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PLANNING FOR THE UNEXPECTED IN CONSTRUCTION PROJECTS: A REVIEW

PLANEJAMENTO PARA O IMPREVISTO EM PROJETOS DE CONSTRUÇÃO: UMA REVISÃO

PLANIFICACIÓN DE IMPREVISTOS EN PROYECTOS DE CONSTRUCCIÓN: UNA REVISIÓN

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ABSTRACT

Global crises, such as pandemic and wars, bring to light how construction projects can be impacted by unexpected events that are typically overlooked by planning teams. Therefore, the goal of this study is to review the literature to understand how uncertainties are being considered in construction planning methods and, what are the next steps to face new crises. By doing so, the authors mapped the traditional variables that are included as uncertainties in planning methods, such as project time and cost, as well as the unusual variables that are not typically included as uncertainties in the methods, such as safety and sustainability issues. The state-of-the-art of planning methods with uncertainties entailed a thorough reading of 103 journal articles found through an adapted systematic literature review, which included, in addition to traditional processes, a scientometric study and a snowballing analysis. As a result, it was discovered that the main uncertainties considered are related to time, cost, and resources. Furthermore, it was possible to observe that there is no single consolidated technique for incorporating uncertainties in planning methods, but rather a combination of different techniques, ranging from the most traditional with analytical analysis to the most contemporary with artificial intelligence algorithms.

RESUMO

Crises globais, como pandemias e guerras, evidenciam como os projetos de construção são afetados por eventos inesperados, normalmente ignorados pelas equipes de planejamento. Portanto, o objetivo deste estudo é revisar a literatura para entender como as incertezas são consideradas nos métodos de planejamento de obra e quais são as próximas etapas para enfrentar novas crises. Assim, os autores mapearam as variáveis tradicionais que são incluídas como incertezas nos métodos de planejamento, como tempo e custo do projeto, bem como as variáveis incomuns que não são normalmente incluídas como incertezas nos métodos, como questões de segurança e sustentabilidade. O estado da arte dos métodos de planejamento com incertezas envolveu uma leitura minuciosa de 103 artigos de periódicos encontrados por meio de uma revisão sistemática adaptada da literatura, que incluiu, além dos processos tradicionais, um estudo cienciométrico e uma análise de bola de neve. Como resultado, descobriu-se que as principais incertezas consideradas estão relacionadas a tempo, custo e recursos. Além disso, foi possível observar que não existe uma única técnica consolidada para incorporar incertezas nos métodos de planejamento, mas sim uma combinação de diferentes técnicas, desde as mais tradicionais com análise analítica até as mais contemporâneas com algoritmos de inteligência artificial.

RESUMEN

Las pandemias y guerras revelan cómo los proyectos de construcción son impactados por eventos inesperados que los planificadores suelen ignorar. Por tanto, el objetivo de este estudio es revisar la bibliografía para comprender cómo se tienen en cuenta las incertidumbres en los métodos de planificación de la construcción y cuáles son los próximos pasos para hacer frente a las nuevas crisis. Para ello, los autores mapearon las variables tradicionales que se incluyen como incertidumbres en los métodos de planificación, como el tiempo y el coste del proyecto, así como las variables inusuales que no suelen incluirse como incertidumbres en los métodos, como las cuestiones de seguridad y sostenibilidad. El estado del arte de los métodos de planificación con incertidumbres supuso una lectura de 103 artículos de revistas encontrados mediante una revisión bibliográfica sistemática, que incluyó, además de los procesos tradicionales, un estudio cienciométrico y un análisis de snowballing. Como resultado, se descubrió que las principales incertidumbres consideradas están relacionadas con el tiempo, el coste y los recursos. Además, se pudo observar que no existe una única técnica consolidada para incorporar las incertidumbres en los métodos de planificación, sino más bien una combinación de diferentes técnicas, que van desde las más tradicionales con análisis analíticos hasta las más contemporáneas con algoritmos de inteligencia artificial.

