Accident prevention in construction: an analysis of the use of digital tools for risk mitigation in the design

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Prevenção de acidentes na construção civil: uma análise da utilização de ferramentas digitais para mitigação de riscos na etapa de projeto

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Abstract

Construction is a sector characterized by a high likelihood of accidents, among the factors that have the potential to reduce such accidents, the design stage is important to reduce risks in the life cycle of the enterprise. The need to reduce risks on the construction site early and proactively has fostered the development of digital tools for designs. This study aimed to conduct a systematic review of the literature on the development and application of digital tools capable of identifying security risks in designs and examine them to point out their characteristics and limitations. The review of the literature was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement. The research showed that although the use of digital tools has great potential for impact on risk mitigation in the design stage, they are still little used and have not reached their maximum potential. In addition, this systematic review indicates possibilities of use, which include the automation of risk verification and provision of security measures, as well as limitations, as the absence of consideration of the dynamism of the work in digital tools. Therefore, the present work presents a basis to help structure future applied research in the area.
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Resumo

A construção civil é um setor que possui alto risco de acidentes, dentre os fatores que possuem potencial para reduzir tais acidentes, a etapa de projeto é importante para diminuir os riscos no ciclo de vida do empreendimento. A necessidade de reduzir riscos no canteiro de obras de forma antecipada e proativa tem fomentado o desenvolvimento de ferramentas digitais para projetos. Este estudo teve como objetivo realizar uma revisão sistemática da literatura sobre o desenvolvimento e aplicação de ferramentas digitais capazes de identificar riscos de segurança em projetos e examiná-los para apontar suas características e limitações. A revisão da literatura foi baseada na declaração Preferred Reporting Items for Systematic Reviews and Meta-Analysis. A pesquisa mostrou que embora o uso de ferramentas digitais tenha grande potencial de impacto na mitigação de riscos na fase de projeto, elas ainda são pouco utilizadas e não atingiram seu potencial máximo. Além disso, esta revisão sistemática aponta possibilidades de uso, que incluem a automatização da verificação de riscos e provisão de medidas de segurança, bem como limitações, como a ausência de consideração do dinamismo do trabalho em ferramentas digitais. Portanto, o presente trabalho apresenta uma base para ajudar a estruturar futuras pesquisas aplicadas na área.

Introduction

Civil construction is recognized as an industry with high risks, being among the most fatal accidents (LUO *et al*., 2022; NIELSEN *et al*., 2023; XIA *et al*., 2023; XU; WANG, 2023; WU *et al*., 2022). According to the Occupational Safety and Health Administration (OSHA), in 2019, 20% of deaths of private industry workers occurred in construction. Among the factors that mitigate this scenario, the design stage has the potential to avoid accidents in this sector. According to Vasconcelos (2013), at least 23.6% of occupational accidents can be avoided if safety measures are taken at the design stage. This step can help reduce accidents on the construction (COMAS, 2022; FERREIRA; AGOSTINI, 2022; RAMOS; RAMOS; LYRA, 2021; SCOPEL, 2015; VASCONCELOS; BARKOKÉBAS JUNIOR, 2015; VELOSO, DE SOUZA, 2018; YANO; DE MELO MOURA, 2021).

Prevention through Design (PtD) is considered one of the strategies against accidents, injuries and occupational diseases in construction (ABUEISHEH *et al*., 2020; ANTWI-AFARI *et al*., 2023; HU *et al*., 2023; POGHOSYAN *et al*., 2018). Eliminating risks in the planning and design phases minimizes them in construction, and the earlier they are identified, the greater the chances of controlling them. (GOLABCHI *et al*., 2018; SAMSUDIN *et al*., 2022; TYMVIOS *et al.,* 2020).

Despite recognition of the potential of PtD, its implementation in designs faces obstacles, among which are lack of awareness of PtD among designers, limited availability of PtD tools, and lack of influence or motivation of contractors (POGHOSYAN *et al*., 2018; NNAJI *et al*., 2023). Despite advances in software, other obstacles to the implementation of PtD are caused by the lack of interoperability between security management and PtD software (LI *et al*., 2022), the use of manual software interventions in most PtD tools (MALEKITABAR *et al*., 2016) and the uncertainty factors generated by the absence of the software's ability to deal with the dynamics of the work execution, products and activities (VAN DE POEL; ROBAEY, 2017).

