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A SYSTEMATIC REVIEW OF MATURITY MODELS ON OCCUPATIONAL SAFETY AND HEALTH, INDUSTRY 4.0 TECHNOLOGIES AND MODERN METHOD OF CONSTRUCTION

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

1 The University of Manchester, Manchester, United Kingdom, 2 The University of Manchester, Manchester, United Kingdom, 3 The University of Manchester, Manchester, United Kingdom, 4 University of the West of England, Bristol, United Kingdom

Abstract

The adoption of Industry 4.0 technologies offers considerable potential to enhance occupational safety and health (OSH) in modern methods of construction (MMC). Maturity models provide a structured approach to guide this transition effectively. Although the previous studies have focused on the development of maturity models for Industry 4.0, OSH management, and MMC, there is a lack of a comprehensive review that thoroughly evaluates and compares the existing maturity models related to Industry 4.0, OSH, and MMC. To fill the mentioned gap, a systematic literature review (SLR) was conducted following the PRISMA guidelines, which identified 30 pertinent articles from Scopus and Web of Science (WoS) databases. This SLR determined the research principle, model development method, and model structure. This state-of-the-art review offers both theoretical and practical contributions. It provides a theoretical contribution by systematically analysing maturity models associated with Industry 4.0, OSH, and MMC, highlighting existing gaps and establishing a foundation for creating a unified framework to evaluate readiness and improve safety outcomes in prefabricated construction. Regarding practical contributions, the review can pave the way for construction managers and safety officers to assess their organisations' current maturity level towards implementing Industry 4.0 technologies for improving OSH within MMC.

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Keywords: industry 4.0, maturity models, modern methods of construction, occupational safety and health, systematic literature review.

1. Introduction

The implementation of Industry 4.0 technologies, which improve efficiency, productivity, and occupational safety and health (OSH), is transforming the construction industry. MMC is at the forefront of this revolution, using prefabrication and offsite manufacturing to increase quality control, reduce waste, and shorten project schedules [1]. MMC, which is known for off-site production, industrialised construction, prefabricated construction, modular construction, and Off-Site construction, has emerged as an innovative strategy to overcome the persistent inefficiencies of traditional on-site practices [2]. Despite these developments, maintaining OSH in MMC remains a problem, since modular construction introduces new hazards associated with prefabrication, transportation, and onsite assembly [3]. The implementation of Industry 4.0 technologies has emerged as a critical solution for tackling these difficulties, allowing for real-time monitoring, predictive risk assessment, and proactive safety actions [4].

Industry 4.0 technologies such as Building Information Modelling (BIM), Digital Twin, the Internet of Things (IoT), Artificial Intelligence (AI), and Virtual Reality (VR) are increasingly being used to improve

Corresponding author email address: haleh.sadeghi@manchester.ac.uk

OSH in modular construction. These technologies provide sophisticated risk identification, automated safety compliance monitoring, and intelligent decision-making, allowing businesses to spot risks before they happen, improve worker training, and streamline safety management operations [5], [6]. IoT sensors and AI-powered safety analytics enable real-time monitoring of worker behaviour, environmental conditions, and equipment status, alerting to possible hazards. Digital Twin technology allows safety managers to simulate hazards, evaluate risk mitigation measures, and optimise actions without stopping construction processes [7], [8].

The use of Industry 4.0 technologies in MMC can result in a number of benefits for OSH management, including proactive hazard detection, safety training, remote safety monitoring, greater regulatory compliance, and fewer onsite accidents [6], [9], [10]. Companies can make more educated safety decisions and reduce human error incidences by automating safety measures and leveraging AI-driven insights [11]. Despite the obvious benefits, the adoption of Industry 4.0 solutions for OSH in modular construction is inconsistent across companies, with technological complexity, high costs, workforce resistance, and cybersecurity concerns serving as major barriers to implementation [12], [13]. Additionally, industry 4.0 technologies can also create new OSH challenges. These changes affect workplace risk variables and necessitate new safety procedures and frameworks [14], [15].

