OCCUPATIONAL SAFETY AND HEALTH IN MODULAR INTEGRATED CONSTRUCTION: A SYSTEMATIC LITERATURE REVIEW

Haleh Sadeghi[1], Clara Man Cheung[2], Akilu Yunusa-Kaltungo[3] and Patrick Manu[4]

1,2 Department of Civil Engineering and Management, School of Engineering, Nancy Rothwell Building, The University of Manchester, Oxford Road, M13 9PL, Manchester, UK

3 Department of Mechanical and Aerospace Engineering, School of Engineering, Nancy Rothwell Building, The University of Manchester, Oxford Road, M13 9PL, Manchester, UK

4 School of Architecture and Environment, University of the West of England, Coldharbour Lane, BS16 1QY, Bristol, United Kingdom

Modular integrated construction (MiC) has garnered significant global interest from scholars and professionals. Despite its advantages, MiC introduces complex occupational health and safety (H&S) challenges due to its unique aspects, such as offsite manufacturing, high precision, standardisation, specialised assembly processes using cranes, and careful integration with existing structures. These complexities can lead to various H&S risks that need to be properly managed. Previous studies have explored H&S issues in MiC projects, but a systematic literature review (SLR) covering the entire lifecycle is lacking. To address this gap, an SLR using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) approach is undertaken. This review reveals various hazards across the MiC lifecycle, including health, ergonomics, machinery, falls, transportation, strikes, assembly, electrical, and design hazards as well as different types of control measures. Moreover, the corresponding future directions for research are also identified. This knowledge equips practitioners with valuable insights into potential hazards that may jeopardise workers' H&S in MiC projects, simultaneously enhancing researchers' understanding of these hazards and control measures and enriching scholarly conversations on construction safety research.

Keywords: construction safety, modular integrated construction, occupational safety and health, systematic literature review.

[1] haleh.sadeghi@manchester.ac.uk

INTRODUCTION

In the constantly changing world of construction, a wide range of technological advancements transform traditional building methods, striving to make construction work more efficient and productive. Among these innovations, MiC has emerged as a beacon of transformation, revolutionising the construction paradigm through its emphasis on modularisation and offsite assembly (Fenner et al., 2017; Wuni et al., 2022). This departure from conventional approaches entails fabricating building modules in controlled factory environments before transporting them to the construction site for assembly, promising a plethora of benefits such as cost-effectiveness, accelerated project completion, and reduced environmental impact (Lee et al., 2019; Smith, 2016).

Moreover, the momentum behind MiC continues to grow, driven by its myriad advantages over traditional methods. With a significant portion of tasks completed in controlled manufacturing environments, MiC reduces vulnerability to external influences such as weather conditions (Fard et al., 2017; Smith, 2010). Focusing primarily on manufacturing facilities not only addresses industry constraints but also capitalises on the strengths of the manufacturing sector (Gibb, 1999; Lee et al., 2019). MiC not only decreases reliance on onsite labour but also leads to shorter building times, saves energy, and improves the quality of the structures (Gibb, 1999; O'Connor et al., 2015). Additionally, the reduced exposure to external environmental factors such as rain and wind provides opportunities to reduce safety incidents in MiC (Becker et al., 2003; Braverman et al., 1997)

However, despite the expected safety advantages of MiC, data from the United States Bureau of Labor Statistics contradicts this view, revealing that higher accident rates are in modular and prefabricated buildings compared to broader construction and manufacturing sectors (Bureau of Labor Statistics, 2017). Additionally, feedback from workers involved in MiC workers suggested that there hasn't been much improvement in safety (Construction, 2011). Consequently, scholars are paying more attention to issues of MiC, focusing on managing safety risks as a key area of study (Liu et al., 2020). To tackle these challenges head-on, this paper aims to conduct a comprehensive exploration of H&S in MiC, drawing insights from existing literature with the following objectives.

