamic catenary charging) is calculated by Eq. (6), considering the charging loss.

$$E_{CHARGED} = t_{ch} \cdot P \cdot \eta_{ch} \quad (6)$$

where t_{ch} is the charging time of a bus at terminal i or section ij , P is the nominal charging power at station i (static a charging) or on section ij (dynamic catenary charging), and η_{ch} is the charging efficiency rate, which expresses all the losses of battery charging. This consists of transformer losses, cable losses, battery monitoring system (BMS) losses, battery component resistance, and voltage drop on various electric components.

The battery capacity and the current SoC influences the chargeable energy. Namely, batteries cannot be overcharged (Eq. (7)).

$$\frac{E_{CHARGED}}{B} \leq 1 - SoC \quad (7)$$

where SoC is the state of charge of the battery; B is the battery capacity.

3.6 Energy balance calculation

The energy balance (ε_{ij}) of a bus in a section is the rate of energy demand and charged energy.

For electric buses with static chargers: The energy balance is calculated by Eq. (8).

$$\varepsilon_{ij} = \frac{E_{DEMAND,ij}}{E_{CHARGED}} \quad (8)$$

ε_{ij} should be equal or higher than 1 in order to charge enough energy to cover the energy demand of the section. Additional time is needed; as the timetable is fixed, a so-called n_{ts} turn shift is applied for the bus.

If the n_{ts} turn shift is 1, bus k skips one departure. If the additional time is not enough to reach $\varepsilon_{ij} \leq 1$, another turn shift is needed. Every turn shift requires an additional bus in the fleet. To analyze whether the energy balance is $\varepsilon_{ij} \leq 1$, the calculation of charged energy (Eq. (6)) should be modified; the headway time is added to the charging time as many times as many turn shifts are needed (Eq. (9)).

$$E_{CHARGED} = (n_{ts} \cdot t_{hw} + t_{ch}) \cdot P_i \cdot \eta_{ch} \quad (9)$$

where t_{hw} is the headway between k and $k + 1$ bus.

Figure 5 depicts a case when the turn shift is 1; each departure is shifted by one. Serving all of the original departures results in the need for an additional bus.

For trolleybuses with dynamic catenary chargers: Besides the battery charging, the running energy should be provided. The energy balance is calculated by Eq. (10).

$$\varepsilon_{ij} = \frac{E_{DEMAND,ij} + B(1 - SOC_i)}{E_{CHARGED,ij}} \quad (10)$$

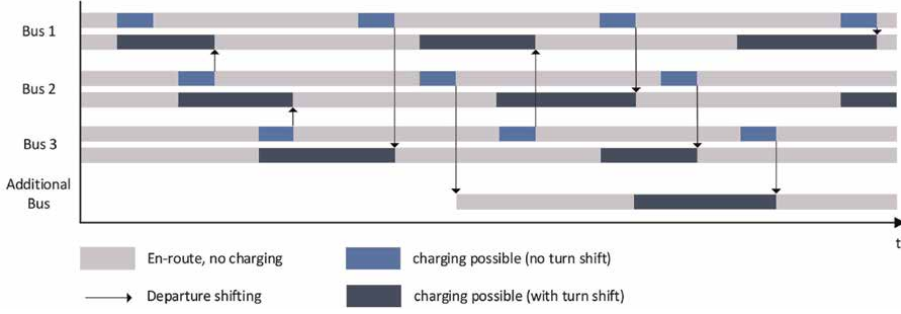


Figure 5.
The alteration of departures resulting from turn shift.

where SoC is the state of charge at the beginning of the section. If $\varepsilon_{ij} \leq 1$ the battery can be fully charged at the end of the section.

Both in the case of static and dynamic charging, if the B is higher than the E_{DEMAND} , the bus can be applied. The current SoC of a bus usually is not lower than a minimum level (e.g. $SoC = 20\%$). This condition is formulated by Eq. (11).

$$B \cdot \eta_{batt} \geq E_{DEMAND,ij} \quad (11)$$

where η_{batt} is the capacity utilization of a battery (if the required minimum SoC is 20% , η_{batt} is 0.8).

3.7 Calculating the number of vehicles needed

For electric buses with static chargers: The n_{ebus} number of e-buses needed is the sum of currently needed conventional buses and the number of turn shifts (Eq. (12)).

$$n_{ebus} = n_{bus} + n_{ts} \quad (12)$$

where n_{bus} is the number of currently needed buses.

For trolleybuses with dynamic catenary chargers: The n_{tbus} number of trolleybuses needed is not changed. The sections with a catenary system should be optimized in order to serve the line with the same number of vehicles.

3.8 Determining the charging vehicles at the same time

For electric buses with static chargers: The $n_{ch}(t)$ number of charging buses at a terminal in period t (e.g., minute) can be calculated based on the number of buses staying at the terminal (Eq. (13))

$$n_{ch}(t) = \sum p(t) \quad (13)$$

Where p is the probability of charging, each bus at the terminal has a probability of charging. The probability value is determined according to the energy balance. A possible representation of the values is presented in **Table 1**. The possibility of a free charging unit can be increased by increasing the difference between p and $\max(\varepsilon)$ in each category because more chargers will be deployed. However, it reduces the utilization rate.

ε	0–0.29	0.3–0.39	0.4–0.54	0.55–0.74	0.75–0.79	0.8–1
p	0.3	0.4	0.7	0.8	0.9	1

Table 1.
Probability of charging.

For trolleybuses with dynamic catenary chargers: The $n_{ch}(t)$ number of connected and charging trolleybuses at section period t is counted (Eq. 14). A p probability is also introduced to express the probability that a vehicle is being charged in period t .

$$n_{ch}(t) = n_{tbus,ij}(t) \cdot p \quad (14)$$

where $n_{tbus}(t)$ is the number of trolleybuses in the section at a given period. The considered t period should be small (maximum 1 minute) as the needed charging power is influenced by the vehicle trajectory. The peak power is given if all the vehicle in the section accelerates.

3.9 Determining the charging devices

In this step, we determine the number of charging devices at terminals and sections where a catenary system is needed.

For electric buses with static chargers: The n_d number of charging devices at a terminal should be able to serve the maximum demand for charging. It can be calculated based on the maximum number of charging buses in a period (Eq. (15)).

$$n_d = \left\lceil \max \left(\sum n_{ch}(t) \right) \right\rceil + 1 \quad (15)$$

For trolleybuses with dynamic catenary chargers: A greedy-like deployment strategy is applied. The section should be selected for catenary deployment where the rate of vehicles can be served, and length is the highest.

If the charged energy on the whole line is more than the energy demand, there is no need to designate a new catenary section (Eq. (16)).

$$\sum E_{CHARGED,ij} \geq \sum E_{DEMAND,ij} + \sum B(1 - SOC_i) \quad (16)$$

If the charged energy is not enough to cover the rest of the section(s) additionally catenary section(s) should be designated.

- Either the catenary system should be extended to select a neighboring section; in this way, the deployment cost can be minimized,
- Or an individual section (without a neighboring section with catenary) should be selected (e.g., where the number of charged vehicles in the same t interval is high); in this way, the deployment cost may be higher as electricity grid investments may occur.

For procurement cost optimization, bidirectional catenary network deployment is suggested. With the summarization of the l_{ij} section lengths where the catenary system should be installed, the l_{ch} total length of dynamic chargers is given.

3.10 Procurement cost estimation

The estimated procurement cost is counted by Eq. (17) for electric bus purchase and static chargers' deployment (P_{ebus}) and by Eq. (18) for trolleybus purchase and catenary network deployment (P_{tbus}).

$$C_{ebus} = n_{ebus} \cdot c_{ebus} + n_{ch} \cdot c_{ch} \quad (17)$$

$$C_{tbus} = n_{tbus} \cdot c_{tbus} + l_{ch} \cdot c_{cat} \quad (18)$$

where c_{ch} is the nominal cost of the static charger, c_{cat} is the nominal cost of a catenary, c_{ebus} is the cost of an electric bus, c_{tbus} is the cost of a trolleybus.

The C_{grid} grid development cost (Eq. (19)) is estimated based on the summarized peak power at a i terminus or in a ij section.

$$C_{grid} = P_{peak} \cdot c_{grid} \quad (19)$$

where c_{grid} is the nominal cost of grid development, including power plant capacity extension and the development of the transmission and distribution network. P_{peak} is the peak power calculated according to Eq. (20).

$$P_{peak} = n_{ch}(t) \cdot P \quad (20)$$

The more detailed cost data are available, the less approximated results are given. Note: additional infrastructure elements, such as charging devices in depot, maintaining, and repairing devices, were out of the scope of this study.

4. Case study

The method developed was applied as a case study in Budapest. Budapest is the capital of Hungary, with an extended public transport network. Besides underground and tram lines, there are approx. Two hundred fifty bus lines covering almost 3000 km and there are 15 trolleybus lines covering almost 100 km. In a general weekday, 2.5 million trips are made in which almost 50% done by buses or trolleybuses.

Eight bus terminals and seven bus line groups were analyzed. In the case of bus line groups, we investigated whether trolleybuses with dynamic catenary systems or electric buses with static terminal chargers are the most beneficial. Altogether 85 bus lines were analyzed.

4.1 Values of the variables and limitations

Timetable and vehicle scheduling at morning peak hours between 6 and 9 were investigated.