Through literature reviews, other authors have identified gaps in knowledge and suggest that future research should consider details about the challenges, opportunities, and feasibility of PtD in relation to occupational safety and health risks (SAMSUDIN *et al*., 2022). As there is a lack of connection between digital technologies and PtD (FARGHALY *et al*., 2022b), it is crucial to identify which data can be collected in a database to facilitate communication and promote the exchange of information between PtD knowledge and software (JIN *et al*., 2022). Additionally, it is important to address questions such as what the ideal time during a project's life cycle is to use PtD and whether the use of PtD can be indicated for people without knowledge in safety and design (TYMVIOS *et al*., 2020). In this context, the objective of this study is to systematically review published research on the development and application of digital tools capable of identifying security risks in designing and examine them to point out their characteristics and limitations.

Security risks in designing

According to Barros (1996), the design, production, and assembly sector in the construction industry is divided into three subsectors. The first subsector, known as civil engineering works or heavy construction, encompasses projects involving horizontal structures. Its focus lies in the execution and installation of infrastructure intended to support other industrial sectors. Examples include urbanization works, public roads, slope stabilization, construction of bridges, viaducts, tunnels, hydraulic works, water capture, conveyance, treatment and distribution, as well as sewer network projects, among others (GALIMI *et al*., 2020; TAMOŠAITIENĖ, 2020).

The second subsector is designated as industrial assembly, responsible for assembling structures that enable industrial facilities, covering areas such as water supply, transmission and distribution of energy, mechanical and electrical structures, telecommunications systems, and metal structures (DANIELSSON; HOLM; SYBERFELDT, 2020; DROUOT *et al*., 2022; PAIVA, 2020). The third subsector, focused on building construction, stands out for its considerable heterogeneity, encompassing a greater number of concentrated projects, particularly in residential, commercial, and industrial buildings (AZEVEDO; MORAES; LIRA, 2021; DOOREN, 2020; SOUTO; CONTO, 2021; HU *et al*., 2023).

According to Vasconcelos (2013), designs can be classified into three types: conception designs, execution designs, and equipment designs. Conception designs refer to the permanent structures of a project, corresponding to architectural, structural, and facility projects (SILVA, 2021; XIE *et al*., 2022). Execution designs are based on the execution design to guide production, such as masonry designs, construction site designs, and safety designs (AKINLOLU *et al*., 2022; CALDAS; TOLEDO FILHO, 2021). Equipment projects, on the other hand, focus on the production of the project, such as machinery, cranes, and concrete mixers (PAIVA, 2020).

In the realm of conception designs, attention to safety risks emerges as a crucial component to prevent accidents and mitigate potential threats from the early stages of the process (HARDISON *et al*., 2022; ISMAIL *et al*., 2022). The literature emphasizes the importance of a thorough risk analysis from the initial conception phase, incorporating proactive measures to mitigate risks in the design (JOHANSEN; SCHULTZ; TEIZER, 2024). Various terms are used to define this strategy, such as prevention through design, safety by design, safety through design, design for safety, and safe design (OSBURN; LEE; GAMBATESE, 2022; SAMSUDIN *et al*., 2022).

The identification and analysis of safety risks in conception designs can range from vulnerabilities in architectural design to issues related to facility safety (LU *et al*., 2021). Collaboration between safety professionals and designers is crucial to integrate effective mitigation approaches from the project's inception (JIN *et al*., 2023). Thus, the incorporation of proactive safety practices not only aims to mitigate accident risks through intervention in the conception project but also reflects a commitment to sustainable and secure construction, essential aspects in an increasingly safety-sensitive contemporary scenario (JIN *et al*., 2023; KHALIL; SAMSUDIN; ZAINONABIDIN, 2022).

Materials and methods

This article was based on the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses - PRISMA statement (PAGE *et al,*. 2021). To this end, a search protocol was structured, as shown in Table 1. To help define the keywords used in the search, the PICo strategy was used (AKOBENG, 2005; AZEVEDO *et al*., 2023). The PICo strategy refers to the acronym Population, Interest, and Context. In the present study, Population has been defined as technology, method, tools, and software. Interest pertains to Prevention through Design and synonyms used in the literature. Context refers to the field of Construction.