- To investigate the geographical spread of scholarly articles and analyse keyword co-occurrence trends by conducting a comprehensive bibliometric review and employing scientometric methodologies.
- To extract crucial insights about H&S within MiC projects, including a detailed examination of MiC-associated H&S hazards and different types of control measures through comprehensive content analysis of relevant literature.

By shedding light on these critical aspects and providing evidence-based recommendations, this paper seeks to contribute to the ongoing discourse on H&S in MiC.

2. METHODOLOGY

To address the aforementioned gap regarding H&S in MiC, the study employs a thorough SLR method guided by the PRISMA guidelines. This approach involves defining specific keywords, selecting pertinent databases, establishing clear inclusion/exclusion criteria, and delineating a well-structured research timeline.

Adhering to the PRISMA principles outlined by Page et al. (2021), the study aims to comprehensively explore H&S in MiC as illustrated in Figure 1.

The methodology comprises several stages, including a bibliometric search, scientometric analysis, content analysis, and a discussion of identified literature gaps, along with suggestions for future research avenues.

The bibliometric search is comprised of three phases, as depicted in Figure 1. Phase one is concerned with the identification of the review keywords related to MiC, H&S, and the construction industry. In the next phase, the database is identified and the relevant literature from one of the reputable databases (i.e. Scopus) is retrieved. In Phase 3, the retrieved papers are systematically screened. This screening process initially yielded a substantial number of publications, which were 2,344 articles. After applying predefined inclusion/exclusion criteria, the number of articles was refined to 991. Following this, 111 articles directly relevant to the study's scope were identified, after eliminating duplicates and non-peer-reviewed sources, and carefully reviewing abstracts.

The next stage focuses on scientometric analysis, utilising the VOS viewer tool to visualise the distribution of articles based on study location and co-occurrence of keyword mapping.

In a subsequent stage of the methodology, content analysis was conducted to extract relevant information from the identified papers. This process utilises both qualitative and quantitative approaches, categorising data and assigning numerical values. Extracted information includes the types of H&S hazards associated with MiC projects.

