BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

Volume 6 • Issue 3 • July 2023 ISSN 2630-5232(Online)

Volume 6 Issue 3 • July 2023 • ISSN 2630-5232 (Online)

Journal of Architectural Environment & Structural Engineering Research

Editor-in-Chief

Müslüm Arıcı

BILINGUAL PUBLISHING GROUP

Volume 6 | Issue 3 | July 2023 | Page1-64
Journal of Architectural Environment &
Structural Engineering Research

Contents

Editorial

1 **Asphalt Pavement Temperature Fluctuation: Impacts and Solutions**
M.A. Alghoul, Kashif Irshad

Articles

4 **Sustainability of Bridges: Risk Mitigation for Natural Hazards**
Sachidanand Joshi, Atharvi Thorat, Harshali Dehadray, Mayuri Tundalwar

17 **Understanding the Challenges of Implementing Green Roofs in Multi-Family Apartment Buildings: A Case Study in Khulna**
Ishmat Ara, Sourav Zaman

31 **Fatigue Safety Assessment of Concrete Continuous Rigid Frame Bridge Based on Rain Flow Counting Method and Health Monitoring Data**
Yinghua Li, Junyong He, Xiaoqing Zeng, Yanxing Tang

41 **Innovation Empowerment in Construction 4.0 by the Corporate Digital Responsibility (CDR)—Approach. A New Field of Scientific Research for the Digital Breakthrough**
Bianca Weber-Lewerenz, Marzia Traverso

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

https://journals.bilpubgroup.com/index.php/jaeser

EDITORIAL

Asphalt Pavement Temperature Fluctuation: Impacts and Solutions

M.A. Alghoul**, *Kashif Irshad

Interdisciplinary Research Centre for Renewable Energy and Power System (IRC-REPS), Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, 31261, Saudi Arabia

Solar radiation, temperature, and relative humidity, depending on severity, can cause asphalt structural damage besides inducing the Urban Heat Island (UHI) effect. Such damage is more common in countries with extreme weather conditions. The ultimate failure of asphalt pavements under extreme weather conditions causes significant economic losses [1].

Apart from weather conditions, **pavement thickness, depth and porosity** also play a significant role in influencing the functional and mechanical properties of pavement systems. Air-void and pavement microstructures do not have continuous spatial and transient properties. Whereas minor changes in the thickness and depth of the asphalt pavement considerably change the elastic properties of the pavement. The impacts of both underestimating and overestimating the depth, porosity and thickness of asphalt pavement are economically detrimental and structurally detrimental. An underestimation of the dimensions of the pavement will lead to unnecessary costs and delays in the project schedule. Whereas, an overestimate can lead to a design that is not going to achieving in the desired life in service [2].

Significant **temperature fluctuations** expose pavements to increasingly unfavorable conditions and degrade their performance and strength. The daily temperature fluctuations during Summer can exceed 20 °C, and in some hot climates, asphalt temperature exceeds 70 °C. Fluctuations in the temperature and its associated effects on pavements are known as thermally instigated pressure. When thermally instigated pressure exceeds the rigidity of the asphalt pavement, a transverse split can occur at its surface, and the temperature at which this occurs is known as the crack temperature. These cracks will propagate throughout the asphalt during its maturing phase and the extra low-temperature cycles [3,4].

The impact of asphalt temperature fluctuation

*CORRESPONDING AUTHOR:
M.A. Alghoul, Interdisciplinary Research Centre for Renewable Energy and Power System (IRC-REPS), Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, 31261, Saudi Arabia; Email: mohammad.alghoul@kfupm.edu.sa; dr.alghoul@gmail.com

ARTICLE INFO
Received: 20 July 2023 | Accepted: 28 July 2023 | Published Online: 10 August 2023
DOI: https://doi.org/10.30564/jaeser.v6i3.5869

CITATION
Alghoul, M.A., Irshad, K., 2023. Asphalt Pavement Temperature Fluctuation: Impacts and Solutions. Journal of Architectural Environment & Structural Engineering Research. 6(3): 1-3. DOI: https://doi.org/10.30564/jaeser.v6i3.5869

on pavement structure includes thermal cracking, fatigue cracking, and ageing. While the impact of asphalt pavement temperature on the surrounding environment includes human comfort, the upsurge of energy demand, emissions of greenhouse gases (GHG) and air pollutants, impaired water quality and pavement life. Temperature-related damages can be mitigated by watering when pavements are being laid, using porous materials, mixing multiple additives, using multiple material configurations and increasing the thickness of asphalt pavement.

Asphalt pavement materials having lower heat transfer coefficient, lower heat conductivity and excellent water retention capabilities respond well in harsh weather climatic conditions. These materials prevent heat from reaching the surface and the surrounding area of asphalt pavement due to its lower heat transfer coefficient and lower heat conductivity. Urban Heat Island effect will be also reduced by using such material resulting in lower near-surface air temperatures and daytime pavement temperatures. This further affects human health by decreasing general discomfort, breathing problems, heat cramps and fatigue, non-fatal heat stroke, and heat-related mortality. In addition, building energy consumption will also be reduced throughout the summer, particularly during hot weekday afternoons, as most building ventilation devices, lighting, and other operation equipment required less energy [5-7].

Potential solutions for pavement temperature include micro filling, lower surface temperature and increasing solar reflectance, porosity, albedo and emittance, increasing the thermal conductivity, evaporation cooling and shading, mechanical cooling, convection cooling, and asphalt solar collector. The **asphalt solar collector** (ASC) concept refers to an asphalt pavement with a piping network system embedded below roads that convert solar energy to thermal energy. A heat transfer process occurs between the pavement and the working fluid flowing within the pipes, which decreases the pavement's temperatures and the thermal radiative losses from the asphalt to its surroundings. Besides the cooling benefit for the asphalt pavements that the ASC can provide, the collected heat from the ASC system and stored in a well-insulated small, medium and large-scale heat bank to be used for different applications and heating purposes [2-4,8].

Future research directions can be drawn as follows:

- Further efforts to enhance the thermo-structural characteristics of asphalt pavement are vital to withstand the effect of solar radiation and temperature.
- As heat transfer in asphalt concrete depends on the structure, future models should incorporate heat data and asphalt conditions.
- The thermophysical properties of asphalt blends need to be investigated in the future for detailed structural analysis.
- The impacts of materials on the surface temperature of pavements should be further investigated.
- Compare to other solutions, solar asphalt technology would cool asphalt temperature by absorbing heat through pavement-pipe systems and concurrently utilize it in different heating applications. ASC systems have been designed and implemented in many countries. Further simulation and experimental investigations are still vital to be carried out.

Conflict of Interest

There is no conflict of interest.

References

[1] Asaeda, T., Ca, V.T., 2000. Characteristics of permeable pavement during hot summer weather and impact on the thermal environment. Building and Environment. 35(4), 363-375.

[2] Solatifar, N., Abbasghorbani, M., Kavussi, A., et al., 2018. Prediction of depth temperature of asphalt layers in hot climate area. Journal of Civil Engineering and Management. 24(7), 516-525. DOI: https://doi.org/10.3846/jcem.2018.6162

[3] Seitllari, A., Boz, I., Habbouche, J., et al., 2022. Assessment of cracking performance indices of

asphalt mixtures at intermediate temperatures. International Journal of Pavement Engineering. 23(1), 70-79.
DOI: https://doi.org/10.1080/10298436.2020.1730838

[4] Sun, Y., Du, C., Gong, H., et al., 2020. Effect of temperature field on damage initiation in asphalt pavement: A microstructure-based multiscale finite element method. Mechanics of Materials. 144, 103367.
DOI: https://doi.org/10.1016/j.mechmat.2020.103367

[5] Hendel, M., 2020. Cool pavements. Eco-efficient Pavement Construction Materials. 97-125.
DOI: https://doi.org/10.1016/B978-0-12-818981-8.00006-0

[6] Nasir, S.D., Xu, W., Vital, B., et al., 2020. Urban road and pavement solar collector system for heat island mitigation: assessing the beneficial impact on outdoor temperature. IOP Conference Series: Earth and Environmental Science. 463(1), 012038.
DOI: https://doi.org/10.1088/1755-1315/463/1/012038

[7] Santamouris, M., Yun, G.Y., 2020. Recent development and research priorities on cool and super cool materials to mitigate urban heat island. Renewable Energy. 161, 792-807.
DOI: https://doi.org/10.1016/j.renene.2020.07.109

[8] Nasir, D.S., Hughes, B.R., Calautit, J.K., 2015. A study of the impact of building geometry on the thermal performance of road pavement solar collectors. Energy. 93, 2614-2630.
DOI: https://doi.org/10.1016/j.energy.2015.09.128

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research
https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Sustainability of Bridges: Risk Mitigation for Natural Hazards

Sachidanand Joshi [*] ***, Atharvi Thorat, Harshali Dehadray, Mayuri Tundalwar***

UBMS Research Group, Mumbai, 400062, India

ABSTRACT

Bridges serve as essential parts of transportation infrastructure, facilitating the movement of people and goods across rivers, valleys, and other obstacles. However, they are also susceptible to a wide range of natural hazards, including floods, earthquakes, and landslides, which can damage or even collapse these structures, leading to severe economic and human losses. A risk index has been developed to address this issue, which quantifies the likelihood and severity of natural hazards occurring in a specific location. The application of risk indices for natural hazards in bridge management involves a data collection process and mathematical modelling. The data collection process gathers information on bridges' location, condition, and vulnerability, while mathematical modelling uses the data to assess the risk of natural hazards. Overall, risk indices provide a quantitative measure of the vulnerability of bridges to natural hazards and help to prioritize maintenance and repair activities. Mitigation measures are then evaluated and implemented based on the risk assessment results. By using this tool, the UBMS research group has developed an algorithm for risk assessment which will be essential in the decision-making process, specifically focused on enhancing Fund Optimization, Deterioration Modelling, and Risk Analysis. These developments effectively fulfill the primary objectives associated with addressing and mitigating hazards. This development also helps bridge managers understand the potential threats posed by natural hazards and allocate resources more efficiently to ensure the safety and longevity of critical transportation infrastructure.

Keywords: Hazards; Risk index; Vulnerability; Mitigation measures; Decision-making process; Fund optimization; Deterioration modelling; Risk analysis

*CORRESPONDING AUTHOR:
Sachidanand Joshi, UBMS Research Group, Mumbai, 400062, India; Email: sachidanand@ubmsresearchgroup.com

ARTICLE INFO
Received: 19 June 2023 | Revised: 28 July 2023 | Accepted: 4 August 2023 | Published Online: 15 August 2023
DOI: https://doi.org/10.30564/jaeser.v6i3.5807

CITATION
Joshi, S., Thorat, A., Dehadray, H., et al., 2023. Sustainability of Bridges: Risk Mitigation for Natural Hazards. Journal of Architectural Environment & Structural Engineering Research. 6(3): 4-16. DOI: https://doi.org/10.30564/jaeser.v6i3.5807

1. Introduction

The paper aims to highlight the urgency and importance of including risk assessment rising from natural hazards within bridge management to render the bridges to be resilient to these natural hazards. The focus of the research has been on earthquakes, floods, cyclones, and landslides, which can have devastating effects on human life and infrastructure.

In recent times vagaries of climate change have impacted the world over. In India too, the entire north India experienced significant devastation from floods, where this year more than 100 people lost their lives and scores were injured as of mid-July, 2023. The floods caused extensive damage to infrastructure, leading to thousands of blocked roads and disruptions in power supply. Around 70,000 tourists were evacuated with the help of the Indian Army and the National Disaster Response Force. Many cities were also severely affected, with roads washed away, leaving residents and tourists stranded. Rural areas also faced the consequences of incessant rains, resulting in waterlogged roads, submerged cars, and flooded fields in large parts of Punjab, Himachal Pradesh.

Many places around the world are witnessing single-day extreme situations like the highest rainfall/snowfall in over five to six decades, very high temperatures, and extreme cyclonic weather/hurricanes and other extremes. Such extremes are witnessed in all corners of the world including Europe, America, Asia, and Australia. Cyclones affect the vast Indian coast frequently and the recent spate of occurrences along both the east and west coasts have resulted in NDMA officials focusing on cyclones. Earthquakes have impacted scores of bridges in the past. Like cyclones, floods, and landslides impact of earthquakes also needs to be addressed in India. The entire Himalayan region is prone to sporadic earthquakes.

These sudden and frequent extremities of weather around the world and in India highlight the pressing need for improved disaster management and mitigation measures in the region. In recent years, the frequency and severity of natural disasters have notably increased, largely attributed to factors like climate change and rapid urbanization [1]. Bridges, as critical infrastructure, play a vital role in facilitating the movement of people and goods [2]. However, their susceptibility to natural hazards demands special attention to ensure the safety and functionality of transportation networks. Most Bridge Management systems [BMS] do not comprehensively address the issue of risk arising from natural occurrences in a proactive manner. It is only when distress is observed that BMS comes up with remedial interventions.

To effectively manage natural hazards and mitigate their impact on bridges, a proactive approach is essential. This approach involves identifying vulnerable areas and implementing appropriate mitigation measures. A promising tool that aids in this process is the Risk Index for hazards [3]. The risk index quantifies the probability and severity of a natural hazard occurring in a specific location. It considers factors such as the likelihood of the hazard occurring, the intensity of the hazard, and the vulnerability of the population and infrastructure in the area [4]. The risk index proves valuable in identifying the most vulnerable areas, prioritizing mitigation measures, and evaluating the effectiveness of emergency response plans.

As a result, the development of risk indices for hazards has become a critical component of hazard research and management. These risk indices have found applications in assessing various natural hazards, including earthquakes, floods, cyclones, and landslides [5].

This paper aims to review the utilization of risk indices for natural hazards within the context of the Global Analytics for Bridge Management [GABM] application. Specifically, the paper focuses on the methodology and application of risk indices for natural hazards in bridge management. Considering the vulnerability of bridges to catastrophic events, this study aims to provide a viable method for data collection related to hazards, mathematical modelling of incorporating risk index within decision-making tool of fund optimization in BMS and providing a proactive scenario for implementing mitigation measures with the incorporation of risk indices in bridge management.

The primary objective is to explore how the utilization of risk indices can enhance the resilience of bridge infrastructure and ensure the safety of the travelling public. This research contributes to building possibly robust transportation networks that can withstand the increasing challenges posed by natural hazards.

1.1 Challenging scenario for bridge management

In today's scenario, climate changes have resulted in creating uncertainty in the way nature behaves. Natural hazards have become more unpredictable, more intense, and more frequent. Achieving or maintaining the sustainability of bridge structures under these circumstances is challenging but essential.

Bridges serve as essential parts of transportation infrastructure, facilitating the movement of people and goods across rivers, valleys, and other obstacles. However, they are also susceptible to floods, earthquakes, landslides, and other similar natural hazards. The impact of natural hazards is not predictable, and sudden and can damage these bridge structures at times leading to the failure of bridges. Such impact cause severe economic and human losses. To address this issue, a proper mitigation or containment protocol is essential. Conventional Bridge Management did address this issue in a limited way [6]. The response of the bridge to the hazard depends on the bridge's design, construction, geology, location, age, and other factors. These factors also need to be accounted for.

The application of risk indices for natural hazards in Bridge Management involves mathematical modelling applied to the data collected, regarding the occurrence of natural hazards, their intensity and frequency. The data collection process gathers information on bridges' location, condition, and vulnerability. Subsequently, mathematical modelling is applied to this data to assess the risk of natural hazards. Evaluation of risk index and vulnerability also enables adaptation of preventive proactive structural strengthening of the bridge structure. Mitigation measures are then evaluated and implemented based on the risk assessment results.

By using this tool within the algorithm for risk assessment, it is possible to contain the possibility of damage and achieve mitigation in a limited way. Proactive usage of the module in the decision-making process is recommended.

1.2 Past and present research

Risk mitigation for natural hazards in bridge management has been researched for a long. One study discusses supporting the life cycle management of bridges through multi-hazard reliability and risk assessment [7]. The study utilizes metamodels as an efficient strategy for developing parameterized time-dependent bridge fragilities for multiple hazards. Threats considered in the case studies include earthquakes, hurricanes, ageing and deterioration, and live loads.

Swagata Banerjee et al. (2013) proposed a highway transportation network composed of many bridges that share the same statistical structural attributes and configurations as the example bridges, which can utilize fragility curves and risk curves to portray the vulnerability and associated risk of these highway bridges to regional multi-hazard events [8].

Paul D. Thompson et al. (2016) explore the concept of risk in the context of transportation facilities, with a particular focus on bridges. Adverse events can be caused by natural hazards such as earthquakes, floods, and wildfires, as well as man-made hazards like overloads and collisions. The Moving Ahead for Progress in the 21st Century Act (MAP-21) emphasizes risk-based asset management without specifying risk performance measures but outlines national performance goals related to safety, infrastructure condition, congestion reduction, and more. Adverse events can affect these national goals, and various tools like accident analysis and life cycle cost analysis can help estimate the consequences of such events. AASHTOWare Bridge Management software (BrM), offers multi-objective performance frameworks to aid in project evaluation and resource allocation. The literature review also highlights the need for improved guidance on engineering risk assessment, post-event evaluation, and rapid recovery strategies for infrastructure assets [7].

The review of past research, provided an extensive overview of the utilization of risk indices for natural hazards, emphasizing the importance of such tools in civil engineering and hazard management. The review highlighted the challenges faced in bridge management due to the increasing unpredictability and intensity of natural hazards. It also described how risk indices are essential in assessing vulnerability, prioritizing resources, and evaluating mitigation measures.

The ground realities in India and the review identified four major natural hazards relevant to bridge management: earthquakes, floods, cyclones, and landslides. Each hazard requires a specific risk index tailored to its characteristics. The review emphasized the need for data integration, hazard mapping, and comprehensive risk assessment to create effective risk indices.

Application of risk indices in bridge management:

Earthquake Risk Indices: These indices consider seismic hazard assessments, structural vulnerability, and potential consequences such as economic impact and life loss. By quantifying the risk, bridge managers can prioritize retrofitting measures and emergency response plans [9].

Landslide Risk Indices: Risk indices for landslides assess bridge structures' susceptibility to potential damage caused by geological events. These studies analyze geological and geotechnical data to identify landslide-prone areas and evaluate bridges' vulnerability in such regions [4].

Cyclone Risk Indices: Risk assessment models for wind-induced vibrations and fatigue damage in long-span and cable-stayed bridges have been developed. These models consider factors such as wind speed, bridge geometry, and structural characteristics to assess bridge vulnerability to high winds [5].

Flood Risk Indices: Risk indices for flood hazards consider factors like flood frequency, intensity, bridge location, and population vulnerability. These indices identify flood-prone areas, optimize mitigation measures, and assess emergency response plans [7].

The literature review underscores the vital role of risk indices in bridge management, as they assess vulnerability, optimize resource allocation, and implement effective mitigation measures for natural hazards like earthquakes, floods, and landslides. The integration of risk indices within the Global Analytics for Bridge Management (GABM) presented, showcases its capability to rank bridges based on their risk levels, facilitating the identification of priority structures in need of immediate attention and targeted interventions. Furthermore, it enables scenario analysis, allowing bridge managers to assess the effectiveness of various mitigation strategies and make informed decisions. It embodies a proactive and data-driven approach, ensuring the safety, sustainability, and resilience of bridge infrastructure, and enabling effective decision-making to safeguard critical transportation infrastructure [10].

2. Risk assessment methodology for natural hazards

Natural hazards such as earthquakes, floods, hurricanes, and landslides can have devastating effects on human life and property. The frequency and severity of natural disasters have increased significantly in recent years due to factors such as climate change and urbanization. The management of natural hazards requires a proactive approach that involves the identification of vulnerable areas and the implementation of mitigation measures by proactively strengthening the bridges which are more susceptible to damage. Bridges are important infrastructure links. Their vulnerability is very high and needs special attention. The Bridge Management system needs to incorporate a module for such risk assessment and analysis. Based on the analysis, the proper action is required for the mitigation of the evaluated risks.

The sustainability of bridges and the effective mitigation of risks associated with natural hazards necessitate a systematic and multidisciplinary approach. This research employs a methodology that encompasses several key components. A thorough examination of deterioration mechanisms and their interaction with natural hazards is conducted. This involves studying the effects of various environmental factors such as temperature fluctuations, moisture, and chemical exposure on bridge materials and structural integrity. By understanding these deterioration processes, suitable preventive and maintenance measures can be identified. The risk assessment also involves considering the consequences of bridge failure, including the impact on transportation networks, economic losses, and potential harm to human life.

The process essentially begins with the collection of historical data and an understanding of the geography of the area surrounding the bridge. This requires the user of GABM to collate the historical event and during the past few years for frequently occurring events. Four major natural hazards are in focus for India. They are earthquakes, floods, cyclones, and landslides. Earthquakes and floods are more predominant in the northern fringes of India abutting the Himalayan ranges extending from Kashmir to Assam. Cyclones are more predominant in the coastal belt of India which is over 15,000 km long. Landslides are in focus in the foothills of all mountain ranges. Over 60% of India is hazard-prone and hence the effort to mitigate the impact. Two types of values are evaluated from this data; namely the frequency of occurrences based on long-term data and the uncertainty coefficient based on the increased frequency over the last few years. Data are also collected regarding the intensity of past events.

The extent of damage that occurred during past events defines the possibility of damage that can occur if No action is taken to mitigate the same. Here an important factor that is accounted for is the propagation of distress in the bridge structure due to the event. Many times, the frequent occurrence of the event leads to a progression of distress that can culminate in a collapse during the future occurrence. Such progression is evaluated and steps to mitigate this progression are also accounted for.

Consequences refer to the impact of the event on the bridge if it were to occur. This includes the potential damage to the bridge, disruption to transportation networks, and potential loss of life or injuries. Consequences can vary based on the specific characteristics of the bridge, such as its structural design, materials used, and traffic volume [11]. The total cost of retrofit is evaluated and termed as consequence cost. This consequence cost is not just the cost of rehabilitation and restoration of the level of service but includes the cost arising from loss of service. GABM has within the database values assigned to the Socio-Economic impact of the bridge on the region of influence. These Socio-Economic parameters enable evaluation of the cost of disruptions arising from future occurrences.

The establishment of a risk index for hazards entails the use of mathematical models to quantify the likelihood and severity of a hazard occurring in a specific location. The risk index is used to assess the potential risks associated with bridges. This index combines information on the likelihood of a risk event occurring and the consequences of that event. By considering both factors, bridge managers can prioritize their resources and take appropriate actions to mitigate risks effectively. Likelihood refers to the probability or frequency of a risk event occurring. It considers various factors such as the condition of the bridge, environmental factors, and usage patterns. For example, a bridge located in an area prone to earthquakes would have a higher likelihood of experiencing a seismic event compared to a bridge located in a seismically stable region.

To develop a risk index, bridge managers typically need to assign numerical values or ratings to both the likelihood and consequences of various risk events. These ratings can be based on historical data, expert opinions, or analytical models. For example, likelihood ratings can be categorized as low, medium, or high, while consequence ratings can be classified as minor, moderate, or severe. Once the likelihood and consequence ratings are assigned, they are combined in a predetermined manner to calculate the risk index for each natural hazard. The formula can be as simple as multiplying the likelihood and consequence ratings together, or it can involve more complex mathematical or statistical models. The resulting risk index provides a quantitative measure of the overall risk level associated with each hazard type.

The risk index, presently is based on a simple combination of likelihood and consequences to provide a systematic approach to identifying, assessing, and prioritizing risks associated with bridges. GABM allows user to use their discretion to modify risk index calculated values to values that are based on their judgement or past historical experience. Based on usage, the refinements in the evaluation of the risk index are inbuilt using an AI tool that captures the evaluated values and compares them with accepted values. Refinement in the evaluation process is statistically AI-driven. Using the application over a period in a particular region will yield a more refined and stable evaluation process. By utilizing this index, bridge managers can make informed decisions and take proactive steps to ensure the safety and longevity of bridge infrastructure.

Following are the steps for calculating Risk Indices.

2.1 Gather historical data

- Collect detailed information about the bridge's design, construction, maintenance history, and materials used (**Figures 1B and 1C**).
- Gather data on environmental conditions such as weather patterns, seismic activity, flood risks, and soil characteristics.

2.2 Identify hazards

- Identify and categorize potential hazards that could affect the bridge (e.g., earthquakes, floods, landslides, and cyclones) (**Figure 1A**).

2.3 Assess vulnerability

- Evaluate the bridge's vulnerability to each identified hazard by using.

a. Likelihood of service disruption.

b. Likelihood of occurrence of the extreme event of a given magnitude that is specified by the hazard scenario, estimated for the bridge.

c. Consequence of service disruption.

d. Weight Factors: Assign relative weights to the different hazard categories and safety based on their importance and potential impact. Weighting factors may vary based on the specific objectives of the risk index.

e. This leads to calculating:

i. Lebh (Likelihood of event happening).

ii. Ldbh (Likelihood of event happening in the bridge's lifetime) (**Table 1**).

iii. Assign values for each bridge based on the following ranges.

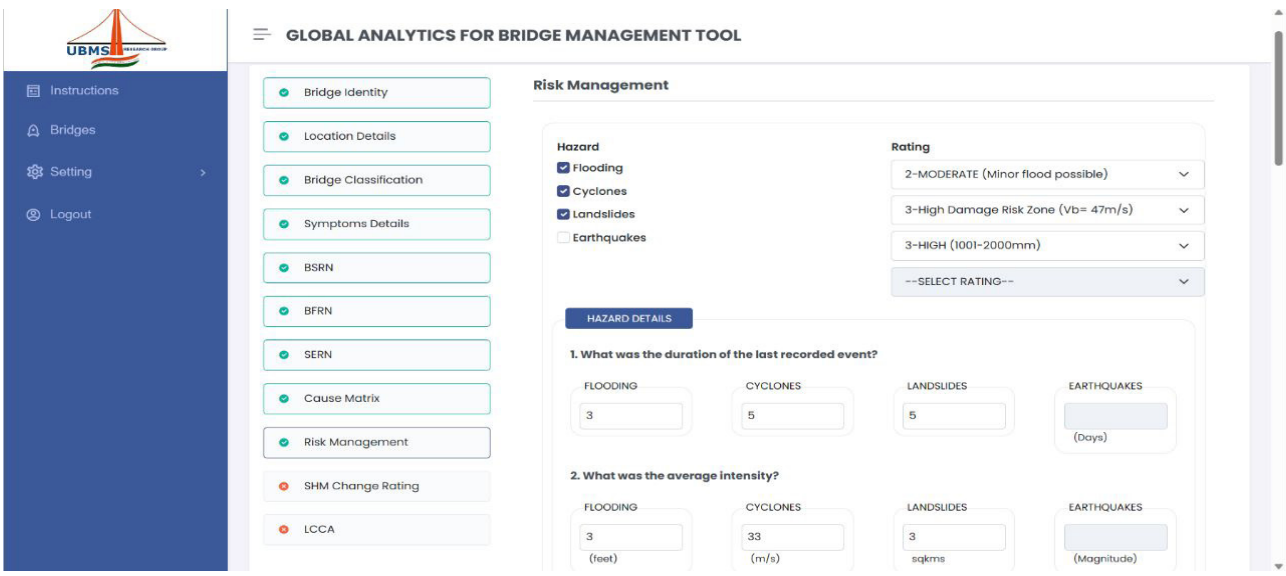


Figure 1A. GABM identify hazards.