The γ consumption rate was estimated based on the general consumption given in [20]. In the case of a single vehicle, the consumption rate is $\gamma = 0.9$ kWh/km, in the case of an articulated vehicle it is $\gamma = 1.3$ kWh/km.

The v_{max} maximal speed was assessed based on the average speed achievable on an ij section.

- if $\bar{v} \leq 25$ km/h, then $v_{max} = 30$ km/h,
- if $25 \text{ km/h} < \bar{v} \leq 30$ km/h, then $v_{max} = 40$ km/h,
- if $\bar{v} > 30$ km/h, then $v_{max} = 50$ km/h.

We considered the auxiliary systems given in Szilassy at Földes' article [19]: HVAC, BMTS, air compressor, power steering, parking brake, wipers, doors, light, vending machine, and passenger information displays. For simplification, the same values were applied for single and articulated e-buses and trolleybuses. The temperature dependence of HVAC and BMTS systems is significant [20, 21]. To determine which temperature should be used during the calculation we analyzed the frequency of daily minimum temperature in winter and maximum temperature in summer between 2008 and 2019. In winter days, the chance is 16% that the daily temperature is lower than -5°C . The lowest degree was -16°C . In summer days, there is 4.2% chance that the daily temperature will be higher than 35°C . The highest degree was 39°C .

Our aim was to plan the network in the worst-case scenario. Thus, we investigated when the energy consumption is higher at lower or higher temperature. We applied step 3 in bus line 44 (articulated) and 144 (single). The estimated energy consumption is given at different temperatures in **Table 2**.

The energy consumption is higher in cold weather. We considered the energy consumption at -5°C . Accordingly, the chance that the energy consumption is higher than expected is 4% in a year. Approximately there are 15 days in a year, only in winter, when the e-buses should save some energy during a run (e.g., lower heating temperature in the passenger cabin).

The P nominal charging power of the catenary network was 100 kW. In the case of static chargers, three different nominal power was considered during the scenario building, $P_i = [100, 300, 450]$ kWh. For a limitation, one type of charging power is applied at a terminus. The η_{ch} charging loss was 0.85 for e-bus at a static charger and 0.7 for trolleybuses at a dynamic charger.

Two-two vehicles with different battery capacity (B) were considered. We assumed that the useful battery capacity is half of the nominal one. The considered battery capacity and the procurement price of one vehicle are summarized in **Table 3**. For simplification, a static vehicle mass was used without considering the passenger load alteration; m vehicle mass is 17 tons for single vehicles and 29 tons for articulated vehicles.

We estimated the considered procurement cost of charging infrastructure based on empirical data and data resulting from a market analysis. The c_{cat} nominal cost of a catenary was 750,000 EUR/km. However, we distinguished how many lines are served an ij section. Thus, the traffic-dependent electricity grid load is considered in a

Line	Temperature [$^{\circ}\text{C}$]										
	-15	-10	-5	0	5	10	15	20	25	30	35
44	26.69	25.59	22.15	19.35	17.19	15.69	14.83	14.61	15.04	16.12	17.85
144	20.23	17.25	14.74	12.71	11.14	10.04	9.42	9.26	9.58	10.36	11.62

Table 2.
Estimated energy consumption at different temperature (example).

		Battery capacity [kWh]		Procurement cost [EUR]
		nominal	useful	
e-bus	single small	200	100	562,500
	single large	250	125	600,000
	articulated small	300	150	750,000
	articulated large	400	200	850,000
trolleybus	single small	50	25	500,000
	single large	100	50	537,500
	articulated small	50	25	587,500
	articulated large	100	50	625,000

Table 3.
Considered battery capacity and procurement cost of the vehicle.

simplified way; the catenary cost is 750,000 EUR/km if 1–2 lines are served, 1,000,000 EUR/km if 3–5 lines are served, and 1,500,000 EUR/km if more than 5 lines are served. Moreover, in the case of a hilly ij section, due to the more complicated terrain conditions, a higher category was considered. The c_{ch} is the cost of a static charger according to the 100, 300, and 450 kWh nominal capacity is 50,000, 200,000, and 450,000 EUR, respectively. c_{grid} nominal cost of grid development was considered 600,000 EUR/MW.

4.2 Result and discussion

The line group running through the city center, connecting the southwest and northeast sides of the city, is described in detail. The considered lines according to the state of the network in June 2022: 5, 7, 7E, 8E, 108E, 110, 110E, 112, 133E (lines served by single buses are underlined). “E” signs mean express lines; not all the stops are served.

Step 1. Modeling: The lines have significant common sections, and some of them also have individual sections. There are lines that have the same terminal(s). Considering the common terminals and sections, three terminals and 16 sections were distinguished. Directions are distinguished on each line. There is only a short 400 m subsection in section XII where a one-directional catenary is located; we neglected it. Section borders were selected at the beginning and end of common sections. The physical model is depicted in **Figure 6**.

The section length is measured on online map; the travel time on a section is given by the schedule for each line. The number of vehicles in a section at the same time considering all the lines is determined based on the timetable. The following sections are hilly sections with relevant slopes: I, II, III, IV, V, VI, X, XI.

Step 2. Scenario building: E-bus scenarios (E-bus A..F) were formed by the different charging capacities, respectively (100 kW – 450 kW, increment is 50 kW).

Two trolleybus scenarios were investigated by indicating bidirectional catenary network for different sections:

- Trolley A: XII, XIII, XIV
- Trolley B: XI, XII, XIII

Consumption	Direction	...	VI. (8E)	VII. (108E)	...	X. (110, 112)	XI. 110, 112	XI. (8E, 108E)	...
b_{ij} [kWh/km]	A	...	0.51	0.36	...	0.49	0.3	0.51	...
	B	...	0.47	0.6	...	0.58	0.3	0.51	...
e_{ij} [kWh/km]	A	...	-0.67	0.02	...	-1.48	-0.22	-0.37	...
	B	...	0.84	-0.02	...	1.85	0.27	0.47	...
$E_{\text{DEMAND},ij}$ [kWh]	A	...	8.74	10.94	...	-0.09	2.15	3.16	...
	B	...	20.13	12.21	...	3.34	3.24	5.01	...
$E_{\text{AUX},ij}$ [kWh]	A	...	6.16	3.08	...	1.54	2.7	2.7	...
	B	...	5	3.08	...	0.77	3.46	3.46	...
$E_{\text{DEMAND},ij}$ [kWh]	A	...	14.9	14.02	...	1.45	4.85	5.85	...
	B	...	25.13	15.29	...	4.11	6.7	8.47	...

Table 4.
Consumed energy values at a section (excerpt).

Direction	5	7	7E	8E	108E	110	110E	112	133E
A	61.17	59.47	25.41	67.58	57.03	26.61	22.76	25.97	75.87
B	66.02	56.09	23.75	68.04	67.87	42.21	25.73	42.21	69.74
Total	127.2	113.6	49.2	135.6	124.6	68.6	48.5	68.2	145.6

Table 5.
Consumed energy on a line.

	Line	Current	Charging power [kW]					
			100	200	300	350	400	450
Buses nr.	5	20	30	25	23	23	23	22
	7	16	24	20	18	18	18	17
	7E	18	24	20	19	18	18	18
	8E	19	29	24	22	22	21	21
	108E	3	4	3	3	3	3	3
	110/110E/112	27	36	32	30	30	30	30
	133E	19	30	24	22	22	21	21

Table 6.
Number of e-buses needed according to charging power.

requirements are over 150% if the charging power is 100 kW and 111% if the charging power is 450 kW. In all lines except 7E and 108E, at least one additional bus is needed after the electrification. The same number of e-buses is enough to serve line 7E with 350 kW charging power, and thus Line 108E with 200 kW charging power.

Bus lines that can be electrified are summarized in **Table 7** indicating the nominal battery capacity of trolley buses needed. In scenario Trolley A, the catenary network cannot provide enough energy to fulfill the autonomous sections in the case of lines 5,

Lines	Trolley A	Trolley B	Trolley B'
5	not served	not served	100 kWh
7	100 kWh	100 kWh	100 kWh
7E	50 kWh	50 kWh	50 kWh
8E	not served	100 kWh	100 kWh
108E	not served	100 kWh	100 kWh
110	50 kWh	50 kWh	50 kWh
110E	50 kWh	50 kWh	50 kWh
112	50 kWh	50 kWh	50 kWh
133E	not served	not served	100 kWh

Table 7.
Nominal capacity of trolleybuses needed.

8E, and 108E. In scenario Trolley B, only line 5 and 133E cannot be served by trolley-buses. In scenario Trolley B', the catenary system is extended at Section IX to Budafoki út/Dombóvári út (additional 4.8 km) and at Section XVI to Erzsébet királyné útja (additional 1 km) to electrify bus lines 133E and 5 as well. The number of trolleybuses is the same as the current number of conventional buses.

Step 8 and 9. Determining the charging vehicles at the same time and the charging devices: The needed charging units at a terminal is the same as the number of buses staying at the terminal at the same time. **Table 8** summarizes the number of charging devices according to charging power. The length of dynamic chargers is the same as the section length: Trolley A: 7.4 km, Trolley B: 8.1 km, Trolley B': 13.9 km (**Figure 7**).

Step 10. Procurement cost estimation: The procurement cost of three e-bus scenarios according to the terminals is summarized in **Table 9**. The table contains the peak power values. Scenario 3 is the most cost effective and has the highest charging power.