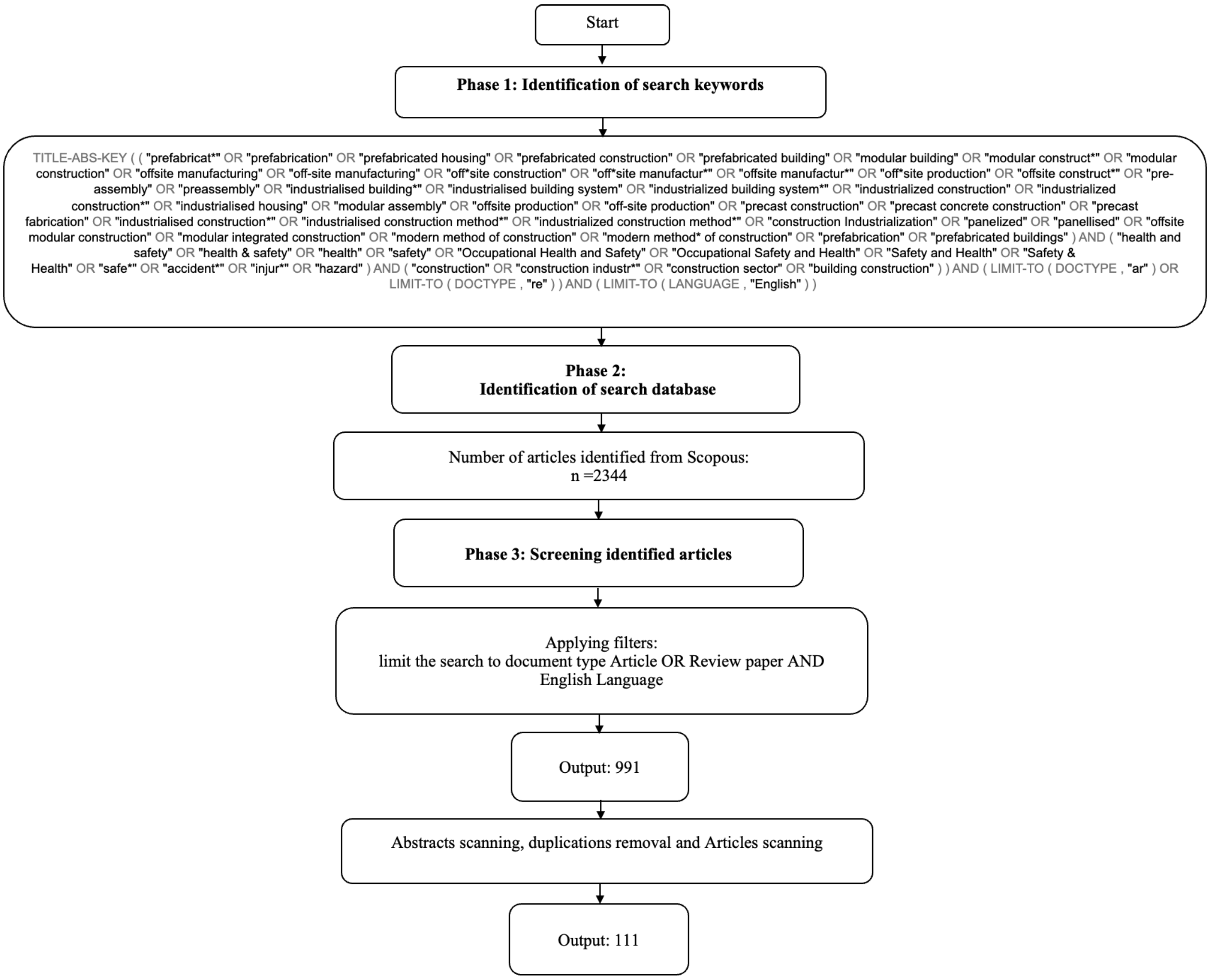

Fig. 1. PRISMA Flowchart

3. RESULT AND DISCUSSION

3.1 Scientometric analysis

The scientometric analysis is two-fold: distribution of articles by study locations; and co-occurrence of keywords analysis.

3.1.1 Analysis of the distribution of articles based on study location

The distribution of articles based on the location of the study can be seen in Figure 2. It is evident that China has the highest number of articles (i.e., 39) in the subject domain. This is followed by Australia, Canada, the United States, and Hong Kong, with 18,15,14, and 14 articles, respectively.

It's noteworthy that despite Hong Kong having the smallest population among the mentioned locations, it ranks fourth, with an equivalent number of articles in the USA. Additionally, the United Kingdom is ranked sixth with seven articles.