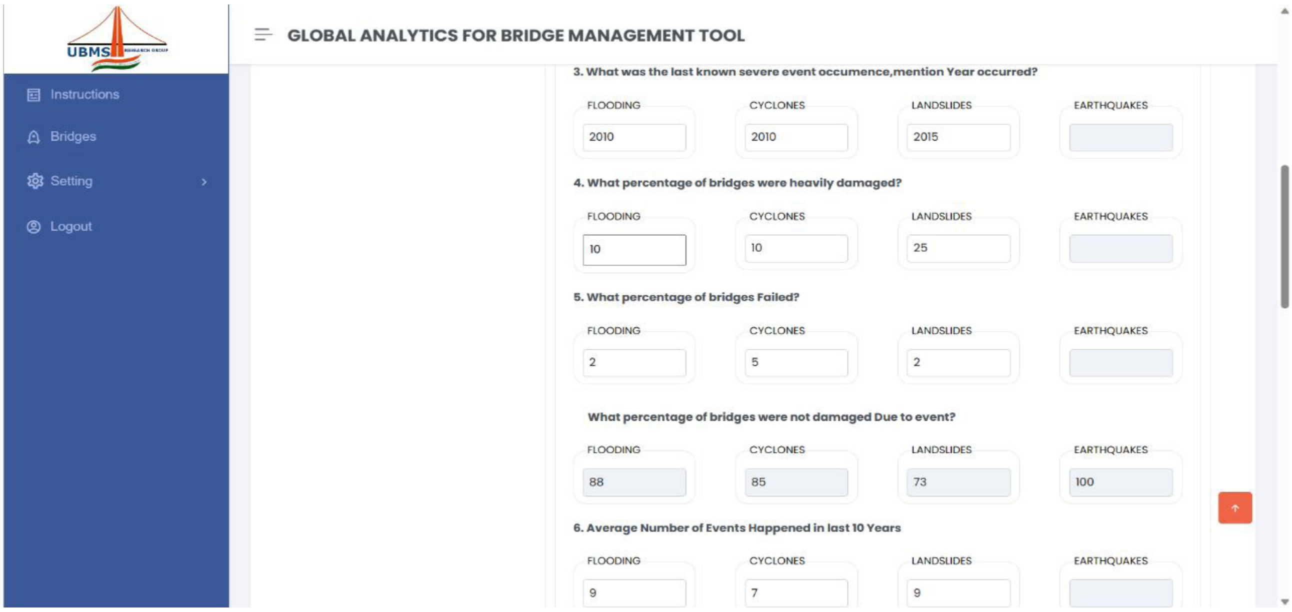


Figure 1B. GABM data collection.

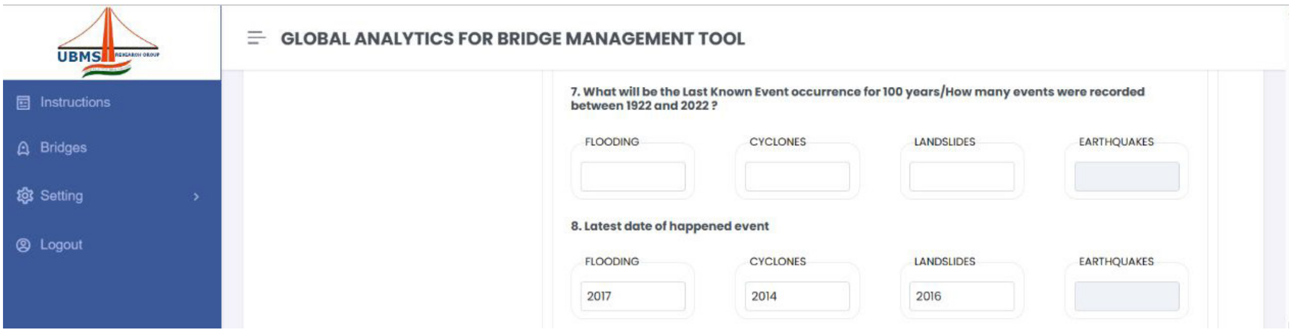


Figure 1C. GABM's latest occurrence.

Table 1. Likelihood of service disruption (LDbh).

Likelihood of service disruption (LDbh)		
Range	Probability	Values
Good	< 5%	0
Satisfactory	< 35%	25
Poor	< 65%	50
Critical	< 95%	75
Failed	>= 95%	100

- Quantify vulnerability factors using engineering analysis and historical data.

2.4 Risk indices

- Evaluate the Risk index for the bridge by multiplying utility by the vulnerability.
- The highest values of the Risk index will be prioritised for rehabilitation and repair (**Figure 1D**).

The risk index quantifies the probability and severity of a natural hazard occurring at a particular location. The risk index considers factors such as the probability of hazard occurrence, the intensity of the hazard, distance from the epicentre and the vulnerability of the population and infrastructure in the area. The risk index can be used to identify areas that are most vulnerable to natural hazards, prioritize mitigation measures, and evaluate the effectiveness of emergency response plans. The risk index is specific to the type of natural hazard. The index will be different for earthquakes, landslides, flooding, cyclone, extreme temperature, or any other hazard (**Figure 2**).

The development of risk indices for hazards has become an essential component of hazard research and management. Risk indices have been used in the

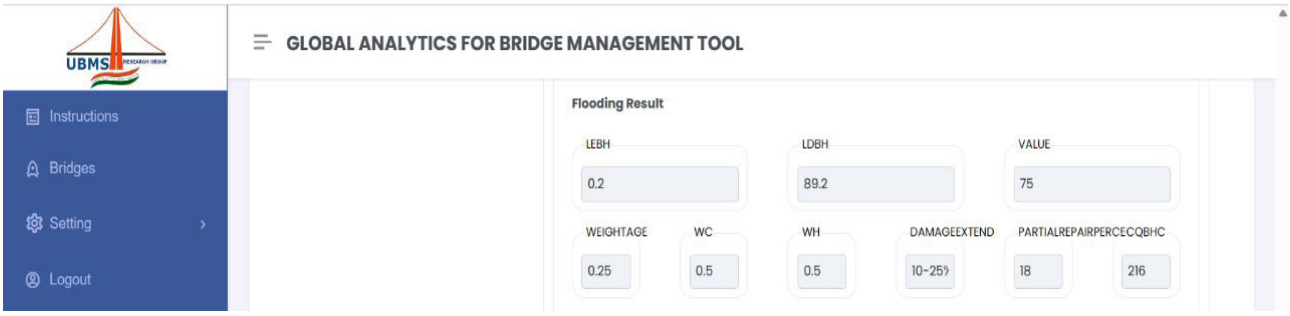


Figure 1D. Results of risk management in GABM.

Figure 2. Bridge damage due to flooding hazard.

assessment of all major natural hazards including earthquakes, floods, cyclones, landslides, and similar hazards. In each of these applications, the risk index provides a quantitative measure of the risk of a hazard occurring in a particular location and helps to identify areas that are most vulnerable to natural hazards [12].

The natural hazard module aims at the utilization of risk indices for the natural hazards in the GABM application. Specifically, the module is focused on the methodology and usage of the risk indices for natural hazards in bridge management. The establishment of a risk index for hazards entails the use of mathematical models to quantify the likelihood and severity of a hazard occurring in a specific location.

The risk index is used to assess the potential risks associated with bridges. This index combines information on the likelihood of the event occurring, its intensity, its proximity to the bridge and the consequences of that event. By considering all the factors, bridge managers can prioritize their resources and take appropriate actions to mitigate risks effectively during the decision-making process. The likelihood of the event occurring refers to the probability or frequency of the event occurring. For example, a bridge located in an area prone to earthquakes would have a higher likelihood of experiencing a seismic event compared to a bridge located in a seismically stable region.

To develop a risk index, the module typically evaluates and assigns numerical values or ratings to the likelihood, intensity, proximity, and consequences of various events (**Figure 3**). These ratings can be based on historical data, expert opinions, or analytical models [10]. For example, likelihood ratings can be categorized as low, medium, or high, while consequence ratings can be classified as minor, moderate, or severe.

Once all the ratings are assigned, they are combined using a predetermined formula to calculate the risk index for each risk event. This formula can be as simple as multiplying the likelihood and consequence ratings together, or it can involve more complex mathematical calculations or statistical models. The resulting risk index provides a quantitative measure of the overall risk level associated with

Figure 3. Bridge damage due to seismic hazard in the corrosion-prone bridge.

each risk event. GABM uses a mathematical model to evaluate the risk index. Based on the risk index, bridge managers can prioritize their efforts and allocate resources accordingly. The fund optimization module enables the bridge manager to reach the objective. Risk events with higher indices indicate a greater need for immediate attention and mitigation measures. This allows the development of risk mitigation and management strategies, such as conducting regular inspections, implementing maintenance programs, or prioritizing repair or replacement projects for bridges with the highest risk levels.

Utilizing the risk index enables informed decisions to initiate proactive steps to ensure the safety and longevity of bridge infrastructure. Mitigation principles involved are also based on taking a more proactive approach towards the vulnerability of the bridge to a particular hazard (**Figure 4**) [13].

The protocol enables bridge management to address the various issues involved more efficiently and effectively. We all understand that damage arising due to hazards cannot be avoided but an attempt to restrict the damage is initiated.

Risk assessment is an integral part of bridge sustainability, facilitating the identification and prioritization of hazards. Quantitative and qualitative risk assessment models are utilized to evaluate the vulnerability of bridge structures to natural hazards. By conducting comprehensive risk assessments, bridge authorities can prioritize mitigation efforts, allocate resources effectively, and implement adaptive strategies to reduce vulnerabilities. The sustainability of bridges can be further enhanced through the implementation of targeted mitigation measures. These may include retrofitting vulnerable components, employing innovative construction materials, and implementing advanced design principles that consider hazard resilience. Additionally, incorporating

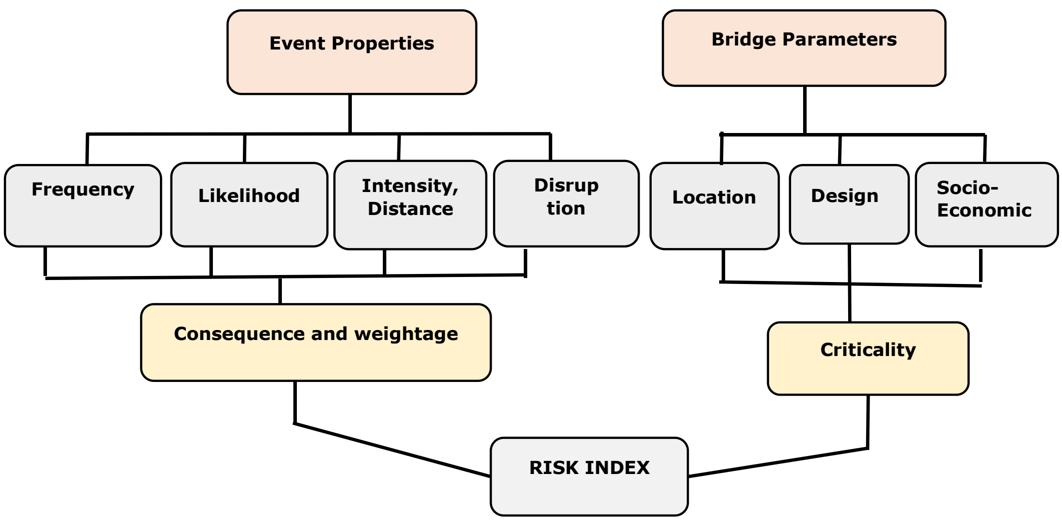


Figure 4. Risk index evaluation flow chart.

nature-based solutions, such as vegetation barriers and erosion control measures, can enhance the durability and sustainability of bridges while promoting environmental compatibility.

Bridge sustainability, environmental, social, and economic considerations are crucial. Furthermore, engaging local communities in decision-making processes and considering their needs and concerns promotes social sustainability. Finally, conducting life cycle cost analyses helps bridge authorities assess the economic feasibility of sustainable practices and make informed decisions regarding long-term maintenance and rehabilitation strategies.

BETA testing for the evaluation of Risk Indices for various hazards and geography is undertaken and the results of this have been utilized to modify/correct the procedures (**Figure 5**).

3. Results

The benefits that can accrue are not possible without the below-listed processes [14-16]:

Data Integration: GABM integrates various data sources related to bridge infrastructure, hazard occurrences and characteristics, and vulnerability assessments.

Risk Assessment Modelling: Utilizes advanced risk assessment models to quantify individual risk hazards. These models consider factors such as hazard probabilities, hazard intensities, proximity to past occurrences, bridge vulnerability, and potential consequences.

Hazard Mapping: Incorporates individual hazard mapping and can present the spatial distribution of various risk hazards. For example, one bridge could be more vulnerable to earthquakes and less or not vulnerable at all to floods and cyclones (**Figures 6 and 7**).

The resulting benefits to the region and bridges on the network are many. The below listing is the key benefits only. Many other ancillary benefits can culminate.

1) Comprehensive Risk Assessment: GABM provides a holistic, quantitative, and qualitative as-

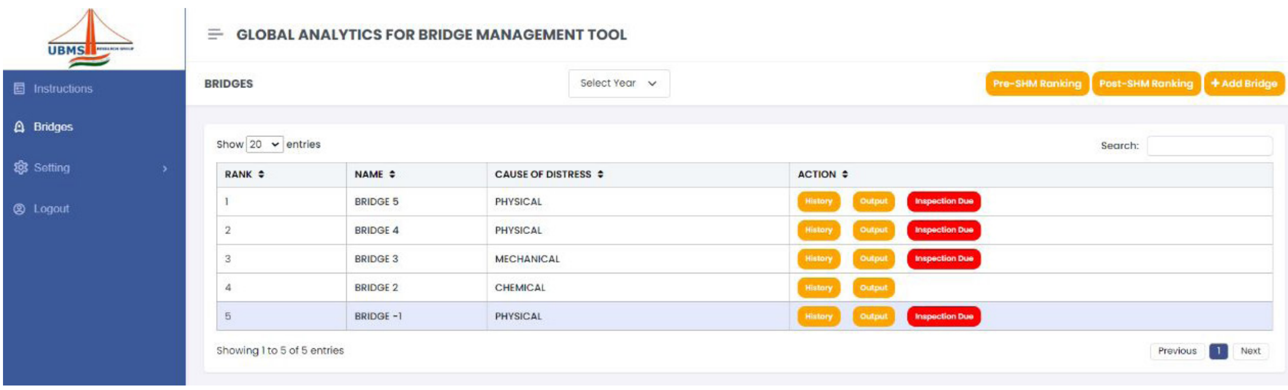


Figure 5. Recorded bridges in GABM.

Figure 6. Cyclone impact on bridges.

Figure 7. Concrete degradation of the bridge due to continued exposure to flood hazard.

sessment of risk by considering multiple hazards, bridge vulnerabilities, and potential consequences.

2) Prioritization of Resources: Allows users, to prioritize resources based on the level of risk.

3) Efficient Risk Mitigation: Implement targeted and cost-effective risk reduction measures.

4) Cost-Benefit Analysis: Helps in cost-benefit analyses for bridge management and maintenance.

5) Comprehensive Risk Assessment: Holistic, quantitative, and qualitative assessment of risk by considering multiple hazards, bridge vulnerabilities, and potential consequences.

6) Improved Decision-Making: Provides a standardized measure that can be used for comparative analysis and decision-making.

7) Enhanced Emergency Response Planning: During hazard events, it enables quick identification of bridges at higher risk, helping them prioritize emergency response efforts.

8) Long-Term Planning and Resilience: Supports long-term planning.

9) Stakeholder Communication: Provides a clear and easily communicable measure of risk. It facilitates effective communication with all stakeholders.

4. Conclusions

The information presented in this paper highlights the devastating impact on human life and infrastructure due to sporadic and erratic natural hazards, particularly in the context of recent events around the world. It emphasizes the urgency to adopt a proactive approach to managing natural hazards, with a focus on bridges' vulnerability, given their critical role in transportation networks. The paper introduces the Risk Index for hazards as a valuable tool to quantify the probability and severity of natural hazards occurring in specific bridge locations. The integration of risk indices within GABM is emphasized, as it provides a systematic and data-driven approach to assess and mitigate risks associated with hazards in bridge management. The integration's main contributions include providing an informed decision-making option for prioritization of resources, efficient risk mitigation, and enhancing the resilience of bridge infrastructure. The risk index results enable the ranking of bridges based on their risk levels. This ranking provides a clear understanding of which bridges are at higher risk and require immediate attention in terms of mitigation measures, maintenance actions, or resource allocation. This ranking is based on the Engineering Impact Index and Financial Impact Index which quantify the effects of deterioration on engineering performance and financial costs associated with repairs or replacement, Sustainability Index assesses the environmental and social sustainability aspects of the bridges. The Risk and Hazard Index represents the level of risk associated with the specific hazards that bridges may face, and Final Cost Index combines all four indexes using a standard ratio, to provide an overall assessment of the cost implications associated with the bridge projects.

The research highlights the benefits of conducting comprehensive risk assessments, engaging in long-term planning, and considering environmental and social sustainability aspects in bridge management. By utilizing risk indices, bridge managers can take proactive steps to address vulnerabilities and allocate resources efficiently, ultimately leading to the safety and sustainability of bridge networks in the face of natural hazards. By incorporating data on hazard occurrences, bridge vulnerability, and potential consequences, it facilitates a comprehensive assessment of individual risk hazards, enabling bridge managers to prioritize resources and implement targeted mitigation strategies. GABM's scenario analysis and decision-making support feature further enhances its effectiveness in evaluating different mitigation measures and improving bridge performance.

Future research directions in this area could focus on refining and expanding the risk assessment models to encompass a broader range of natural hazards and bridge types. The development of more sophisticated risk indices that consider additional factors such as climate change projections, soil conditions, and structural materials would enhance the accuracy and effectiveness of risk evaluations.

Additionally, further research could explore the integration of real-time data and advanced sensor technologies into the risk assessment process. By incorporating real-time data on weather patterns, water levels, and seismic activity, bridge managers could have a more dynamic and responsive approach to risk management, enabling them to take timely preventive measures during hazardous events. This approach can lead to improved emergency response planning, quicker identification of high-risk bridges during hazardous events, and better coordination with emergency management agencies.

Bridge managers can use risk indices to conduct cost-benefit analyses for various mitigation strategies. By considering potential risks and associated costs of bridge failures or disruptions, informed decisions can be made regarding investments in maintenance, repair, and retrofitting, which contributes to the overall safety and longevity of bridge networks. It is essential to acknowledge the potential limitations of using risk indices for bridge management and risk assessment. Future research directions and practical implications should be discussed. Limitations may include uncertainties in data quality, modelling assumptions, and challenges in real-world implementation. Addressing these limitations and further research on refining risk assessment methodologies will be crucial for enhancing the practical applicability of risk indices and ensuring their effectiveness in real-life scenarios.

Conflict of Interest

There is no conflict of interest.

References

[1] Asrani, N.P., Venkatasubramanian, C., Muthu, D., et al., 2018. Risk management â€" decision making using analytical hierarchy process. International Journal of Engineering & Technology. 7(3.12), 188.
DOI: https://doi.org/10.14419/ijet.v7i3.12.15917

[2] Rahman, J., Billah, A.M., 2023. Development of performance-based fragility curves of coastal bridges subjected to extreme wave-induced loads. Journal of Bridge Engineering. 28(3), 04023005.

[3] Patel, K., 2013. A study on risk assessment and its management in India. American Journal of Civil Engineering. 1(2), 64-67.

[4] Pablo Jr, R.M., 2009. Risk assessment of highway bridges: A reliability-based approach. The Technology Interface Journal. 10(2), 165-172.

[5] Heldt, T., 2019. Enabling Better Bridge Management by Understanding Risk by Tim Heldt [Internet]. Available from: http://ipweaq.intersearch.com.au/ipweaqjspui/handle/1/5378

[6] Thompson, P.D., Western, J., Bye, P., et al., 2016. Assessing Risk for Bridge Management: Final Report [Internet]. Available from: https://onlinepubs.trb.org/Onlinepubs/nchrp/docs/NCHRP2007Task378FinalReport.pdf

[7] Kameshwar, S., Padgett, J.E., 2014. Multi-hazard risk assessment of highway bridges subjected to earthquake and hurricane hazards. Engineering Structures. 78, 154-166.

[8] Banerjee, S., Ganesh Prasad, G., 2013. Seismic risk assessment of reinforced concrete bridges in flood-prone regions. Structure and Infrastructure Engineering. 9(9), 952-968.

[9] Joshi, S., Thorat, A., Dehadray, H., et al., 2023. GABM tool for Risk Mitigation of Natural Hazards of Bridges [Internet]. Available from: https://constrofacilitator.com/gabm-tool-for-risk-mitigation-of-natural-hazards-of-bridges/

[10] Asprone, D., Jalayer, F., Prota, A., et al., 2010. Proposal of a probabilistic model for multi-hazard risk assessment of structures in seismic zones subjected to blast for the limit state of collapse. Structural Safety. 32(1), 25-34.

[11] Akintoye, A.S., MacLeod, M.J., 1997. Risk analysis and management in construction. International Journal of Project Management. 15(1), 31-38.

[12] Raupach, M., Büttner, T., 2014. Concrete repair to EN 1504: Diagnosis, design, principles and practice. CRC Press: Boca Raton.

[13] Risk and Hazard Management [Internet]. Available from: https://www.otago.ac.nz/health-safety/hazards/

[14] Amiri, M.J.T., Abdollahzadeh, G., Haghighi, F., et al., 2019. Bridges risk analysis in view of repair and maintenance by multi criteria decision making method (case study? Babolsar Bridges). International Journal of Transportation Engineering. 7(1), 91-114.

[15] Choudhry, R.M., 2019. Risk analysis related to cost and schedule for a bridge construction project. Perspectives on risk, assessment and management paradigms. IntechOpen: London.

[16] Alfieri, L., Cohen, S., Galantowicz, J., et al., 2018. A global network for operational flood risk reduction. Environmental Science & Policy. 84, 149-158.

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Understanding the Challenges of Implementing Green Roofs in Multi-Family Apartment Buildings: A Case Study in Khulna

Ishmat Ara[1]***, Sourav Zaman***[2*]

[1] *Department of Architecture, Northern University of Business and Technology Khulna, Khulna, 9100, Bangladesh*

[2] *Department of Architecture, Bangabandhu Sheikh Mujibur Rahman Science and Technology University, Gopalganj, 8100, Bangladesh*

ABSTRACT

Green roofs are widely recognized for their multifaceted benefits to the environment, economy, and society, constituting the fundamental pillars of sustainability. These roofs contribute to the enhancement of bio-physical diversity, provision of food resources, regulation of temperature and rainfall-runoff patterns, creation of wildlife habitats, and augmentation of aesthetic and recreational value. While Bangladesh, with its favourable climatic conditions and rapid urbanization, possesses immense potential for harnessing the advantages of green roofs, their adoption remains limited in both research and practical applications within the country. Addressing this research gap, the present study aims to investigate the barriers impeding the implementation of green roofs in existing or new multi-family apartment buildings, focusing specifically on the city of Khulna. Through a combination of case studies and a comprehensive questionnaire survey administered to diverse stakeholders including apartment dwellers/owners, architects, developers, and government officials with varying levels of expertise, this research sheds light on the obstacles hindering Green Roof Implementation (GRI). The identified barriers encompass a lack of governmental policies, inadequate technological advancements, inaccurate estimation of economic benefits, and individual resistance. In light of the perspectives of various GRI stakeholders, strategic proposals encompassing policy, technical, economic, and social dimensions are presented to surmount these barriers. The outcomes of this study contribute to the dissemination of knowledge pertaining to the impediments to GRI implementation, thereby inspiring further research endeavours and enabling decision-makers to formulate robust policies facilitating the widespread adoption of green roofs.

Keywords: Barriers; Green roof; Implementation; Khulna; Public perspective; Sustainability; Sustainable development; Urban green

*CORRESPONDING AUTHOR:

Sourav Zaman, Department of Architecture, Bangabandhu Sheikh Mujibur Rahman Science and Technology University, Gopalganj, 8100, Bangladesh; Email: write2souravzaman@gmail.com

ARTICLE INFO

Received: 15 July 2023 | Revised: 8 August 2023 | Accepted: 16 August 2023 | Published Online: 18 August 2023

DOI: https://doi.org/10.30564/jaeser.v6i3.5844

CITATION

Ara, I., Zaman, S., 2023. Understanding the Challenges of Implementing Green Roofs in Multi-Family Apartment Buildings: A Case Study in Khulna. Journal of Architectural Environment & Structural Engineering Research. 6(3): 17-30. DOI: https://doi.org/10.30564/jaeser.v6i3.5844

1. Introduction

Cities worldwide are grappling with a range of social and environmental challenges, including global warming, energy shortages, deforestation, local climate change, air pollution, and natural hazards [1,2]. These issues are exacerbated by the inevitable process of urbanization aimed at improving living standards and economic prosperity, particularly in developing countries. To tackle these challenges and ensure urban resilience and livability, numerous measures have been implemented. For instance, many cities have developed plans for sustainable or low-carbon eco-cities with resilient homes, aiming to reduce environmental, economic, and social impacts and minimize resource consumption [3]. These initiatives span various sectors, such as urban greening through city forests [4], urban flooding mitigation through sponge cities [5], green roof implementation (GRI) [6], sustainable transportation systems to reduce energy consumption and carbon footprints [7], and sustainable construction for eco-friendly human settlements [8]. Green roofs, also known as eco-roofs, living roofs, or roof gardens, serve as additional layers on rooftops and are considered an ecological and sustainable approach to enhancing the urban and built environment [9]. Therefore, it is crucial to explore the implementation of green roofs (GRI) in practice to address pressing urban issues and promote sustainability.

Bangladesh, a tropical nation known for its abundant rainfall, high humidity, and notable seasonal variations such as summer, monsoon, winter, and spring, encounters unique difficulties. Specifically, Khulna endures a damp, scorching, and humid tropical climate. The presence of climate migrants occupying available spaces for shelter contributes to an increase in land surface temperatures in the region [10]. Within the group of Least Developed Countries (LDCs), Bangladesh is ranked as the 6th Most Vulnerable Country (MVC), exposing it to severe consequences [11]. In Bangladesh, rooftops are conventionally utilized for various purposes such as cloth drying, barbecuing, and occasional social gatherings. However, contemporary approaches to greening buildings emphasize integrating plant life and the infrastructure that sustains it into the building's design without compromising its conventional utility [12]. Particularly in cities where space is limited, green roofs offer significant private and public social, economic, and environmental benefits. Green plants are recognized for their therapeutic value [13], provision of urban wildlife habitats, enhancement of air quality, thermal insulation [10], natural filtration, increased city biomass, mitigation of climate change impacts, and regulation of indoor building climates through insulation against extreme weather conditions [14]. It is imperative to improve environmental quality by reintroducing nature into urban areas.

Information on green roof practices in Bangladesh is currently limited. Only a few studies have touched upon this subject to some extent within the context of Bangladesh [15,16]. Therefore, any research in this field would be considered a significant advancement. Despite the benefits offered by green roof technology, its implementation is not widespread in either existing or new buildings in Bangladesh, and there has been limited research specifically focused on the country's context. While green roofs are not a new concept in Bangladesh, their utilization in residential areas of Khulna remains unsatisfactory. Hence, this study examines the feasibility of green roofs and identifies potential barriers to their implementation in Bangladesh, with a specific focus on Khulna. To understand potential barriers, this study aims to assess residents' perceptions and formulate strategic recommendations for implementing green roofs on both new and existing apartment buildings, considering policy, technical, economic, and social factors.

2. Literature review

2.1 Definitions relevant to GRI

The loss of open spaces, along with the desire for greening, has ushered in the green roof (GR) idea, in which rooftops are used as alternative locations for planting vegetation [6]. The GR refers to building roofs that have a growth media and are entirely or partially covered in vegetation [9]. Additionally, GR also referred eco roof, living roof, and roof garden, serves as an extra layered structure on rooftops [12]. It is a cutting-edge design method for attaining multiple objectives in terms of the environment, the economy, and society. By placing trees on the rooftops, green roofing first appeared in the Roman Empire and the Gardens of Babylon [17]. Construction of GR on multi-story buildings with large flat roofs is now possible due to advancements in methods and expertise in material (such as concrete and cement) and structure (such as reinforced and pre-stressed) [18].