Though there are lines that can be served by lower power without increasing the number of e-buses needed, our aim was to unify the charging power at each terminal; in this way, the buses do not have to be assigned to a charger. It is noted that the additional buses increase the total cost significantly. In the case of the electrification only with e-buses, all together 18 static terminal chargers with 450 kW power and 129 e-buses are needed.

The procurement cost of trolleybus versions is detailed in **Table 10**. We assumed that the final aim is to replace all buses; accordingly, if a line cannot be replaced by

Terminal	Served lines	Charging power					
		100	200	300	350	400	450
Kossuth utca	5	11	6	4	4	3	3
Bosnyák tér	110/110E/112	10	6	4	4	3	3
Nyírpálota út	7, 7E, 8E, 108E, 133E	39	20	14	12	14	12

Table 8.
Number of static chargers at terminals.

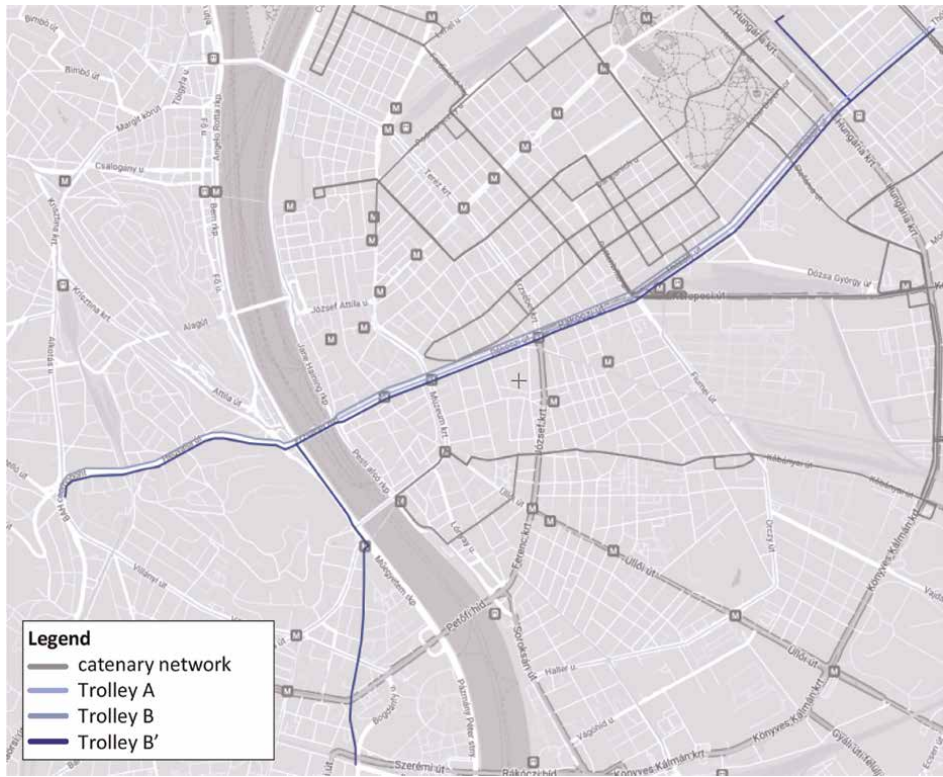


Figure 7.
Trolleybus scenarios.

Terminal	Kossuth utca			Bosnyák tér			Nyírpalota út		
Scenario	1	2	3	1	2	3	1	2	3
Charging power [kW]	100	300	450	100	300	450	100	300	450
Charging devices nr.	11	4	3	10	4	3	39	14	12
Peak power [kW]	1100	1200	1350	1000	1200	1350	3900	4200	5400
Charging devices cost [Mill. EUR]	0.55	0.8	0.9	0.5	0.8	0.9	0.195	0.28	0.36
Grid cost [Mill. EUR]	0.66	0.72	0.81	0.6	0.72	0.81	2.34	2.52	3.24
E-buses nr.	30	23	22	36	30	30	107	81	77
E-buses cost [Mill. EUR]	22.5	17.3	16.5	86.2	65.2	62.0	89.6	67.7	64.5
Total cost [Mill. EUR]	23.7	18.8	18.2	87.3	66.7	63.7	90.8	73.0	71.3

Table 9.
Procurement cost of e-bus scenarios according to terminals.

trolleybuses, we considered the replacement of e-buses. In scenario Trolley A, 61 additional e-buses, 3 static chargers at Kossuth utca for lines 5, and 6 static chargers at Nyírpalota út for lines 8E, 108E, and 133E are needed. In scenario, Trolley B 43 additional e-buses are needed and 3–3 static chargers at Kossuth utca and Nyírpalota út for lines 5 and 133E are needed. Trolleybus scenarios and scenario E-bus are

	Trolley A	Trolley B	Trolley B'	E-bus
Catenary length [km]	7.4	9.6	13.9	—
Peak power [kW]	74,075	154,310	239,400	—
Static charger nr. (450 kW)	9	6	—	18
Trolleybuses nr.	61	83	122	
E-buses nr.	67	43	—	129
Catenary cost (with grid cost) [1000 EUR]	7400	14,400	20,850	—
Static charger cost	2700	1800	—	5400
Grid cost at terminals [1000 EUR]	2430	1620	—	4860
Trolleybuses cost [1000 EUR]	34,075	47,825	72,200	—
E-buses cost [1000 EUR]	50,625	30,225	—	142,950
Total cost [1000 EUR]	97,230	95,870	93,050	153,210

Table 10.
Procurement cost of trolleybus scenarios.

summarized in **Table 10**. Scenario E-bus is the best e-bus scenario and showed for comparison purposes.

The cheapest scenario is Trolley B' in which the catenary system is the longest but there is no need for e-buses and static terminal chargers. Comparing trolleybus scenario with e-bus scenario, the total cost of scenario B' is only 2/3 of the total cost of scenario E-bus. The main reason is the higher procurement of e-buses which is originated from the large battery capacity which cost is high. Accordingly, the best option to electrify this line group is the application of trolleybuses with autonomous running capacity and dynamic catenary system through the central common sections.

4.2.1 Summary

Considering all the eight terminals analyzed, the number of needed static chargers is 53 (32 chargers with 300 kW nominal power and 21 chargers with 450 kW nominal power); the chargers' cost is 12,780,000 EUR, the cost of grid development is 11,430,000 EUR. The peak demand is 19,050 kW. All lines can be served by e-buses with smaller battery capacity. The estimated cost of the 253 e-buses needed is 142,877,000 EUR; the basic parameters of the vehicles are:

- 172 single buses with 200 kW nominal capacity
- 81 articulated with 300 kW nominal capacity

Currently there are 243 conventional buses serving these lines. The increment is only 4.1% (10 buses).

In most of the line groups, electrification with trolleybuses and dynamic charging is more affordable. However, there are some lines that cannot be electrified by trolleybuses (67, 122, 169E) as the individual sections are very long. In total 40 km of new bidirectional catenary network should be built, which cost 59,750,000 EUR. The

estimated cost of the 310 trolleybuses needed is 170,086,000 EUR; the basic parameters of the vehicles:

- 66 single buses with 50 kW nominal capacity
- 52 single buses with 100 kW nominal capacity
- 50 articulated buses with 50 kW nominal capacity
- 142 articulated buses with 100 kW nominal capacity

Serving the lines with e-buses requires 28 e-buses (16,763,000 EUR) and static charging station development at two terminals (4,600,000 EUR). Each line needs 1 additional e-buses.

Thus, the estimated total electrification cost is 341,424,000 EUR. Note, additional infrastructure development costs at the depot is required.

5. Conclusion

In this chapter, a planning method was introduced to electrify the urban bus network. The method developed provides a line-group optimization considering the characteristics of the vehicle, charging infrastructure, and bus service (lines, timetable, etc.). Battery electric buses and trolleybuses with autonomous running capacity; moreover, static terminal chargers and dynamic catenary chargers were involved in the optimization.

The method was applied as a case study in Budapest, Hungary. Eight bus terminals and seven bus line groups (85 lines) were analyzed to be served by electric buses or trolleybuses. The main finding regarding the case study is that 4% more battery electric buses are needed without changing the service characteristics. If e-buses serve all the lines, 253 vehicles and 53 terminal chargers are needed. However, we found that electrification with trolleybuses and dynamic charging is more affordable except for 3 lines. In total 40 km of the new bidirectional catenary network should be built to serve 310 trolleybuses.

The method can be further optimized by dissolving the limitations and refining the estimated variables, such as grid costs, and available grid capacity. Another further aim is to create a charging scheduling method, as it can further optimize the number of charging devices and vehicles.

Acknowledgements

The authors express their gratitude for BKK Budapest Centre for Transport to provide bus line-related data.

Conflict of interest

The authors declare no conflict of interest.