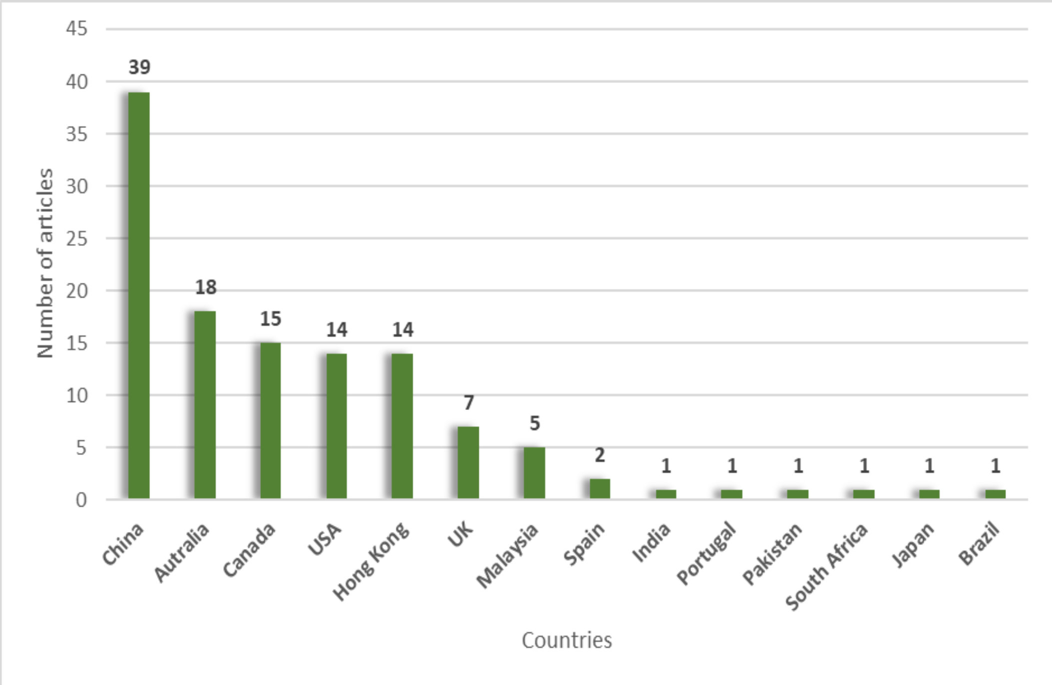

Fig. 2. Distribution of articles based on the country

3.1.2 Co-occurrence of keywords analysis

To understand how research topics are connected, evolved, and organised, an analysis of keyword co-occurrence was undertaken using VOS viewer (Owolabi et al., 2022). Keyword co-occurrence maps were generated by compiling keywords from Scopus. Determining how often keywords appear lacks standardised criteria (Khan et al., 2021; Wuni et al., 2019a). Nevertheless, this study followed the recommended methodologies outlined by Oraee et al. (2017), and Hosseini et al.(2018) for conducting keyword co-occurrence mapping. Using the fractional counting method, a total of 1102 keywords were identified. Applying a minimum co-occurrence threshold of 5, 60 keywords met this criterion. Consequently, four significant clusters of keyword co-occurrences were identified, as depicted in Figure 3, totalling 60 items and 933 links, with a combined link strength of 273.50. Larger circles in Figure 3 represent greater significance. Notably, terms such as "Construction industry," "Modular construction," "Risk assessment," and "prefabricated construction" are commonly cited in relevant literature. The size of each circle indicates how frequently the keyword appeared as an author keyword in research articles (Wuni et al., 2019b). Notably, the four distinct clusters are distinguished by different colours, indicating keywords that frequently occur together. For instance, keywords within the yellow cluster, such as risk assessment, accident prevention, occupational risks, construction safety, health risks, safety engineering, safety risks, and manufacture consistently co-occur. This understanding could help researchers select suitable keywords for their articles, thereby enhancing indexing and article retrieval. Importantly, the highly frequent co-occurring keywords correspond with those used in the literature search conducted for this study.