The complexities and variations in the use of Industry 4.0 technologies for OSH in MMC underscore the need for a systematic approach to assessing and guiding organisations on their digital transformation journey. Many companies struggle to assess their readiness for deploying new technologies, and they frequently lack a clear roadmap for advancement. Without a standardised framework, firms may struggle to identify the most significant areas for improvement, solve resource constraints, and ensure compliance with changing safety regulations [13], [16], [17] With this in mind, a systematic literature review on the developed maturity models in the areas of Industry 4.0 adoption, OSH management and MMC is required, which help organisations to develop their roadmap for improving their capabilities in these areas. Such a methodology would not only assist organisations in assessing their digital maturity, but would also enable policymakers, safety specialists, and construction managers to prioritise actions and investments to improve OSH performance in modular projects. This can guide them to develop a thorough assessment tool that is aligned with industry requirements, allowing for a progressive and deliberate transition to digital safety solutions [17].

This literature review seeks to critically examine and synthesise existing maturity models that explore these three areas, highlighting the research design, model development method, and models' structure. As a result, this study helps to establish an integrated maturity framework designed for the future of smart, safe, and industrialised construction.

2. Literature review

Despite the potential benefits of automation, real-time monitoring, and AI-driven risk assessment, which are core components of Industry 4.0, there is still a dearth of understanding of their long-term effects on worker safety [18], [19]. Therefore, many industries are not aware of their maturation process concerning Industry 4.0 and OHS, particularly within the context of MMC. Given that MMC is a relatively new approach, organisations face difficulties in identifying key areas for technology adoption that can enhance OHS in an increasingly digitalised construction environment [15], [20], [21]. This gap emphasises the need for adaptable models that allow firms to assess their current situation and plan for future changes, as Industry 4.0 technologies expand rapidly. Considering this, MMs can provide systematic frameworks for assessing an organisation's progress in adopting Industry 4.0 technologies for enhancing OSH in the MMC context [18], [22]–[24].

The effective implementation of Industry 4.0 technologies differs by industry, underlining the necessity for adaptive MMs that address sector-specific difficulties while adhering to OHS requirements [25]. According to research, while Industry 4.0 technologies such as AI and IoT bring new opportunities, they also introduce new hazards, necessitating continuous modifications to safety measures [22], [26]–[28]. Many conventional MMs remain stagnant, failing to keep up with technological changes and advancements. Given the quick rate of Industry 4.0 development, companies need adaptable and dynamic MMs to account for these changes [26].

Several MMs have been created expressly for safety culture assessment. Fleming and Lardner proposed a three-stage safety culture maturity model based on research conducted at an offshore operating business. This paradigm describes three levels of safety culture: dependent, independent, and interdependent [29]. Fleming later created a more complete Safety Maturity Model, which evaluates an organisation's maturity in ten areas of safety culture. These elements include managerial commitment, communications, production *vs* safety, Learning organisation, safety resources, participation, perceptions about safety, trust, individual relationships and job satisfaction [30].

Westrum's model [31] divides organisational safety culture into three stages: pathological, bureaucratic, and constructive, each representing a distinct level of information flow, problem-solving, and participation with safety standards. Hudson improved on this paradigm, dividing it into five stages, including pathological, reactive, calculative, proactive, and generative, in which safety is fully integrated into an organisation's operations [32]. Another group of researchers explained how an organisation's safety culture maturity may be measured using five important factors: information, organisational learning, involvement, communication, and commitment. These issues are handled at various degrees of maturity— pathological, reactive, bureaucratic, proactive, and sustainable — resulting in a structured framework for enhancing safety and accident prevention [24]. While these models are useful in traditional sectors, they lack the flexibility to adapt to Industry 4.0's rapidly changing technological backdrop, rendering them unsuitable for dynamic and digitised work settings in the MMC context.