Nomenclature

B	battery capacity
b	braking loss per kilometer
c_{cat}	nominal cost of a catenary
c_{ch}	nominal cost of static charger
c_{grid}	nominal cost of grid development
E_{AUX}	auxiliary energy consumption
E_{DEMAND}	total energy demand
E_{DRIVE}	driving dynamic energy consumption
e	elevation loss per kilometer
i	serial number of bus stop
l_{ch}	total length of dynamic charger
l	section length
n_{bus}	number of currently needed buses.
n_{ebus}	number of e-buses needed
n_{ch}	number of static chargers needed
n_{tbus}	number of trolleybuses needed
n_{ts}	turn shift
$n_{ch}(t)$	number of charging vehicles in period t
$n_{tbus,ij}(t)$	number of trolleybuses in the section at a given period
p	probability of charging
P_{AUX}	power demand of the auxiliary systems
P_{peak}	peak power of the electric grid
SoC	state of charge of the battery
t	time period in general
t_{ch}	charging time
t_{hw}	headway between buses
t_{ij}	travel time in ij section
γ	consumption rate per kilometer
ε_{ij}	energy balance
η_{batt}	capacity utilization of a battery
η_{ch}	charging efficiency
η_{PC}	efficiency of the power converter

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The Use of Polymers, Nano-Polymers, and Nano-Modified Emulsion for Gravel Road Maintenance: A Review

Armand Augustin Fondjo and Elizabeth Theron

Abstract

The study reviews the application of polymers and nanomaterials for improving the maintenance of gravel roads. Gravel and unpaved roads comprise a significant proportion of road networks in the sub-Saharan region, and the efficient maintenance is crucial for enhancing the performance and transportation of goods and people. Limited studies have reviewed the utilization of polymers and nanomaterials in gravel road maintenance. To synthesize this diverse literature, we reviewed 81 articles, triangulated their conclusions, and identified the effective approach. As a general review, the study did not include experimental validation. The review demonstrates that polymers, nano-polymers, and nano-modified emulsions can be used to enhance the performance, durability, and safety of gravel roads. Laboratory investigations, including Accelerated Pavement Testing (APT) and long-term durability assessments, are essential to ensure the effective use of road stabilizers. Additionally, the application of Pavement Management System (PMS) software provides an optimized evaluation, repair, and efficient overall management of gravel road maintenance. This study reveals that each type of stabilizer polymer, nano-polymer, and nano-modified emulsion has its own merits and limits. The use of nano-materials has been found to be more cost-effective than the annual expenses associated with re-graveling and re-grading conventional gravel roads. With pronounced cooperation among researchers, industrialists, scientists, technologists, and environmentalists, research strategy should be adopted to incorporate a standardized application of stabilizers in modern industries. Geoenvironmental assessment related to chemical stabilization methods is crucial for chemical stabilizers. This research provides guidelines for the selection and application of polymers and nanotechnology in gravel road maintenance.

Keywords: gravel road maintenance, polymers, nano-polymers, nano-modified emulsion, soil stabilization

1. Introduction

Road access in sub-Saharan Africa is approximately 34%, which is lower than the 50% average in other developing regions. High transport costs also limit road maintenance, repair, and expansion [1]. According to SATCC [2], Africa needs to build and maintain significant paved road infrastructure (**Figure 1**). The higher cost of infrastructure and limited funds have hindered the development of competitive transport infrastructure in sub-Saharan Africa [3]. Most rural roads in developing countries are unpaved. Yet the roads provide access to services and support local economies [4]. South Africa’s road infrastructure is well developed compared to most countries in sub-Saharan Africa and meets international standards, particularly in urban areas [5].

South Africa’s road network consists of approximately 70% gravel roads. These roads typically serve traffic volumes under 400 Vehicles Per Day (VPD), and exceeding this limit usually requires an upgrade to a paved surface [6]. According to Paige-Green [7], the main issue is the excessive road width (10–14 m), which leads to surface flattening and higher maintenance, whereas overly narrow roads induce rutting, gravel loss, and poor surface conditions. Stull et al. [8] and Mamabolo [9] noted that post-apartheid endeavors to boost rural economic development in South Africa still face major challenges, as infrastructure and projects remain concentrated in urban areas. Ezeuduji and Mgabhi [10] reported that rural development remains a crucial issue in developing countries, particularly in rural communities with limited economic activities. Pillay [11] and Myburgh [12] mentioned that despite endeavors to improve road infrastructures in South Africa, financial constraints have hindered progress, resulting in poor road conditions in rural communities. Roads are funded through public funds for all users, but the public-private partnership is a key strategy to enhance the road infrastructure investment for rural development. Myburgh [12] found that over 60% of gravel roads in South African provinces are in poor condition, with Northern Cape, Mpumalanga, and Eastern Cape exceeding 80%. In Mangaung, 19.67% of roads are gravel, limiting safe access to essential services. **Figure 2** illustrates the provincial road conditions. BusinessTech [13] stated that only 1% of South Africa’s unpaved roads are re-graveled annually, resulting in a 100-year cycle for

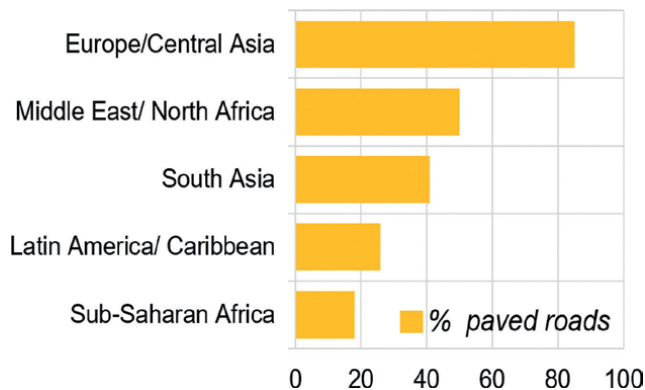


Figure 1. Sub-Saharan Africa, including the SADC region, lags considerably behind Asia and Latin America in terms of road coverage and density [2].

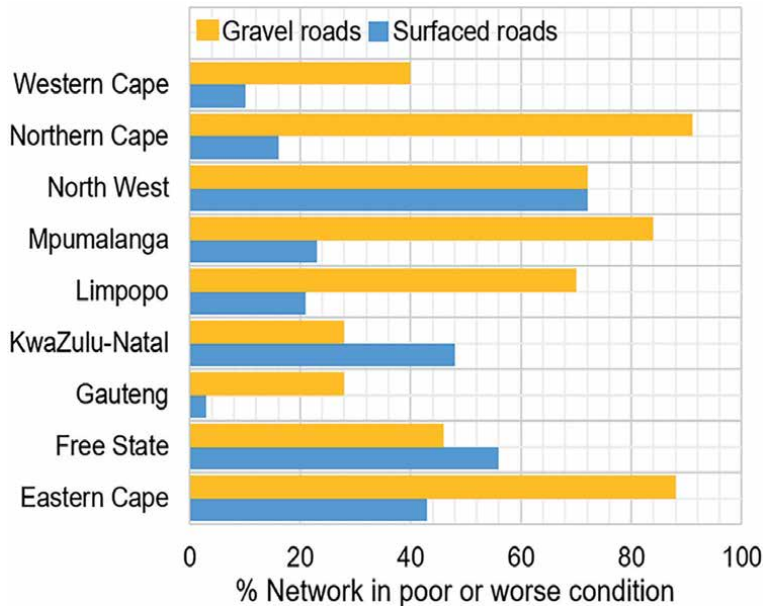


Figure 2.
Roads in poor or worse conditions 2022 in South Africa [12].

each road. Additionally, approximately 132,000 km of roads remain unclaimed and unmaintained, as they lack oversight from road authorities.

In the Free State province, Mosianedi [14] highlighted that over 40% of the roads are in poor condition, primarily due to underfunding, limited technical capacity, inadequate maintenance, and increasing traffic loads. According to the Mangaung Metropolitan Municipality [15], approximately 17% (1195 km) of the road network consists of gravel roads, mainly located in townships and outskirts, while the remaining 48,883 km are paved roads. Carlesso et al. [16] mentioned that these gravel roads often exhibited severe distress, leading to higher vehicle maintenance costs, safety risks, dust pollution, and road user discomfort. In another study, Khoza [17] highlighted that poorly maintained roads in Mangaung municipality deteriorate faster, leading to higher long-term costs due to the increased expense of repair works. Fondjo [18] highlighted that the 250-million-year-old siltstone and mudstone of the Beaufort and Ecca groups in the Karoo Sequence underlie the Free State, forming an expansive soil profile due to surface disintegration. Diop et al. [19], Fondjo [20], Fondjo and Theron [21], and Fondjo et al. [22] mentioned that expansive soils pose a significant challenge in South Africa, particularly in Free State communities, where they have damaged subsidized housing and roads, leading to economic and social impacts. Diop et al. [19] reported highly expansive soils in Free State, KwaZulu-Natal, South Gauteng, and North West, highlighting the need to consider their swell-shrink behavior in gravel road design. This study reviews gravel road maintenance with a focus on polymer stabilizers, nano-polymer stabilizers, nano-modified emulsion stabilizers, and the application of information technology in road maintenance management. As a review, the study does not present experimental validation. The study synthesizes previous research, triangulates their findings, reports the effective stabilization methods, and highlights their merits and limitations.

2. Review of gravel roads maintenance

Shingloo [23] observed that the design of gravel roads received little attention, and no standardized structural design procedures are regularly used in Southern Africa. Proper maintenance of gravel roads contributes to improving road durability, performance, ensuring safety, efficiency, and compliance with environmental standards, and addressing the needs of nearby communities. GTAC [24] conducted an investigation on provincial roads in South Africa. The findings indicated that the provincial road department manages 222,677 km (29.7%) of South Africa's roads, with only 48,954 km paved. Just 39% of paved and 15% of gravel roads required regular maintenance, and the population relies on roads in poor condition. The Technical Recommendations for Highway TRH20 [25] and CSIR [26] highlighted that gravel roads require regular maintenance, including re-graveling, grading, stabilization, and dust control to prevent erosion and ensure safety. Ndlovu [27] describes gravel roads as natural earth roads with a roadbed layer and a Gravel-Wearing Course (GWC), with a performance depending on the suitability of the GWC materials and the underlying geological formations.