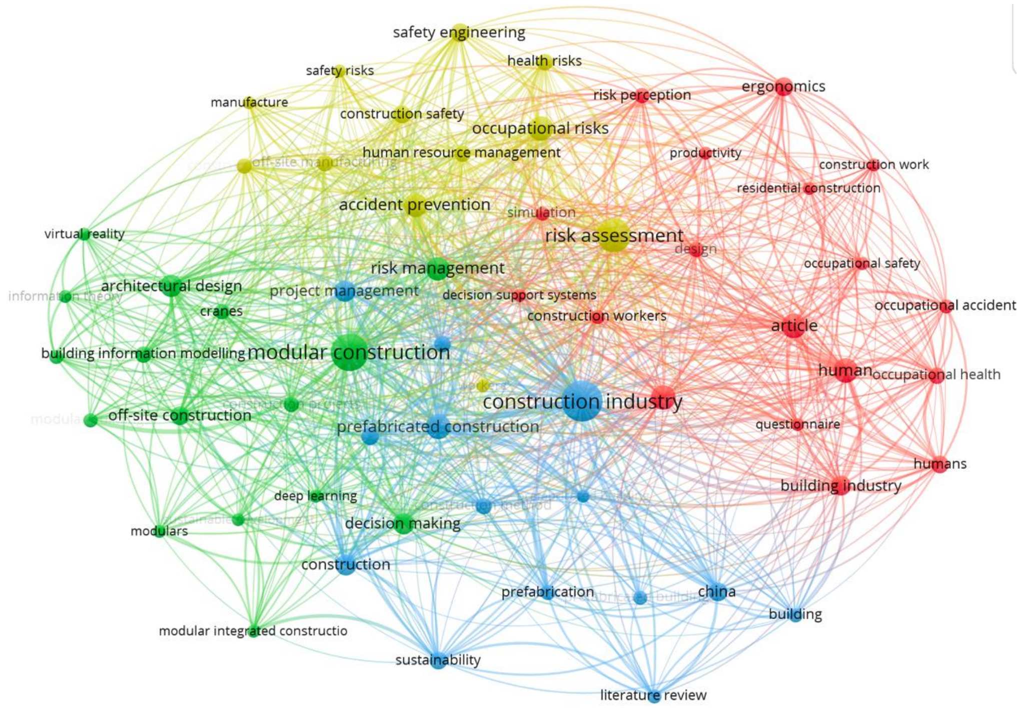

Fig. 3. Co-Occurance of keywords

3.2 Content analysis

3.2.1 H&S hazards introduced by MiC

While MiC and traditional construction pose risks to workers, MiC's hazards are typically more diverse and unique. This is mainly due to its offsite manufacturing and assembly processes. On the other hand, traditional construction hazards are more commonly linked to onsite activities.

The SLR reveals some of the hazards specifically introduced by MiC. For instance, one group of hazards caused by MiC is health hazards. Some of these hazards have been observed during the manufacturing phase, which include excessive heat in buildings, and dust exposure hazards (Li et al., 2022). Abas and Blismas, (2021) witnessed that during the manufacturing phase, workers are exposed to chemical substances while they are involved in the cleaning and oiling of moulds, as well as the application of a skim coat for component finishing. The other hazard is exposure to ultraviolet (UV) radiation due to welding during bar cutting, bar bending, mould setting, and mould dismantling. Additionally, workers are exposed to the heat from cylinder gas while setting the mould. Moreover, it is observed that workers are exposed to excessive noise as a result of screwing during bar cutting, bar bending and mould setting. Workers might also face health hazards, such as exposure to UV light from working in sunlight during the component installation phase.

Despite the prevalence of automated machinery in MiC projects, workers are often exposed to risks such as repetitive movements and uncomfortable body positions. These ergonomic hazards in MiC are significant contributors to musculoskeletal issues associated with work, including injuries and disorders affecting muscles, tendons, and nerves (Li et al., 2022). The ergonomic hazards are observed during manufacturing tasks particularly bar cutting and transportation, with a particular emphasis on loading and unloading panels. Another aspect of concern is the manual handling of heavy panels during transportation. Additionally, workers involved in concrete vibration during component production face hazards associated with vibrations (Abas and Blismas, 2021).

Equipment and machinery hazards are the other group of hazards observed in MiC projects, which encompass improper use of equipment and defective materials, cranes interfering with each other, overloading structures, absence of safety devices, and temporary site structures (e.g. shelters and temporary offices). Equipment and machinery hazards are evident across multiple phases of MiC, from manufacturing and transportation to installation, involving the use of tools such as cutting machines and cranes.

Another group of H&S hazards related to MiC projects are fall hazards that can occur due to working at height (Abas and Blismas, 2021). Falling from heights poses risks throughout various stages of modular construction, including manufacturing, transportation, and installation. Elevated platforms or unstable workspaces during the manufacturing phase lead to fall-related accidents. Loading and unloading the modules during the transportation phase and inadequate protective measures during module installation, result in frequent fall accidents (Chatzimichailidou and Ma, 2022).