Green roofs (GR) are mainly classified into two major groups: extensive and intensive roofs, also referred to as naturalistic or self-established vegetation [19,20]. The term "green roof" encompasses various definitions. According to Jim [21], it refers to any human-made building product installed on a roof, involving the construction of a structural framework with adequate mechanical strength. Another definition by Yu et al. describes a green roof as a roof that is either entirely or partially covered with vegetation and a growth medium [22]. This roof can have a flat or sloped surface, serving both as a functional roof and as a support system for vegetation. A green roof is composed of various elements that work together. These components include plants, a substrate enriched with nutrients, a water supply to support root growth, and a drainage layer to eliminate excess water (as shown in **Figure 1**).

Green roofs provide an ideal environment for supporting plant growth. **Table 1** presents a classification and comparison of the two main types of green roofs based on their intended functions and associat-

Table 1. Comparison between intensive and extensive GR [23].

Intensive GR	Extensive GR
Thickness less than 15 cm	Thickness greater than 15 cm
Accommodates large plants, shrubs, and trees	Accommodates low-growing plants such as succulents, herbs, and grasses
Weight: 200-500 kg/m²	Weight: 60-150 kg/m²
Approx. cost: 540 $/m²	Approx. costs 130-165 $/m²
Retains water from 70-130 l/m²	Retains water from 27-45 l/m²
More irrigation, fertilization, and maintenance required	Minimal irrigation, nutrient, and maintenance

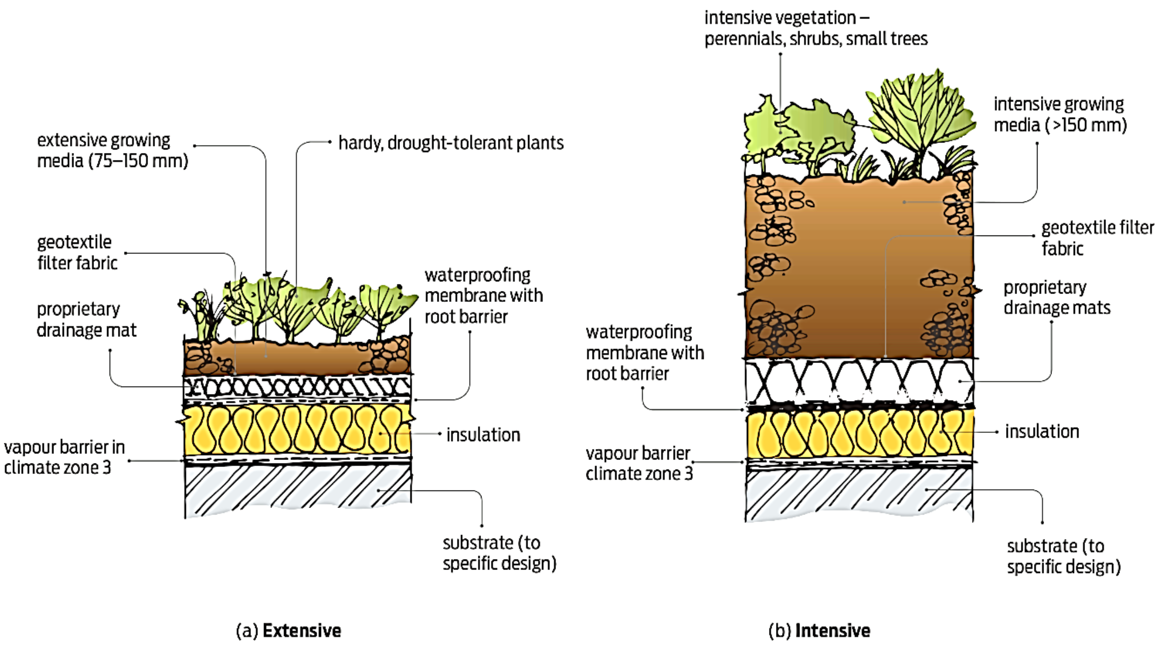


Figure 1. Green roof types [24].

ed costs. This comparison considers factors such as structural systems, types of vegetation, vastness, and installation costs. It is important to acknowledge that the overall cost of green roofs can vary across countries and among different green roof installers due to variations in material types and availability. Despite the potential advantages they offer, the implementation of green roofs, also known as Green Roof Implementation (GRI), has not received widespread attention. Therefore, it is crucial to consider strategies to encourage users to adopt and utilize green roofs, specifically GRI, in order to realize environmental, economic, and social advantages.

2.2 Identification of the barriers

The implementation of green roofs faces barriers in the economic, social, technical, and political domains, which hinder its widespread adoption. Rowe (2011) found that while green roofs have the potential to reduce pollutants, there are technical challenges that need to be addressed, such as plant selection, development of planting substrates, and the use of grey water [6]. Additionally, political and economic obstacles also need to be overcome. One of the challenges associated with green roofing is the high initial and ongoing costs, as well as the risk of roof leakage, despite its potential benefits in reducing urban flooding, rainwater runoff, energy consumption, and improving environmental performance. Ascione et al. (2013) conducted a study on the technical and economic feasibility of green roofs and concluded that in areas with insufficient rainfall, the additional costs for irrigation make green roofs less economically viable compared to conventional roofing systems. Even in regions with sufficient rainfall, offsetting the initial installation cost of green roofs became challenging [1]. These findings support the claim that green roofs face difficulties in becoming a cost-effective alternative to conventional roofing systems [25].

After conducting a comprehensive literature review, this study identifies a list of potential barriers, which can be categorized into four main areas: lack of government policy, inadequate technological advancements, incorrect assessment of economic benefits, and individual unwillingness (as shown in **Table 2**).

Table 2. Barriers to green roof implementation from literature review.

Categories	Barriers	Reference
Administrative	● Insufficient policy incentives for developers and owners to prioritize green roofs. ● Outdated local reports and guidelines on Green Roof Implementation (GRI) hinder widespread adoption. ● Limited scientific data is available to assess the feasibility of green roofs in the local context. ● Structural limitations of older buildings pose challenges for retrofitting green roofs.	[26,27,28,29] [30] [31,29] [32]
Technological	● Weak wind resistance of extensive green roof systems. ● Limited rooftop space for green roofs on high-rise buildings. ● Potential for bacterial and mosquito breeding on green roofs. ● Potential pollution caused by roofing materials	[26] [26] [30] [33,34, 35]
Economic	● Financial involvement in design, construction ● Cost of maintenance and irrigation ● Inadequate assessment of the full life cycle cost of green roof performance.	[36,37] [36,38,39,40,29] [41,42]
Social	● Limited awareness of extensive green roof systems in both public and private sectors. ● Insufficient promotion and support from the government and social communities. ● Lack of willingness from individuals to bear the costs associated with implementation.	[26] [43,44] [45]

3. Materials and methods

Previous research studies aimed at identifying root barriers, also known as fundamental barriers, have employed various methods such as literature review [46], interviews, questionnaire surveys, and focus group discussions (FGD) [26,31]. Given that social interaction is subjective and dependent on interpretation, a social constructivist approach has been adopted in this study. According to Robson (2011), this approach is best suited for scenarios where there are multiple versions and perceptions of reality rather than a single "reality". Researchers consider multiple perspectives and integrate individual realities to construct an overall understanding. Since this research aims to capture observations and individuals' subjective experiences, it is inherently qualitative in nature.

The research methodology employed in this study combines a literature review, FGD, and questionnaire surveys to identify barriers. The literature review provides a theoretical basis for identifying potential barriers, while field studies validate the findings from the literature review. Data collection is conducted through questionnaire surveys, FGDs, and observations to analyze the significance of each potential barrier. A comprehensive literature review of previous studies was conducted to identify potential barriers to the implementation of green roofs. A purposive sampling technique was used for the FGD, targeting specific individuals in different stakeholder groups. The stakeholder groups included multi-family building users, architects involved in green roof implementation, developers interested in or working on green roof projects, and government personnel responsible for green roof initiatives.

After performing a literature review and focus group discussion, a thorough survey was carried out in the research area to learn about people's perceptions and obstacles to installing green roofs on Khulna's multi-family apartment complexes. To gather data and ensure the validity of the survey results, a questionnaire consisting of 14 questions was designed, incorporating insights from the literature. The questionnaire covered various aspects, including the participants' general understanding of and ability to distinguish between intensive and extensive green roofs, barriers affecting green roof implementation, and measures to enhance green roof practice for both new and existing buildings. In order to ensure the reliability of the survey results, the questionnaire was divided into two sections.

The questionnaire consisted of two sections. The first section aimed to collect basic information about the participants and their previous employment, serving as a foundation for the survey. The second section delved into specific inquiries regarding green roofs. Participants were asked to rate their responses on a five-point Likert scale, covering familiarity, frequency, and agreement ranging from "not at all familiar" to "very familiar", "never" to "always", and "strongly disagree" to "strongly agree". They were also encouraged to provide additional guidelines and suggestions beyond the questionnaire options to enhance green roof implementation. Please see Appendix A for details of the survey questionnaire. Additionally, field observations were conducted on multi-family apartment buildings in the Khulna residential area. Interviews with architects involved in the design and construction of these buildings were also conducted to complement and verify the observational findings, providing further insights.

3.1 Study area

Being the third largest metropolitan city in Bangladesh, Khulna is geographically marked in the southwest region of the country. It is located on the banks of the Rupsha and Bhairab Rivers, and serves as an important port city. Positioned along the axis of Jessore-Mongla port, Khulna is also the second largest seaport in Bangladesh. With almost a million residents, the city has an area of around 65 square kilometres. Only a few planned residential areas have been developed by Khulna Development Authority (KDA) in Khulna city corporation area. The planned residential areas developed by KDA are Nirala, Boyra and Sonadanga residential areas. Sonadanga is developed in three phases is being developed now. To examine the barriers to implementing green roofs, Sonadanga (Phase II) (**Figure 2a**) and Nirala

Residential area (**Figure 2b**) have been taken in this research study area.

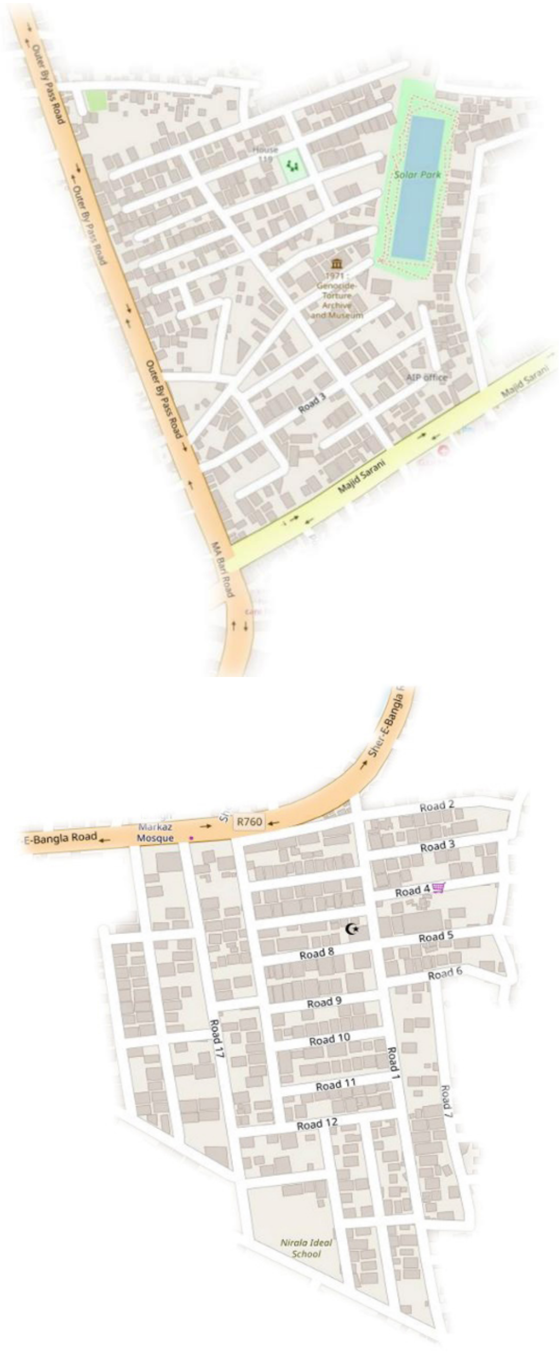


Figure 2. Study area: a. Sonadanga Phase II, b. Nirala.

3.2 Analysis

The following Relative Important Index (RII) were applied for analysis regarding the stakeholders (architects, builders, building users, etc.) connected with the case study, as well as their prior experience from comparable types of projects. It should be noted that input for the research was obtained on a (1-5) Likert scale. As a result, because parametric approaches are impractical and inapplicable for analysing respondents' preferences, the relative important index method was employed to determine the relative importance of the factors affecting green roof implementation in Khulna.

The Relative Important Index (RII) is a non-parametric approach frequently used by construction and facilities management academics to analyse structured questionnaire responses for data including ordinal attitude assessments. Relative Important Index (RII) was used to evaluate the level of agreement of green roof implementation using the following equation.

$$RI\,I = \sum_{1}^{5} W_iX_i / 4\sum_{1}^{5} X_i \qquad (1)$$

where, i = index of response category, and i = 5, 4, 3, 2, and 1 for strongly disagree, disagree, somewhat agree, agree, and strongly agree, in the case of agreement responses. W_i = weight given to the ith response and W_i = 4, 3, 2, 1, and 0, X_i = frequency of the ith response.

4. Results

The survey conducted among professionals and apartment dwellers in Khulna, Bangladesh, aimed to identify the barriers to green roof implementation. The participants included architects, builders, government personnel, and apartment dwellers/owners. The findings revealed that while professionals were generally aware of green roofs and some had experience with them, not all apartment dwellers were familiar with the concept. Despite the awareness among participants, the implementation of green roofs remained a challenge. The survey results, presented in **Table 3**, ranked the barriers affecting green roof implementation in Khulna. The lack of building standards and regulations emerged as the primary constraint, ranking first. The perception of increased construction and maintenance costs was ranked second, although it may be a misconception among the participants due to the nature of the construction industry in Bangladesh.

Table 3. Barriers to green roof implementation in multi-family apartments.

Barriers	**RII**	**Level of agreement**	**Rank**
Lack of building standards and regulations	0.80	Strongly Agreed	1
Incentives and guidelines from governments	0.75	Strongly Agreed	2
Increase in construction and maintenance cost	0.71	Agreed	3
Lack of willingness	0.67	Agreed	4
Lack of scientific research	0.65	Agreed	5
Lack of awareness about sustainable environment	0.60	Agreed	6
Limited local expertise	0.56	Somewhat agreed	7
Poor accessibility to the rooftop	0.53	Somewhat agreed	8
Adaption of plants	0.40	Disagreed	9
Plants and plantation techniques	0.40	Disagreed	10

Other barriers, such as the lack of a sense of community, challenges related to plant adoption and plantation techniques, and insufficient experience and knowledge, were ranked lower. It is important to note that these barriers should not be overlooked, and attention should be given to addressing them. However, greater emphasis should be placed on addressing regulatory control issues, promoting a willingness to adopt green roofs, and increasing awareness about the benefits of a sustainable environment.

5. Discussion

The survey conducted among 65 multi-family apartment residents and professionals yielded valuable insights regarding the barriers to green roof implementation. By triangulating the data from the literature review, survey responses, and participant suggestions, several common barriers to green roof implementation in Khulna were identified. These barriers include limited technical expertise, inadequate knowledge and information, high construction and maintenance costs, a lack of awareness and willingness, misconceptions about green roofs, and challenges related to plant adoption and plantation techniques. One of the major barriers highlighted by the participants was the absence of proper building standards and regulations specifically for green roofs. This suggests a need for comprehensive guidelines and regulations that specifically address the implementation and maintenance of green roofs. Additionally, participants emphasized the importance of promoting the benefits of green roofs to increase awareness and encourage their adoption. Participants expressed that inadequate information and a shortage of technical expertise hindered the successful implementation of green roofs. Addressing this barrier would require providing training and educational resources to professionals and individuals involved in the construction and maintenance of buildings.

To overcome these barriers, it is crucial to focus on developing and implementing building standards and regulations specific to green roofs. Providing technical training and increasing knowledge sharing platforms can help enhance the technical expertise in implementing green roofs. Efforts should also be made to raise awareness about the benefits of green roofs among stakeholders and the general public. By addressing these barriers, the implementation of green roofs can be promoted in Khulna and contribute to a more sustainable urban environment.

- The government doesn't have any regulatory control over building standards and regulations on green roofs. Current building codes like Bangladesh National Building Code (BNBC 2020), there has no provision for including facilities for green roofs in apartment buildings. Thus, the provision can be made in BNBC and can be enacted to make green roofs mandatory for apartment buildings.
- Lack of incentives and guidelines from the government. Therefore, the government could include some means of incentives and guidelines to promote green roof implementation on a large scale.
- Increase in construction and maintenance costs in green roof implementation, seems a misconception stated by professionals and could apply some local methods to minimize

the cost of it.

- Building owners' and professionals' ignorance about sustainable environments. Articulation of multiple benefits of green roofs towards urban sustainability among the respondents is needed to encourage its implementation.
- Absence of willingness among apartment owners. Providing building regulations and incentives could influence the adoption of green roof implementation among apartment owners.
- Limited local expertise in the context of Khulna.
- Although the climate in Bangladesh is conducive to the installation of green roofs, there is a lack of scientific study in this area.

6. Conclusions

The study clearly highlights the significant contributions of green roof implementation to environmental sustainability. Although Khulna is relatively new to the concept of green roofs, there is potential for improvement by addressing the barriers that hinder their implementation. The research paper explores these barriers specifically in the context of multi-family apartment buildings in Khulna. The survey results reveal that the lack of government standards and regulations, higher construction and maintenance costs, lack of awareness and willingness, and limited research in this area are the major obstacles to implementing green roofs. It is evident from the responses of both residents and professionals (architects, builders, and government personnel) that green roofs offer more benefits than hindrances. Therefore, overcoming these barriers becomes crucial in order to encourage building owners and professionals in Khulna to adopt green roofs. The findings of this paper provide a comprehensive understanding of the current green roof scenarios in Khulna and shed light on the barriers to their implementation. These findings can serve as a foundation for future research, suggesting specific regulatory controls and necessary educational initiatives to overcome the identified barriers. In conclusion, the study emphasizes the need to address the barriers to green roof implementation in Khulna and highlights the potential for future research and action. By overcoming these barriers, the adoption of green roofs can be encouraged, leading to a more sustainable and environmentally friendly built environment in the city.

Author Contributions

The principal author, Ishmat Ara formulated the research problem and started the first phase of method identification under her Masters in Human Settlement post-graduation thesis under Khulna University. She elaborately shared the problem identification and formulated an overall problem-solving framework. She also wrote the first draft of the research article.

On the other hand, Sourav Zaman carried out the survey and interviews on-site. He re-wrote the article and put his thoughts on the data processing and analysis.

Conflict of Interest

There is no conflict of interest.

Funding

This research received no external funding.

Acknowledgement

We cordially acknowledge the important guidance and direction of Dr. Sheikh Serajul Hakim and S. M. Nazimuddin under the thesis of Msc. Hs degree in Khulna University.

References

[1] Ascione, F., Bianco, N., de'Rossi, F., et al., 2013. Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? Applied Energy. 104, 845-859. DOI: https://doi.org/10.1016/j.apenergy.2012.11.068

[2] He, B.J., Wang, J., Liu, H., et al., 2021. Localized synergies between heat waves and urban heat islands: Implications on human thermal

comfort and urban heat management. Environmental Research. 193, 110584.
DOI: https://doi.org/10.1016/j.envres.2020.110584

[3] He, B.J., Zhao, D.X., Zhu, J., et al., 2018. Promoting and implementing urban sustainability in China: An integration of sustainable initiatives at different urban scales. Habitat International. 82, 83-93.

[4] Straka, T.J., Marsinko, A.P., Childers, C.J., 2005. Individual characteristics affecting participation in urban and community forestry programs in South Carolina, US. Arboriculture & Urban Forestry. 31(3), 131.

[5] He, B.J., Zhu, J., Zhao, D.X., et al., 2019. Co-benefits approach: Opportunities for implementing sponge city and urban heat island mitigation. Land Use Policy. 86, 147-157.

[6] Rowe, D.B., 2011. Green roofs as a means of pollution abatement. Environmental Pollution. 159(8-9), 2100-2110.
DOI: https://doi.org/10.1016/j.envpol.2010.10.029

[7] Greene, D.L., Wegener, M., 1997. Sustainable transport. Journal of Transport Geography. 5(3), 177-190.

[8] Zhao, D.X., He, B.J., Johnson, C., et al., 2015. Social problems of green buildings: From the humanistic needs to social acceptance. Renewable and Sustainable Energy Reviews. 51, 1594-1609.
DOI: https://doi.org/10.1016/j.rser.2015.07.072

[9] Shafique, M., Azam, A., Rafiq, M., et al., 2020. An overview of life cycle assessment of green roofs. Journal of Cleaner Production. 250, 119471.

[10] Afroz, D., Zaman, S., Ahmed, N.N. (editors), 2022. Vertical gardening: An easy and affordable module for domestic installation in the context of Khulna City. ZEMCH 2021 International Conference; 2021 Oct 26-28; Dubai, UAE.

[11] Kreft, S., Eckstein, D., Melchior, I., 2017. Global Climate Risk Index 2017 [Internet]. Available from: https://germanwatch.org/sites/default/files/publication/16411.pdf

[12] Dunnett, N., Kingsbury, N., 2002. Planting green roofs and living walls. Timber Press: Portland.

[13] Hitchmough, J., Field house, K., 2000. Plant user handbook. Blackwell Science: Hoboken.

[14] Mowla, Q.A. (editor), 2005. Ecological imperatives for sustainable environment. International Conference on Geography and Environment—Issues and Challenges; 2005 Dec 9-11; Dhaka, Bangladesh.

[15] Islam, K.T., Afroz, R., 2019. Impact of Green Roof on Urban Canopy Layer Microclimates in a Planned Residential Area of Dhaka, Bangladesh [Internet]. Available from: https://www.researchgate.net/publication/303402690

[16] Rashid, R., 2012. Thermal performance of green roof at Dhaka city in Bangladesh [Ph.D. thesis]. Johor Bahru, Malaysia: Universiti Teknologi Malaysia.

[17] Jim, C.Y., 2017. Green roof evolution through exemplars: Germinal prototypes to modern variants. Sustainable Cities and Society. 35, 69-82.
DOI: https://doi.org/10.1016/j.scs.2017.08.001

[18] Li, W.C., Yeung, K.K.A., 2014. A comprehensive study of green roof performance from environmental perspective. International Journal of Sustainable Built Environment. 3(1), 127-134.
DOI: https://doi.org/10.1016/j.ijsbe.2014.05.001

[19] Gagliano, A., Detommaso, M., Nocera, F., et al., 2016. The adoption of green roofs for the retrofitting of existing buildings in the Mediterranean climate. International Journal of Sustainable Building Technology and Urban Development. 7(2), 116-129.

[20] Lehmann, S., 2014. Low carbon districts: Mitigating the urban heat island with green roof infrastructure. City, Culture and Society. 5(1), 1-8.

[21] Deng, Y., Wu, J., 2014. Economic returns to residential green building investment: The developers' perspective. Regional Science and Urban Economics. 47, 35-44.

[22] Saadatian, O., Sopian, K., Salleh, E., et al., 2013. A review of energy aspects of green roofs. Renewable and Sustainable Energy Reviews. 23, 155-168.

[23] Hossain, M.A., Shams, S., Amin, M., et al., 2019. Perception and barriers to implementation of intensive and extensive green roofs in Dhaka, Bangladesh. Buildings. 9(4), 79.
DOI: https://doi.org/10.3390/buildings9040079

[24] Alide, E., 2017. The Gen of Green Roofs [Internet]. Available from: https://www.buildmagazine.org.nz/index.php/articles/show/the-gen-on-green-roofs

[25] Bianchini, F., Hewage, K., 2012. Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach. Building and Environment. 58, 152-162.
DOI: https://doi.org/10.1016/j.buildenv.2012.07.005

[26] Zhang, X., Shen, L., Tam, V.W., et al., 2012. Barriers to implement extensive green roof systems: A Hong Kong study. Renewable and Sustainable Energy Reviews. 16(1), 314-319.
DOI: https://doi.org/10.1016/j.rser.2011.07.157

[27] Ntoulas, N., Nektarios, P.A., Spaneas, K., et al., 2012. Semi-extensive green roof substrate type and depth effects on Zoysia matrella 'Zeon' growth and drought tolerance under different irrigation regimes. Acta Agriculturae Scandinavica, Section B-Soil & Plant Science. 62(sup1), 165-173.

[28] Fernandez-Cañero, R., Emilsson, T., Fernandez-Barba, C., et al., 2013. Green roof systems: A study of public attitudes and preferences in southern Spain. Journal of Environmental Management. 128, 106-115.

[29] Vijayaraghavan, K., 2016. Green roofs: A critical review on the role of components, benefits, limitations and trends. Renewable and Sustainable Energy Reviews. 57, 740-752.

[30] Xiao, M., Lin, Y., Han, J., et al., 2014. A review of green roof research and development in China. Renewable and Sustainable Energy Reviews. 40, 633-648.
DOI: https://doi.org/10.1016/j.rser.2014.07.147

[31] Williams, N.S., Rayner, J.P., Raynor, K.J., 2010. Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia. Urban Forestry & Urban Greening. 9(3), 245-251.
DOI: https://doi.org/10.1016/j.ufug.2010.01.005

[32] Dabaieh, M., Alwall, J., 2018. Building now and building back. Refugees at the centre of an occupant driven design and construction process. Sustainable Cities and Society. 37, 619-627.
DOI: https://doi.org/10.1016/j.scs.2017.11.002

[33] Gnecco, I., Berretta, C., Lanza, L.G., et al., 2005. Storm water pollution in the urban environment of Genoa, Italy. Atmospheric Research. 77(1-4), 60-73.
DOI: https://doi.org/10.1016/j.atmosres.2004.10.017

[34] Göbel, P., Dierkes, C., Coldewey, W.G., 2007. Storm water runoff concentration matrix for urban areas. Journal of Contaminant Hydrology. 91(1-2), 26-42.
DOI: https://doi.org/10.1016/j.jconhyd.2006.08.008

[35] Schriewer, A., Horn, H., Helmreich, B., 2008. Time focused measurements of roof runoff quality. Corrosion Science. 50(2), 384-391.
DOI: https://doi.org/10.1016/j.corsci.2007.08.011

[36] Carter, T., Keeler, A., 2008. Life-cycle cost-benefit analysis of extensive vegetated roof systems. Journal of Environmental Management. 87(3), 350-363.
DOI: https://doi.org/10.1016/j.jenvman.2007.01.024

[37] Nurmi, V., Votsis, A., Perrels, A., et al., 2013. Cost-benefit Analysis of Green Roofs in Urban Areas: Case Study in Helsinki [Internet]. Available from: http://hdl.handle.net/10138/40150

[38] Clark, C., Adriaens, P., Talbot, F.B., 2008. Green roof valuation: A probabilistic economic analysis of environmental benefits. Environmental Science & Technology. 42(6), 2155-2161.
DOI: https://doi.org/10.1021/es0706652

[39] Niu, H., Clark, C., Zhou, J., et al., 2010. Scaling of economic benefits from green roof implementation in Washington, DC. Environmental Science & Technology. 44(11), 4302-4308.
DOI: https://doi.org/10.1021/es902456x

[40] Wong, N.H., Tay, S.F., Wong, R., et al., 2003. Life cycle cost analysis of rooftop gardens in Singapore. Building and Environment. 38(3), 499-509.