According to PRISMA, the research was developed in three phases: identification, screening and included. In the identification phase, the keywords combined with Boolean operators "AND" and "OR" were used to define the search string: (Technology OR Method OR Tool OR Software) AND ("Prevention through Design" OR "Safety by Design" OR "Safety through Design" OR "Design for Safety" OR "Safe design") AND Construction, limiting the results to articles from primary studies published in Portuguese, English or Spanish. No temporal restrictions were applied. For the definition of databases, we sought to identify international databases that have relevance to the construction area and have journals with indexed articles, following these criteria, we adopted seven databases for research: ASCE Library, Engineering Village, Scopus, Springer Link, Taylor & Francis, Web of Science and Wiley Online Library.

In the screening phase, by reading the title and abstract of the articles on the web platform of the databases, the literature was excluded according to the exclusion criteria indicated in Table 1: do not have keywords in the title and summary of the researched literature (EC1), this criterion aims to streamline the identification of articles with clear alignment to the research focus; Studies that address theoretical methods not yet developed for use in practice (EC2) ,this criterion ensures the inclusion of literature with immediate relevance and applicability to the field, promoting the examination of tools and methods ready for implementation; Studies that specifically focus on digital tools for PtD rather than those broadly addressing human error identification (EC3) aim to narrow the research scope; And studies addressing digital risk identification tools in infrastructure construction projects (EC4), the study's primary focus is on digital tools applied in the design phase for PtD, with an emphasis on civil construction projects. Infrastructure projects, which often involve large-scale and distinct considerations, fall outside the intended scope. After that, the articles were retrieved from the databases for full reading and exclusion according to the exclusion criteria indicated in Table I: secondary or tertiary study articles (EC5), this criterion prioritizes primary studies for a more direct examination of original research contributions.

Table 1. Research Protocol. Source: The authors.

Item	Content
Objective	Conduct a systematic review on digital tools for PtD application in designs.
Key-words	Technology, Method, Tool, Software, Prevention through Design, Safety by Design, Safety through Design, Design for Safety, Safe design e Construction
Database	Engineering Village, Scopus, Web of Science, ASCE Library, Springer Link, Wiley Online Library e Taylor & Francis.
Inclusion Criteria	(IC1) Have the theme of the Development of a digital tool for PtD in the design phase.
Exclusion Criteria	(EC1) Articles that do not have the search keywords in their title or abstract; (EC2) Theoretical methods; (EC3) Digital tools for human error; (EC4) Digital tools in heavy construction design; (EC5) Articles from secondary or tertiary studies; (EC6) Articles not addressing digital tools; (EC7) Articles that do not address PtD in the design stage.
Research Questions	*What are the main features and limitations of PtD tools? *What is the most used technology for developing tools for PtD? *What improvements can be made to tools PtD? *What are the limitations and challenges related to compiling information in a database for accident prevention through the design? *What is the ideal time during the project life cycle to use PtD? *Can the use of PtD be recommended for people without knowledge in safety and design?

Articles that do not address digital tools (EC6), this criterion ensures that the selected literature contributes directly to the study's exploration of digital tools in the context of PtD; And articles that do not address PtD in the design phase (EC7), this criterion ensures that the selected literature aligns with the primary focus of the study, which is the development and application of digital tools in the design stage for safety considerations. After the screening phase, the remaining articles were included for quantitative and qualitative analysis, described in the next topics.

Results and discussion

Quantitative analysis of the results

The systematic review was conducted in November 2022. In the identification phase, 814 results were initially found, as illustrated in Figure 1. There were 98 results using the Engineering Village database, 101 in Scopus, 86 in Web of Science, 108 in ASCE Library, 159 in Springer Link, 94 in Wiley Online Library, and 168 in Taylor & Francis. Then, in the screening phase, the exclusion criteria were assigned according to the reading of the title and abstract of the articles, and all remaining articles were retrieved from the databases to apply the other exclusion criteria after the complete reading. After the screening phase, 19 articles were obtained for qualitative synthesis.

Concerning the articles included per database, Scopus, Web of Science, and Engineering Village were the primary contributors to the research literature. The Springer Link and Wiley Online Library databases were not included in the systematic review, as indicated in Figure 2. Scopus demonstrated the highest efficiency at 16.83%, leading other databases such as Web of Science (16.28%) and Engineering Village (13.27%). ASCE Library followed at 4.63%, while Taylor & Francis showed the least efficiency at 0.60%.

Most of the articles were published in Automation in Construction (5), followed by Construction Management and Economics (2), Journal of Construction Engineering and Management (2), Journal of Information Technology in Construction (2), Applied Sciences (1), Construction Economics and Building (1), Construction Innovation (1), Engineering, Construction and Architectural Management (1), Ergonomics (1), International Journal of Construction Management (1), Journal of Architectural Engineering (1) e Journal of Computing in Civil Engineering (1).