Furthermore, some researchers pointed out module transportation hazards, such as unsafe loading and unloading practices (e.g., the specialised iron frame for transportation not being properly secured during loading and unloading of components), the potential for module damage during transportation, component instability during the transport and delivery of panels to the site, errors in driver behaviour, and incorrect loading of precast wall panels onto trucks (Chatzimichailidou and Ma, 2022).

As stated by Li et al. (2022), another hazard introduced by MiC is struck by an object due to the tipping of heavy machinery or equipment and the dropping of unsecured prefabricated components during the lifting process. During the installation phase, the crane boom or cables may fail, increasing the risk of accidents caused by being struck (Hu et al., 2023).

Vithanage et al. (2022) found that participation in MiC projects could lead to electricity-related hazards, such as electrocution. These hazards may arise from entangled electric cords and air hoses, contact with power lines, and involvement in tasks, including cutting, bending, and welding rebar during the manufacturing process (e.g. electric shock from welding and screw bolts while mould setting). In addition to that during component installations, workers may also experience electric shock due to the installation of bracing or propping (Abas and Blismas, 2021)

Furthermore, various researchers have highlighted a range of hazards associated with the building process and assembly, which are mostly observed during the assembly phase of MiC projects. These hazards include situations such as improper lifting methods, insufficient safety measures at construction sites, misalignment during assembly, excessive stacking of prefabricated components, and the involvement of inexperienced workers in module hoisting (Becker et al., 2003; Zhang and Pan, 2021).

The lack of attention to safety during the design phase, coupled with design inaccuracies and variations, significantly compromises the quality and safety of manufacturing, transporting, and assembling prefabricated components. This situation may give rise to various risks, including flaws in component quality and incorrect division of components. Research indicates that despite the provision of adequate on-site safety equipment, hazards associated with design flaws persist (Song et al., 2022).

After a comprehensive analysis of the literature, it becomes clear that the majority of articles emphasise health-related hazards as a significant hazard associated with MiC projects, as illustrated in Figure 4.