DOI: https://doi.org/10.1016/S0360-1323(02)00131-2

[41] Peri, G., Traverso, M., Finkbeiner, M., et al., 2012. The cost of green roofs disposal in a life cycle perspective: Covering the gap. Energy. 48(1), 406-414.
DOI: https://doi.org/10.1016/j.energy.2012.02.045

[42] Labuschagne, P., Zulch, B., 2016. Green rooftop systems: A South African perspective. Energy Procedia. 96, 710-716.
DOI: https://doi.org/10.1016/j.egypro.2016.09.131

[43] Hendricks, J.S., Calkins, M., 2006. The adoption of an innovation: Barriers to use of green roofs experienced by Midwest architects and building owners. Journal of Green Building. 1(3), 148-168.

[44] Shafique, M., Kim, R., Rafiq, M., 2018. Green roof benefits, opportunities and challenges—A review. Renewable and Sustainable Energy Reviews. 90, 757-773.
DOI: https://doi.org/10.1016/j.rser.2018.04.006

[45] Zhang, L., Fukuda, H., Liu, Z., 2019. Households' willingness to pay for green roof for mitigating heat island effects in Beijing (China). Building and Environment. 150, 13-20.
DOI: https://doi.org/10.1016/j.buildenv.2018.12.048

[46] Good, N., Ellis, K.A., Mancarella, P., 2017. Review and classification of barriers and enablers of demand response in the smart grid. Renewable and Sustainable Energy Reviews. 72, 57-72.

Appendix A

Questionnaire survey on multi-family apartment in Khulna

Dear Concerns:

Thank you very much for participating in the questionnaire survey. This is to investigate the barriers of the implementation of green roofs in practices. Please feel free to contact us through ishmatara-13Ku@gmail.com or write2souravzaman@gmail.com for more information if you need. You are highly appreciated for your great help and support.

In the questionnaire, you may select the degree of agreement and disagreement with "✓" for each barrier. For example, as shown in the following table, if you do not agree P is a barrier, please mark "✓" in the column of "Disagree"; if you strongly agree Q is a barrier, please mark "✓" in the column of "Strongly agree".

For making sure of the reliability of the questionnaire, please select your work type first.

Part 1: Basic Information:

1. Which field do you belong to?

- Architects
- Residents/Owner
- Developer
- Researcher

2. Are you working for the government or private Organization?

3. How many multi-storeyed apartment projects have you been involved in?

Part 2: Green Roof

1. How familiar are you with the types of green roofs:

(a) Extensive green roof (b) Intensive green roof

Green roof types	Not at all familiar	Slightly familiar	Somewhat familiar	Moderately familiar	Very familiar
(a) Extencive Green roof					
(b) Intensive Green roof					

2. How often do you see each type of green roof in Khulna?

Green roof types	Never	Rarely	Sometimes	Often	Always
a.Extencive Green roof					
b. Intensive Green roof					

3. Have you ever been involved in a project with a green roof?

4. General perception about green roofs:

	Strongly disagree	Disagree	Somewhat agree	Agree	Strongly agree
Increases aesthetics					
Reduces urban heat island effect					
Improves rainwater runoff problems in the city					
Improves air quality					
Increases wildlife and biodiversity					
Improves energy efficiency of building					
Improves public health in the city					
Improves noise absorption					
Adds unnecessary cost without much benefit					
Adds value/marketability of the property					

5. Technological barriers to implementing GR:

Barriers	Strongly disagree	Disagree	Somewhat agree	Agree	Strongly agree
Technical difficulty during construction process of green roof systems					
Weak weight capacity of existing buildings for applying green roof systems					
Weak affordability of green roofs to withstand wind load					
Difficulty in the adoption of vegetation in green roofs					
Supplemental irrigation on the roof of buildings					
Nutrient leakage from the green roof on runoff water quality					
Inadequate construction technique					
Poor drainage of green roof systems					
Lack of experience and knowledge					

6. Standard and code barriers in implementing GR:

Barriers	**Strongly disagree**	**Disagree**	**Somewhat agree**	**Agree**	**Strongly agree**
Lack of consolidated standards and regulations for designing and installing green roof systems					
Lack of consolidated standards and regulations for manufacturing and adopting green roof materials					
Incomplete standards and regulations relevant to green roofs					

7. Cost Barriers to implementing Green Roofs:

Barriers	Strongly disagree	Disagree	Somewhat agree	Agree	Strongly agree
Increase design and construction cost					
Increase of maintenance cost					
Increase of purchase cost of premises					
Increase of operating cost					

8. Attitude Barriers to implementing Green Roofs:

Barriers	Strongly disagree	Disagree	Somewhat agree	Agree	Strongly agree
Concerns over the water leakage of the roofs among property owners					
Concerns over the safety of buildings among property					
Lack of green awareness among public					
Concern on overspending the cost of green roof systems among property owners and developers					

9. Feasibility to green roofs in Khulna:

	Strongly disagree	Disagree	Somewhat agree	Agree	Strongly agree
Do you think the government should promote extensive green roofs in Khulna city?					
Do you think extensive green roof systems are feasible to implement for existing buildings?					
Do you support implementation of extensive green roofs for existing buildings?					
Would you support to construct a green roof on the building where you live?					

10. Measure to enhance implementation of green roof system for new and existing apartment buildings:

	Strongly disagree	Disagree	Somewhat agree	Agree	Strongly agree
Increase awareness about sustainable environment					
Incentives from government to developers					
Incentives from government to owners of existing buildings					
Bonus to developers (e.g., reduced government fee) who construct certain green roof areas					
Percentage of green space should be mandatory for property development project					
New building codes for developers/contractors					
Green roof regulations to improve rainwater runoff problem					
Include green roof in the educational curricula for anyone entering the construction industry					

11. Please suggest any other measure you feel is important to apply green roof.

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Fatigue Safety Assessment of Concrete Continuous Rigid Frame Bridge Based on Rain Flow Counting Method and Health Monitoring Data

Yinghua Li[1], Junyong He[2*], Xiaoqing Zeng[3], Yanxing Tang[4]

[1] *Shixing County Administrative Service Center, Shixing, Shaoguan, Guangdong, 512500, China*

[2] *Guangdong College of Industry and Commerce, Guangzhou, Guangdong, 510510, China*

[3] *Shixing County Statistics Bureau, Shixing, Shaoguan, Guangdong, 512500, China*

[4] *Shixing County Hospital of Traditional Chinese Medicine, Shixing, Shaoguan, Guangdong, 512500, China*

ABSTRACT

The fatigue of concrete structures will gradually appear after being subjected to alternating loads for a long time, and the accidents caused by fatigue failure of bridge structures also appear from time to time. Aiming at the problem of degradation of long-span continuous rigid frame bridges due to fatigue and environmental effects, this paper suggests a method to analyze the fatigue degradation mechanism of this type of bridge, which combines long-term in-site monitoring data collected by the health monitoring system (HMS) and fatigue theory. In the paper, the authors mainly carry out the research work in the following aspects: First of all, a long-span continuous rigid frame bridge installed with HMS is used as an example, and a large amount of health monitoring data have been acquired, which can provide efficient information for fatigue in terms of equivalent stress range and cumulative number of stress cycles; next, for calculating the cumulative fatigue damage of the bridge structure, fatigue stress spectrum got by rain flow counting method, S-N curves and damage criteria are used for fatigue damage analysis. Moreover, it was considered a linear accumulation damage through the Palmgren-Miner rule for the counting of stress cycles. The health monitoring data are adopted to obtain fatigue stress data and the rain flow counting method is used to count the amplitude varying fatigue stress. The proposed fatigue reliability approach in the paper can estimate the fatigue damage degree and its evolution law of bridge structures well, and also can help bridge engineers do the assessment of future service duration.

Keywords: Long-span continuous rigid frame bridge; Rain flow counting method; Fatigue performance; Health monitoring system; Strain monitoring data

*CORRESPONDING AUTHOR:

Junyong He, Guangdong College of Industry and Commerce, Guangzhou, Guangdong, 510510, China; Email: 418474986@qq.com

ARTICLE INFO

Received: 10 August 2023 | Revised: 30 August 2023 | Accepted: 15 September 2023 | Published Online: 12 October 2023

DOI: https://doi.org/10.30564/jaeser.v6i3.5890

CITATION

Li, Y.H., He, J.Y., Zeng, X.Q., et al., 2023. Fatigue Safety Assessment of Concrete Continuous Rigid Frame Bridge Based on Rain Flow Counting Method and Health Monitoring Data. Journal of Architectural Environment & Structural Engineering Research. 6(3): 31-40. DOI: https://doi.org/10.30564/jaeser.v6i3.5890

1. Introduction

Due to the influence of materials ageing, environmental corrosion, increasing traffic flow and other factors, at present, a large number of concrete structures in China and other countries in the world are gradually ageing, and the deterioration of structures is becoming more and more serious [1,2], resulting in damage accumulation and resistance attenuation. Therefore, the fatigue properties of concrete structures and their components have been paid more and more attention by people around the world.

The fatigue reliability assessment of reinforced concrete structures has been studied by many experts and scholars, and many research results have been published [3-9]. Generally, the fatigue failure of concrete structures is mainly caused by the stress cycle. In most cases, the stress cycle of the concrete structure is a variable amplitude stress cycle, for example, temperature, vehicle live load, etc., rather than the constant amplitude stress cycle used in the test, and the combination of variable amplitude stress is too much, and so it is difficult to simulate in the test. Hence, there are few research results on the fatigue performance of concrete bridges based on in-situ measured data. John P. Li Z X, Chan T H T et al. [10,11] paid attention to developing a methodology for fatigue damage assessment and life prediction of bridge-deck sections of existing bridges with monitoring data of online HMS, and applied the method to the Tsing Ma Bridge for the fatigue damage assessment. By using the Palmgren-Miner rule and S-N curves, Guo, Tong, Li, et al. [12] made an assessment for welded joints in orthotropic steel decks based on monitored field data from the Runyang Bridge. Kwon K and Frangopol D M [13] focus on fatigue reliability assessment of steel bridges by using probability density functions of equivalent stress range based on field monitoring data and they suggested the method should be applied to two bridges. Yang D, Youliang D, Aiqun LI, et al. [14] suggest a reliability assessing methodology of fatigue life for welded details in steel box girder based on the long-term monitoring data, and the application research is presented with examples of welded rib-to-deck details in Runyang Bridges. Newhook and Rahman Edalatmanesh [15] explained that the concepts of reliability and HMS can be integrated to do bridge assessments and make decision systems. Junges P et al. [16] assess the fatigue life of the bridges with only 120 days of monitoring data and using S-N curves from international standards. Mankar A. et al. [17] suggested a probabilistic reliability framework for the assessment of future service duration for civil infrastructure, including probabilistic modelling of actions with a large amount of monitoring data, and also containing probabilistic modelling of fatigue resistance by test data, and a case study is presented for the steel-reinforced concrete slab.

In brief, the in-situ monitoring data of prestressed concrete bridge structures are either with short monitoring time or no monitoring data. Hence, in the paper, applying a large amount of strain monitoring data, based on structural fatigue damage accumulation theory, a method is presented to study the evolution of fatigue properties and the cumulative changing law of fatigue damage of a prototype bridge, which is Long-span continuous rigid frame bridge with HMS.

2. Basic theory of fatigue effects

2.1 Miner theory

The cumulative damage theory of fatigue is needed to estimate the effects of varying amplitude stress cycles on structures. The theory of linear fatigue cumulative damage means that under cyclic load, fatigue damage can be linearly accumulated, and each stress is independent and unrelated to the other. When the cumulative damage reaches a certain value, fatigue damage of specimens or components will occur. A typical linear cumulative damage theory is Palmgren-Miner theory, referred to as the Miner theory [18]. Under variable amplitude load, the damage formula caused by n cycles can be written as follows:

$$D=\sum\frac{n_i}{N_i} \tag{1}$$

The theory states that if the material is subjected to a load of magnitude $\sigma_{\alpha i}$ with repeating N_i times of failure, the damage can be distributed linearly to each cycle; that is, the damage to the material per cycle is $\frac{1}{N_i}$. If the load of magnitude $\sigma_{\alpha i}$ rings n_i, the damage of the material is $\frac{n_i}{N_i}$. Under different load effects, the damage is $\frac{1}{N_1}, \frac{1}{N_2}, \ldots$ respectively. When the total damage reaches 1, the structure fatigue failure occurs. That is, the criterion of material fatigue failure is:

$$D = \sum \frac{n_i}{N_i} = \frac{1}{N_1} + \frac{1}{N_2} + \cdots + \frac{n}{N_n} = 1 \qquad (2)$$

where, D is the damage degree of the structure; n_i is the number of stress cycles that the structure actually experiences with the magnitude $\Delta\sigma_i$; N_i is the fatigue life of the structure under the action of $\Delta\sigma_i$.

2.2 Fatigue damage theory of concrete materials used in the prototype bridge

In order to conduct fatigue reliability analysis of bridge members or structural details, it is necessary to understand the time history of stress amplitude in the member or structure, and conduct statistical analysis of load effects $\Delta\sigma_e$; that is, the variation situation of amplitude variation repeated stress in the details under the action of actual loads. By monitoring the stress history of the main components or details, the stress time history curve of the components or details under the action of actual load effects can be obtained.

In addition to the fatigue stress spectrum, S-N curves and damage criteria are also needed for fatigue damage analysis. An overview of experimental research on the fatigue working characteristics of concrete under multi axial complex stress states has been conducted by Song Yupu et al. from the Dalian University of Technology [19], which comprehensively and deeply describes the changes in mechanical properties of concrete under multi-axial fatigue states, and the S-N curve method for calculating the fatigue strength of concrete under various working states has been established. The research results can be applied to the fatigue design of concrete bridges, crane beams, offshore platforms, concrete sleepers, nuclear safety shells, pressure vessels, and other structures, and provide references for the formulation of relevant specifications. So, in this paper, the research results of Song Yupu et al. are adopted. The ratio of minimum stress to maximum stress is taken as the third variable in the S-N curve. The S-N relationship of concrete under pressure can be expressed as follows:

$$\sigma_{\max} / f_{cm} = 1 - \beta(1-R)\lg N \qquad (3)$$

In the formula, f_{cm} is uniaxial compressive strength of concrete; $R = \sigma_{\min} / \sigma_{\max}$ is the minimum stress to maximum stress ratio in the stress cycle; $\beta = 0.072$ is the material constant. The fatigue damage criterion adopts Miner linear cumulative damage criterion, as shown in Equations (1) and (2).

Assuming that the maximum and minimum stresses of the mid-span web and bottom plates of the bridge acquired by the monitoring system are $\Delta\sigma_{i\max}$ and $\Delta\sigma_{i\min}$ respectively, according to Miner theory and Equation (3), we can get:

$$N_{\Delta\sigma_i} = 10^{\frac{1-\frac{\Delta\sigma_{i\max}}{f_{cm}}}{\beta(1-R_{\Delta\sigma_i})}} \qquad (4)$$

where, $N_{\Delta\sigma_i}$ is the number of fatigue failure cycles under the amplitude varying stress $\Delta\sigma_i$, $R_{\Delta\sigma_i} = \Delta\sigma_{i\min} / \Delta\sigma_{i\max}$. Then, the fatigue damage of the positions embedded with sensors caused by one load of the amplitude varying stress $\Delta\sigma_i$ is as follows:

$$D_{\Delta\sigma_i} = \frac{1}{N_{\Delta\sigma_i}} = 10^{-\left(\frac{1-\frac{\Delta\sigma_{i\max}}{f_{cm}}}{\beta(1-R_{\Delta\sigma_i})}\right)} \qquad (5)$$

Combining the Miner's rule of linear damage accumulation and Equation (5), an evaluation formula is formulated as follows:

$$L(T_s) = 1 - \sum_{i=1}^{m}\sum_{j=1}^{n} 10^{-\left(\frac{1-\frac{\Delta\sigma_{ij\max}}{f_{cm}}}{\beta(1-R_{\Delta\sigma_{ij}})}\right)} \qquad (6)$$

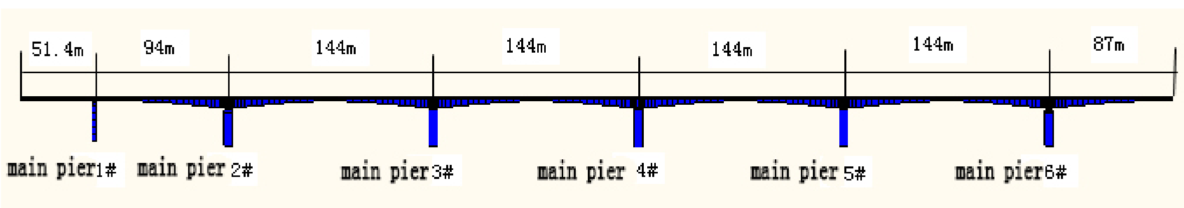
In the formula, T_s is the service duration of the bridge structure; m is the observed number of the different amplitude varying stress $\Delta\sigma_{ij}$; n is the observed number of the specific amplitude stress $\Delta\sigma_{ij}$.

3. Background bridge introduction with HMS

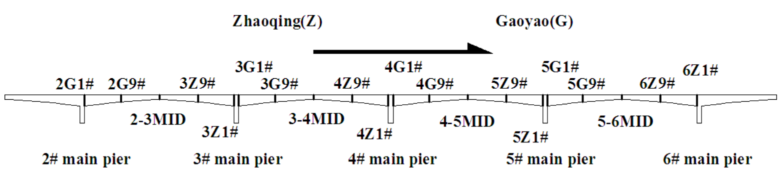
3.1 The health monitoring system installed on the bridge

The sample bridge adopted in the paper is located in Guangdong Province. The structure of the main beam of the bridge is a (51.4 + 94 + 4 × 144 + 87) m, shown in **Figure 1a** pre-stressed concrete continuous box-beam system, with 8 main piers and 7 main spans. The box girder is a single box and single room section, and the full width of the box girder is 12.5 m, and the width of the bottom plate is 6.8 m. The transverse slope of the bridge floor is 2.0%, and the longitudinal slope of the bridge floor is 0.15%. The whole bridge has 6 closing sections, and the main beam cross section heights change from 8 m to 2.8 m in accordance with the 1.6 order power parabola from the cantilever root to the mid-span. The base plate thickness varies from 1 m to 0.32 m, and the web plate thickness varies from 0.9 m to 0.45 m. The prestressed tendons are $15\Phi^{j}15.24\,\text{mm}$ steel strands with strength: $R_y^b = 1860\,\text{MPa}$, $2\Phi^{j}12.7\,\text{mm}$ steel strands with strength: $R_y^b = 1395\,\text{MPa}$ and high strength rebar respectively.

The measuring points of the bridge HMS in the main beam are arranged at the root of the cantilever, L/2 span, L/4 span and other key positions, and the bridge has 8 cantilever end sections, 8 L/4 sections and 4 L/2 sections respectively, as shown in **Figure 1b**. **Figure 1c** is the actual photo of the concrete bridge, and the embedded positions of sensors on each section are shown in **Figure 2**. The string type strain gauge (JMZX-215) used in the bridge HMS is shown in **Figure 3**, which can measure the temperature simultaneously and so it is able to compensate for temperature effects. The measuring time interval of the sensor is 1 hour. The parameters of the sensor are shown in **Table 1** and the basic parameters of high performance concrete applied in the bridge are displayed in **Table 2** [20,21]. Among them, the tensile



(a) the length of each span of the bridge



(b) Sketch of the cross section locations with the embedded sensors

(c) The actual photo of the concrete bridge

Figure 1. Sketch of the cross section locations with the embedded sensors and the the length of each span.

Table 1. Parameters of the strain gauge.

Name	Range	Sensitivity	Gauge length	Remarks
Intelligent digital vibrating strain gauge	± 1500 $\mu\varepsilon$	1 $\mu\varepsilon$	157 mm	Strain gauge embedded in concrete

Table 2. The basic parameters of high performance concrete used in the bridge.

Parameters	Young's modulus (units: MPa)	Tensile strength (units: MPa)	Compressive strength (units: MPa)
Mean value	3.45×10^4	3.278	55.12
Standard deviation		0.361	6.063

and compressive strength parameters of the concrete used in the bridge are obtained from actual measurements. The HMS installed in the bridge is still operating normally.

The monitoring data of this bridge has the characteristics of large data volume and multiple types of data. In order to effectively store data, meet multi-user and multi-task requests, and achieve remote real-time display, query, download, and other functions of data, The research group has designed a centralized data management system. The system is composed of three parts: data storage, remote display, and early warning.

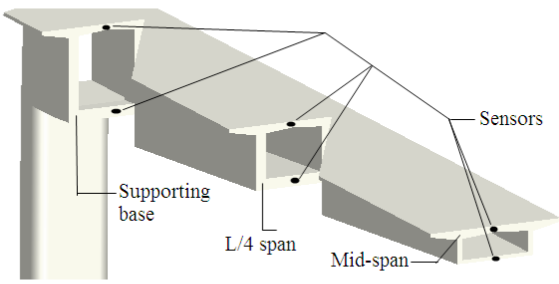


Figure 2. The embedded sensors are locations in the bridge half-span.

Figure 3. Picture of the JMZX-215 sensor.

3.2 The monitoring data processing

In the paper, the data acquired from the sensors named 2-3MID-1, 2-3MID-2, 5-6MID-2, 4Z9h-1 and 4G1h-1 are taken as samples to display the profile of the monitoring data, and the selected time period is from March 2006 to April 2010. The pre-processed method of transforming the initial data into strain data is elaborated in detail in the papers [22,23]. **Figure 4** shows the outline of the strain data after several pre-processed steps. The data interval in the figure below is mainly due to the loss of monitoring data caused by system failure.

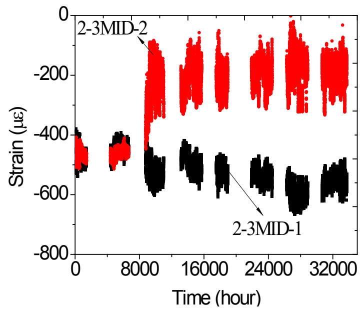


Figure 4. The profile of strain data transformed from the monitored data.

It is assumed that concrete material in the early stage of bridge operation is in the stage of linear elastic change. Combining the Young's modulus value in **Table 2** and the transformed strain data, we can get the stress data. In this paper, the data collected by sensor number 2-3 mid-1 located in the mid-span top plate between the main pier 2# and the main pier 3#, and sensor number 3-4 mid-2 located in the bottom plate between the main pier 3# and the main pier 4# are selected as samples, because the measured data converted to stress data of the mid-span sensors is similar to the principal stress. The selected data of the sensors are located in the middle of the span, and so the converted stress date is basically similar to the principal stress at this position. **Figures 5 and 6** show the outline of the stress data after pre-processing. As the sensor is embedded in the concrete, the measured data is a comprehensive reflection of the influence factors such as temperature, vehicle load, shrinkage and creep etc. Since the traffic of the background bridge was opened in June 2006, we adopted the data from 2009 for fatigue safety analysis, because the traffic flow, shrinkage and creep and other factors tended to be stable at this time. In order to facilitate data processing by using the rain flow counting methodology, the stress time-history diagram obtained takes stress as the horizontal coordinate and time as the vertical coordinate, as shown in **Figures 4 and 5**. The sample size is 5067 in **Figure 4** and the sample size is 2660 in **Figure 5**, and it is sufficient for statistical analysis.

The compressive stress safety reserve values are converted by the data collected by the sensors during the time after the background bridge is completed and before traffic release. The traffic opening time of the background bridge is in September 2006, and so the stress data acquired at this time is used as the compressive stress safety reserve in accordance with the positions of the sensors 3-4 mid-2 and 2-3 mid-1, and the specific data are shown in **Table 3**. After deducting the compressive stress safety reserve, the stress data can be used for statistics.

Table 3. The compressive stress safety reserve values are in accordance with the positions of the sensors 3-4 mid-2 and 2-3 mid-1.

Sensor number	3-4 mid-2	2-3 mid-1
Compressive stress safety reserve (units: MPa)	–15.1589	–15.8639

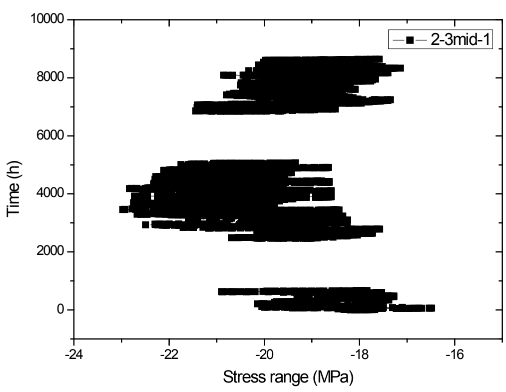


Figure 5. The profile of stress-time curve collected from the sensor 2-3 mid-1 in the whole year 2009.

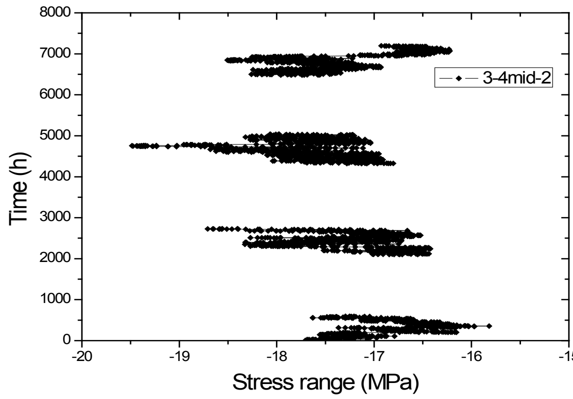


Figure 6. The profile of stress-time curve collected from the sensor 3-4 mid-2 in the whole year 2009.

4. Results and discussion

4.1 Introduction to rain flow counting method

Two British engineers M. Matsuishi and T. Enodo first presented [24] the rain flow counting method in the 1950s. The rain flow counting method's main function is simplifying the measured load history into several load cycles for estimating the fatigue life and compiling the fatigue test load spectrum. According to the two-parameter methodology, dynamic strength (amplitude) and static strength (mean value) are considered, which is in line with the inherent characteristics of fatigue load itself. The methodology is widely used in engineering, particularly in fatigue life calculation. The basic counting rules are as follows:

(1) The rain flow successively flows down the slope from the inner side of the peak position of the load time history;

(2) Rain flow starts from a peak point and stops flowing when it encounters a peak greater than its initial peak;

(3) When the rain stream meets the rain stream flowing down above, it must stop flowing;

(4) Take out all the full cycles and record the amplitude of each cycle;

(5) Equivalent the remaining divergent convergence load time history after the first stage to a convergent and divergent load time history, and then the rain flow count in the second stage is carried out.

The total number of counting cycles is the sum of the counting cycles of the two counting phases.

The main point of the rain flow method is that each part of the load-time history is counted and counted only once, and the damage caused by a large amplitude is not affected by the small loops that truncate it, and the truncated small loops are superimposed on the larger loops and half loops. Therefore, according to the cumulative damage theory, the S-N curve obtained from the constant amplitude experiment and the processing results of the rain flow method can be input into the electronic computer to estimate the fatigue life of the component. Finally, the rain flow counting method is realized by programming with Matlab software [25].

4.2 Statistical results and analysis of stress data with rain flow counting method

For the stress time history data in **Figures 5 and 6**, we treated them with rain flow counting method, and then we got the amplitude varying stress $\Delta\sigma_{ij}$ and the mean with a quantity of 422 each of the data of **Figure 5**, the amplitude varying stress $\Delta\sigma_{ij}$ and the mean with a quantity of 362 each of the data of **Figure 6**. Then, we perform a histogram statistical analysis on the obtained data of the amplitude varying stress $\Delta\sigma_{ij}$ and the mean, the specific statistical results are shown in **Figures 7 and 8**:

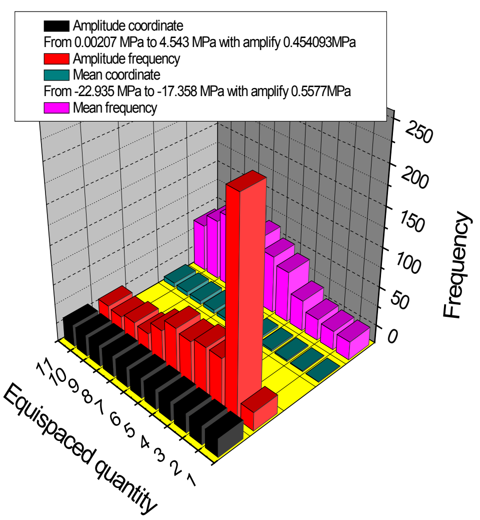


Figure 7. The histogram of the data dealt with in the whole year 2009 of the sensor 2-3 mid-1.