Pinard and Hongve [4] reported that a gravel road consists of a wearing course and a structural (base) layer placed over *in situ* material, with the same material sometimes used for both layers. Since gravel roads lack a hard surface (e.g., concrete or asphalt), the wearing course must be maintained at a thickness greater than 50 mm throughout the road's service life to ensure the integrity of the structural layers. In a similar study, Skorseth [28] documented the critical approach in gravel road maintenance. It was found that the most fundamental aspect of gravel road maintenance and construction is achieving the proper shape of the road cross-section (**Figure 3**). The road surface should have an adequate crown to ensure effective drainage toward the shoulders. Skorseth [28] emphasized the importance of using the best available materials for construction. In addition, gravel must be transported properly to prevent material segregation during processing and maintain the material quality. Mbiyana et al. [30], Skorseth [28], and Albatayneh et al. [31] recommended applying water to achieve optimum moisture content, followed by proper compaction when placing a new layer of gravel. This technique is cost-effective in improving the performance and durability of the gravel road.

According to Paige-Green [32], South Africa has an extensive network of over 500,000 km of unsealed roads, primarily located in rural and low-income areas. The safety, ride comfort, and maintenance costs of these roads are significantly influenced

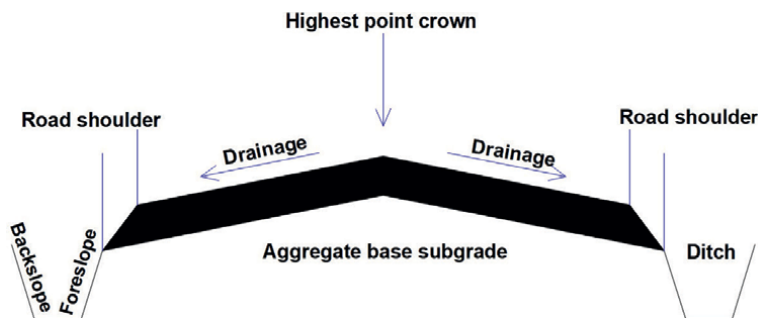


Figure 3.
Cross-sectional structure of gravel road [29].

by material quality and construction methods. Whereas more than 50 alternative soil stabilizers are available nationally, their high testing costs often lead suppliers to overlook quality control. Despite this, commonly used dust palliatives have proven effective in improving safety and reducing maintenance expenses. To optimize cost-efficiency, the management of gravel roads should involve the use of optimal materials and suitable stabilizers, with each road upgraded to a paved surface when appropriate [32].

Pinard et al. [33] used the Dynamic Cone Penetrometer (DCP) to assess *in situ* conditions and optimize gravel road design. Comparing subgrade strength with design-enabled new pavement profiles. Validated across southern African roads, this cost-effective method uses existing road strength and purpose-fit specifications to reduce the construction costs with a marginal risk of early failure compared to conventional methods. Pinard and Hongve [4] explored a cost-effective, sustainable gravel road design that maintains the quality standards. Gravel roads, lacking a hard surface, typically serve up to 300 vehicles daily (< 10% heavy). Paving may be cost-effective in areas with poor materials. Chemical stabilizers, often used for dust control, can also strengthen the surface and reduce gravel loss. Some are more economical when mixed despite the high initial cost. Due to the variation of chemical types and applications, no guidance is available. The performance and potential environmental impacts of chemicals should be assessed [4].

Madyibi [34] utilized statistical analysis and quantitative methods to evaluate the maintenance frequency and condition of gravel roads in Intsika Yethu Municipality (IYM). The study revealed that these roads lack regular maintenance, becoming slippery and regularly flooded during rainfall, which renders some sections unusable. Most gravel roads in IYM have not been maintained for the last 5 years, contrary to the Technical Recommendations for Highways (TRH20) [25], which mention the need for routine maintenance to ensure serviceability. Furthermore, municipalities should update a list of local roads, their conditions, and a planned maintenance approach, even for roads not directly managed by them [34]. Service provision and road development projects in South Africa remain centered primarily in urban areas [8, 9]. Improving rural roads can boost socioeconomic growth and sustainability for rural communities [35]. In a similar study, Saeed et al. [29] and Albatayneh et al. [31] mentioned that gravel roads are crucial links for sparsely populated areas and facilitate the transportation of agricultural and forestry products. Gravel roads are typically constructed for low traffic volumes, offering a cost-effective alternative to paved roads.

According to Mbiyana et al. [30] and Albatayneh et al. [31], gravel roads generally exhibit low durability and require frequent maintenance. Besides, the service life of gravel roads can be improved through the well-compacted road surface, applying surface seals to create water-resistant layers, and implementing routine maintenance strategies. Ndlovu [27] examined the method used by the KZN-DoT to prioritize upgrading gravel roads to paved roads. The findings indicate that gravel road performance is sensitive to traffic volume, climatic conditions, and the quality of the GWC material. Ndlovu [27] and Paige-Green [7] identified gravel loss as the most critical factor in determining re-graveling frequencies and long-term costs. Assessing the optimal timing for upgrading a gravel road to a paved surface should be conducted during the project design. This task involves proactively predicting each gravel road's deterioration pattern to plan for future maintenance and estimate upgrading costs. Ndlovu [27] reported that the re-graveling frequency for KwaZulu-Natal provincial gravel roads with shale or dolerite GWC, based on predicted gravel loss, varies with traffic volume: every 6–8 years for roads carrying 200–400 VPD, 4–5 years for 400–600 VPD, and 3–4 years for traffic exceeding 600 VPD. Considering the high

long-term maintenance costs of gravel roads, upgrading to a more durable surface is often justified. Paige-Green [7] emphasized that predicting gravel loss is critical for both the design of gravel roads and effective maintenance planning.

The review of gravel road maintenance indicates gravel roads are cost-effective for low-traffic areas but require long-term maintenance, justifying upgrades to more durable surfaces. Gravel road design lacks standardized protocols and receives little attention in the sub-Saharan region. Proper gravel road maintenance and construction rely on achieving the correct road cross-sectional shape and compacting the new gravel layers at optimal moisture content. This cost-effective method improves road performance and durability. Moreover, gravel loss is the key factor in re-graveling frequency and long-term costs. Chemical stabilizers can control dust, improve soil properties, strengthen the wearing course, and reduce gravel loss. Finally, the dynamic cone penetrometer helps optimize gravel road design by assessing *in situ* conditions and comparing subgrade strength with design requirements to determine a suitable gravel layer profile.

3. Review of gravel road stabilization using polymers and nanotechnology

Onyejekwe and Ghataora [36], Fondjo et al. [37, 38], and Fondjo [18] reported that chemical stabilization is a widely used technique for improving the physical and mechanical properties of soils by incorporating chemical additives such as lime, cement, fly ash, polymers, nano-based polymers, and nano-modified emulsions (NMEs). When NMEs contain nano-structured polymers or polymer-nanoparticle composites, they can be classified as nano-based polymers. This section reviews the stabilization of gravel roads using polymer stabilizers, nano-polymer stabilizers, and nano-modified emulsion stabilizers. **Figure 4** presents the various soil stabilization methods used in road construction.

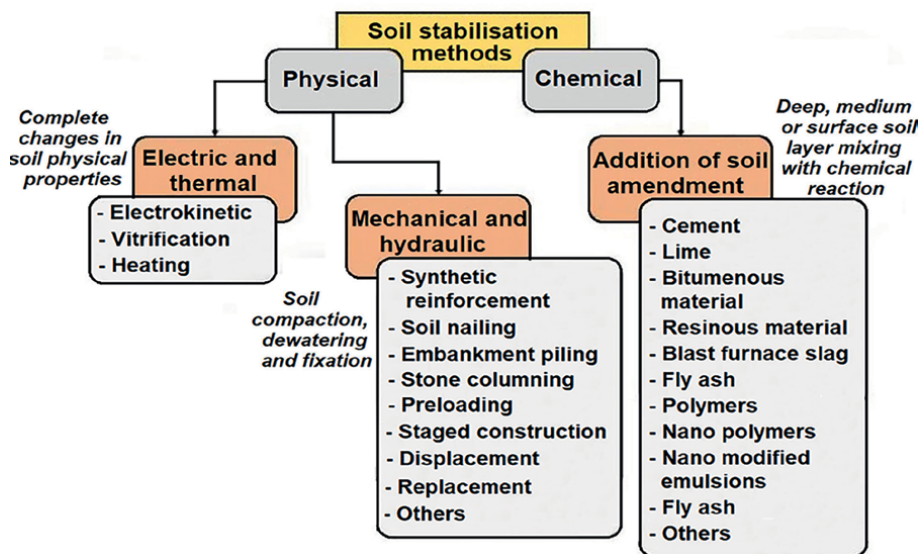


Figure 4. Soil stabilization through various methods [37].

3.1 Polymer stabilizers

Fondjo and Theron [39], Aleroeva et al. [40], and Anwar et al. [41] mentioned that polymers used in road construction are synthetic or natural macromolecules composed of repeating structural units (monomers) designed to enhance the performance and durability of road materials. As reported by Kamal and Bas [42], polymers could be incorporated into binders such as bitumen, aggregates, or soil to enhance the pavement properties that include strength, stiffness, water resistance, and overall durability. Huang et al. [43] and Phantachang et al. [44] reported that polymer stabilizers are typically more expensive than traditional stabilizers such as lime and cement due to many parameters, such as the raw materials, chemical formulations that enhance performance, and the high-precision manufacturing, which increases the cost compared to the relatively simple calcination process of lime and cement. Onyejekwe and Ghataora [36] and Huang et al. [43] observed that the primary reason for hesitancy in adopting polymer stabilizers is the scarcity of reliable, independent scientific studies on their effectiveness. Nevertheless, according to CSIR [26], polymers can enhance road durability by improving resistance to moisture and erosion through hydrophobic effects in the soil matrix, preventing moisture damage in the road pavement.