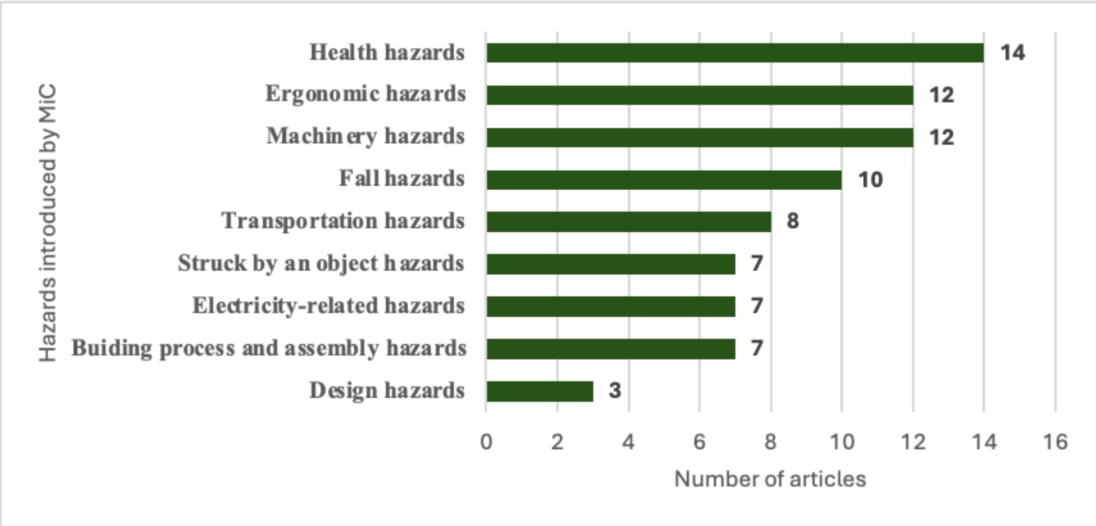

Fig. 4: Hazards introduced by MiC

3.2.2 Control measures to mitigate hazards introduced by MiC

Workers are protected by a comprehensive safety protocol involving hazard elimination, safer practices adoption, engineering controls, administrative controls, and provision of personal protective equipment in the construction industry (Nnaji and Karakhan, 2020). After delving into the body of literature, it was found that most of the studies on MiC projects emphasise administrative measures—such as managerial role modelling, regular meetings, clear communication, and video surveillance—in reducing unsafe behaviours (Lu et al., 2023). Additionally, engineering controls such as BIM-based technologies and the use of PPE for chemical and welding hazards are crucial (Shaari et al., 2016). Furthermore, the strategies focusing on hazard elimination through 3D visualisation and applying lean principles for waste reduction and efficiency enhancement further enhance safety (Han et al., 2015; Nahmens and Ikuma, 2009). Improved housekeeping practices also contribute significantly to hazard reduction (Nnaji and Karakhan, 2020).

4. LIMITATIONS AND FUTURE WORKS

The study points out several limitations that need addressing and suggests corresponding avenues for future exploration. Despite the increasing adoption of construction technology, its specific integration for safety management in MiC projects remains limited. Future inquiries could delve into innovative technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), and wearable devices to enhance safety monitoring, communication, and decision-making in MiC projects. Furthermore, the adequacy of current training programmes and competency development initiatives for MiC project workers warrants additional investigation. Subsequent studies could assess the effectiveness of training methods in preparing workers to navigate the complexities of MiC environments safely, identifying gaps and suggesting tailored training interventions. Additionally, there is a lack of structured approaches for collecting and sharing knowledge about safety and lessons learned from MiC projects. Future research endeavours could devise knowledge management frameworks and platforms to facilitate the exchange of best practices, safety innovations, and incident learning among MiC project stakeholders, thus promoting continuous improvement in safety performance. The current body of literature lacks a decision tool to deal with the safety management of MiC projects, hence there is a need to develop a safety risk management tool in future.

5. CONCLUSIONS

In summary, the examination of H&S issues in MiC projects unveils a nuanced landscape with multiple hazards associated with MiC that require adequate management. Despite the benefits associated with MiC, such as cost-effectiveness and expedited project completion, its unique processes introduce various H&S hazards for workers. These hazards arise from factors such as offsite manufacturing environments, precision and standardisation challenges, and unique assembly processes involving cranes and lifting equipment. The presence of these hazards poses threats to workers involved in MiC projects, emphasising the critical need for effective safety management. Through an SLR following the PRISMA approach, this study provides comprehensive insights into the H&S hazards throughout the lifecycle of MiC projects as well as the exploration of different control measures used for managing the hazards.

The findings highlight a range of hazards associated with MiC, encompassing health hazards from exposure to heat, chemicals, UV radiation, and noise, as well as ergonomic and equipment-related hazards. Transportation, falling, and electrical hazards also pose significant threats during different project phases. Additionally, design flaws and variations pose H&S threats across manufacturing, transportation, and assembly. With this in mind, most of the studies have identified health hazards as potential hazards associated with MiC. This is due to the unique characteristics of MiC processes, such as offsite manufacturing environments and precision challenges, which can potentially lead to various health risks for workers. Additionally, the use of different materials, equipment, and assembly methods in MiC projects may also contribute to the emergence of health hazards. Furthermore, it was found that the implementation of administrative controls is the most commonly reported control measure in literature among other types of control measures.

This study challenges the sufficiency of traditional safety management practices given MiC's unique environment and processes. By highlighting specific hazards and gaps in existing safety measures as well as providing different types of control measures, the paper calls for a reevaluation of safety measures and training programmes tailored to the needs of MiC projects.

The study's implications extend to policymakers, construction managers, safety professionals, and researchers who need to collaborate to implement the proposed recommendations.

By addressing the identified research gaps and implementing evidence-based recommendations, stakeholders can collaborate to mitigate hazards and cultivate safer working environments in MiC projects.

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