In addition to safety culture models, numerous MMs evaluate Industry 4.0 maturity. The System Integration Maturity Model for Industry 4.0 (SIMMI 4.0) assesses enterprises based on four dimensions, such as vertical and horizontal integration, digital product development, and cross-sectional technology and five maturity stages, from the basic level of digitisation to fully optimised digitisation [33]. Similarly, the Acatech Maturity Assessment Guide describes six successive stages, ranging from computerisation to full adaptability, to assist firms in planning their digital transformation [18]. Additionally, Schumacher et al., [16] developed a model considering nine dimensions: strategy, leadership, customers, products, operations, culture, people, governance, and technology, with five maturity levels ranging from non-adoption to complete Industry 4.0 integration. While existing maturity models, such as the Industry 4.0 Maturity Model [16] and the Smart Modern Construction Enterprise Maturity Model (SMCeMM) [34], provide broad assessments of digital readiness, they fail to address the specific safety challenges and technological requirements of modular construction, highlighting the need for a more holistic approach.

Apart from the safety culture models and Industry 4.0 models, some models have focused on the maturity assessment of the modern method of construction. For instance, The Industrialised Construction Maturity Model (ICMM) evaluates the maturity of off-site construction projects, which has been divided into two sections: enablers (i.e. leadership, cooperation, planning, and technology) and results (i.e. product quality, societal impact, organisational performance, and project management). The model was categorised into four levels, such as initial, upgraded, integrated, and optimal, and was validated by a multi-case study of prefabricated projects in Shanghai [35]. Moreover, [20] developed an Off-site construction (OSC) readiness maturity model, which was comprised of four attributes, such as operational challenges, broad execution strategy, planning certainty, and operational efficiency and three maturity levels, including no clear application, frequent application but lack of standard practice, clear established practices and procedures. In another study, a prefabrication development maturity model was developed, which is comprised of four attributes_ Technology capability, operation management capability, sustainable construction capability, and economic capability_ and five maturity levels ranging from very low to very good [36].

While these models have evaluated the maturity of organisations related to safety culture, industry 4.0 and modern methods of construction individually, no systematic review has been conducted that integrates these three areas, resulting in a substantial gap between research and industrial practice. To close this gap, this study will conduct a systematic literature review on maturity models related to the adoption of Industry 4.0 technologies, OSH enhancement, and MMC. This review can help enterprises, policymakers, and industry stakeholders prioritise investments, optimise OSH policies, and create a safer and more technologically advanced modular construction industry.

3. Methodology

A systematic approach grounded on the PRISMA paradigm is conducted in this study in order to review the body of research on the utilisation of maturity models regarding the adoption of industry 4.0 technologies for improving OSH in MMC companies. The approach utilised in this SLR is guided by the principles outlined by Page et al., [37]. As stated by Becker et al., [38] and Hevner et al., [39], designing the Maturity Model requires a systematic approach, including comparing them with existing models and thoroughly documenting the design process [38], [39]. With this in mind, conducting an SLR is a well-suited, transparent and unbiased method for identifying the gaps [40][41]. The PRISMA method is comprised of specifying search terms, choosing pertinent databases, specifying explicit inclusion and exclusion criteria, and creating a well-organised chronology.

As depicted in Figure 1, the review is comprised of two phases. The first phase is concerned with the bibliometric search (i.e. identifying and screening the articles, verifying their eligibility and final list of records). The second phase focuses on the content analysis of the identified articles, which is comprised of research design, model development method, and existing Maturity Models' structure.