Regarding the analysis of the period of publication of the articles included in the research, indicated in Figure 3, it is possible to visualize that the first work involving the development of a digital tool for low publication rate until the last decade, where the research theme was more explored, being highlighted in the years 2020 and 2022 as a period of greater production, with three articles published in each of them.

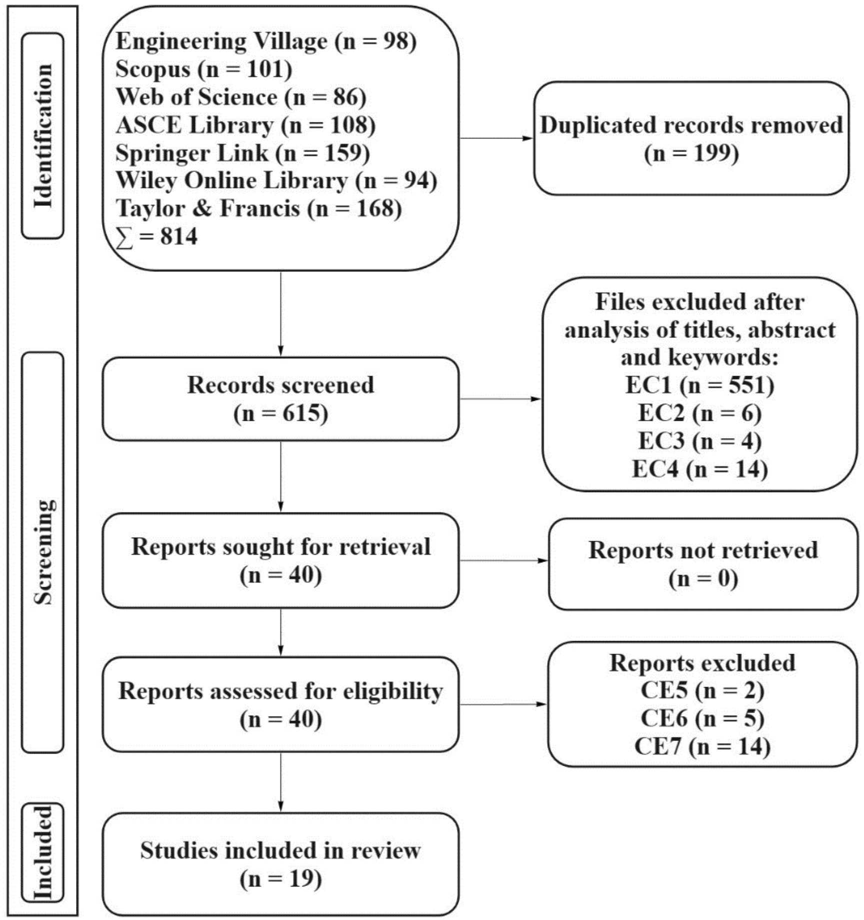

Figure 1. Fluxogram PRISMA. Source: The authors.

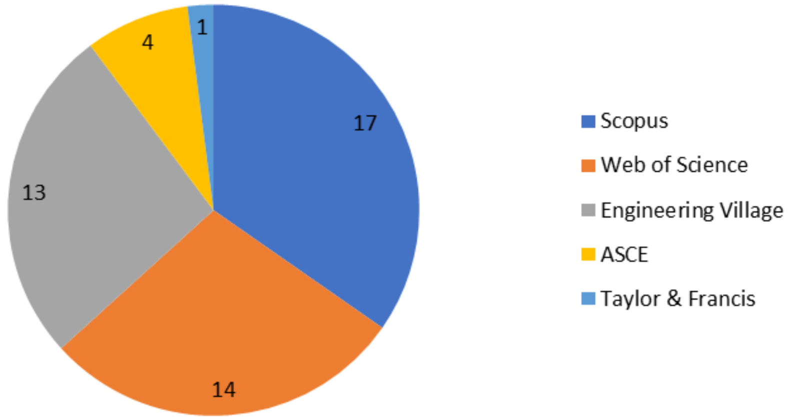

Figure 2. Number of articles included in the search per database. Source: The authors.