Huang et al. [43] highlighted the application of polymers in soil stabilization, identifying the formation of sodium and/or calcium aluminosilicate gels as the primary mechanism. These gels bind soil particles into a denser and stronger matrix, thereby enhancing the soil strength, reducing permeability, minimizing swelling and shrinkage, and improving the durability. Nonetheless, there is a need for future research to establish the standardized testing protocols, evaluate *in situ* performance, address durability concerns, and investigate the stabilization mechanisms of polymer-treated soils. Mousavi et al. [45] and Musavi et al. [46] studied the effects of CBR PLUS and Road Packer Plus (RPP) on subgrade stabilization. Both polymers reduced the soil's Atterberg limits and improved Maximum Dry Unit Weight (MDU). CBR PLUS concentrations of 0.0096 and 0.0500% increase the MDU by 0.76 to 3.43% and RPP concentrations of 20.78 to 41.57% by 20.78 to 41.57%. RPP achieved CBR values from 1.52 to 44%, while CBR PLUS achieved 24.62 to 2.69%. CBR PLUS also reduced the free swelling index by up to 33.48%, indicating a significant reduction in swelling potential. Both polymers improved the soil properties depending on their concentration.

Kocak and Grant [47] and Huang et al. [43] reported significant challenges hindering the practical application of polymer-based soil stabilization. These include a scarcity of independent research, inconsistent product labeling, and a lack of standardized evaluation methods. Furthermore, the variability in supplier guidelines, high material costs, susceptibility to biodegradation, and sensitivity to moisture present additional barriers to the application. Mohamed and Tamboura [48] investigated the application of polymers to pavement subgrade soil. Various commercial polymers, such as ARTS LLC, EPS PM 50, EPS PM 70, ROCAMIX, and TECOFIX, were assessed through lab investigation. The results portrayed an improvement in physical and mechanical soil properties. ROCAMIX enhances water retention, while ROCAMIX, TECOFIX, and EPS PM50-PM70 improve soil strength, and the performance increases with polymer concentration. Nonetheless, field tests or Accelerated Pavement Test (APT) help to validate the performance of polymers in engineering applications [49, 50]. Advanced equipment can facilitate the synthesis of these polymers for efficient soil stabilization methods.

Abd El-Rahman et al. [51] and Phantachang et al. [44] reported that polymer emulsion can be applied quickly and effectively to the surface, making the stabilizer effective for time-sensitive projects. In addition, it typically requires a shorter curing time compared to traditional stabilizers, improving project completion with minimal disruption to traffic or other ongoing activities. In another study, Festus [52], Parvej et al. [53], Kashi et al. [54], and Gulia et al. [55] highlighted that polymers are highly effective in controlling dust generation on gravel roads by binding fine soil particles together. This binding action stabilizes the surface and prevents the particles from becoming airborne, which improves both air quality and visibility in the surrounding area. According to Tan et al. [56], Fondjo et al. [37], and Asteray and Elsaigh [57], some synthetic polymers may not be biodegradable. As a result, these materials can persist in the environment for extended periods, accumulating in soil and water systems and potentially contributing to long-term environmental pollution. **Table 1** summarizes the advantages and disadvantages of using polymers for gravel roads.

3.2 Nano-polymer stabilizers

Ganesh [58] observed that nanotechnology has gradually yet taken over various industries worldwide. This technological revolution has advanced especially rapidly in developed countries, where nano-scale markets have developed significantly over the past decade. Despite often being viewed as cutting-edge, nanotechnology is not a new concept; it has evolved into a general-purpose technology with widespread applications such as road construction. Anwar et al. [41] and Kamal and Bas [42] mentioned that nano-polymers are polymeric materials that incorporate nanometer-scale particles or structures to improve the chemical and physical properties of traditional polymers. Nano-polymers help to improve soil stabilization, dust suppression, mechanical strength, durability, and resistance to environmental degradation. Yousif and Abed [59] emphasized that, due to their unique molecular interactions and high surface area, nano-polymers exhibit higher performance compared to conventional polymers, making them highly effective for unpaved or gravel road stabilization, asphalt modification, and road maintenance. In a recent report, Government Gazette [60] described the Nano-Based Polymer (NBP) as a stabilizer and soil-bonding agent blended with elastomers. NBP is a water-based, modified polymer formulation that derives its strength primarily from mechanical compaction. NBP consists of multi-sized nano-polymers coated with micro-surfactants, which decreases surface tension and enables water to act as a medium for penetrating the sub-base layer. This process improves the stabilization of pavement base and sub-base layers using *in situ* materials for both paved and unpaved roads. The product infiltrates the base and sub-base through capillary action. The elastic properties of the NBP, characterized by its Young's modulus, provide the pavement with flexibility under repeated loading.

Fondjo and Theron [39] and Jordaan and Kilian [3] highlighted that maintaining good transport infrastructure is crucial for economic growth. Despite the advancements of nanotechnology over the past decade, the road construction sector in sub-Saharan region has not fully adopted these innovations effectively. Nanotechnology-based products were tested successfully and used in some countries (e.g., India, USA), allowing the increment of marginal materials utilization in pavement-wearing courses. Nano-based polymers in South Africa have been tested on various roads in regions such as Gauteng and Limpopo, using different

Advantages	References
<i>Improved the soil strength and load-bearing capacity:</i> Polymer stabilizers bind soil particles together, thereby enhancing effective cohesion (c'), shear strength (τ), Unconfined Compressive Strength (UCS), and the California Bearing Ratio (CBR).	Aleroeva et al. [40], Huang et al. [43], Mousavi et al. [45], Musavi et al. [46], Kamal and Bas [42], Anwar et al. [41], Kocak and Grant [47], Mohamed and Tamboura [48], Fondjo and Theron [39]
<i>Reduced dust emission:</i> Polymer stabilizers effectively bind fine particles, reducing dust generation and consequently enhancing air quality and traffic visibility.	Festus [52], Gulia et al. [55], Parvej et al. [53], Kashi et al. [54]
<i>Enhance water resistance:</i> Some synthetic polymer stabilizers create hydrophobic layers that reduce moisture infiltration and erosion, thus improving water resistance in unpaved and gravel roads.	Aleroeva et al. [40], CSIR [26], Kamal and Bas [42], Anwar et al. [41]
<i>Improve the road service life:</i> Gravel roads treated with polymer stabilizers show improved resistance to gravel loss, resulting in reduced maintenance frequency and extended service life.	Aleroeva et al. [40], Huang et al. [43], Kamal and Bas [42], Anwar et al. [41], Kocak and Grant [47]
<i>Fast application and reduced the curing time:</i> Polymer stabilizer emulsions can be applied quickly and typically require a shorter curing time, thereby minimizing traffic disruption.	Abd El-Rahman et al. [51], Phantachang et al. [44]
<i>Reduce the soil materials plasticity:</i> The polymer stabilizer reduced the soil's plasticity (Atterberg limits), with significant improvements observed at the highest polymer concentrations.	Mousavi et al. [45], Musavi et al. [46]
Disadvantages	References
<i>Higher initial cost:</i> Polymers are often more expensive than traditional stabilizers such as lime or cement, potentially limiting their use in large-scale or budget projects. Their higher performance, durability, and practical application may justify the higher cost.	Huang et al. [43], Phantachang et al. [44]
<i>Environmental concerns:</i> Some polymers may not be biodegradable because they resist natural decomposition and can persist in ecosystems for decades, contributing to long-term environmental pollution.	Tan et al. [56], Fondjo et al. [37], Asteray and Elsaigh [57]
<i>Required advanced equipment:</i> The Accelerated Pavement Test (APT) helps to validate the long-term performance of polymers in road construction. The test helps simulate real-world conditions, enabling pavement engineers to evaluate durability, resilience, and structural integrity more efficiently.	Jordaan et al. [49], Rust et al. [50], Fondjo and Theron [39]
<i>Standard testing protocols:</i> The absence of standardized testing protocols to evaluate the performance of polymer stabilizers effectively remains a challenge.	Onyejekwe and Ghataora [36], Huang et al. [43], Fondjo et al. [37], Kocak and Grant [47]

Table 1.
Advantages and disadvantages of using polymers for gravel roads.

materials under diverse climate conditions, and have shown promising results in road performance. Zeng et al. [61] reviewed the application of nano-polymers in road construction and reported that their use increases the density of the soil matrix, thereby enhancing the subgrade soil properties. The incorporation of nanomaterials into asphalt mixtures was found to significantly improve water stability, rutting resistance, and fatigue resistance. Compared to conventional stabilizers such as lime and cement, nanomaterials portray notable advantages in road maintenance, providing greater durability and a better cost-performance ratio. In a similar study, Jordaan and Steyn [62] highlighted that the use of nano-polymers in road maintenance plays a significant role in protecting the existing wearing courses of both gravel and paved roads. The effectiveness of stabilizer stems from the inherent properties of nanomaterials, including their hydrophobic (water-repellent) property and the ability of nano-scale particles to penetrate the existing surface and restore water resistance.