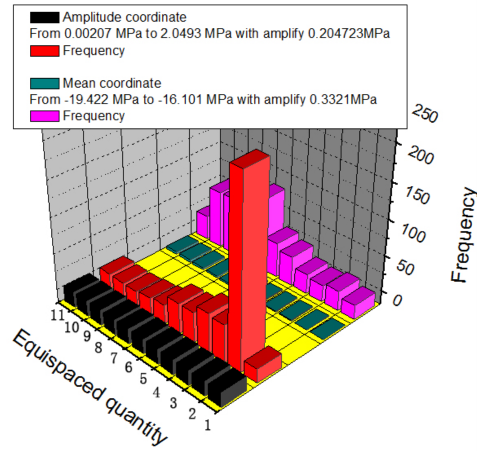


Figure 8. The histogram of the data dealt with in the whole year 2009 of the sensor 3-4 mid-2.

As seen from **Figures 7 and 8**, the range of stress amplitude $\Delta\sigma_{ij}$false variation is 0.0027 ~ 4.543 MPa and the range of mean variation is –7.0711 ~ –1.4941 MPa in **Figure 7**; the range of stress amplitude $\Delta\sigma_{ij}$ false variation is 0.0027 ~ 2.0493 MPa and the range of mean variation is –4.2631 ~ –0.9421 MPa of **Figure 8**.

4.3 Fatigue damage calculation and evolution law of the prototype bridge

Due to the sensor used in the background bridge equipped with the function of collecting temperature data simultaneously, Li et al. [26] have carried out statistical analysis by using 1 year's temperature monitoring data, and it is found that there are two wave peaks, as shown in **Figure 9**. In the meanwhile, the range of seasonal temperature variation of the bridge is obtained by statistics of the monitoring temperature data, and the temperature stress envelope of the top plate and bottom plate of the bridge is calculated by simulation software, seen in **Figure 10**. It can be seen from the temperature stress envelope diagram that the maximum temperature combined stress variation of the top and bottom in the mid-span is about 6 MPa. Therefore, we believe that the temperature induced stress changes account for a major part of the internal force of the bridge structure. Due to the slow change period of temperature and other changes, the computation times of fatigue damage calculation in this paper are calculated by half a year.

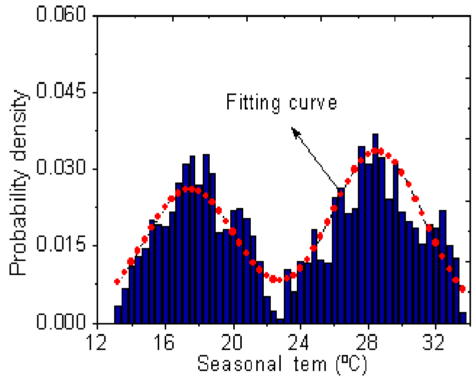


Figure 9. The measured seasonal temperature probability density with the fitting curve of the prototype bridge.

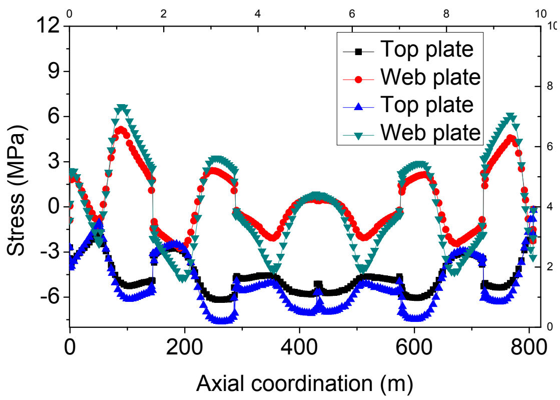


Figure 10. The outline of the temperature stress envelope of the top plate and bottom plate of the bridge.

Combining Equation (5), using the data processed in Section 4.2, we can get the fatigue damage variation law corresponding to the embedded sensor position during the design basis period of 100 years, as seen in **Figures 11 and 12**.

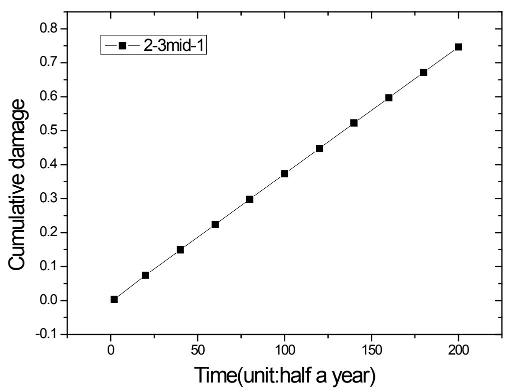


Figure 11. The change of the cumulative damage in 100 years is calculated by the monitoring data of 2-3 mid-1.

At the mid-span top plate, the one-year damage value is 0.0037338 which is obtained by using the monitoring data of the sensor 2-3 mid-1, and the cumulative damage value during the design basis period (100 years) is 0.7468; At the mid-span web plate, the one-year damage value is 0.0002648 which is obtained by using the monitoring data of the sensor 3-4 mid-2, and the cumulative damage value during design basis period (100 years) is 0.053. Based on the data in **Figures 11 and 12**, using Equation (6), we got $L(T_s) > 0$ in the design basis period of the bridge. Then, we can draw a conclusion that the calculated damage variation rules and damage degree are in line with the design requirements of relevant specifications of the concrete bridge structures. At the same time, compared with the bridge web plate, the position of the top plate is more sensitive to fatigue damage, and the main reason may be the large variation range of live load stress at the position of a top plate of the bridge.

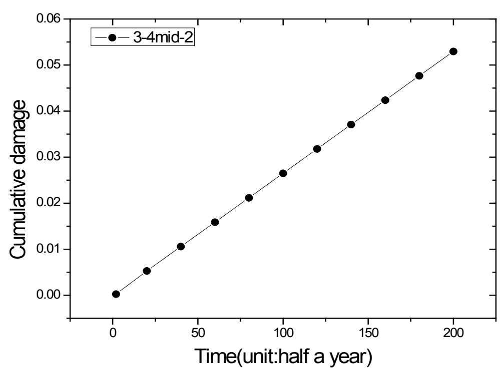


Figure 12. The change of the cumulative damage in 100 years is calculated by the monitoring data of 3-4 mid-2.

5. Conclusions

Adopting a large amount of strain monitoring data collected from the HMS of the bridge, combining fatigue damage theory and Miner rule, in the article, we proposed a method for calculating the fatigue damage of bridge structures, and the main conclusions are:

(1) By using S-N curves of the concrete material used in the bridge and linear accumulation damage with the Miner rule, the formulas of fatigue damage calculation and accumulation are derived.

(2) Based on a large amount of stress data transformed from the strain monitoring data, using the

rain flow counting method, the fatigue stress spectrum of the bridge was obtained, and it is found by calculation that the damage degree is consistent with the design requirements of the specifications, and also found that the position of the top plate is more sensitive to fatigue damage.

(3) The fatigue damage value calculated in this paper may be small, mainly due to the small number of traffic flow statistics and the deterioration of concrete material strength. So, it is necessary to use actual traffic flow survey data and the change law of concrete strength to correct the fatigue damage value during different service periods of the bridge calculated in this paper.

(4) In the next step of work, we should focus on the framework for the integration of fatigue damage analysis and HMS concepts into bridge maintenance management decision making. At the same time, considering the components and system reliability would be helpful for the development of maintenance strategies during the fatigue design basis period.

Conflict of Interest

There is no conflict of interest.

Acknowledgement

The authors are very grateful for the strong help of the collaborators. Without their help, this article could not been finished.

References

[1] Moodi, F., Knapton, J., 2003. Research into a management system for diagnosis, maintenance, and repair of concrete structures. Journal of Construction Engineering and Management. 129(5), 555-561.

[2] Rokugo K , Hatano H , Banthia N., 2008. Report on the Collapse of de la Concorde Overpass in Canada (Japanese) [Report on the collapse of de la concorde overpass in Canada]. Concrete Journal. 46(12), 35-41.
DOI: https://doi.org/10.3151/coj1975.46.12_35

[3] Gong, J.X., Wang, H.C, Li, J.B., 2005. He zai dui xiu shi huan jing xia gang jin hun ning tu liang xiu shi de ying xiang (Chinese) [Effect of load on corrosion of reinforced concrete beams in corrosive environment]. Journal of Southeast University (Natural Science Edition). 35(3),421-426.

[4] Song Y.P, Han J.G., 2021. Pi lao he zai zuo yong xia bu tong xing gang liang de po huai guan xi (Chinese) [Failure relationship of different types of steel bars in beams under fatigue load]. Journal of Harbin Institute of Technology. 44(8), 96-100.

[5] Study on Fatigue Behavior of Corroded RC Beam [Internet]. Available from: https://www.researchgate.net/profile/V-Feldgun/publication/283292537_A_new_equation_of_state_for_cementitious_materials_-_a_multiscale_approach/links/565184cc08aefe619b161800/A-new-equation-of-state-for-cementitious-materials-a-multiscale-approach.pdf#page=475

[6] Gao, Z., Liang, R.Y., Patnaik, A.K., 2016. Effects of sustained loading and pre-existing cracks on corrosion behavior of reinforced concrete slabs. Construction and Building Materials. 124, 776-785.

[7] Sun, J., Ding, Z., Huang, Q., 2019. Development of EIFS-based corrosion fatigue life prediction approach for corroded RC beams. Engineering Fracture Mechanics. 209, 1-16.

[8] Guo, Z., Ma, Y., Wang, L., et al., 2020. Crack propagation-based fatigue life prediction of corroded RC beams considering bond degradation. Journal of Bridge Engineering. 25(8), 04020048.

[9] Wen, B., 2021. Gang jing hun ning tu jie gou pi lao tui hua ji li ji xing neng ti shen ji shu (Chinese) [Fatigue degradation mechanism and performance improvement technology of reinforced concrete structures] [Ph.D. thesis]. Nanjing: Southeast University.

[10] Li, Z.X., Chan, T.H., Ko, J.M., 2001. Fatigue analysis and life prediction of bridges with structural health monitoring data—Part I: Meth-

odology and strategy. International Journal of Fatigue. 23(1), 45-53.

[11] Chan, T.H., Li, Z.X., Ko, J.M., 2001. Fatigue analysis and life prediction of bridges with structural health monitoring data—Part II: Application. International Journal of Fatigue. 23(1), 55-64.

[12] Tong, G., Aiqun, L., Jianhui, L., 2008. Fatigue life prediction of welded joints in orthotropic steel decks considering temperature effect and increasing traffic flow. Structural Health Monitoring. 7(3), 189-202.

[13] Kwon, K., Frangopol, D.M., 2010. Bridge fatigue reliability assessment using probability density functions of equivalent stress range based on field monitoring data. International Journal of Fatigue. 32(8), 1221-1232.

[14] Deng, Y., Ding, Y., Li, A., et al., 2011. Fatigue reliability assessment for bridge welded details using long-term monitoring data. Science China Technological Sciences. 54, 3371-3381.

[15] Newhook, J.P., Edalatmanesh, R., 2013. Integrating reliability and structural health monitoring in the fatigue assessment of concrete bridge decks. Structure and Infrastructure Engineering. 9(7), 619-633.

[16] Junges, P., Pinto, R.C.A., Miguel, L.F., 2018. Fatigue life assessment of reinforced concrete bridges from monitoring data. Maintenance, safety, risk, management and life-cycle performance of bridges. CRC Press: Boca Raton. pp. 634-641.

[17] Mankar, A., Bayane, I., Sørensen, J.D., et al., 2019. Probabilistic reliability framework for assessment of concrete fatigue of existing RC bridge deck slabs using data from monitoring. Engineering Structures. 201, 109788.

[18] Miner, M.A., 1945. Cumulative damage in fatigue. Journal of Applied Mechanics. 12(3), 159-164.

[19] Song Y.P, 2004. Gang jin hun ning tu jie gou (Chinese) [Reinforced Concrete Structure]. Beijing: China Machine Press.

[20] GB 50010-2010 (2015) Code for Design of Concrete Structures [Internet]. Available from: https://www.codeofchina.com/standard/GB 50010-2010(2015).html

[21] CCCC Highway Planning and Design Institute, 2012. Standard of the Ministry of Communications of P. R.C. specifications for design of highway reinforced concrete and prestressed concrete bridges and culverts (JTG 3362-2018). China Communications Press: Beijing.

[22] Liu, Z.J., Li, Y.H., Tang, L.Q., et al., 2014. Localized reliability analysis on a large-span rigid frame bridge based on monitored strains from the long-term SHM system. Smart Structures & Systems. 14(2), 209-224.

[23] Li, Y., Peng, K., He, J., et al., 2021. Maintenance management research of a large-span continuous rigid frame bridge based on reliability assessment by using strain monitored data. Journal of Architectural Environment & Structural Engineering Research. 4(2), 20-31.

[24] Zhang Y., 2015. Che liang zong cheng xing neng jian ce ji shu (Chinese) [Vehicle assembly performance detection technology]. Beijing: National Defense Industry Press. Available from: https://www.amazon.fr/%E8%BD%A6%E8%BE%86%E6%80%BB%E6%88%90%E6%80%A7%E8%83%BD%E6%A3%80%E6%B5%8B%E6%8A%80%E6%9C%AF-%E5%BC%A0%E9%9B%A8/dp/B01AUNRXP6

[25] About MATLAB [Internet]. Available from: https://ww2.mathworks.cn/products/matlab.html

[26] Li, Y.H., 2021. Ji yu chang qi jian kang jian de hun ning tu lian xu gang gou liang qiao xing neng fen xi yu yan hua gui lv yan jiu (Chinese) [Performance analysis and evolution of continuous rigid frame girder bridges based on long-term health monitoring]. Guangzhou: South China University of Technology. Available from: https://cglhub.com/auto/db/detail.aspx?db=950008&rid=1283605&agfi=0&cls=0&uni=True&cid=0&showgp=True&prec=False&md=152&pd=208&msd=152&psd=208&mdd=152&pdd=208&count=10&reds=submodeling

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Innovation Empowerment in Construction 4.0 by the Corporate Digital Responsibility (CDR)—Approach. A New Field of Scientific Research for the Digital Breakthrough

Bianca Weber-Lewerenz * ***, Marzia Traverso***

Institute of Sustainability in Civil Engineering InaB, Faculty of Engineering, RWTH Aachen University, Aachen, 52062, Germany

ABSTRACT

The Architecture, Engineering and Construction Industry (AEC) undergoes digital transformation, one of the major drivers for technical innovation and dynamism to all working processes. Emerging technologies were only used to a limited extent due to the lack of will to innovate and the unavailability of appropriate orientation guiding users with a more comprehensible framework. The research defined a new gap in scientific research with the concept of Corporate Digital Responsibility (CDR) in Construction 4.0—a term representing the digitization of the branch. The traditionally conservative, highly fragmented industry is predestined for this given the advanced technology, human potential and appreciation of values. Understanding the complex possibilities of innovation and recognizing the potential impact on the sustainability of buildings and the built environment promotes the adoption of corporate responsibility. The implementation of digital strategies, secured by an adapted legal framework, would accelerate the overall human, societal and digital transformation. This primary research investigates the challenges affecting the adoption of Artificial Intelligence (AI). The study highlights in which fields CDR can significantly catalyze innovation to achieve efficient, economic construction life cycles. The study used a mix of methods with a structured literature analysis and expert interview surveys enabling a critical-reflexive analysis of key factors. It evaluates the key tasks to master technological feasibility. By assessing multiple expert perspectives, the study takes stock of the acceptance of new technologies. The findings are expected to inspire corporates, researchers and practitioners across disciplines. Necessary corporate steps are outlined in the study to lay the path for defining their own digital strategy. The study shows that new research questions require a holistic approach.

Keywords: Construction; CDR; Innovation; Digitization; AI; Digital transformation; Human transformation; Ethics; SDGs

*CORRESPONDING AUTHOR:

Bianca Weber-Lewerenz, Institute of Sustainability in Civil Engineering InaB, Faculty of Engineering, RWTH Aachen University, Aachen, 52062, Germany; Email: bianca.christina@gmx.de

ARTICLE INFO

Received: 31 July 2023 | Revised: 20 September 2023 | Accepted: 30 September 2023 | Published Online: 17 October 2023

DOI: https://doi.org/10.30564/jaeser.v6i3.5915

CITATION

Weber-Lewerenz, B., Traverso, M., 2023. Innovation Empowerment in Construction 4.0 by the Corporate Digital Responsibility (CDR)—Approach. A New Field of Scientific Research for the Digital Breakthrough. Journal of Architectural Environment & Structural Engineering Research. 6(3): 41-64. DOI: https://doi.org/10.30564/jaeser.v6i3.5915

1. Introduction

Digital technologies and AI in Civil Engineering enable us to reflect on what we expect from them, allocating their support to human work, increasing safety, and determining ways to deal with risks and unintended consequences. When AI technology meets human interaction—with human, societal and environmental impacts—ethical and moral questions arise. Increasing technical feasibility leads to an increase in ethical social responsibility [1,2]. This debate is not new, but such a new approach in Civil Engineering offers a new area of scientific research. It is only since 2020 and 2021 that the interest in researching practically applied value-based engineering and scientific publications significantly increased [3,4].

Despite emitting 40% of global CO_2, consuming 50% of the global raw materials and 40% of energy [5], and a lack of skilled personnel, only each fifth company applies Building Information Modelling (BIM), not consistently throughout all working and project processes, the Construction branch still maintains a culture of resistance to change [6] and to using digital methods [7] and AI [8,9] though playing a pivotal role in achieving sustainability goals. The complexity of data, communication and reciprocal interdependencies between diverse factors of a project challenges the branch [10]. The branch's poor reputation is due to the overly manual nature of documentation and the absence of adequate digital adoption linked to decreased quality of work processes [11]. The irresponsible cost, time and quality management, limited availability of resources, inefficient supply chains [12] and low promotion of decarbonization are increasingly problematic [13]. Digital technologies and AI could improve and ease human work significantly. AI enables object and image identification, forecast and simulation modeling, machine and deep learning, augmented reality, Metaverse, ChatGPT, data structuring and smart communication in buildings and cities. These technologies, among other targets and not limited to urban infrastructure and environments, aim for transparency, ease human work, and increase efficiencies in all fields to achieve Sustainable Development Goals (SDGs). The study found that the application of digital technologies and AI significantly improves sustainable buildings and building life-cycles through efficient energy, building material and waste management, which directly impact the sustainability of architectural structures. For example, up to 20% of energy savings may be achieved through AI-based, self-learning technologies and CO_2 optimization using predictive maintenance. Additionally, AI optimizes the efficiency of processes by structuring complex data as a basis for human decision-making, building and infrastructure operations such as smart buildings. New technologies help to prevent cost and time overruns, e.g., by predictive monitoring and forecast models. They increase building safety by detecting safety hazards. In addition, AI and digital technologies enable highly efficient environmental impact assessments. Using sensors, detection and predictive modeling, these technologies help to identify potential environmental risks and propose remedial measures. Facilitating human work, structuring complex data, visualizing projects and providing real-time data are the advantages of AI. European and global AI strategies represent milestones to strengthen the sustainable application of AI (**Figure 1**).

Data and technical feasibility get more and more complex, and human, ethical, societal, environmental and legal impacts increase. So does the societal and environmental pressure on the branch to build sustainably [14,15]. This study investigated both how to adapt to these new human and technical changes responsibly and why the will to innovate [16] is key to success. People change and enable digital technological innovation [17]. Adapting the work of Franklin and Barratt [18,19], technology can add or remove value to work and life and have unintended consequences. Construction is a specific branch bearing high potential to develop and implement innovative technologies in agile environments [20] but also carrying an even greater obligation to meet its social, human, economic, and environmental responsibilities [21] and achieve the SDGs [22]. The study considers morals and values to offer guidance for dealing responsibly with digitization and AI [23], but

Important Milestones of the European & Global AI Strategy

July 2023 – Web 4.0 and Virtual Worlds EU-Strategy
June 2023 - US National Artificial Intelligence Advisory Committee (NAIAC) First Report
June 2023 - Amendment to Proposed AI Act as passed by European Parliament for a regulation of the European Parliament and of the Council on laying down harmonised rules on artificial intelligence (Artificial Intelligence Act) and amending certain Union legislative acts
March 2023 – Open Letter of the Future of Life Institute: Call for pausing giant AI experiments for at least six months
March 2023 - Statement of the German Ethics Council: Human and Machine - Challenges posed by Artificial Intelligence
November 2022 – German National Digital Strategy (Part of the International Digital Strategy)
November 2022 - Digital Markets Act DMA (EU)
October 2022 – Digital Services Act DSA (EU)
September 2022 - Virtual and Augmented Reality Industrial Coalition (EU)
July 2022 – New European Innovation Agenda (EU)
June 2022 – Strategic Forecast 2022: Interlocking of Green and Digital Change in the new geopolitical context (EU)
November 2021 – AI Act
November 2021 – Digitization Strategy (Coalition Contract 2021)
September 2021 – New Standard IEEE7000-2021. Value-based Engineering.
April 2021 - Promoting a European approach to AI
April 2021 - Proposal for a regulation with harmonized rules for AI
April 2021 - Updated Coordination Plan for AI
October 2020 – 2nd Assembly of the European AI Alliance
February 2020 - White Paper on AI: a European approach to excellence and trust
June 2019 – 1st Assembly of the European AI Alliance
May 2019 – OECD AI Principles
April 2019 – Communication: Building trust in human-centric artificial intelligence
April 2019 – Ethical guidelines for trustworthy AI
December 2018 – Coordination plan on AI ("AI - Made in Europe" - press release)
December 2018 - Stakeholder Consultation: Draft Ethical Guidelines for Trustworthy AI
November 2018 - European Digital Strategy
June 2018 – Launch of the European AI Alliance
June 2018 – Establishment of the High Level Expert Group on AI (AIHLEG)
April 2018 – European AI Strategy (press release "AI for Europe")
April 2018 - Commission Staff Working Document: Liability for Emerging Digital Technologies
April 2018 – Declaration of cooperation on AI

Figure 1. European and global AI strategy milestones.

Source: Bianca Weber-Lewerenz.

Construction 4.0 still lacks orientation in navigating new technologies knowing its risks and limitations, e.g., by ethical principles. High level institutions call for reflecting human-machine interaction [24] and even pausing giant AI developments [25]. Education and access to new knowledge [26,27], awareness, trustworthiness, safety and societal responsibility [28] represent the main pillars of overcoming conservative attitudes [29], strengthening innovation, improving efficiencies, achieving SDGs and shaping a sustainable environment [30,31]. It is said that AI in Construction will have a share of around 4.51 billion euros by 2026 [32]. The study found that ethical considerations are vital at the design stage of digital methods and AI as society becomes more and more reliant on technology. Consequently, with this research, a scientific niche in "Ethics in AI in Construction" has been defined. The research concludes that CDR lays the groundwork for value creation, efficient life cycles, sustainable ecosystems, protection of resources and strengthening diversity and inclusion. To address the identified gap and answer the research question of "*How shall a framework of corporate digital responsibility (CDR) be designed to support ethical digital innovation in Construction?*", it is paramount to critically investigate the specific objectives of this study: 1) Critically review the digital methods and AI applications, 2) identify challenges affecting the will to innovate and adopt innovative technologies, 3) understand the potentials, risks and impacts and 4) identify key elements and their interrelationship to set up a comprehensive, value-based CDR policy framework.

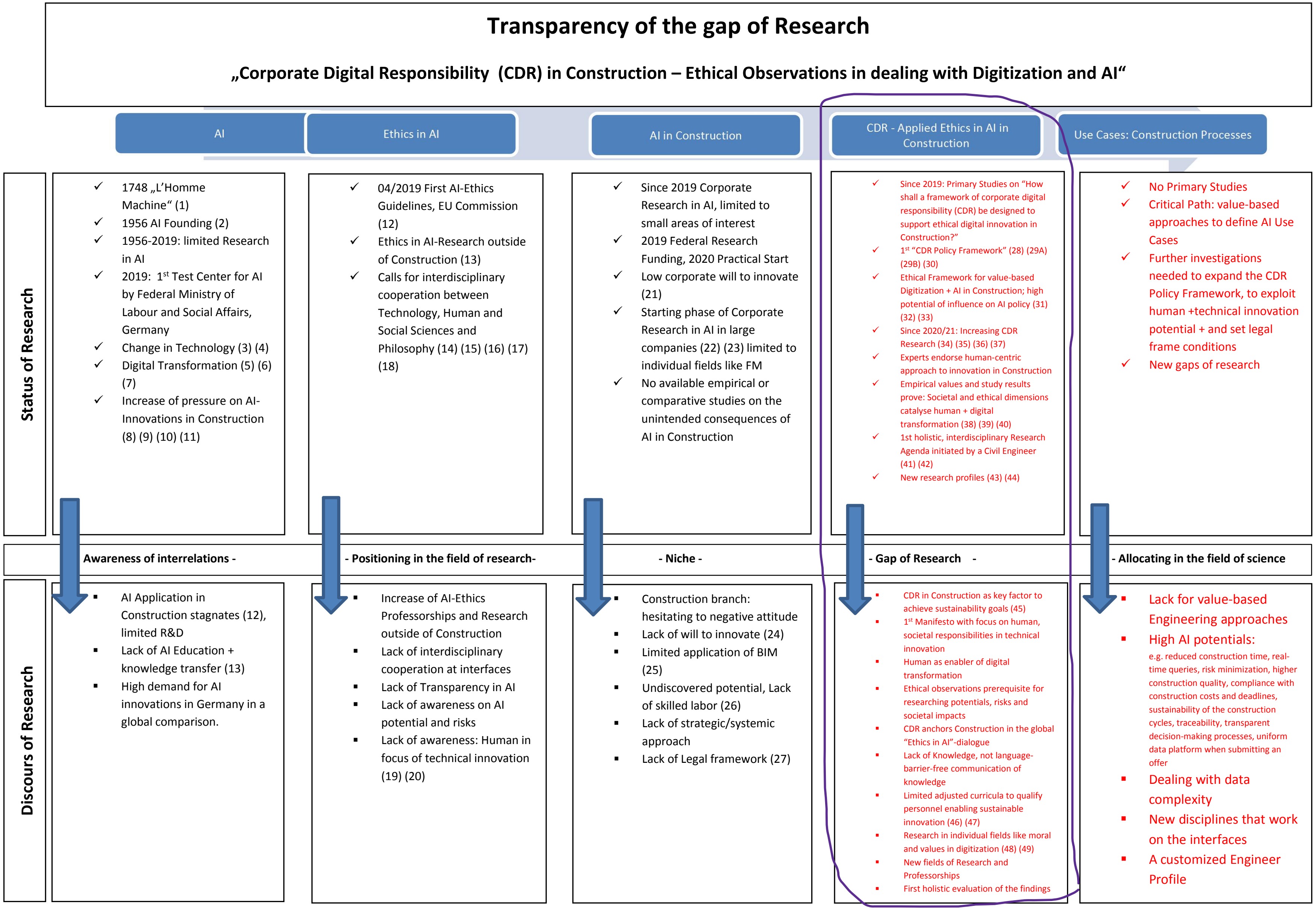
The study is divided into five steps: introduction, with a brief overview of the Construction Industry, new technological trends with their impacts, ethical observations and scientific approaches in technical fields. The second step establishes systematic review methods leading to the third step to assess and evaluate the information and, finally steps four and five, the results, discussion and conclusions.