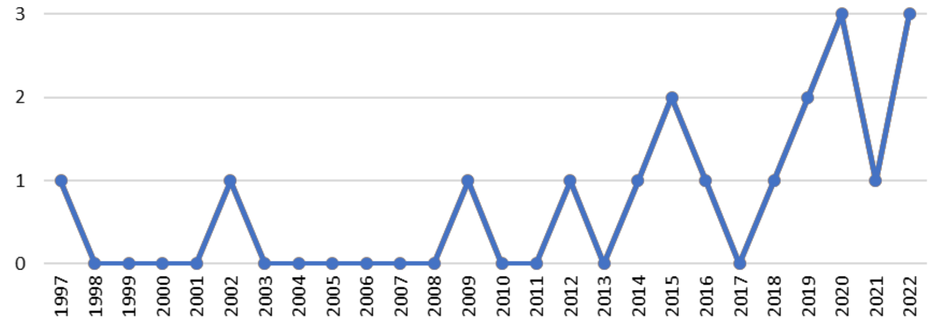

Figure 3. Publication period. Source: The authors.

Regarding the number of authors by nationality, being the United States, with 24 authors, the country with more authors developing studies on the research theme, followed by China (11), United Kingdom (11), Singapore (9), England (6), South Korea (3), Portugal (3), Bangladesh (2), India (1) and Israel (1). In Figure 4, the list of keywords present in the articles of the qualitative analysis is presented. Among the greatest recurrences, there are the terms: Construction safety (6), prevention through design (5), Safety (5), Design for safety (5), BIM (4) and Building information modelling (4).

Figure 4. Keyword cloud. Source: The authors.

Qualitative analysis of the results

Among the studies included in the systematic review, 12 address the Development and Application of a tool for PtD and these only address the Development of the tool, as shown in Figure 5.

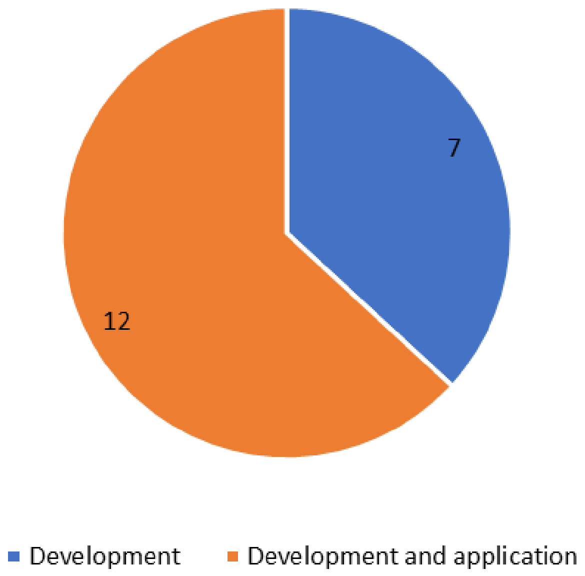

Figure 5. Relationship of development and application of PtD tools. Source: The authors.

The literature analyzed indicates that the use of digital tools for PtD allows to assist in the identification of potential safety risks in the project, in an automated or manual way, as well as in an automated approach, there is possibility of the tool to present methods of prevention and mitigation corresponding to the identified risks (LEE *et al*., 2020). The identification of prevention and mitigation methods in the design phase is necessary not only to assist in risk control, it helps security managers to anticipate safety planning, increasing the productivity of the construction team and reducing reconstruction costs (GAMBATESE *et al*., 1997; TEO *et al*., 2016).

Table 2 identifies the articles included in this research, arranging them according to the authors, year of publication, resource used to use the digital tool, the possibility of automatic risk checking, provision of safety suggestions or risk mitigation measures, automatic correction capability in the project, sources used to compile the digital tool database and articles that addressed the development and/or application of digital tools.

Looking at Table 2, it turns out that 52.63% of the tools are able to automate risk checking 73.68% are able to provide security measures. It is possible to realize that the technology BIM is present in 52.63% of the studies and in 80.00% of the studies that have automated risk verification, of these, only one tool presented the possibility of performing adjustments automatically in the project. The use of BIM stands out in helping prevention through the project, as it can contribute to improving workflow management in the planning stage, reducing efforts in the safety planning stage and integrating stakeholders in the project (TEO *et al., 2016*). PtD tools that make use of BIM work with three-dimensional projects, being able to conduct a better visibility of risk situations in the project, (HARE *et al*., 2020; HOSSAIN *et al*., 2018; QI *et al*., 2014), in addition to promoting the development of reports with three-dimensional details, with less time and effort, compared to manual methods (RODRIGUES *et al*., 2020).