Taherkhani and Javanmard [63] reported that CBR PLUS provides permanent waterproofing for soils and aggregate surfaces on gravel roads. They observed a 4% reduction in the liquid limit with increasing CBR PLUS concentration and concluded that the nano-polymer decreases both the plasticity index and the permeability of the treated materials. In a similar study, Musavi et al. [46] observed that the addition of CBR PLUS in soil material reduces the liquid limit and plasticity index. Soils with high liquid limits typically contain a significant clay fraction and exhibit low bearing capacity. Consequently, a decrease in the liquid limit enhances the mechanical resistance of the soil [64, 65]. The stabilization of gravel road surfacing materials using the nano-polymer CBR PLUS requires an additional curing time of about 2 weeks. As the CBR PLUS content increases, the soil dry unit weight and shear strength increase, and the soil permeability reduces [66]. Furthermore, Musavi et al. [46] demonstrated that incorporating CBR PLUS increases both the OMC and the MDU of soil. For this stabilizer, Piratheepan et al. [67] reported an optimal mixture of 50% gravel, 30% sand, and 20% clay to achieve peak strength. The California Bearing Ratio (CBR) is also enhanced with higher concentrations of CBR PLUS, demonstrating an improvement in the subgrade's material strength and bearing capacity. The finding is consistent with precedent studies by Taherkhani and Javanmard [63] and Musavi et al. [46], which reported that the elevated CBR values resulting from the nano-polymer allow for a decrease in gravel material. Consequently, this reduces the required thickness of the surfacing layer for gravel roads. Consequently, this reduces the required thickness of the surfacing layer for gravel roads. In a similar study, Lotfalian et al. [68] studied the impact of nano-polymer CBR PLUS on gravel road surfaces. Tests (Atterberg limits, Proctor compaction, CBR) on soil samples with different CBR PLUS concentrations (0.25–1.00%) showed that higher doses reduced fine-grained content and liquid limit while improving the dry unit weight and CBR values. The 1.00% concentration was most effective, but further research on higher doses is needed. Although CBR PLUS has a higher initial cost than the conventional methods, its low maintenance needs offer long-term economic benefits. **Table 2** provides the merits and limitations of using nano-polymers for gravel roads.

3.3 Nano-modified emulsion stabilizers

Porto et al. [69], Jordaan and Steyn [70], and Jordaan and Wynand [71] mentioned that nano-modified emulsions (NMEs) stabilizers, containing nanoparticles such as nano-silica, nano-clay, carbon nanotubes, or nano-polymers, enhance the

Advantages	References
<i>Improved the soil strength and load-bearing capacity:</i> Nano-polymer stabilizers bind soil particles together, thereby enhancing effective cohesion (c'), shear strength (τ), Unconfined Compressive Strength (UCS), and the California Bearing Ratio (CBR).	Piratheepan et al. [67], Taherkhani and Javanmard [63], Jianqiao et al. [64], Musavi et al. [46], Lotfalian et al. [68], Zeng et al. [61], Anwar et al. [41], Kamal and Bas [42], Jordaan and Steyn [62], Mohamed and Tamboura [48], Government Gazette [60], Yousif and Abed [59], Fondjo and Theron [39]
<i>Reduced dust emission:</i> Nano-polymer stabilizers effectively bind fine particles, reducing dust generation and consequently enhancing air quality and traffic visibility.	Anwar et al. [41], Kamal and Bas [42], Taherkhani and Javanmard [63]
<i>Enhance water resistance:</i> Some synthetic nano-polymer stabilizers create hydrophobic layers that reduce moisture infiltration and erosion, thus improving water resistance in unpaved and gravel roads.	Taherkhani and Javanmard [63], Zeng et al. [61], Jordaan and Steyn [62], Yousif and Abed [59]
<i>Improve the road service life:</i> Gravel roads treated with nano-polymer stabilizers show improved resistance to gravel loss, resulting in reduced maintenance frequency and extended service life.	Ganesh [58], Lotfalian et al. [68], Zeng et al. [61], Anwar et al. [41], Kamal and Bas [42], Yousif and Abed [59]
Disadvantages	References
<i>Time dependent of curing process:</i> The delay in the curing process of nano-polymers stabilizers affects early strength development, and delayed traffic opening.	Lahalih and Ahmed [66]
<i>Higher initial cost:</i> Nano-polymers are often more expensive than traditional stabilizers such as lime or cement, potentially limiting their use in large-scale or budget projects. Their higher performance, durability, and practical application may justify the higher cost.	Asteray and Elsaigh [57], Tan et al. [56]
<i>Required advanced equipment:</i> The Accelerated Pavement Test (APT) helps to validate the long-term performance of nano-polymers in road construction. The test helps simulate real-world conditions, enabling pavement engineers to evaluate durability, resilience, and structural integrity more efficiently.	Jordaan et al. [49], Rust et al. [50]
<i>Environmental concerns:</i> Some nano-polymers may not be biodegradable because they resist natural decomposition and can persist in ecosystems for decades, contributing to long-term environmental pollution.	Fondjo et al. [37], Yousif and Abed [59]
<i>Standard testing protocols:</i> The absence of standardized testing protocols to evaluate the performance of nano-polymer stabilizers effectively remains a challenge.	Onyejekwe and Ghataora [36], Huang et al. [43], Fondjo et al. [37]

Table 2.
Advantages and disadvantages of using nano-polymers for gravel roads.

chemical, mechanical, and durability properties of soil, asphalt, and base layers, and help in gravel road construction for surface treatments, cold mix asphalt, and maintenance. Furthermore, Porto et al. [69] emphasized that most global research on nanotechnology applications in pavement engineering has primarily focused on enhancing binders in asphaltic materials. Jordaan and Steyn [70] and Horak et al. [72] reported that NME improves workability, adhesion, water resistance, aging resistance, and load-bearing capacity by modifying the bitumen microstructure. Moreover, NME enhances dispersion, reduces viscosity, and strengthens bonding with aggregates, thereby providing better rutting resistance, improved fatigue resistance, and sustainability, aligning with the design for durable, cost-effective pavements. Fondjo and Theron [39], Okem [73], and Okem et al. [74] highlighted the recent successful use of NMEs in several South African trial projects, positioning them as a promising solution for durable roads. This practical success is supported by laboratory findings; Rust et al. [50] and Jordaan et al. [49] note that the technology's effectiveness has been further confirmed through APT across southern Africa.

Jordaan and Steyn [70] investigated the stabilization of naturally available materials for road pavements using nano-modified emulsions (NMEs), such as organo-functional nano-silane emulsions. In their study, they highlighted the key importance of chemical compatibility between material mineralogy and NME for achieving desired engineering properties. NMEs not only forms strong chemical bonds but also reduces the harmful effects of secondary minerals. Furthermore, laboratory tests showed the significant strength gains, APT validated road durability. As a result, NMEs stabilization improved pavement performance, cut material costs by 50%, and reduced both unit and lifecycle road costs by allowing the use of local materials. In a similar study, Jordaan et al. [75] reported the utilization of NMEs to stabilize granular road pavement materials, focusing on chemical properties. Incorporating a material-compatible organ-functional nano-silane combined with a suitable hydroxy conversion treatment (HCT) into the stabilizing agent can effectively activate the necessary chemical bonds during the stabilization process. This approach enables the treatment and improvement of even low-quality materials, thereby improving engineering properties such as compressive strength, tensile strength, and durability in pavement layers. Kidgell et al. [76] reported that nano-silanes enhance the load-bearing capacity and reduce the plasticity of dolomite and clays in pavement subgrade roads. Furthermore, Jordaan et al. [77] reported an approach to identify, prevent, and address gravel road construction problems (material and non-material) by assessing their causes and recommending cost-effective solutions. In their study, APT helped to evaluate the improvement in the performance of unsuitable granular material stabilized using NMEs. As a result, the use of NMEs helps contractors achieve road stabilization works cost-effectively. Nonetheless, it remains important that the causes and mechanisms of the observed distress are identified promptly.

Okem et al. [74] and Okem [73] examined the improvement of substandard base course materials using nanoemulsions to develop a durable wearing course for unsurfaced roads. Two stabilizers, Nano A and Nano B, sourced from South African manufacturers, were incorporated into soil samples at concentrations ranging from 0.7 to 1.5% by mass. The properties of Nano A and Nano B stabilizers are summarized in **Table 3**. The optimal contents were determined as 1% for Nano A and 1.2% for Nano B. Furthermore, Okem et al. [74] mentioned that Nano A and Nano B enhanced

Name	Nano A	Nano B
Color/appearance	Dark gray	Thickmilky brown liquid
Flammability	None	None
Odor	Slightly	Slightly
Solubility in water	Yes	Yes
Toxicity	None	None
Boiling point	Same as water	Same as water
pH	8–9	10–11

Table 3.
Properties of soil nano-stabilizers [73].

the bearing strength of the material by up to 53 and 92%, respectively. Significant improvements were also recorded in both indirect tensile strength and unconfined compressive strength tests. In addition, Nano B exhibited the ability to induce a hydrophobic effect within the soil matrix, thereby reducing water damage in the treated layer and improving the long-term durability of road pavements. The findings recommend nano A for subbase stabilization ($\text{CBR} \geq 45\%$ at 95% Mod AASHTO) and nano B for base course stabilization ($\text{CBR} \geq 80\%$ at 98% Mod AASHTO). Besides, this approach can improve the performance of gravel roads.