2. State of the art

To fully grasp the gap in research, the study describes technical and ethical backgrounds and the milestones in the history of BIM and AI. Expert interviews with an interdisciplinary dialogue were carried out with representatives from construction practice, various disciplines, education, research and politics in order to open up this new field of research.

Many scientific articles on construction-specific challenges and the application of emerging technologies have been published, but more with technical decision support [33], operational [34-35,7] and safety focus [36]. Very little other research investigated the human factor and impacts of technology on society. Recent literature research focuses on new technical approaches for optimizing construction productivity and cost efficiencies [37,38], digital transformation balancing economic, environmental and societal impacts [39], e.g., through new digital business models [40], mostly from a stakeholder's perspective [41]. Ethics and social responsibility in Civil Engineering are broadly discussed in the context of holistic and comprehensive sustainability [42] rather than focusing on responsible development and application of innovative technologies to fully exploit their broad potential across the branch. When this research started in 2019, there was no literature in Construction investigating the human factor of digital transformation, nor analyzing unintended consequences of digital innovation. No literature was available to identify key elements that strengthen the human acceptance of innovative technologies in corporate environments, or on the concept of CDR tailored to Construction. No literature in the field could be found researching the multiple ethical, societal, and humane aspects of how a sustainable digital transformation enables reaching SDGs and to what extent the branch assumes its societal and ethical responsibility. **Figure 2** puts focus on such niche by visualizing the phases of development of the field of interest from its early beginning: Focus is given to column "CDR—Applied Ethics in AI in Construction". For each stage of the involved scientific field—from "AI" to "Ethics in AI" to "AI in Construction" to "CDR—Applied Ethics in AI in Construction"—the upper row introduces the corresponding state-of-the-art titled "Status of Research" while the bottom row titled "Discourse of Research" presents both results of ongoing research and shortly defines needs of missing scientific research. The left-hand side columns "Status of Research" and "Discourse of Research" are selected titles to split thematically and differ between the upper (status) from the lower sections (further required research). In the context of CDR, literature references and milestones are discussed, and ethical observations, gaps and limitations are critically argued to derive its first manifesto customized to CDR in Construction. In its last column, this figure highlights a potential new field of further research investigating "Use Cases", eventually by construction processes. This one has been crystallized as critical by the interviewees due to the expected practical corporate benefits. The interviewed experts focus on human, trust and societal responsibilities in all technical innovation considered as enablers of digital transformation. Further research could strengthen such approaches.

This study's primary contributions advance the body of knowledge with the first CDR policy framework [43]. This research aims for the ethical positioning to shape a human-focused digital transformation. It is all the more ground-breaking since it is dedicated to construction with an overlapping area such as AI ethics, which in other industries is sometimes awash with literature but seems to offer little that is new. This new field investigated the previously less recognized potentials and also the new risks, e.g., data transparency, protection of human and individual rights and natural resources, and adequate infrastructure (data capacity, high speed transfer, energy consumption for increased storage ventilation and cooling). This work assesses the ethical issues involved in digital transformation by setting up an interdisciplinary cooperation network with scientific representatives e.g., in ethics, philosophy, theology and law working already in the field of AI technologies and therefore their expertise in the designated interface is considered as adding value. It is also the first expert survey in the branch with respect to human and societal dimensions in AI and the overall transformation. It supports a deeper understanding of


Transparency of the gap of Research
„Corporate Digital Responsibility (CDR) in Construction – Ethical Observations in dealing with Digitization and AI“
AI
Ethics in AI
AI in Construction
CDR - Applied Ethics in AI in Construction
Use Cases: Construction Processes
Status of Research
✓ 1748 „L'Homme Machine“ (1)
✓ 1956 AI Founding (2)
✓ 1956-2019: limited Research in AI
✓ 2019: 1st Test Center for AI by Federal Ministry of Labour and Social Affairs, Germany
✓ Change in Technology (3) (4)
✓ Digital Transformation (5) (6) (7)
✓ Increase of pressure on AI-Innovations in Construction (8) (9) (10) (11)
✓ 04/2019 First AI-Ethics Guidelines, EU Commission (12)
✓ Ethics in AI-Research outside of Construction (13)
✓ Calls for interdisciplinary cooperation between Technology, Human and Social Sciences and Philosophy (14) (15) (16) (17) (18)
✓ Since 2019 Corporate Research in AI, limited to small areas of interest
✓ 2019 Federal Research Funding, 2020 Practical Start
✓ Low corporate will to innovate (21)
✓ Starting phase of Corporate Research in AI in large companies (22) (23) limited to individual fields like FM
✓ No available empirical or comparative studies on the unintended consequences of AI in Construction
✓ Since 2019: Primary Studies on “How shall a framework of corporate digital responsibility (CDR) be designed to support ethical digital innovation in Construction?”
✓ 1st “CDR Policy Framework” (28) (29A) (29B) (30)
✓ Ethical Framework for value-based Digitization + AI in Construction; high potential of influence on AI policy (31) (32) (33)
✓ Since 2020/21: Increasing CDR Research (34) (35) (36) (37)
✓ Experts endorse human-centric approach to innovation in Construction
✓ Empirical values and study results prove: Societal and ethical dimensions catalyse human + digital transformation (38) (39) (40)
✓ 1st holistic, interdisciplinary Research Agenda initiated by a Civil Engineer (41) (42)
✓ New research profiles (43) (44)
✓ No Primary Studies
✓ Critical Path: value-based approaches to define AI Use Cases
✓ Further investigations needed to expand the CDR Policy Framework, to exploit human +technical innovation potential + and set legal frame conditions
✓ New gaps of research
Awareness of interrelations -
- Positioning in the field of research-
- Niche -
- Gap of Research -
- Allocating in the field of science
Discours of Research
▪ AI Application in Construction stagnates (12), limited R&D
▪ Lack of AI Education + knowledge transfer (13)
▪ High demand for AI innovations in Germany in a global comparison.
▪ Increase of AI-Ethics Professorships and Research outside of Construction
▪ Lack of interdisciplinary cooperation at interfaces
▪ Lack of Transparency in AI
▪ Lack of awareness on AI potential and risks
▪ Lack of awareness: Human in focus of technical innovation (19) (20)
▪ Construction branch: hesitating to negative attitude
▪ Lack of will to innovate (24)
▪ Limited application of BIM (25)
▪ Undiscovered potential, Lack of skilled labor (26)
▪ Lack of strategic/systemic approach
▪ Lack of Legal framework (27)
▪ CDR in Construction as key factor to achieve sustainability goals (45)
▪ 1st Manifesto with focus on human, societal responsibilities in technical innovation
▪ Human as enabler of digital transformation
▪ Ethical observations prerequisite for researching potentials, risks and societal impacts
▪ CDR anchors Construction in the global “Ethics in AI”-dialogue
▪ Lack of Knowledge, not language-barrier-free communication of knowledge
▪ Limited adjusted curricula to qualify personnel enabling sustainable innovation (46) (47)
▪ Research in individual fields like moral and values in digitization (48) (49)
▪ New fields of Research and Professorships
▪ First holistic evaluation of the findings
▪ Lack for value-based Engineering approaches
▪ High AI potentials:
e.g. reduced construction time, real-time queries, risk minimization, higher construction quality, compliance with construction costs and deadlines, sustainability of the construction cycles, traceability, transparent decision-making processes, uniform data platform when submitting an offer
▪ Dealing with data complexity
▪ New disciplines that work on the interfaces
▪ A customized Engineer Profile

(1) Julien Offray de La Mettrie (1748). L'Homme Machine. Der Mensch eine Maschine (Dt.). Reclams Universal-Bibliothek Publishing. Last edition as of 18. March 2015

(2) McCarthy, J. et al. (1955). A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence in 1956. http://www-formal.stanford.edu/jmc/history/dartmouth/dartmouth.html

(3) Jonas, H. (1987). Warum die Technik ein Gegenstand für die Ethik ist : fünf Gründe. Technik und Ethik, Vol.2, p. 81-91.

(4) Hubig, C. (2004). In: Reidel, J.: Ethische Ingenieurverantwortung. Handlungsspielräume und Perspektiven der Kodifizierung.

(5) Thiel, F. (2017). Building Information Modeling (BIM) - Rechtliche und technische Aspekte des digitalen integralen Planens und Bauens. In: Journal zfv 6/2017, Wißner-Publishing GmbH & Co. KG, p. 336 – 345

(6) Attaran, M. and Deb, P. (2018). Machine Learning: The New 'Big Thing' for Competitive Advantage. 5. 277-305. DOI: 10.1504/IJKEDM.2018.10015621

(7) Manning, C. (2020). Artificial Intelligence Definitions. Stanford University, Human-Centered AI. https://hai.stanford.edu/sites/default/files/2020-09/AI-Definitions-HAI.pdf

(8) European Commission (2022). Neue Europäische Innovationsagenda (2022). https://www.eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0332.

(9) European Commission (2022) Neue Strategische Vorausschau 2022: Verzahnung von grünem und digitalem Wandel im neuen geopolitischen Kontext (2022). https://www.ec.europa.eu/info/files/strategic-foresight-report-2022_en.

(10) Building Europe's Digital Sovereignty Conference (2022). Task Force on Digital Commons (2022). https://www.presidence-francaise.consilium.europa.eu/en/news/the-building-europe-s-digital-sovereignty-conference/.

(11) Feroz, A.K. et al. (2021). Digital transformation and environmental sustainability: A review and research agenda. Journal for Sustainability 13(3), 1530sqq. (2021). DOI: 10.3390/su13031530.

(12) Hatami, M. et al. (2019). State-of-the-art review on the applicability of AI methods to automated construction manufacturing. In : Computing in Civil Engineering: Data, Sensing, and Analytics, pp. 368-375. DOI : 10.1061/9780784482438.047

(13) Luckin, Rose, et al. "Intelligence unleashed: An argument for AI in education." (2016).

(12) European Commission (2019). Ethics guidelines for trustworthy AI. Report by High-Level Expert Group on AI. https://digital-strategy.ec.europa.eu/en/library/ethics-guidelines-trustworthy

(13) Heilinger, JC. The Ethics of AI Ethics. A Constructive Critique. Philos. Technol. 35, 61 (2022). DOI : 10.1007/s13347-022-00557-9

(14) Grunwald, A. and Hillerbrand, R. (2013). Handbuch Technikethik. 1. Edition 2013, J. B. Metzler Publishing, Stuttgart

(15) Spiekermann, S. (2019): Digitale Ethik - Ein Wertesystem für das 21. Jahrhundert. Droemer Publishing, Munich.

(16) Funk M. (2022). Roboter- und KI-Ethik als philosophische Disziplin (Bedeutung 1). In: Roboter- und KI-Ethik. Springer Vieweg Publishing, Wiesbaden. DOI: 10.1007/978-3-658-34666-9_2

(17) Grunwald, A. (2020). Verantwortung und Technik: zum Wandel des Verantwortungsbegriffs in der Technikethik. In: Seibert-Fohr A. (eds) Entgrenzte Verantwortung. Springer Publishing, Berlin, Heidelberg. DOI: 10.1007/978-3-662-60564-6_13

(18) Nothelle-Wildfeuer, U. et al. (2020). Zum Umgang mit KI-Technologien – ethische Prinzipien und Leitlinien aus christlicher Perspektive. https://d-nb.info/1222438321

(19) Sherratt, D., Rogerson, S. & Fairweather, N.B. The challenge of raising ethical awareness: A case-based aiding system for use by computing and ICT students. SCI ENG ETHICS 11, 299–315 (2005). DOI : 10.1007/s11948-005-0047-7

(20) Rogerson, S. (2021). Rebooting ethics education in the digital age. Academia Letter, Article 146. DOI: 10.20935/AL146

(21) Harvard School (2016). Disrupting the Construction Industry through the use of Digitization. https://d3.harvard.edu/platform-rctom/submission/disrupting-the-construction-industry-through

(22) Abioye, S. et al. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. Journal of Building Engineering. Vol. 44. DOI: 10.1016/j.jobe.2021.103299

(23) Borja Garcia de Soto (2019). Implications of Construction 4.0 to the workforce and organizational structures. International Journal of Construction Management, Vol. 22, Iss. 2, p.205-217, DOI: 10.1080/15623599.2019.1616414

(24) Brockmann, C. et al. (2016). Innovation in construction megaprojects. In : Journal of Construction Engineering and Management, Vol. 142, Iss. 11. DOI : 10.1061/(ASCE)CO.1943-7862.0001168

(25) Liu, S. et al. (2015). Critical barriers to BIM implementation in the AEC industry. In : International Journal of Marketing Studies, Vol. 7, Iss. 6. DOI : 10.5539/ijms.v7n6p162

(26) Brucker J. et al. (2021). Review of the Construction Labour Demand and Shortages in the EU. Journal of Buildings, Vol. 11, Iss. 1, p.205-217. DOI: 10.3390/buildings11010017. 2

(27) Azhar, S., Khalfan, M., & Maqsood, T. (2012). Building information modeling (BIM): now and beyond. In : Australiasian Journal of Construction Economics and Building, Vol. 12, Iss. 4, p. 15-28. DOI : 10.3316/informit.013120167780649

(28) Weber-Lewerenz, B. (2021). Corporate digital responsibility (CDR) in construction engineering - Ethical guidelines for the application of digital transformation and artificial intelligence (AI) in user practice. In: Springer Nature SN Applied Sciences. Volume 3, 801, Issue 10, 2021. https://doi.org/10.1007/s42452-021-04776-1

(29A) 2019 Founding of „iEthics"Concept to shape CDR in Construction

(29B) 2020 Founding of the Excellence Initiative for sustainable, human-led AI in Construction

(30) Weber-Lewerenz, B. (2022). Accents of Added Value in Construction 4.0. Springer Vieweg Publishing Wiesbaden.

(31) Weber-Lewerenz, B. (2022). Wertakzente im Bauwesen 4.0. Springer Vieweg Publishing Wiesbaden.

(32) Enquête-Commission of the Federal German Bundestag (2020). Artificial Intelligence - Social Responsibility and Economic, Social and Ecological Potentials, Final Report of the Enquête Commission as of 28 October 2020. Document No. 19/23800

(33) Life Academy of the Vatican of Archbishop Vincenzo Paglia in Rom (2020). Roman-Catholic Church: Rome Call for AI Ethics. Rom, 1. Edition 28 February 2020

(34) Weber-Lewerenz, B. (2020). Position Paper „Response of Construction Industry onto the White Paper for a trustful AI by European Commission" (European Commission (2020). White Paper on Artificial Intelligence - a European approach to excellence and trust. Brussels, 1. Edition 19 February 2020). In: Weber-Lewerenz, B. (2022). Accents of Added Value in Construction 4.0. Springer Vieweg Publishing Wiesbaden.

(35) Xiao, J. et al. (2022). Exploring Driving Factors of Digital Transformation among Local Governments: Foundations for Smart City Construction in China. In: Journal of Sustainability 2022, Vol. 14, Iss. 22, 14980. DOI: 10.3390/su142214980

(36) Chen, X. et al. (2022). Developing a readiness model and a self-assessment tool for adopting digital technologies in construction organizations, Journal for Building Research & Information, DOI: 10.1080/09613218.2022.2136130

(37) Yang, R. and Wibowo, S. (2022). User trust in artificial intelligence: A comprehensive conceptual framework. The International Journal on Networked Business: Electron Markets. DOI: 10.1007/s12525-022-00592-6

(38) Kaiyang, W. et al. (2022). Towards Sustainable Development through the Perspective of Construction 4.0: Systematic Literature Review and Bibliometric Analysis. Buildings Journal. MDPI Press. www.researchgate.net/publication/364340457

(39) Giannakidis, A.; Weber-Lewerenz, B.; Stolze D. (2021).AI in Construction in Germany. Study with Fraunhofer Institute Stuttgart IAO. http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-6306697.pdf

(40) Rosha, A. and Lobanova, L. (2022). Ethical Responsibility of a Company in the Context of Digital Transformation of Work: Conceptual Model. In: Journal of Sustainability, Vol 14, Iss. 18. DOI: 10.3390/su141811365

(41) Weber-Lewerenz, B. (2022). Chapter 4: Engineering Science and Philosophy/Ethics – How do they fit together? In: Accents of Added Value in Construction 4.0. Springer Vieweg Publishing Wiesbaden.

(42) Nothelle-Wildfeuer, U. (2022). Chapter 13: The Human in the Centre ?! (Christian)-Ethical Reflections on the Antropological and Ethical Challenges of AI. In: Accents of Added Value in Construction 4.0. Springer Vieweg Publishing Wiesbaden.

(43) https://reser.net/expertises/innovation-ecosystem-open/

(44) https://www.inab.rwth-aachen.de/en/bianca-weber-lewerenz-cv/

(45) UN United Nations (2016): The 17 SDGs. https://sdgs.un.org/goals

(46) Bajpai, A. and Misra, S.C. (2022). Evaluation of success factors to implement digitalization in the construction industry. Journal for Construction Innovation. DOI: 10.1108/CI-02-2022-0042-the-use-of-digitization/

(47) Kohnke, O. (2017). It's not just about technology: The people side of digitization. In: G. Oswald and M. Kleinemeier (edt.). Shaping the digital enterprise. Springer Publishing, p. 69–91. DOI: 10.1007/978-3-319-40967-2_3

(48) Lehmann, A. et al. (2013). Social aspects for sustainability assessment of technologies—challenges for social life cycle assessment (SLCA). In: International Journal of Life Cycle Assessment, Vol. 18, p. 1581–1592. DOI: 10.1007/s11367-013-0594-0

(49) Veluwenkamp, H. and van den Hoven, J. (2023). Design for values and conceptual engineering. In: Journal of Ethics and Information Technology, Vol. 25. DOI: 10.1007/s10676-022-09675-6

Figure 2. Gap of research.

Source: Bianca Weber-Lewerenz.

the human-technology interaction between humans and technology in Construction. Recent activities and initiatives in the field of "Ethics in AI" e.g. by the German Ethics Commission [44], the European Union and the United Nations, and the Catholic Church [45] represent important strategies inspiring considerations in construction as part of the AI Strategy.

Major differences between this and other earlier review papers on this topic could not be drawn since such a topic represents a novelty in construction and has not yet been researched within this scientific discipline. The gaps this research addresses are recognized based on evidence in research and practice. While there are bibliometric reviews of sustainability and general ethical management in the construction industry, there is no holistic approach but a focus on technology and sustainability assessment methods. Therefore, the present study aimed to systematically review the literature in the field of ethics in AI in construction. In addition, it discusses the further development of qualitative methods of ethics in AI in construction and presents the state of the art in the surrounding area. It defines the gaps identified in the literature, which, however, only make up a very small part of this literature. The study evaluated and assessed ethical observations made in construction and defined key elements to apply emerging technologies to assume responsibility as a branch. The study's authors addressed ethical and societal questions towards ethicists, philosophical scientists, and theologists. Because of their engagement in debating AI ethics and human-technology interaction, it becomes clear that their considerations add value to this investigation and broaden the holistic scientific discourse. It is an essential part of ethics to evaluate human action and to methodically reflect on moral action. Certain values are an important prerequisite for achieving other values, so-called "enablers" of other values along the value chain. Circular economy, smart cities, and climate protection are just a few areas of interest in terms of ecological transformation, not only requiring improvements via technologies but also successful human transformation. Thus, this research studied new approaches to fully exploit the branch's human and technological innovation potential. Since its early stage, the published research findings raised awareness highlighting the diverse impacts and were able to add value to the scientific community. This study complemented previous work performed outside of Construction Engineering disciplines and without societal, humane, value-based considerations applied to Construction. However, because of the results' relevance to the overall sustainability in construction, the new approaches could only be defined by evaluating these previous results in comparison with developments and tendencies in Construction. Additionally, the status of research consists of limited application fields of AI—far away from its broad untapped potentials—and is limited by the lack of empirical or comparative research on the unintended consequences of AI and other innovative technologies and the lack of corporate individual digital strategies. In an early market phase, scientists are usually more familiar with the challenges of new applications than representatives from practice—due to the lack of practical experiences and users. This study designed and conducted expert interviews to investigate the status of corporate implementation of responsible digitization, get familiar with corporate practices and assess the degree of their assumption of responsibility towards the human factor. Such data are of particular interest for these scientific considerations. The reasons are diverse why experts consider recommendations and observed trends important for holistic understanding and share them in the surveys. One reason is, that the research field establishes a new territory. Only a minority of companies use BIM routinely. AI does not yet belong to daily working routine, but is often used for research purposes in test runs. Here, large companies take full advantage of their own research department in the first stages of developing new technologies having the required financial background. Thus, corporate case studies helped to analyze the niche of research by applying the qualitative, structured research methodology.

The observations made on practical applications provided adequate sources for this research. As a peripheral area, the scientific field is still new, and, at the start of this research, there was only theme-related literature in other scientific disciplines, such research design with expert interviews seemed to be the most suitable method enabling new findings such as the motivations behind the use of technologies and the ethical societal impacts. Not only can evaluations of the results of such methods critically inform tendencies, human needs, and critical reflections on which technology makes sense, but also inspire new scientific approaches. Comparisons help to draw conclusions and make final generalizations basis for formulating trends. Public hybrid conferences and joint interdisciplinary scientific studies dealing with similar research questions were used as inputs for this research. It led to mapping key factors partly transferrable to the construction industry. The validity of the results could be confirmed by the exchange with scientists.

Technical and ethical backgrounds of the study

Offray de La Mettrie [46] introduced the term "man machine" into literature, broadly seen as the earliest time using the term "AI". Charles M. Eastman has been considered a BIM pioneer since around 1970 [47]. Working with BIM results in a uniform platform with project visualization, accessible to all project participants offering efficient project life cycles and processes. The term "AI" was first used in 1956 by John McCarthy, and other scientists for the first AI conference [48], who defined it as "the science and technology of creating intelligent machines" and "the science of making machines do things that would require intelligence if done by a human". A number of ethical guidelines have been published in recent years, but as normative recommendations aimed at exploiting the "disruptive" potential of new AI technologies. However, this research found that especially in the Construction Industry, ethics and values are key to maintaining a "healthy", sustainable machine-human interaction.

Technology is not value-free. Ethical, societal observations in technology are made in an interdisciplinary environment that mirrors the research question itself, based on the theories and approaches from human-technology interaction, Ethics in AI and robotics [49,50], digital and corporate ethics and philosophy. Ethical and technical perspectives enable a holistic approach to answer the research question. The following studies were very helpful in developing the CDR approach: Armin Grunwald and Hans Jonas [51-53], Technology Assessment [54], Technical Ethics [55], Value-based Engineering [56], BIM and the Digitization in Construction [57], Aristoteles and "Nicomachean Ethics" [58], Corporate Responsibility in Digital Change [59], Digital Ethics [60]. Ideally, the human-centered engineering approach helps to get to the bottom of the problem comprehensively as ethical, societal, and democratic values are the pivotal point of sustainability of all concerned fields of digital transformation. The research's new findings led to a joint study with the Fraunhofer IAO Stuttgart [61]. The "*Excellence Initiative for Sustainable, Human-Led AI in Construction*" was founded in 2020 to give the research field a name and promote its expansion [62].

The study transferred reflections of Ethicists and Philosophers onto the branch and—with similar assessments shared by Nothelle-Wildfeuer [63]—demonstrates the practice-orientation. Moreover, this research builds bridges between Engineering and Ethics.

3. Methodology

3.1 Data collection

The lack of research, application and users of AI in civil engineering, which is rather limited compared with other industry branches, represents additional challenges [64-65]. In early market phases, scientists assess new technologies and methods' opportunities differently than practitioners. With the start of this research in 2019, comparative research in other disciplines was limited [66]. AI research in AEC, being still in its infancy, offers very few empirical values from research and even less from application. Thus, an existing data set cannot be assessed as part of a quantitative method. Moreover, such evaluation would lead to insufficient analysis of the status quo, solution approaches and trends. With this open challenge itself requiring a "next generation" research method mutual dependencies between human and digital transformation enable the access to new knowledge. Furthermore, the focus of this research is on applied sciences without deriving a theoretical model. With the objective to define gaps in the body of knowledge and identify future research trends, such a method is the most effective approach. It assesses the recent methods to evaluate the tendencies of suitable applied methods in this field [67-72]. This study applied expert interview surveys, direct observations and a literature analysis. The literature review supported to summarize existing research in closely related fields of interest [73-74]. It provided a conceptual framework facilitating direct future work to deepen research [75].

An additional challenge consists in the branch's structure and traditional behavior: This requires particularly close practical and corporate culture relevance, tailored to the typically small-scale Construction Industry. Current performed research on CDR in other fields such as Business Ethics [76-77], Communication and Media Ethics [78], Finance [79], Digital Ethics [80] and Information Communication and Technology (ICT) [81] do not provide an adequate understanding of CDR transferrable to Construction.

3.2 Expert interviews

The interviewed experts' familiarity with AI in Construction as well as with ethics, their corporate role, or in digital fields, research, development, and education, and their knowledge of processes, decision-making structures and tendencies were selection criteria for identifying and recruiting them for participating in the study. Both this chosen process and involving cross-discipline expertise led to new empirical values. These were evaluated against the background of explicitly stated criteria, such as the compatibility with social values and sustainability. Following the hermeneutic approach [82], expert surveys were developed and conducted to obtain more discussions on emerging technologies. Questions on how they define their digital strategy and to which degree they assume societal, political, environmental and digital responsibilities were included. Holistic approaches were derived contributing to the CDR concept. For systematically generating data, information was obtained about the current status of corporate implementation of technological innovations and the degree of success. In this scientific investigation, the is of particular interest. This applies to corporate experts' knowledge of management, project and decision-making processes and structures. The interviewees' shared knowledge makes up the majority of interview responses. and helped to identify impacts on people and society, to derive concrete constructive approaches. This research required some deviation from applying only one method for generating data thoroughly in this early phase of technical innovations [83-85]. A mix of qualitative methods emerged as the most beneficial methodical approach [86-87]. To relate it to the anticipated outcomes [88] and allocate the question of research in this niche, broad data were collected to define fields of problems. The applied method has been discussed in detail in a former article by the authors in this journal [89]. For an extract of the main expert interview questions, reference is made to the same publication.

The high degree of open design for the interviews and focus on practical aspects was another benefit [90]. Fifty expert interview surveys as part of the applied qualitative method were conducted over a period from 2019 to 2021 with a response rate of 90% by selected national and international experts from areas of innovation and digitization. Representatives of Engineering Associations, newly formed corporate and governmental departments for digital transformation, academic institutions, and Ethics and AI Institutes. The young age of the interviewees, between 30 to 45 years old, academically trained in new innovative fields of Engineering and IT mirrors the early phases of AI and digitization. Focus was put on 20 AI and ethics experts and 30 representatives from politics and business. The main research question guided the design of the interview survey questions. The questionnaire was developed along the main fields of interest: Digitization, AI, ethical observations, standards and guidelines, the potential of new technologies, corporate behavior regarding innovation, responsibilities, limits of new technologies and curricula. The focus was on the motives and expectations of the respondents. The interviewees' responses to further improve the structure of the questionnaire and sharpen some questions.

The evaluation was carried out as a summary content analysis [91] following an inductive procedure to draw a general conclusion [92]. The interview responses were documented in writing. Selected text passages were assigned to different categories, e.g., the interviewee's branch, role, qualification and technologies (e.g., AI, BIM, digital methods, others). These were split into subcategories: status of R & D (individual corporate timelines), innovation, practical experiences, expectations and trends. The collected data was reflected, and the content was analyzed [93]. Connections and similarities between the determined data were analyzed based on an interpretative evaluation following the hermeneutic approach [94-95]. A prescript and postscript were created to match pre-interview expectations with received responses. Similar results were obtained when the interviews were repeated with similar questions.