According to some authors, the automated process of PtD tools that make use of BIM can be used by designers who do not have extensive knowledge of construction and safety, because the digital tool can identify all the risks that were inserted in its programming, because the digital tool can identify all the risks that were inserted in its programming. (JIN *et al*., 2019; SACKS *et al*., 2015). However, for other authors, the use of PtD tools that are based on BIM models is directly linked to the information contained in the model, such as geometry, schedule and standardization of nomenclatures, if there is absence or misunderstanding of information in the BIM model, the digital tool for PtD cannot perform the analysis accurately (TEO *et al*., 2016). Therefore, even though most digital PtD tools enable the automation of the project analysis process, their use needs to be audited by a safety expert with knowledge of the design and BIM model information. Additionally, since the model information directly impacts the automated analysis of digital tools, PtD should be planned during the design phase where the model information is defined and standardized.

Table 2. Articles selected for systematic literature review. Source: The authors

Authors	**Resource**	**Automatic Risk Check**	**Provision of security measures**	**Automatic correction in the design**	**Database**	**Approach to the article**	
						Development	**Application**
Gambatese *et al.* (1997)	Design for Construction Safety ToolBox	No	Yes	No	Occupational Safety and Health Administration (OSHA) regulations (Code 1994), the U.S. Army Corps of Engineers Safety and Health Requirements Manual (Safety 1992).	x	
Hadikusumo and Rowlinson (2002)	Virtual reality (WorldToolKit) + World Up™ + DFSP	No	Yes	No	Unsafe acts and unsafe conditions from several literature, such as Adams's theory of accident causation, Hong Kong Housing Authority's accident report, Construction Site Safety (safety notes) of UK, OSHA and Construction Site Safety Regulation of Hong Kong.	x	
Nussbaum *et al.* (2009)	Web platform (ASP.NET)	No	Yes	No	No especific.	x	
Dewlaney and Hallowell (2012)	Adobe Live-Cycle	No	No	No	Interviews with experienced designers and constructors.	x	
Qi *et al.* (2014)	BIM (Revit or ArchiCAD) + Solibri or BIM Server	Yes	Yes	No	Scientific literature, the U.K. HSE and from examining Occupational Safety and Health (OSHA) regulations.	x	X
Sacks *et al.* (2015)	BIM (Revit) and Virtual reality	No	No	No	No especific.	x	X
Dharmapalan *et al.* (2015)	Web platform	No	No	No	Scientific literature.	x	
Teo *et al.* (2016)	BIM (Revit or archicad)	Yes	Yes	No	No especific.	x	X
Nguyen, Tran and	Bayesian network	Yes	Yes	No	Factors and influence dia-	x	X

Chandrawinata (2016)	(MATLAB)				gram for falls from height proposed in literature.		
Hossain *et al.* (2018)	MySQL	Yes	Yes	No	Expert Opinions.	x	X
Jin *et al.* (2019)	BIM (Revit) + Synchro PRO	Yes	Yes	No	Historical injury/fatality database.	x	X
Yuan *et al.* (2019)	BIM (Revit)	Yes	Yes	No	Safety regulations, safety construction manuals, drawings, technical specifications, knowledge and skills of construction site workers	x	X
Hare, Kumar and Campbell (2020)	Web platform	No	No	No	Systematic review of academic and industry literature, interview of experienced Health and Safety Executive (HSE) Construction Division inspectors, construction OSH professionals and facilities managers.	x	x
Rodrigues *et al.* (2020)	BIM (Revit)	Yes	Yes	Yes	Portuguese safety legal regulations (DL273/2003 and DL 41821/1958) and the OSHA 1926–501 (2019) regarding performing work at height, openings and excavations.	x	x
Lee *et al.* (2020)	BIM	Yes	Yes	No	Risk assessment examples of disasters in domestic construction sites along with safety guidelines for each disaster and construction accident database.	x	Lee *et al.* (2020)
Lu *et al.* (2021)	BIM (Revit) + Microsoft Visual Studio 2017	Yes	Yes	No	The Injury and Fatality Database and the Construction Planning Database from the US.	x	x
Collinge *et al.* (2022)	BIM (3D REPO)	No	Yes	No	CIRIA C755, Design for Construction Safety, CDM 2015 and relevant HSE standards.	x	x