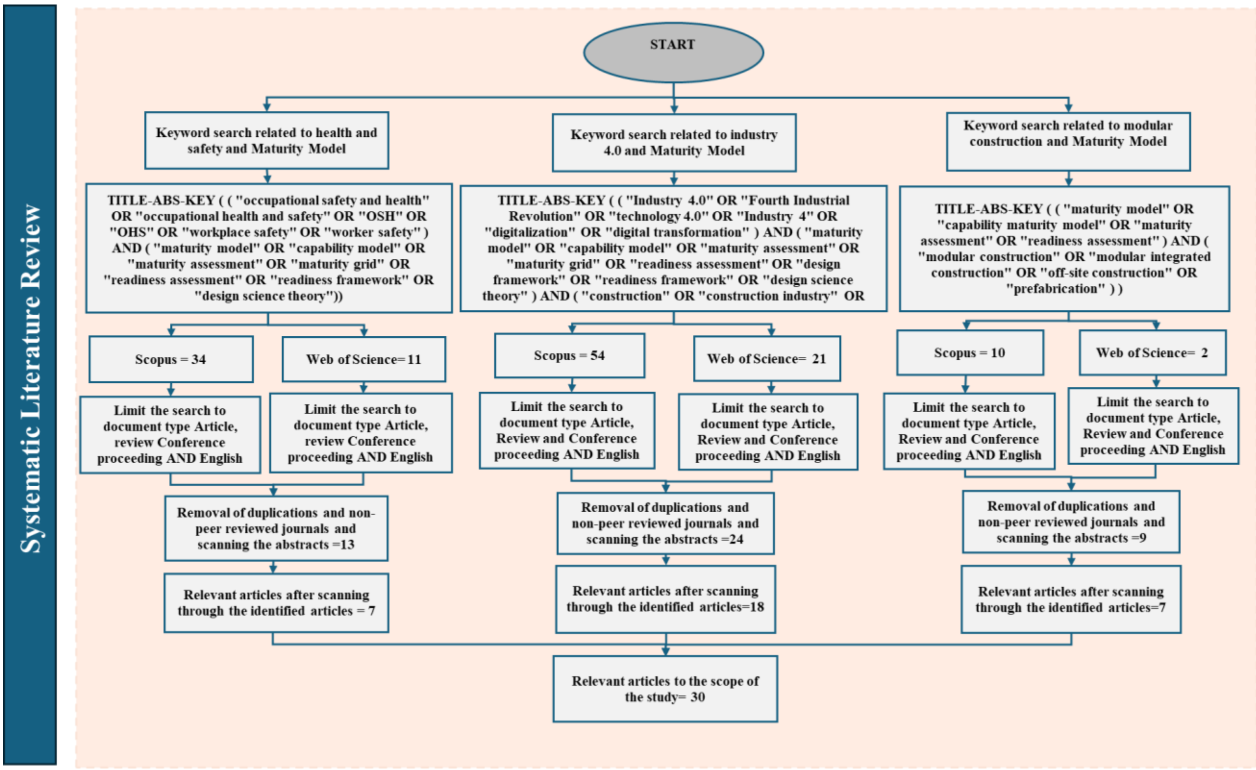

Fig. 1: Methodology Framework

3.1 Phase 1: bibliometric search

This work applied an SLR approach influenced by the PRISMA approach, which is a widely accepted methodology utilised in systematic reviews and meta-analysis studies [42]. Two leading databases, such as Scopus and Web of Science (WoB), were utilised in this study for bibliometric search due to their broad coverage, technological dependability, and diversity in fields like industrial safety, technology, and construction. Three groups of keywords are selected for the bibliometric search, as can be seen in Figure 1. One group of keywords is related to maturity models in the domain of Industry 4.0, the other one is related to the maturity models related to Occupational safety and health and the third group of keywords is concerned with MMC maturity models.

After searching the keywords related to the health and safety and maturity model, 34 studies were found in Scopus, and 11 studies were identified in WoS databases. Similarly, by searching the keywords related to Industry 4.0 and the maturity model, 54 and 21 studies were found in Scopus and WoS, respectively. Furthermore, 10 studies were found in Scopus, and two studies were identified in WoS databases after searching the keywords related to MMC and maturity models.

After applying the filters, removing the duplications and scanning through the studies for three search streams, 30 relevant studies were found, as can be seen in Figure 1.

3.2 Phase 2: content analysis

In order to systematically obtain information from the related publications in this area, this study used advanced content analysis [43]. A content analysis extracts the major features and draws meaningful conclusions from visual, audible, and written information. Content analysis might be qualitative or quantitative, depending on the study's needs [44], [45]. Furthermore, content analysis might be effective for organising information and identifying patterns and trends in texts [46]. A full-text review of each article was performed to extract relevant information. The obtained data was methodically compiled into charts to provide a structured summary of the findings. Eventually, these visual representations were employed to help identify important patterns and trends.

4. Result and discussion

4.1 Content analysis result

Content analysis was employed to explore patterns and trends in the selected articles, identifying themes, sub-themes, relationships, classifications, and comparisons [47], [48]. Articles addressing Industry 4.0 maturity models and OSH maturity models were thoroughly analysed, comparing their frameworks and models to highlight strengths, weaknesses, and any commonalities or differences. Out of 132 eligible articles, 30 articles specifically focused on Industry 4.0, OSH management or Modular construction maturity models were identified. These 30 articles were then analysed to extract the important concepts, including the Research Principle, model development method, and model structure.