The study's analysis of recurring, particularly concise statements resulted in a very practical-oriented approach to defining key factors enabling human and digital transformation and needs for action. The study gained deep insights into critical reflections on allocated fields of responsibilities [96]. With the help of corporate and group comparisons, similarities and differences between individual respondents could be worked out, and final generalizations could be derived [97]. An important aspect of the success of the interviews was the simplicity and clarity of the survey, the results were easy to evaluate, data analysis was very straightforward, and the costs were relatively low.

3.3 Literature and data analysis

To identify existing AI applications and digital methods, their potential and impacts, database queries were run on Scopus, Google Scholar and WebofScience. Directly ranging from 1960 to 2023 modern AI research can be traced to the 1950s [98]. Over 60% of AI application research in Construction was done in the last decade [64]. **Figure 2** contains additional literature references which are listed separately from the general literature appendix in order to ensure that this presentation is self-explanatory. The inclusion criteria consisted of selecting publications based on abstract, title or full-text articles delivering values of experience in the applied areas in Construction. The research process included the definition of a database, the definition of review inclusion criteria and search parameters, the definition of the review exclusion criteria and content analysis. Databases with broad coverage of relevant academic articles were selected. The search terms "Construction", "Corporate Digital Responsibility", "Digital Twin", "AI", "BIM", "Innovation", "Smart Cities", "Smart Buildings", "Metaverse", "Augmented Reality", "Virtual Reality", "Ethics", "Responsible Digitization", "Value" and "Moral" were used to establish the conceptual boundaries of the review. Each article (article, conference paper, or review) should contain at least one search term. It finally led to selected literature dedicated to assessing innovative technologies' practical applications, impacts and existing cultural boundaries that both reduce the will to innovate and, thus, hinder the adoption in corporate environments. Cross discipline literature nourished new knowledge of the societal, ethical reflections on new technologies applied in Construction [99-101]. Filtering was done excluding literature not part of the fields of Engineering, digital transformation, ethics, technology ethics, or not written in English or German. The second criterion was the removal of articles in which the search terms only appeared in the references section. With a group of philosophers, theologians, ethicists, technology assessment experts and experts from the fields of AEC—only a few in this technical conservative industry were open for ethical, value-based reflections—the research started mapping out the terrain and debating the approach to a conceptual framework for the new field "Ethics in AI in Construction" anchoring the Construction branch in the general scientific debate on trustworthy AI. A start of this progress has been made, as an Internet search in this field results in the publications of the author appearing immediately. Other resulting literature sources are either dedicated only to certain areas or too far from the subject.

This led the research to identify the research gaps through best practice use cases. Following Kitchenham [102], real-life experiences and observations provide adequate resources to meet the study's objectives.

4. Results and discussion

4.1 Results

This method helped to best allocate the CDR approach in construction but is subject to certain limitations. It was not always possible to classify answers in one category. Another limitation is that the results are derived from the perspectives of the 50 respondents. Different results could have been achieved by a study with a larger group of interviewees. The interviewees' statements were repeated very quickly, and let us conclude that a theoretical saturation was reached, thus, a larger sample would not have significantly influenced the results. Each potential review topic was discussed, and a feasible or not feasible responding approach was determined.

Determining the topic to be feasible depended on the setup of this research in Civil Engineering, and the availability of high-quality first-hand practical expertise. Some investigated areas needed further modification, e.g., adjustments to education and curricula, diversity and inclusion, digital infrastructure and customized digital strategies in relation to the size of the company. Feasible topics met all outlined criteria, e.g., SDGs, societal and human values. There are sufficient studies in other disciplines to justify the review in Construction and make a novel contribution without replicating an existing review. With its strengths and limitations, the research shapes a transparent, structured process with given key factors, in this CDR policy framework. Its implementation offers orientation to define a corporate digital strategy and catalyze responsible digital innovation towards reducing the environmental footprint of construction infrastructure, its energy usage and overall environmental sustainability. CDR aims to engage stakeholders and decision-makers in order to successfully master human and digital transformation in the branch. However, the approach of CDR recognizes the identified field of tension between expectations and fears facing new technologies (**Figure 3**) and specifically aims to allocate the requirements of the Construction branch, thus, the process may not be generalizable to other disciplines.

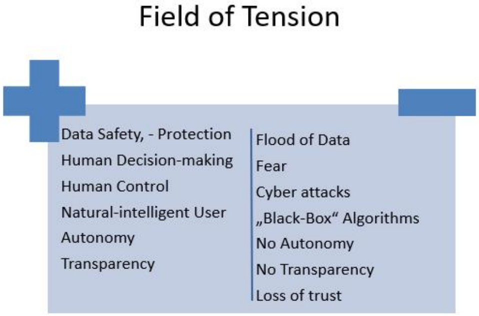


Figure 3. Field of tension.

Source: Bianca Weber-Lewerenz.

Modifications of the processes of digital and human transformation aim to improve sustainability. In order to keep the approach manageable this research used only one round of interviews and preliminary searches. Hence, some uncertainty about the evidence base for the different topics remains; feasibility can only be estimated based on available research. Furthermore, the selected stakeholders were limited to a small number of Best Practices considered as leaders in researching innovative technology. A broader panel of stakeholders would have likely provided additional input. Finally, as outlined, all described key elements were set against national and global strategy papers, political and societal initiatives compounding the challenges of providing timely systematic reviews for practitioners and policymakers.

This primary research is a transparent, structured approach to identify and prioritize a comprehensive CDR policy framework customized in construction strengthening the value-based corporate digital strategy (**Figure 4**). The study identified key factors catalyzing profitability, efficiency and safety in a branch that lacks the will to innovate, qualified personnel, and has limited access to new knowledge.

Joint interdisciplinary scientific studies and co-authoring themed books gave access to new sources dealing with similar research questions. The research findings gained with greater reliance on the qualitative aspect underpinned by interpretation, significantly supplemented the current state of research and enhanced the broader discourse. The exchange with experts confirmed the validity of the results as unchanged at any time.

Some scientists therefore assume that this research will play a leading role [103]. Disciplines like medicine, law, information and communications technology (ICT) [104], social sciences, theology, ethics and philosophy recognized that discussing emerging technologies from a cross-disciplinary perspective is a prerequisite to conducting scientific holistic research. The research critically argues that technology's social and ethical impacts [105] have been neglected and now, with new technologies, need more attention to recognize the impacts of corporate cultural change in engineering and increase the will to innovate are prerequisites for resilience, agility and growth of companies [106]. With this research Civil Engineers made ethical, social and legal observations in the context of digital transformation in Construction towards a new way from the technical perspective to philosophically question the branch's rapid technical innovations recognizing long-term effects on humans and society, adding to the increasing pressure to assume responsibility. The survey inspires to companies practice-oriented solutions to move the branch's innovation forward. Interviewees from science and practice emphasized the need for bringing together the three correlating aspects "construction—new technologies—human factor" as the most productive and favorable approach to ensure the most success-critical factors of trust and knowledge. A professor of social psychology claims that many managers believe that human capital talk is psychotic nonsense. Others see that creativity, motivation and innovation are only possible through the involvement of employees and a corporate culture that relies on partnership and ethically oriented leadership [107]. This underlines the research's findings as the technological change in society has severe impacts on the change in economic value relevance. The increasing

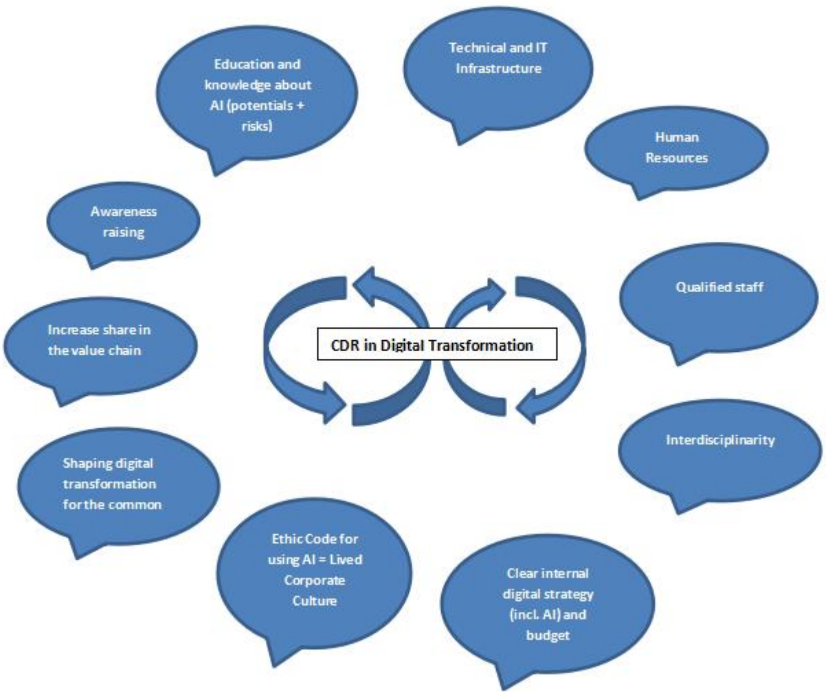


Figure 4. Key factors of CDR in digital transformation in Construction.

Source: Bianca Weber-Lewerenz.

importance of people as the core resource in the corporate value chain is positively recognizable. The voluntary corporate communication of intangible values in annual reports could strengthen the assumption of corporate responsibility. The CDR concept supports such a confidence-building approach. Adding value requires creating value, and vice versa. Transferred to the context of digital transformation, maintaining value-based engineering, which is the core of the new standard IEEE 7000-2021 [108], represents an asset. One, that creates new measurable profit and transparency on how and where one must invest in the human resource in order to create such assets and to responsibly shape technical and human change. Thus, CDR aims to practice a credible partnership of ethics (humans) and AI (technology) and increase their human capital index. Recognizing the unequally fast-growing technological development, evaluating the status quo demonstrates the increasing importance of such an approach [109] requiring further research. These principles are expected to be taken up by legislators and those who set the standards. When assessing the future viability of companies, intangible assets and human capital have gained importance. Reputation, innovative strength and competitiveness, know-how and competence, diversity, equal opportunities, inclusion and integrity are considered as indicators of how the company assumes digital responsibility in dealing with fundamental human rights, its environmental footprint and sustainability. It is an indicator of entrepreneurial success far beyond capital and profits. Particularly in times of crisis, it becomes apparent who successfully masters these challenges and can rely on innovative entrepreneurial skills. Two figures point out some areas from the perspective of the interviewees: **Figure 5** shows the result, when discussing technological feasibility, and **Figure 6** shows allocating limitations and ethical observations. Expectations of technological progress and research are high, and so is the related human need for orientation.

As a result of the evaluated interview surveys, the following indicators for embedding AI in Construction could be summarized. They show a general idea of the interviewees' allocated positive impacts of AI in the construction branch, against the status quo that only a small part of them actually develop, apply or deal with another form of AI.

Figure 5. Digital transformation in Construction.

Source: Bianca Weber-Lewerenz (created by Word Cloud).

Figure 6. Discussing limitations and ethical observations in Construction.

Source: Bianca Weber-Lewerenz (created by Word Cloud).

The indicators for embedding AI in Construction are diverse and complex:

- Minimize errors where people fail,
- Structured data complexity,
- Routine and standardized machine processes,
- Increase Cost and Time efficiency towards sustainable, responsible resource management,
- Increase knowledge and communication,
- Increase safety, transparency and quality of Construction,
- Monitor climate targets,
- Achieve SDGs,
- Increase new job profiles,
- Increase efficiency and attractiveness through innovation,
- Increase the branch's reputation,
- High social contribution to the change towards a climate-friendly society.

The evaluation concluded that the protection of values and human rights can only be guaranteed and the human, technology and society interactions broadly accessed by the CDR policy framework, beyond voluntary commitments and guidelines. CDR is anchored in knowledge, trust and transparency with implications for value-based decision-making, and societal and environmental sustainable innovation strategies promoting responsible practices in Construction. Drawing the comparison that digital twins' simulation of buildings or smart cities means simulating human-oriented living and working environments [110] clarifies that social, societal, and cultural aspects beyond technical feasibility need attention. The research was able to refute the hypothesis that only software developers can supply data for the development of algorithms for AI applications in Construction. Expert interviews indicated that the industry itself can supply useful data. Although some interviewees perceive AI as "far away" from the branch and argue on the uniqueness of each project, ethical and moral aspects of technical innovation imply the increasing societal and environmental responsibilities of the branch.

4.2 Discussion

Recognizing the availability of new digital methods and AI tools to enlarge data networks, such technologies foot on recent fields of application. The newly won experiences enable to research its new potentials such as collaborative design, new business models and broadening CDR. These may finally lead to achieving SDGs, efficiency and high quality in more agile, resilient environments (**Figure 7**).

In the context of technical decision-making processes interviewees stress the complexity of weighing up potential and damage. However, applying innovative digital technologies responsibly means increasing the efficiency, profitability and safety of project life cycles. The CDR approach provides an orientation for a new culture of learning and thinking in corporate environments guided by ethical principles. One may critically argue that the discussion is not reserved for one discipline which would hinder the inclusive, diverse, agile working environment that companies expect in order to master the challenges. Corporate responsibility is increasingly influ-

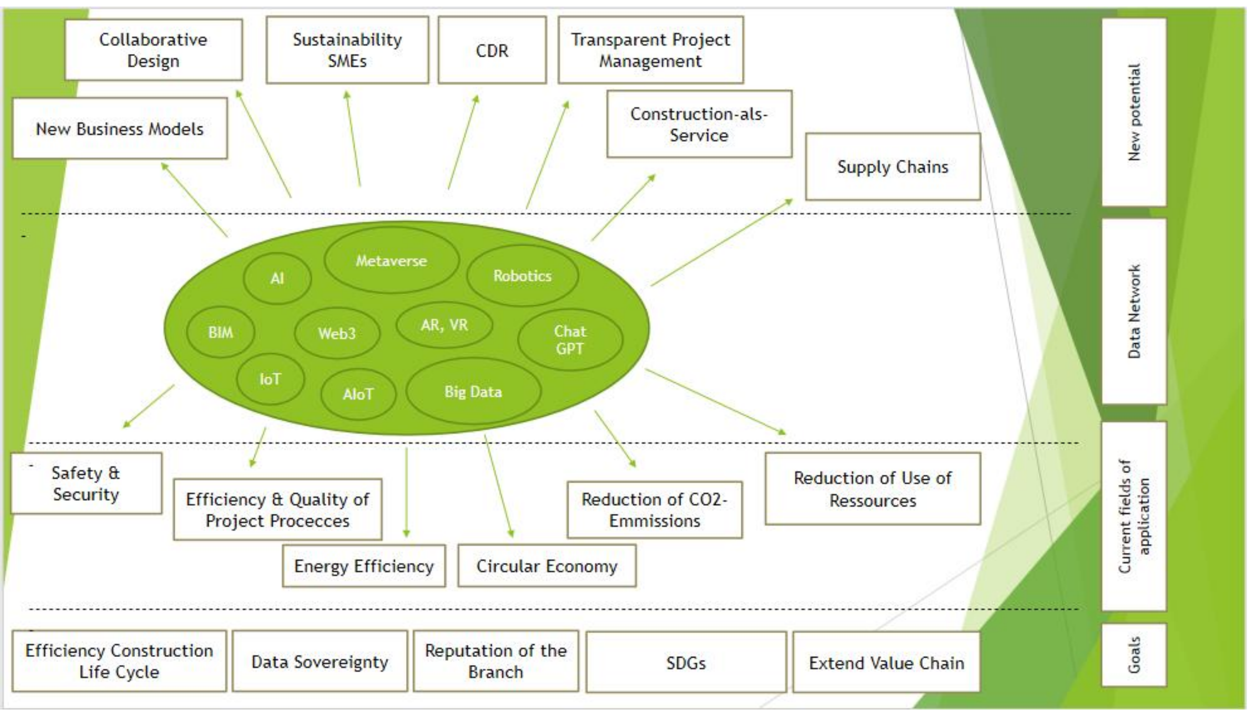


Figure 7. Data network value chain in Construction.

Source: Bianca Weber-Lewerenz.

enced by societal expectations to reach political, environmental, climate and sustainability goals. Some interviewees argue that ethics and value guidelines already exist. However, the research found that like the complexity of technical feasibility and its impacts on ethical orientation is subject to continuous change. The interview results put focus on the needs and hurdles in the Construction Industry:

- Value-based research and development and the sensible use of innovative technologies.
- CDR communication of ethics without language barriers.
- CDR as a living corporate culture.

Technical progress affects fundamental rights, human rights, occupational safety, data protection and data security in different ways. New measures apply to ensure security, data protection and transparency. Therefore, it is important to emphasize that AI in Construction helps solve many problems, but does not create new problems if risks are taken into account. This research's new insights help to break down prejudices and reservations.

This research lays the groundwork in Civil Engineering for researching new value-based approaches for achieving the UN SDGs and improving the branch's reputation. The interviewees noted technical innovation and adequate qualification are the pillars of success and sustainability. Despite ample interdisciplinary research, the discourse in the branch is still hesitant. However, this work recognizes the biggest limitations: AI is in its early development stage with rare experiences only available in a few large companies. The quantity of interviewed experts was small at the stage of conducting the interviews. Ethical observations could only be made outside of the Construction discipline, with Ethicists, Philosophers and social scientists, who are not familiar with the Construction branch. The majority of large and SMEs are still unable to handle projects consistently digitally though the pandemic proved that resilience and flexibility are key for being able to work without significant interruptions.

As the research deepens, the central question remains: How shall a framework of corporate digital responsibility (CDR) be designed to support ethical digital innovation in Construction? The result is that there cannot be one uniform framework applied to the branch, but instead CDR enhances individual corporate strategies with legal, educational, and societal guidelines. There are no quantitative systematic studies on this subject that target classifying the main characteristics of studies published in the literature. In addition, almost every scientific field individually and independently research sets its own standards. The Construction Industry still remains largely passive. Though Digital Twins and AI have been developed, there are no experiences with predictive methods increasing time and cost efficiencies, productivity, quality of construction, energy management and environmental protection. In recent years, ethical standards have been developed listing principles that technology developers should adhere to whenever possible and ensure corporate governance and compliance. However, do these ethical guidelines answer the new questions arising from developing and implementing technical innovation? Do these have an impact on assuming responsibility in the field of AI in Construction? The short answer is no. This research recommends potential fields of needed legal regulations as part of the CDR Policy framework to assume responsibility as a branch, as the EU Commission is striving for with the Digital Innovation Agenda 2022 [111], the Strategic Foresight 2022 [112] and the Task Force for Digital Common Goods [113]. The research finds that digital self-determination is increasingly considered as a task for the entire legal system to protect personal and project-related data and avoid data misuse. Thus, clarification is crucial to establish criminal law enforceable regulations as to who, where, for what and to what extent bears rights and obligations and is liable in case of disregard. In Germany there are no uniform standards regarding digital technologies and clients' and contractors' methods differ from project to project. Thus, faster problem solving cannot be achieved. To overcome these obstacles, accelerate digital transformation, create more jobs in innovative technology areas and increase cost and resource efficiency in the construction lifecycle it is important to understand the impacts of and setting up adapted legislation: Legal certainty in AEC drives innovation and sustainability in equal measure. The study suggests setting a milestone with CDR that catalyzes efficient life cycles of buildings and improves ecological footprints [114].

According to Kiron, corporate digital responsibility is supported by a lived culture of values guided by ethical principles, but they are only used to a limited extent [115]. Value-based decision-making processes in corporate culture should be institutionalized globally [116]. The cultivation of a dynamic, agile, open and innovative corporate culture strengthens curiosity for additional knowledge, for constant innovation. The study's ethical observations are consistent with the views of the experts interviewed, but reveal broader ethical implications. Since the branch plays a crucial role in achieving the SDGs, the study goes a step further. It questions the existing legal framework, which is not in line with today's technical feasibility and is not in line with human, social and environmental values, but in particular, it establishes the direct link between the efficiency of the Construction Industry, building and material life cycles and the overall impact on people, society and environment. CDR represents the essential value-oriented orientation necessary for promoting a sustainable ecosystem in the digital age. The key is the sensible use of AI and the capture of company values (human, knowledge, innovation, share of added value to the society), and not the use of technology for the sake of technical progress and, as was the case for a long time, not purely profit-oriented. Therefore, a new thinking culture is required. If company management trains new technologies, communicates opportunities and risks and acts value-based, it generates new value and motivates new innovation. It lays fertile ground to use innovation for competitiveness and growth and to accelerate the achievement of the SDGs. The conclusion can be drawn, that the design of the societal, social, ethical and legal framework affects the overall dynamic of industry and society as a whole. The CDR approach in Construction 4.0 shifts focus from technical design to human, societal responsibility. It anchors the Civil Engineering discipline in the global "Ethics in AI" debate. It considers trustworthy AI and adjusted curricula as the most success-critical pillars of sustainable human and digital transformation. The research's approaches go beyond previous scientific investigations on general morals and values in digitization and define new fields of research. Due to the interdisciplinary exchange and the necessary close cooperation at interfaces, the otherwise usual disciplinary boundaries are no longer applicable. The human, social gain can now be presented even more transparently, as human values enable innovation and sustainable business growth in the Construction Industry.

5. Conclusions

The following key points emerged from the expert interviews, the literature analysis and the development of the CDR concept. The study found that trustworthy, responsibly used AI empowers human and technical innovation. Hence, this CDR policy framework has the transformative potential to drive ethical and responsible digital transformation in the Construction Industry. In fact, this research has practical implications for the Construction Industry and beyond, as it catalyses the transfer of knowledge into the application as well as the education sector and provides the key elements of practical expertise. It represents a value chain itself. The study's results support the need for the applied CDR. It strengthens resilient, agile and sustainable ecosystems that are not only limited to corporate environments but also serve to align decision-making and innovation with the common good. This CDR concept pursues a long-term strategy towards guiding the people shaping Construction with value-based reflections in dealing with modern technologies and the associated transformation processes. The constant cross-disciplinary search for new, innovative approaches remains the core of expanding this scientific niche. The methodical approach revealed practical corporate pioneers in the Construction Industry. However, the complexity of technical feasibility, data security and protection of social and human values can only be dealt with sustainably with the help of ethical and legal orientation. To cope with changed corporate environments and job profiles the study recommends adapting curricula and rebooting ethics education. The construction industry could set a milestone with an innovative agenda and take credit for its entrepreneurial, social, legal and political responsibility.

Further in-depth research is recommended in the field of data sovereignty, human rights and diversity, and trust in technical innovation. The suggested CDR concept could elevate the branch to the next higher level of shaping sustainable ecosystems.

A novelty with this study is that for the first time ethical, societal observations in dealing with Digitization and AI are made, unexpectedly, from a civil engineer's perspective, but Complementing interdisciplinary discussion on technologies impacts. The growing awareness in the construction branch on innovations, new knowledge and the fact that the human factor is critical for utmost orientation and confidence-building measures, turned out to be the pivotal point of a sustainable digital transformation.

Author Contributions

This research article has been conceptualized and written by Bianca Weber-Lewerenz, supervised and reviewed by Prof. Marzia Traverso (Ph.D.). Both authors have done revisions of the draft.

Conflict of Interest

The authors declare having no conflict of interest.

Ethical Statement

The first author of this study conducts external research, is company-independent and is not financially supported by third-party funds, companies or other institutions. This enables neutral, critical, and inclusive research and promotion of ethical debate about AI technologies.

Funding

This research received no external funding.

Acknowledgement

The authors appreciate all of the interviewees, expertise shared with this research, sharing the vision of the "Excellence Initiative for Sustainable, human-led AI in Construction" and moving digital innovations forward. Statistics and reports were of great support with data and facts to underline the statements and recommendations made in this paper. Some public statements, which come from the internet, literature and archive research, also underline the quality and statistical values of the expertise and survey values obtained.

References

[1] Kohnke, O., 2017. It's not just about technology: The people side of digitization. Shaping the digital enterprise. Springer Publishing: Berlin. pp. 69-91.
DOI: https://doi.org/10.1007/978-3-319-40967-2_3

[2] Lehmann, A., Zschieschang, E., Traverso, M., et al., 2013. Social aspects for sustainability assessment of technologies—challenges for social life cycle assessment (SLCA). The International Journal of Life Cycle Assessment. 18, 1581-1592.
DOI: https://doi.org/10.1007/s11367-013-0594-0

[3] McAleenan, P., 2020. Moral responsibility and action in the use of artificial intelligence in construction. Proceedings of the Institution of Civil Engineers-Management, Procurement and Law. 173(4), 166-174.
DOI: https://doi.org/10.1680/jmapl.19.00056

[4] Veluwenkamp, H., van den Hoven, J., 2023. Design for values and conceptual engineering. Ethics and Information Technology. 25(1), 2.
DOI: https://doi.org/10.1007/s10676-022-09675-6

[5] Murtagh, N., Scott, L., Fan, J., 2020. Sustainable and resilient construction: Current status and future challenges. Journal of Cleaner Production. 268, 122264.
DOI: https://doi.org/10.1016/j.jclepro.2020.122264

[6] Young, D., Panthi, K., Noor, O., 2021. Challeng-

es involved in adopting BIM on the construction jobsite. EPiC Series in Built Environment. 2, 302-310.

[7] Kamat, V.R., Martinez, J.C., 2001. Visualizing simulated construction operations in 3D. Journal of Computing in Civil Engineering. 15(4), 329-337.
DOI: https://doi.org/10.1061/(ASCE)0887-3801(2001)15:4(329)

[8] Chan, A.P., Ma, X., Yi, W., et al., 2018. Critical review of studies on building information modeling (BIM) in project management. Frontiers of Engineering Management. 5(3), 394-406.
DOI: https://doi.org/10.15302/J-FEM-2018203

[9] Abioye, S.O., Oyedele, L.O., Akanbi, L., et al., 2021. Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. Journal of Building Engineering. 44, 103299.
DOI: https://doi.org/10.1016/j.jobe.2021.103299

[10] Hossain, M.U., Ng, S.T., Antwi-Afari, P., et al., 2020. Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. Renewable and Sustainable Energy Reviews. 130, 109948.
DOI: https://doi.org/10.1016/j.rser.2020.109948

[11] Thonipara, A. et al., 2020. Digitalisierung im Handwerk—ein Forschungsüberblick, No. 36, Göttinger Beiträge zur Handwerksforschung (German) [Digitization in crafts—a research overview, No. 36, Göttingen Contributions to Crafts Research] [Internet]. Economic Institute for SMEs and Crafts at the University of Göttingen (ifh) [cited 2023 Aug 17]. Available from: https://www.econstor.eu/bitstream/10419/235251/1/1761153927.pdf

[12] Cataldo, I., Banaitis, A., Samadhiya, A., et al., 2022. Sustainable supply chain management in construction: An exploratory review for future research. Journal of Civil Engineering and Management. 28(7), 536-553.
DOI: https://doi.org/10.3846/jcem.2022.17202

[13] Lai, X., Liu, J., Georgiev, G., 2016. Low carbon technology integration innovation assessment index review based on rough set theory—an evidence from construction industry in China. Journal of Cleaner Production. 126, 88-96.
DOI: https://doi.org/10.1016/j.jclepro.2016.03.035

[14] Ortiz, O., Castells, F., Sonnemann, G., 2009. Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials. 23(1), 28-39.
DOI: https://doi.org/10.1016/j.conbuildmat.2007.11.012

[15] Centobelli, P., Cerchione, R., Ertz, M., et al., 2023. What we learn is what we earn from sustainable and circular construction. Journal of Cleaner Production. 382, 135183.
DOI: https://doi.org/10.1016/j.jclepro.2022.135183

[16] Nikas, A., Poulymenakou, A., Kriaris, P., 2007. Investigating antecedents and drivers affecting the adoption of collaboration technologies in the construction industry. Automation in Construction. 16(5), 632-641.
DOI: https://doi.org/10.1016/j.autcon.2006.10.003

[17] Rogerson, S., 2022. Ethical digital technology in practice. CRC Press: Boca Raton.

[18] Franklin, U.M., 1999. The real world of technology. House of Anansi Press: Toronto.