Jordaan and Wynand [71] investigated the importance of the particle sizes of all components in a nano-modified emulsions (NMEs) stabilized road pavement layer. They found that the effectiveness of NMEs in stabilizing Naturally Available Granular Materials (NAGM) mainly depends on the material's mineralogy and the particle sizes of both the granular materials and the stabilizing agent. The effect of particle size on the NME-stabilized layer is often overlooked. Furthermore, Jordaan and Wynand [71] also emphasized that, regardless of mineralogy, the particle sizes of NAGM, nano-silane modifier, and binder are crucial for effective NMEs road stabilization. Varying NAGM properties require an adjusted Material Compatible (MC) NMEs stabilizer (MC-NME) to achieve the best engineering properties. The optimal NAGM fractions for designing an effective MC-NME stabilizer include 0% passing the 0.075 mm sieve and 0% problematic or secondary minerals in the 0.075 mm fraction. In a related study, Horak et al. [72] highlighted that the incorporation of NMEs technology in the new draft TRH24 [78] positions it as a cost-effective solution for upgrading gravel roads to surfaced standards. NME-treated materials enhance the performance of marginal quality granular materials by making them naturally waterproof and flexible, in contrast to cement-treated materials, which are prone to cracking and potential crushing. In addition, Horak et al. [72] reported that in South Africa, the shrinking gravel supply and maintenance reduce road network sustainability. NMEs performance and durability in gravel road maintenance rely on nano-level mineral compatibility and strength requirements. Moreover, NME improves gravel road performance by enhancing strength, durability, and resistance to water and erosion without causing cracks like bituminous materials, enabling the maintenance of low-traffic roads (up to 3 MESA) without modifying road profiles or drainage, and reducing costs by 50% compared to traditional re-graveling. **Table 4** presents the advantages and disadvantages of using NMEs for gravel roads.

Advantages	References
<i>Enhanced the performance of construction materials:</i> Nano-modified emulsions (NMEs) stabilizers helps achieve the desired bearing capacity with minimal use of stabilizing agents. Reduces the formation of cracks. Promotes the effective utilization of locally available materials while minimizing the associated risks.	Jordaan and Kilian [3], Jordaan and Steyn [70], Horak et al. [72], Fondjo and Theron [39]
<i>Enhanced mechanical and physical properties:</i> Nano-modified emulsion stabilizers bind soil particles together, thereby enhancing effective cohesion (c'), shear strength (τ), Unconfined Compressive Strength (UCS), and the California Bearing Ratio (CBR).	Porto et al. [69], Kidgell et al. [76], Jordaan and Steyn [70], Jordaan et al. [75], Okem [73], Jordaan and Wynand [71], Okem et al. [74]
<i>Improved moisture resistance:</i> Some synthetic NMEs stabilizers create hydrophobic layers that reduce moisture infiltration and erosion, thus improving water resistance in unpaved and gravel roads.	Jordaan and Steyn [70], Horak et al. [72], Okem et al. [74], Okem [73]
<i>Dust suppression:</i> Nano-polymer stabilizers effectively bind fine particles, reducing dust generation and consequently enhancing air quality and traffic visibility.	Zeng et al. [61], Jordaan and Steyn [62]
<i>Improve the road service life:</i> Gravel roads treated with NMEs stabilizers show improved resistance to gravel loss, resulting in reduced maintenance frequency and extended service life.	Jordan and Kilian [3], Porto et al. [69], Jordaan et al. [75], Jordaan and Steyn [70], Jordaan and Wynand [71], Horak et al. [72]
<i>Enhanced the flexibility of construction materials:</i> Provide a waterproof layer while maintaining construction flexibility. Reduce energy consumption and overall costs. Ensure the long-term stability of polymer-modified asphalt.	Das et al. [79], Fondjo and Theron [39]
Disadvantages	References
<i>Time dependent of curing process:</i> The delay in the curing process of NMEs materials affects early strength development, compaction challenges, durability, and delayed traffic opening. Disrupt construction schedules and increase project costs.	Jordaan and Wynand [80]
<i>Reduced the fatigue resistance:</i> The incorporation of NMEs into bitumen could lead to a reduction in its fatigue resistance, potentially making the modified bitumen more prone to failure and cracking under cyclic loading conditions.	Das et al. [79]
<i>Higher initial cost, but cost effective:</i> NMEs are often more expensive than traditional stabilizers such as lime or cement, potentially limiting their use in large-scale or budget projects. Their higher performance, durability, and practical application may justify the higher cost.	Jordaan et al. [77], Horak et al. [72]
<i>Standard testing protocols:</i> The absence of standardized testing protocols to evaluate the performance of NMEs stabilizers effectively remains a challenge.	TRH24 [78], Horak et al. [72], Huang et al. [43], Fondjo and Theron [39]

Table 4.
Advantages and disadvantages of using nano-modified emulsions (NMEs) for gravel roads.

4. Importance of information technology in gravel road maintenance management

Mosianedi [14] mentioned that the Road Network Evaluation Tools (RONET) model, developed by the Energy, Transport, and Water Department, Transport Anchor (ETWTR) of the World Bank for the sub-Saharan Africa Transport Policy Program (SSATP), aids decision-makers to assess the current characteristics of the road network, optimize maintenance and rehabilitation, monitor road network condition, plan resource allocation, assess macro-policies consequences, and evaluate road charge revenue. Kasenge [81] investigated the impact of information technology shortcomings on pavement maintenance in South Africa. The study revealed that most road agencies do not utilize conventional Pavement Management System Software (PMSS), despite the wide availability of international products. Although a few locally developed programs exist, the adoption of PMSS remains limited, with only some institutions beginning to implement it. Nevertheless, the RONET model offers a valuable framework for optimizing the assessment, repair, durability, and management of gravel roads in several municipalities, including Mangaung, even in the absence of PMSS.

5. Conclusion

This study covers a comprehensive overview of the use of polymers, nano-polymers, and nano-modified emulsions in gravel road maintenance. This review will help researchers and professionals delve into the applications of polymers and nanomaterials in gravel roads. Polymer and nanomaterial stabilizers show potential for improving road pavements in sub-Saharan Africa, but their application in gravel roads remains limited. Gravel roads are cost-effective for low-traffic areas, but they require routine maintenance due to the loss of gravel from a gravel-wearing course. Chemical stabilizers can improve strength and reduce dust, and subgrade evaluation using DCP optimizes the gravel's road design. In addition, improving gravel road durability requires assessing the compatibility of polymers and nanomaterials with *in situ* gravel, ensuring proper grain-size distribution and strength, and achieving optimal compaction with a well-shaped, crowned cross section for drainage. Nonetheless, the optimal nano-polymer mix of 1.00% significantly increased the soil's dry unit weight and CBR values. Nano-modified emulsions (NMEs) enhance the performance of roads and are over 50% cheaper per km than annual maintenance.

This study reveals that polymers, nano-polymers, and nano-modified emulsions exhibit advantages and limitations in gravel road maintenance. Nano-material stabilization is cost-effective than re-graveling. A pronounced cooperation among researchers should be adopted to incorporate a standardized application of polymers and nanomaterials in gravel road maintenance. In sub-Saharan Africa, pavement management system software such as the World Bank's RONET model can assist in optimizing gravel road maintenance and management. Public-private partnerships offer a promising strategy to boost road infrastructure investment. While this study provides valuable insights, it is important to acknowledge its limitations. The study is limited by its regional specificity, the absence of experimental validation, and the lack of a comprehensive environmental cost analysis. Future research should focus on these limitations.

Acknowledgements

The authors thank the Central University of Technology, Free State, for sponsoring this research project.

Nomenclature

AASHTO	American Association of State Highway Transportation Officials
APT	accelerated pavement testing
ART LLC	polymer material designed to improve the physical and mechanical properties of road pavement's subgrade
CBR	California Bearing Ratio
CSIR	Council for Scientific and Industrial Research
DCP	dynamic cone penetrometer
EMS	emergency medical services
ETWTR	transport, and water department, transport anchor
EPS PM 50, 70	modified polymer emulsion and polyvinyl copolymer-based stabilizers
GTAC	Government Technical Advisory Centre
GWC	gravel-wearing course
HCT	hydroxy conversion treatment
KZN-DoT	KwaZulu-Natal Department of Transportation
MC	material compatible
MC-NME	material compatible of nano-modified emulsion
MESA	mobility for emergency and safety applications
MMM	Mangaung metropolitan municipality
NAGM	naturally available granular materials
Nano A	nano-emulsions stabilizer A
Nano B	nano-emulsions stabilizer B
NBP	nano-base polymer
NCAT	National Centre for Asphalt Technology
NMEs	nano-modified emulsions
PMSS	pavement management system software
PMS	pavement management system
ROCAMIX	polymer material designed to improve the strength of road pavement subgrade.
ROTI	road transport investments
RONET	road network evaluation tools
RPP	road packer plus
SAHRC	South African human rights commission
SATCC	Southern Africa transport and communications commission
SSATP	Sub-Saharan Africa transport policy program
TECOFIX	polymer material designed to enhance the physical and mechanical properties of road pavement's subgrade.
TRH	technical recommendations for highways
UCS	unconfined compressive strength
VPD	vehicles per day

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*Edited by Amin K. Akhnoukh
and Saúl Antonio Obregón-Biosca*

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Assed Haddad, Civil Engineering Series Editor

Published in London, UK

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