4.1.1 Research design and model development method

As can be seen in Figure 2, the majority of the reviewed studies (i.e. 22 studies) adopted the design-oriented principle, while the remaining studies utilised a conceptual framework (see Figure 2). Another observation is that the methods used for the development of the maturity model in the previous studies predominantly relied on one or a combination of the following methods: SLR, comparative literature review (CLR), Interview, focus group, Delphi, MCDM methods, Bayesian and factor analysis (see Figure 3). As can be seen in Figure 3, most of the studies that have developed maturity models have conducted SLR as part of their research methodology. It was also noticed that Interviews, CLR, and MCDM methods are among the top four popular methods used as part of the maturity development methods used in this area.

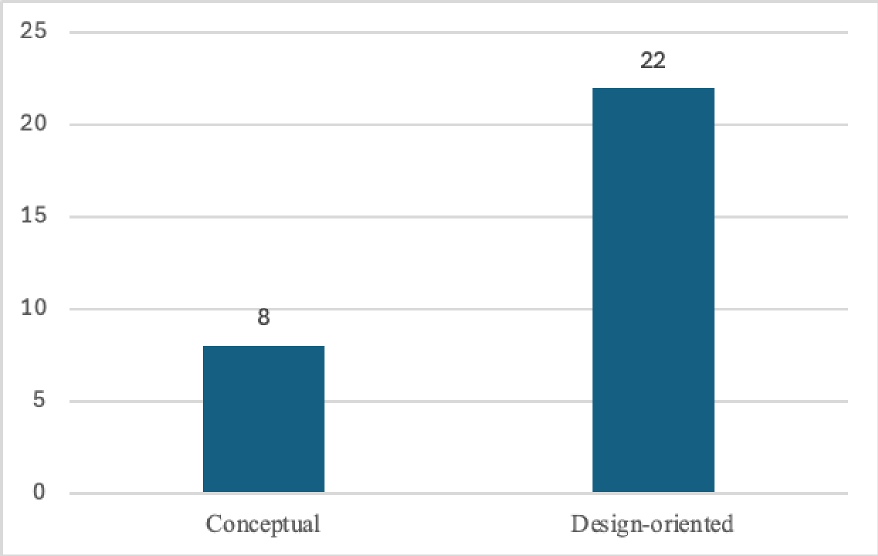

Fig. 2: Research design

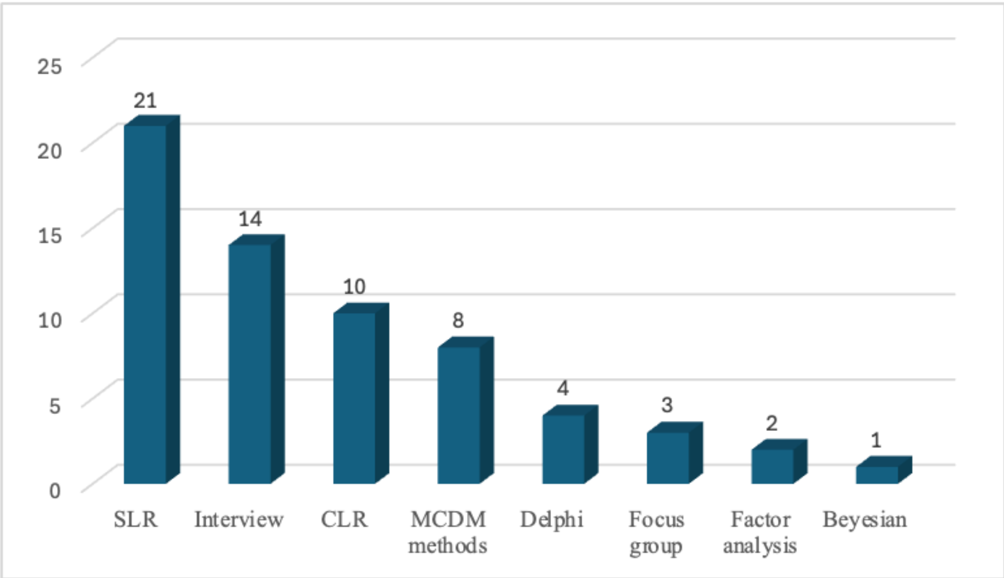

Fig. 3: Model development method

4.1.2 Existing maturity models' structure

4.1.2.1 Maturity models' application focus area and type

The type and application focus area in the previously developed maturity models have also been explored in this study. It was observed that the focus of most of the developed maturity models in this area has been on the construction industry as can be seen in Figure 4. For instance, the digital transformation maturity model (DTMAM) was developed by Han et al., [49] and Chen et al., [50] for evaluation of the maturity of the construction enterprises. Similarly, a digital construction company maturity model (DCCMM) was developed to assess the degree of digitalisation in construction companies [51]. Furthermore, another study leads to the development of the Digital Transformation Level of Readiness Framework (DTRLF) to assist construction companies in understanding the implementation of digital transformation inside their respective domains and support decision-makers in establishing action to adapt related technologies in their respective project phases [52]. In another study, a digital maturity model was applied to ship design and construction companies for progress evaluation in digital transformation [53].