Farghaly *et al*. (2022a)	BIM (3D REPO)	No	No	No	CIRIA C755and CDM 2015.	x	
Hossain and Ahmed (2022)	BIM (Solibri)	Yes	Yes	No	No especific.	x	x

Although they have the possibility of automatically identifying risks in the design, the absence of considering the dynamism of the work is indicated as one of the main limitations of the PtD tools (DHARMAPALAN *et al*., 2015; HADIKUSUMO; LEE *et al*., 2020; ROWLINSON, 2002; NUSSBAUM *et al*., 2009; QI *et al*., 2014; SACKS *et al*., 2015; YUAN *et al*., 2019). To mitigate this limitation, we can consider the location and time variables in the PtD tool, through these two variables, it will be possible to Yesulate a partially real construction process (HADIKUSUMO; ROWLINSON, 2002). Therefore, it is recommended to integrate the schedule with the BIM model to maximize the potential use of the tools PtD (COLLINGE *et al*., 2022; JIN *et al*., 2019; QI *et al*., 2014; YUAN *et al*., 2019).

To enable automatic risk checking and provision of safety measures, it is necessary to collect data and information about the work environment, the processes that occur in it, safety guidelines and historical injury data. Databases are important tools for storing and organizing this data. They allow information to be easily accessed and analyzed, assisting in the risk identification process and in the preparation of preventive measures (JIN *et al*., 2019). Thus, the use of databases in the development of prevention programs through the project is fundamental to ensure the safety and well-being of workers. When producing a database, authors identified limitations regarding the insufficiency of available data on risk identification through the design, claiming that there are safety guidelines fragmented in several literature, an exhaustive work is required to compile them into a single database (LEE *et al*., 2020). During compilation of this information, it is noticeable that there are data that have regional restrictions, not adapting to the needs, when a user of the PtD tool uses it for another region (HOSSAIN *et al*., 2018). Therefore, it is important to design the databases to allow the updating of their information by users from other regions (COLLINGE *et al*., 2022).

Another limitation of databases for PtD tools, is that they can become obsolete easily, because, when there is a review of regulations or guidelines, it will be necessary to update the database, which may cause rework and manual effort (YUAN *et al*., 2022). However, some authors indicate that the possibility of creating a mechanism to analyze the rules parametrically can make database information more flexible to adapt to different countries and to the updates of standards and guidelines (HOSSAIN; AHMED, 2022, LEE *et al*., 2020).

Conclusions

Design decisions made by designers influence the entire life cycle of a construction project, so the introduction of the PtD concept in the design phase increases the possibility of eliminating risks. In this context, this paper reviewed 19 articles that developed and used new digital tools to help designers identify safety risks in the project and change design decisions to eliminate risk before construction.

Through the low number of published studies, this article shows that the development of tools for PtD still has areas to be deepened and limitations to be studied. Most PtD digital tools analyzed already have automated risk checking and provide suggestions to mitigate them. However, there are still studies to be carried out, contemplating the schedule and conditions of the workplace, aiming to make the tool more effective when considering risks arising from the dynamism of construction. Despite the automation provided by the PtD tool, its use is indicated for safety specialists with knowledge in design and BIM model information.

BIM technology is present in most digital tools, assisting not only in the three-dimensional visualization of the building, but also having significant utility by allowing information to be linked to the model elements, facilitating automatic analysis by digital tools. In addition, the use of BIM for the PtD should not be seen as an isolated application, since the beginning of the model development, it is important to link information in the model for analysis in digital tools for making risk verification an integral part of BIM technology.

In future research, location and time information can be considered, such as schedule, work logistics, use of equipment and information on soil and terrain components, to reduce the limitation of PtD tools in yesulating the work dynamism. Considering that there are still few PtD tools developed and limitations to be studied, it is suggested to make the digital tools available to designers from different countries, and during their use, collect feedback on the experiences, to obtain improvements for the applicability of the PtD tool in projects of various types and in different regions.

Finally, efforts to build a database of security elements more complete and easily upgradeable need to be carried out to allow greater acceptance of designers to new technologies and to allow automatic project reviewers to keep up with new construction activities and revisions of regulations. Although they do not occur as quickly as they should, advances in PtD technologies and digital tools in construction are important. Previous research shows the historical need to increase construction safety, and scientists are interested in providing new approaches. This demonstrates the great potential of the PtD study area to contribute to future scientific achievements.

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