[19] Barratt, J., 2007. Design for an ageing society. Gerontechnology. 6(4), 188-189.
DOI: https://doi.org/10.4017/gt.2007.06.04.002.00

[20] Hofstadler, C., Motzko, C., 2021. Agile digitalisierung im baubetrieb: Grundlagen, in-novationen, disruptionen und best practices (German) [Agile digitization in construction: Basics, innovations, disruptions and best practices]. Springer Publishing: Wiesbaden.
DOI: https://doi.org/10.1007/978-3-658-34107-7

[21] Liu, J., Wu, P., Jiang, Y., et al., 2021. Explore potential barriers of applying circular economy in construction and demolition waste recycling. Journal of Cleaner Production. 326, 129400.
DOI: https://doi.org/10.1016/j.jclepro.2021.129400

[22] Organization for Economic Co-operation and Development (OECD) AI Principles [Internet]. OECD; 2023 [cited 2023 Aug 17]. Available from: https://www.oecd.ai/en/dashboards/ai-principles

[23] Weber-Lewerenz, B., 2022. Accents of added value in Construction 4.0—Ethical observations in digitization and AI. Springer Nature Publishing: Wiesbaden.
DOI: https://doi.org/10.1007/978-3-658-39407-3

[24] Ethics Council: Artificial Intelligence Must not Diminish Human Flourishing [Internet]. German National Ethics Council; 2023 [cited 2023 Aug 17]. Available from: https://www.ethikrat.org/en/press-releases/press-releases/2023/ethics-council-artificial-intelligence-must-not-diminish-human-flourishing/

[25] Pause Giant AI Experiments: An Open Letter [Internet]. Future of Life Institute; 2023 [cited 2023 Aug 17]. Available from: https://www.futureoflife.org/open-letter/pause-giant-ai-experiments

[26] Rogerson, S., 2021. Rebooting Ethics Education in the Digital Age [Internet]. Academia Letter [cited 2023 Aug 17]. Available from: https://www.academia.edu/44986988/Rebooting_ethics_education_in_the_digital_age

[27] Blundell, B.G., 2020. Ethics & Lifelong Learning. Itnow. 62(4), 22-23.

[28] Shen, L.Y., Tam, V.W., Tam, L., et al., 2010. Project feasibility study: The key to successful implementation of sustainable and socially responsible construction management practice. Journal of Cleaner Production. 18(3), 254-259.
DOI: https://doi.org/10.1016/j.jclepro.2009.10.014

[29] Lima, L., Trindade, E., Alencar, L., et al., 2021. Sustainability in the construction industry: A systematic review of the literature. Journal of Cleaner Production. 289, 125730.
DOI: https://doi.org/10.1016/j.jclepro.2020.125730

[30] Araujo, A.G., Carneiro, A.M.P., Palha, R.P., 2020. Sustainable construction management: A systematic review of the literature with meta-analysis. Journal of Cleaner Production. 256, 120350.
DOI: https://doi.org/10.1016/j.jclepro.2020.120350

[31] Backes, J.G., Traverso, M., 2021. Life cycle sustainability assessment—a survey based potential future development for implementation and interpretation. Sustainability. 13(24), 13688.
DOI: https://doi.org/10.3390/su132413688

[32] Artificial Intelligence in Construction Market to Reach $4.51 Billion by 2026 [Internet]. Construction News; 2019 [cited 2023 Aug 17]. Available from: https://www.forconstructionpros.com/latest-news/news/21080665/artificial-intelligence-ai-in-construction-market-to-reach-451-billion-by-2026

[33] Kamat, V.R., Martinez, J.C., 2002. Scene graph and frame update algorithms for smooth and scalable 3D visualization of simulated construction operations. Computer-Aided Civil and Infrastructure Engineering. 17(4), 228-245.
DOI: https://doi.org/10.1111/1467-8667.00272

[34] Chau, K.W., Cao, Y., Anson, M., et al., 2003. Application of data warehouse and decision support system in construction management. Automation in Construction. 12(2), 213-224.
DOI: https://doi.org/10.1016/S0926-5805(02)00087-0

[35] Castro-Lacouture, D., Skibniewski, M.J., 2003. Applicability of e-Work models for the automation of construction materials management systems. Production Planning & Control. 14(8), 789-797.
DOI: https://doi.org/10.1080/09537280310001647869

[36] Delgado, J.M.D., Oyedele, L., Ajayi, A., et al., 2019. Robotics and automated systems in construction: Understanding industry-specific challenges for adoption. Journal of Building Engineering. 26, 100868.
DOI: https://doi.org/10.1016/j.jobe.2019.100868

[37] Bock, T., 2015. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. Automation in Construction. 59, 113-121.
DOI: https://doi.org/10.1016/j.autcon.2015.07.022

[38] Bilal, M., Oyedele, L.O., Qadir, J., et al., 2016. Big Data in the construction industry: A review of present status, opportunities, and future trends. Advanced Engineering Informatics. 30(3), 500-521.
DOI: https://doi.org/10.1016/j.aei.2016.07.001

[39] Gomez-Trujillo, A.M., Gonzalez-Perez, M.A., 2021. Digital transformation as a strategy to reach sustainability. Smart and Sustainable Built Environment. 11(4), 1137-1162.
DOI: https://doi.org/10.1108/SASBE-01-2021-0011

[40] Nikmehr, B., Hosseini, M.R., Martek, I., et al., 2021. Digitalization as a strategic means of achieving sustainable efficiencies in construction management: A critical review. Sustainability. 13(9), 5040.
DOI: https://doi.org/10.3390/su13095040

[41] Prebanić, K.R., Vukomanović, M., 2021. Realizing the need for digital transformation of stakeholder management: A systematic review in the construction industry. Sustainability. 13(22), 12690.
DOI: https://doi.org/10.3390/su132212690

[42] Alencar, M.H., Priori Jr, L., Alencar, L.H., 2017. Structuring objectives based on value-focused thinking methodology: Creating alternatives for sustainability in the built environment. Journal of Cleaner Production. 156, 62-73.
DOI: https://doi.org/10.1016/j.jclepro.2017.03.221

[43] Weber-Lewerenz, B., 2021. Corporate digital responsibility (CDR) in construction engineering—ethical guidelines for the application of digital transformation and artificial intelligence (AI) in user practice. SN Applied Sciences. 3, 1-25.
DOI: https://doi.org/10.1007/s42452-021-04776-1

[44] Data Ethic Commission of German Government, 2019. Assessment on data ethic. Brandenburg University: Berlin.

[45] The Pontifical Academy for Life in Rom, 2020. Rome Call for AI Ethics. Rome, 1st Edition, 28 February 2020. Available from: https://www.romecall.org/the-call/#:~:text=The%20call%20%7C%20Rome%20Call&text=The%20Call%20for%20AI%20Ethics,ethical%20approach%20to%20artificial%20intelligence.

[46] Offray de La Mettrie. J., 1748. Der Mensch eine maschine (German) [L'Homme machine]. Reclams Universal-Bibliothek Publishing: Ditzingen.

[47] Eastman, C., 1974. An Outline of the Building Description System [Internet]. Research Report No. 50. Available from: https://eric.ed.gov/?id=ED113833

[48] Manning, C., 2020. Artificial Intelligence Definitions [Internet]. Stanford University, Human-Centered AI [cited 2023 Aug 17]. Available from: https://hai.stanford.edu/sites/default/files/2020-09/AI-Definitions-HAI.pdf

[49] Funk, M., 2022. Roboter- und KI-Ethik als philosophische Disziplin (Bedeutung 1). Roboter- und KI-Ethik (German) [Robot and AI ethics as philosophy discipline (Meaning 1)]. Springer Vieweg Publishing: Wiesbaden.
DOI: https://doi.org/10.1007/978-3-658-34666-9_2

[50] Funk, M., 2022. Welchen Regeln und Gesetzen müssen Maschinen folgen? (Bedeutung 4). Roboter- und KI-Ethik (German) [Which rules and regulations do machines have to follow? (Meaning 4)]. Springer Vieweg Publishing: Wiesbaden.
DOI: https://doi.org/10.1007/978-3-658-34666-9_5

[51] Grunwald, A., Hillerbrand, R., 2021. Überblick über die Technikethik. Handbuch Technikethik (German) [Overview on technology ethics. Handbook technology ethics]. J.B. Metzler Publishing: Stuttgart.
DOI: https://doi.org/10.1007/978-3-476-04901-8_1

[52] Grunwald, A., 2020. Verantwortung und Technik: zum Wandel des Verantwortungsbegriffs in der Technikethik. Entgrenzte Verantwortung (German) [Responsibility and technology: To the change of the term responsibility in technology ethic. Unlimited responsibility]. Springer Publishing: Berlin, Heidelberg.
DOI: https://doi.org/10.1007/978-3-662-60564-6_13

[53] Jonas, H., 1987. Warum die Technik ein Gegenstand für die Ethik ist: fünf Gründe. Technik und Ethik (German) [Why technology is a subject for Ethics: Five reasons. Technology and Ethics]. 2, 81-91.

[54] Grunwald, A., 2010. Technikfolgenabschätzung: Eine Einführung (Vol. 1) (German) [Technology assessment: An introduction (Vol.1)]. Sigma

Publishing: Kanagawa.
[55] Holz, H.H., Hubig, C., 2013. Technik-und Wissenschaftsethik. Ein Leitfaden, 1993. Nachdenken über Technik (German) [Technology and science ethics. A Guide, 1993. Reflection on technology]. Nomos Verlagsgesellschaft mbH & Co. KG Publishing: Baden-Baden. pp. 449-454.
[56] Hubig, C., Reidel, J., 2003. Ethische Ingenieurverantwortung. Handlungsspielräume und Perspektiven der Kodifizierung.(Gemany) [Ethical responsibility in engineering. Scope for action and perspectives of codification]. Berlin: edition sigma
[57] Blankenbach, J., Becker, R., 2020. BIM und die Digitalisierung im Bauwesen. Handbuch Industrie 4.0: Recht, Technik, Gesellschaft (German) [BIM and digitization in construction. Handbook Industry 4.0: Law, technology and society]. Springer Publishing: Berlin, Heidelberg. DOI: https://doi.org/10.1007/978-3-662-58474-3_40
[58] Lockwood, T. C., 2005. A Topical Bibliography of Scholarship on Aristotle's Nicomachean Ethics: 1880 to 2004. Journal of philosophical research. 30, 1-116. DOI: https://doi.org/10.5840/jpr20053048
[59] Unternehmensverantwortung im digitalen Wandel Ein Debattenbeitrag zu (German) [Corporate Digital Responsibility] [Internet]. Available from: https://www.bertelsmann-stiftung.de/fileadmin/files/user_upload/UN_Verantwortung_im_digitalen_Wandel.pdf
[60] Spiekermann, S., 2021. Value-based Engineering: Prinzipien und Motivation für bessere IT-Systeme (German) [Value-based engineering: Principles and motivation for better IT systems]. Informatik Spektrum, 44(4), 247-256. DOI: https://doi.org/10.1007/s00287-021-01378-4
[61] Giannakidis, A., Weber-Lewerenz, B., Stolze D., 2021. AI in Construction in Germany [Internet]. Study by Fraunhofer Institute Stuttgart IAO [cited 2021 Apr 17]. Available from: https://publica.fraunhofer.de/entities/publication/a3da80e4-54b7-4d15-9d84-83cb36b84bd9/details
[62] Weber-Lewerenz, B., 2020. Corporate digital responsibility in construction engineering: Ethical principles in dealing with digitization and AI. International Journal of Responsible Leadership and Ethical Decision-Making (IJRLEDM). 2(1), 32-49. DOI: https://doi.org/10.4018/ijrledm.2020010103
[63] Nothelle-Wildfeuer, U., 2021. Künstliche Intelligenz (KI/AI)—eine Herausforderung für die Ethik. Personen gestalten Institutionen—Institutionen prägen Personen (German) [Artificial Intelligence AI—A Challenge for Ethics. People shape institutions—institutions shape people]. Friedrich Pustet Publishing: Regensburg. pp. 225-241.
[64] Regona, M., Yigitcanlar, T., Xia, B., et al., 2022. Opportunities and adoption challenges of AI in the construction industry: A PRISMA review. Journal of Open Innovation: Technology, Market, and Complexity. 8(1), 45. DOI: https://doi.org/10.3390/joitmc8010045
[65] Javed, A.A., Pan, W., Chen, L., et al., 2018. A systemic exploration of drivers for and constraints on construction productivity enhancement. Built Environment Project and Asset Management. 8(3), 239-252. DOI: https://doi.org/10.1108/BEPAM-10-2017-0099
[66] Lobschat, L., Mueller, B., Eggers, F., et al., 2021. Corporate digital responsibility. Journal of Business Research. 122, 875-888. DOI: https://doi.org/10.1016/j.jbusres.2019.10.006
[67] McGowan, J., Sampson, M., 2005. Systematic reviews need systematic searchers. Journal of the Medical Library Association. 93(1), 74.
[68] Olanipekun, A.O., Sutrisna, M., 2021. Facilitating digital transformation in construction—a systematic review of the current state of the art. Frontiers in Built Environment. 7, 660758. DOI: https://doi.org/10.3389/fbuil.2021.660758
[69] Oesterreich, T.D., Teuteberg, F., 2016. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. Computers in Industry. 83, 121-139.

DOI: https://doi.org/10.1016/j.compind.2016.09.006

[70] Pan, M., Linner, T., Pan, W., et al., 2020. Structuring the context for construction robot development through integrated scenario approach. Automation in Construction. 114, 103174.
DOI: https://doi.org/10.1016/j.autcon.2020.103174

[71] Opoku, D.G.J., Perera, S., Osei-Kyei, R., et al., 2023. Barriers to the adoption of digital twin in the construction industry: A literature review. Journal of Informatics. 10(1), 14.
DOI: https://doi.org/10.3390/informatics10010014

[72] Kor, M., Yitmen, I., Alizadehsalehi, S., 2023. An investigation for integration of deep learning and digital twins towards Construction 4.0. Smart and Sustainable Built Environment. 12(3), 461-487.
DOI: https://doi.org/10.1108/SASBE-08-2021-0148

[73] Papadonikolaki, E., Krystallis, I., Morgan, B., 2020. Digital Transformation in Construction-Systematic Literature Review of Evolving Concepts [Internet]. Proceedings of the Engineering Project Organization Conference (EPOC) 2020. Engineering Project Organization Society (EPOS) [cited 2023 Aug 17]. Available from: https://discovery.ucl.ac.uk/id/eprint/10113245

[74] Maskuriy, R., Selamat, A., Ali, K.N., et al., 2019. Industry 4.0 for the construction industry—how ready is the industry? Applied Sciences. 9(14), 2819.
DOI: https://doi.org/10.3390/app9142819

[75] Torraco, R.J., 2016. Writing integrative literature reviews: Using the past and present to explore the future. Human Resource Development Review. 15(4), 404-428.
DOI: https://doi.org/10.1177/1534484316671606

[76] Mihale-Wilson, C., Hinz, O., van der Aalst, W., et al., 2022. Corporate digital responsibility: Relevance and opportunities for business and information systems engineering. Business & Information Systems Engineering. 64(2), 127-132.
DOI: https://doi.org/10.1007/s12599-022-00746-y

[77] Dörr, S., 2021. Go for impact! Show effectiveness. Corporate digital responsibility. Springer: Berlin. pp. 171-180.
DOI: https://doi.org/10.1007/978-3-662-63853-8_6

[78] Filipovic, A., Altmeppen, K.D., 2019. Corporate digital responsibility. Zur Verantwortung von Medienunternehmen in digitalen Zeiten (German) [Corporate digital responsibility. Responsibilities of media corporates in the digital age]. Journal of Communicatio Socialis. 52(2).
DOI: https://doi.org/10.5771/0010-3497-2019-2-202

[79] Merbecks, U., 2023. Corporate digital responsibility (CDR) in Germany: Background and first empirical evidence from DAX 30 companies in 2020. Journal of Business Economics. 1-25.
DOI: https://doi.org/10.1007/s11573-023-01148-6

[80] Spiekermann, S., 2022. Digitale Ethik und die Künstliche Intelligenz. Philosophisches Handbuch Künstliche Intelligenz (German) [Digital ethics and AI. Philosophical handbook AI]. Springer Publishing: Wiesbaden. pp. 1-24.

[81] Jones, P., Wynn, M.G., 2023. Artificial intelligence and corporate digital responsibility. Journal of Artificial Intelligence, Machine Learning and Data Science. 1(2), 50-58.

[82] McCaffrey, G., Raffin-Bouchal, S., Moules, N.J., 2012. Hermeneutics as research approach: A reappraisal. International Journal of Qualitative Methods. 11(3), 214-229.
DOI: https://doi.org/10.1177/160940691201100303

[83] Johnson, R.B., Onwuegbuzie, A.J., Turner, L.A., 2007. Toward a definition of mixed methods research. Journal of Mixed Methods Research. 1(2), 112-133.
DOI: https://doi.org/10.1177/1558689806298224

[84] Corbin, J., Strauss, A., 1998. Basics of qualitative research: Techniques and procedures for developing grounded theory. Sage Publications: Thousand Oaks.

[85] Creswell, J.W., Poth, C.N., 2016. Qualitative inquiry and research design: Choosing among five approaches. Sage Publications: Thousand Oaks.

[86] Jamshed, S., 2014. Qualitative research method-interviewing and observation. Journal of Basic and Clinical Pharmacy. 5(4), 87.

DOI: https://doi.org/10.4103/0976-0105.141942

[87] Buckley, J.W., Buckley, M.H., Chiang, H.F., et al., 1976. Research methodology and business decisions. National Association of Accountants: Canada.

[88] Crotty, M.J., 1998. The foundations of social research: Meaning and perspective in the research process. The foundations of social research. Sage Publications: Thousand Oaks.

[89] Weber-Lewerenz, B., Traverso, M., 2023. Best Practices in Construction 4.0—Catalysts of digital innovations (Part I). Journal of Architectural Environment & Structural Engineering Research. 6(1).
DOI: https://doi.org/10.30564/jaeser.v6i1.5362

[90] Hancock, B., Ockleford, E., Windridge, K., 2001. An introduction to qualitative research. Trent Focus Group: London.

[91] Mayring, P., 2015. Qualitative content analysis: Theoretical background and procedures. Approaches to qualitative research mathematics education. Springer Publishing: Dordrecht. pp. 365-380.

[92] Thomas, D.R., 2003. A general inductive approach for qualitative data analysis. American Journal of Evaluation. 27(2).
DOI: https://doi.org/10.1177/1098214005283748

[93] Musonda, I., Okoro, C.S., 2022. A hermeneutic research on project management approaches applied in a business process re-engineering project. Business Process Management Journal. 28(8), 66-89.
DOI: https://doi.org/10.1108/BPMJ-11-2021-0694

[94] Heckmann, F., 1992. Interpretationsregeln zur Auswertung qualitativer Interviews und sozialwissenschaftlich relevanter „Texte“. In: Hoffmeyer-Zlotnik, J.H.P. (eds) Analyse verbaler Daten (German) [Interpretation rules for evaluating qualitative interviews and social science-relevant “texts”. In: Hoffmeyer-Zlotnik, J.H.P. (edt.) Analysis of verbal data].

[95] ZUMA-Publikationen. VS Verlag für Sozialwissenschaften.
DOI: https://doi.org/10.1007/978-3-322-90092-0_6

[95] Paterson, M., Higgs, J., 2005. Using hermeneutics as a qualitative research approach in professional practice. Qualitative Report. 10(2), 339-357.

[96] Roller, M.R., Lavrakas, P.J., 2015. Applied qualitative research design: A total quality framework approach. Guilford Publications: New York.

[97] Creswell, J.W., Poth, C.N., 2016. Qualitative inquiry and research design: Choosing among five approaches. Sage Publications: Thousand Oaks.

[98] McCarthy, J., 2007. What is Artificial Intelligence? [Internet]. Available from: https://www-formal.stanford.edu/jmc/whatisai.pdf

[99] Emaminejad, N., Akhavian, R., 2022. Trustworthy AI and robotics: Implications for the AEC industry. Automation in Construction. 139, 104298.
DOI: https://doi.org/10.1016/j.autcon.2022.104298

[100] Wang, K., Guo, F., 2022. Towards sustainable development through the perspective of construction 4.0: Systematic literature review and bibliometric analysis. Buildings. 12(10), 1708.
DOI: https://doi.org/10.3390/buildings12101708

[101] Ågerfalk, P.J., Conboy, K., Crowston, K., et al., 2022. Artificial intelligence in information systems: State of the art and research roadmap. Association for Information Systems. 50(1).
DOI: https://doi.org/10.17705/1CAIS.05017

[102] Kitchenham, B., 2004. Procedures for Performing Systematic Reviews [Internet] [cited 2023 Aug 17]. Available from: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=29890a936639862f45cb9a987dd599dce9759bf5

[103] Bednárová, M., Serpeninova, Y., 2023. Corporate digital responsibility: Bibliometric landscape-chronological literature review. International Journal of Digital Accounting Research. 23, 1-18.
DOI: https://doi.org/10.4192/1577-8517-v23_1

[104] Rogerson, S., 2009. A review of information ethics. Journal of Information and Management. 30(3), 6-18.

DOI: https://doi.org/10.20627/jsim.30.3_6

[105] Sherratt, D., Rogerson, S., Fairweather, N.B., 2005. The challenge of raising ethical awareness: A case-based aiding system for use by computing and ICT students. Science and Engineering Ethics. 11, 299-315.
DOI: https://doi.org/10.1007/s11948-005-0047-7

[106] Asikhia, O., Nneji, N., Olafenwa, A., et al., 2021. Change management and organisational performance: A review of literature. International Journal of Advances in Engineering and Management. 3, 67-69.
DOI: https://doi.org/10.1108/BPMJ-11-2021-0694

[107] Leitl, M., 2007. Humankapital? (German) [Human capital?] [Internet]. Harvard Business Manager [cited 2023 Aug 17]. Available from: https://www.manager-magazin.de/tan-for/humankapital-a-8ecfb3e4-0002-0001-0000-000052601707

[108] Spiekermann, S., Winkler, T., 2022. Value-based engineering with IEEE 7000. IEEE Technology and Society Magazine. 41(3), 71-80.
DOI: https://doi.org/10.1109/MTS.2022.3197116

[109] Marrone, A., 2020. Corporate governance variables and integrated reporting. International Journal of Business and Management. 15(5), 26-36.
DOI: https://doi.org/10.5539/ijbm.v15n5p26

[110] Brilakis, I., Pan, Y.D., Borrmann, A., et al., 2019. Built Environment Digital Twinning [Internet] [cited 2023 Aug 17]. Available from: https://publications.cms.bgu.tum.de/reports/2020_Brilakis_BuiltEnvDT.pdf

[111] A New European Innovation Agenda [Internet]. European Commission; 2022. Available from: https://www.eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0332

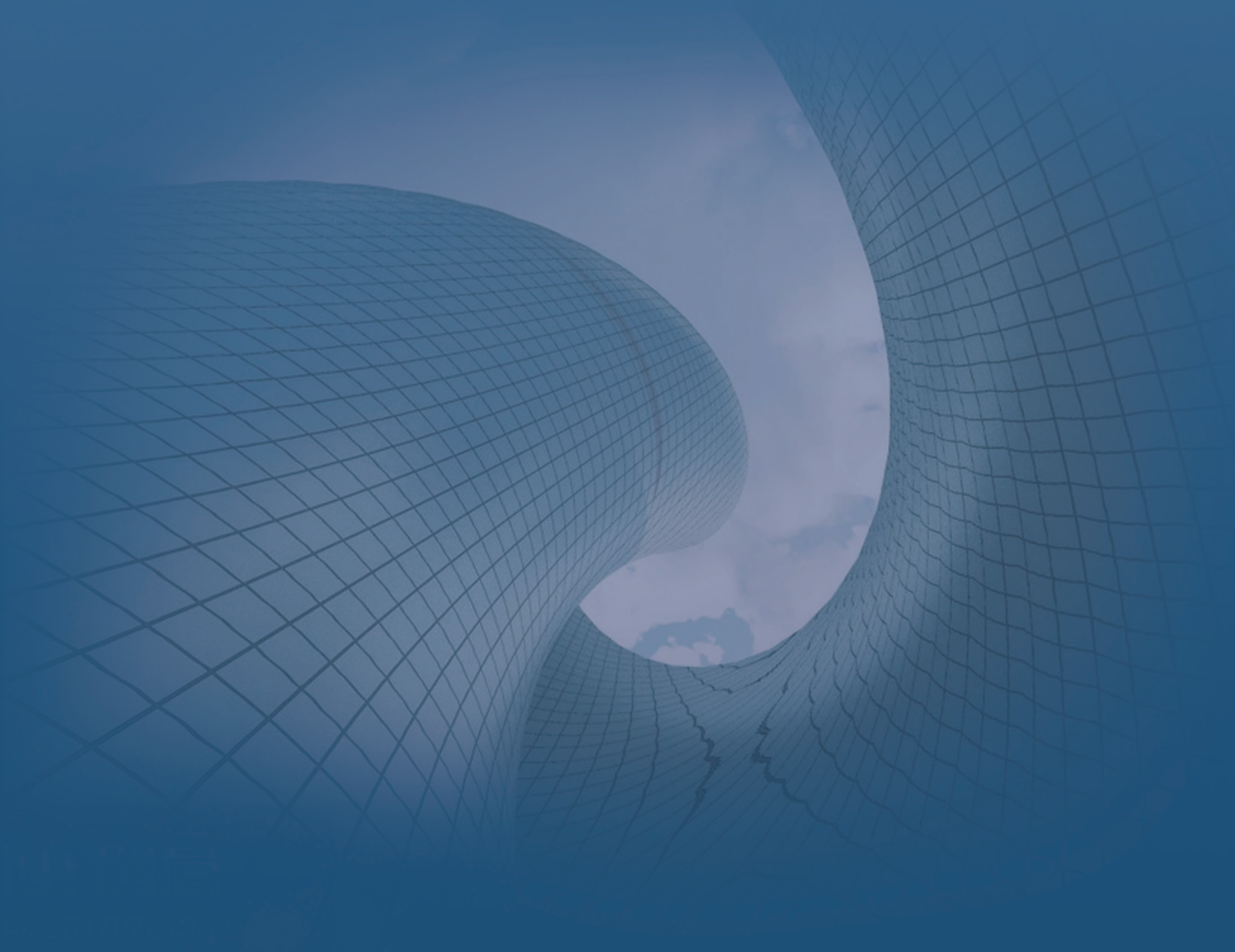
[112] A Strategic Foresight Report 2022: Twinning the Green and Digital Transitions in the New Geopolitical Context [Internet]. European Commission; 2022 [cited 2023 Aug 17]. Available from: https://www.ec.europa.eu/info/files/strategic-foresight-report-2022_en

[113] Building Europe's Digital Sovereignty Conference, 2022. Task Force on Digital Commons in 2022 [Internet] [cited 2023 Aug 17]. Available from: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3898

[114] Weber-Lewerenz, B., Vasiliu-Feltes, I., 2022. Empowering digital innovation by diverse leadership in ICT—A roadmap to a better value system in computer algorithms. Humanistic Management Journal. 7(1), 117-134.
DOI: https://doi.org/10.1007/s41463-022-00123-7

[115] Kiron, D., Kruschwitz, N., Reeves, M., et al., 2013. The benefits of sustainability-driven innovation. Own the future: 50 ways to win from the Boston Consulting Group. John Wiley & Sons: Hoboken.
DOI: https://doi.org/10.1002/9781119204084.ch15

[116] Schumacher, T., 2013. Lehrbuch der Ethik in der sozialen Arbeit (German) [Textbook on ethics in social work]. Beltz Juventa Publishing: Bad Langensalza.



BILINGUAL
PUBLISHING
GROUP

Tel:+65 65881289

E-mail: contact@bilpublishing.com

Website:https://journals.bilpubgroup.com

2630-5232