Few developed maturity models have focused on small and medium enterprises (SMEs). For instance, one study conducted by Devapriya and Palliyaguru, [54] sought to pinpoint important digitisation issues pertinent to small and medium-sized construction companies and create a digitalisation maturity model fit for SMEs running in the Sri Lankan building sector, therefore enabling a means of evaluating the state of digitalisation. Some developed Maturity models have focused on general sectors, such as the safety analytics readiness assessment framework developed by Ezerins et al., [55] for assessing system readiness for improving occupational safety and health in organisations. The focus of some other maturity models was on the manufacturing enterprises; for instance, a descriptive maturity model was developed by Klötzer and Pflaum, [56] to address the digital transformation of manufacturing industry supply chains. Furthermore, very few maturity models were developed for maturity assessment in retailers [57] and service [58] industries.

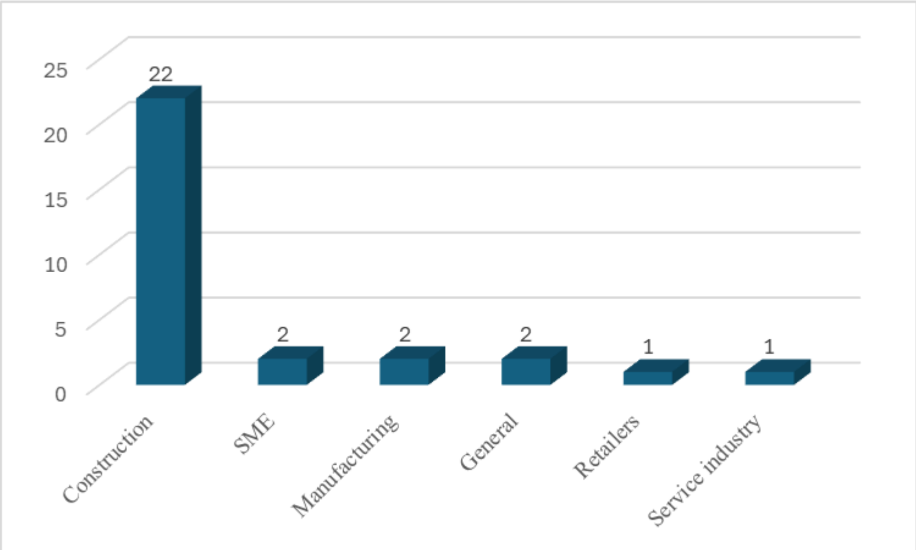

Fig. 4: Application focus area for the reviewed maturity models

4.1.2.2 Number of maturity levels and attributes of maturity models

Based on the review of the developed maturity models, it was observed that the authors had structured their maturity models using three [20], four [58], five [59], or six [50] maturity levels, as can be seen in Figure 5. Moreover, most of the maturity models developed related to the areas of OSH, modular construction, and industry 4.0 technologies have utilised five maturity levels (see Fig 5). For instance, Han et al., [49] divided organisations into five maturity stages ranging from initial to optimised, while Das et al., [59] utilised five maturity levels, such as ad-hoc, driven, transforming, integrated, and innovative for maturity model development.

As regards the attributes used in the previous maturity models, it was observed that different studies utilised different attributes based on the nature of their maturity model. For instance, most of the maturity models that have developed maturity models in this domain have included the following attributes in their studies: technology [50], [52]–[54], [60], [61], organisation [49], [50], [52], [53], [59], [60], people [59]–[61] and infrastructure [20], [23], [49], [52], [55]. These attributes might have been shown with different terminologies in different studies. For instance, Chen et al., [50] determined five attributes, such as technology, organisation, strategy, customer and product, and sustainable development for digital transformation maturity assessment. In another study, the following attributes were considered for assessing the level of digital maturity: organisation, technologies, strategies, management system, and product [53]. Furthermore, Chen et al., [62] developed a readiness model for the adoption of digital technologies in organisations by determining five dimensions, such as technology, organisation, environment, leadership, and workforce. Another study developed a capability maturity model for digital transformation in the construction industry using five critical dimensions, such as industry environment, strategy and organisation, digital infrastructure, business process and management digitisation, and digital performance [49].

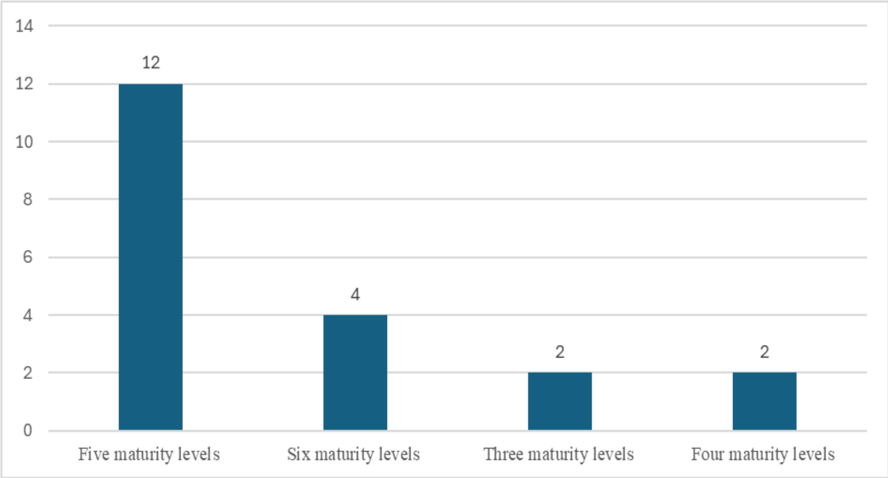

Fig. 5 Number of maturity levels

5. Conclusion

This systematic literature analysis investigated the present picture of maturity models developed for Industry 4.0 technologies, OSH management, and Modern Methods of Construction. A total of 132 relevant studies were first evaluated, with 30 studies found to be directly connected to maturity model development in the targeted areas. A rigorous content analysis revealed several critical insights into research principles, methodological approaches for model development, and model structures.

The majority of the evaluated studies followed a design-oriented research paradigm, with SLRs, interviews, CLR, and MCDM methodologies being the most widely employed methods in model creation. The developed maturity models' focus areas were mostly on the construction industry, with little attention paid to the service, and retail sectors.

In terms of structure, maturity models typically used five-level hierarchies that represented stages from initial to optimal maturity. The qualities employed differed between studies, but elements such as technology, organisation, people, and infrastructure were frequently mentioned. Notably, the language for these traits varied, highlighting the need for better standardisation and clarity in future studies.

Overall, this analysis demonstrates an increasing interest in developing maturity models to improve the adoption of Industry 4.0 technologies and safety improvements in the construction industry. Nonetheless, there is a need for validated, and context-specific frameworks that integrate Industry 4.0, OSH, and MMC. Future research should concentrate on closing methodological gaps, improving model applicability across several industries, and aligning maturity traits with real-world construction issues. A unified maturity model that incorporates Industry 4.0, OSH, and MMC might be used as a strategic tool to guide construction companies toward safer, smarter, and more sustainable practices.

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