Citation (APA): Carmo, C. S. T., do. & Sotelino, E. D. (2023). Planning for the unexpected in construction projects: a review. *Brazilian Journal of Production Engineering,* 9(4), 107-130.

INTRODUCTION

During the current global crisis caused by the Covid-19 pandemic and the Ukraine war, the construction industry turns on the lights to improve predictability and risk contingency in contracts. Commodities experienced rapid price fluctuations, prompting financial investors to shift their portfolios into low-risk industries. However, as is well known, the construction industry is characterized by randomness and uncertainty, increasing the level of vulnerability to unforeseeable events, which is unappealing to investors.

Many factors contribute to the inherent uncertainties that arise during construction work. For example, Laufer and Cohenca (1990) conducted a survey and found that completion of the design phase, previous experiences, labor supply, weather conditions, and planner subjectivity are all factors that have a high impact on construction planning results. As a result, it is almost mandatory in today's turbulent times to consider uncertainties in construction planning methods to include the variability of that industry more explicitly and, thus, attract more investment.

Defining uncertainty is a difficult task. Uncertainty is the lack of knowledge about a situation in which one does not understand the values, possible ranges, or whether the outcome will be positive or negative (Zheng & Carvalho, 2016). Unlike risk, which is commonly associated with negative known scenarios (threats), uncertainties occur before risks (Feng et al., 2018) and can lead to threats or opportunities (Zheng & Carvalho, 2016). In other words, one only knows the risks if uncertainties are understood beforehand. While risk is equivalent to numerical variability, uncertainty can be associated with chaos and without any control over the probabilistic events (De Meyer et al., 2002).

Note that there are different levels of uncertainty. According to Walker et al. (2013), it is divided into five levels: the lowest level (1) refers to a single system model that guide to only one direction; and higher level (5) occurs when there is no known system model or even known outcomes. The latter is also known as deep uncertainty, as defined by Lempert et al. (2003), and is the one applicable to construction planning of unusual projects, such as infrastructure projects, according to Feng et al.(2022). This is because in these projects other contexts beyond the technical issues such as human, political, social, and environmental issues must also be considered, thus, increasing the difficulty in defining uncertainties and the choice of model to be used.

So, how do construction planners deal with uncertainties when planning? This is the central question for the current study, which is divided into five sections. Thus, the objective of the paper is to provide a comprehensive overview of the state of art on construction planning with uncertainties and to identify gaps of knowledge. The research context is presented in the first section and a theorical background is presented in the second one. The research methodology is explained in the third section. Following, the fourth section contains the main discussions on uncertainties in construction planning methods. The fifth section then summarizes the study's development as well as the main contributions and limitations.

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THEORICAL BACKGROUND

CONSTRUCTION INDUSTRY AND ITS CHALLENGES WITH PLANNING METHODS

According to the McKinsey report (Ribeirinho et al., 2020), the construction industry accounts for 13% of worldwide Gross domestic product (GDP), and according to the Brazilian statistical report (CBIC, 2023), an average of 5.3% in Brazil. Behind these figures are societal effects such as job creation and income generating. Furthermore, the building business has been hit hard by worldwide crises such as the COVID-19 epidemic. According to the Brazilian Statistics Institute (IBGE, 2023), COVID-19 caused a 2% drop in GDP construction participation. Then, as indicated in the McKinsey global construction reports (Ribeirinho et al., 2020), the implications of these occurrences are typically industry demands for new technology aimed primarily at increasing efficiency. Indeed, as stated by Shibani et al. (2020) and Edmund et al. (2018), during the worst global crises in history, new technologies "appeared" in the building industry to enhance productivity and, as a result, pull the economic recovery.

However, there is sometimes a harmful aftereffect from the never-ending quest for better productivity. According to Enshassi et al. (2009), there was an increase in work accidents in the construction industry during the same time periods. Even if developing countries have a lower construction representativeness, the negative effects of global crises may be stronger in developing countries than in wealthy ones. As a result, construction planners play a critical role in taking these issues and uncertainties into account in the planning methods and, thus, during the construction phase.

One of the early studies on uncertainty in construction planning was conducted by the Fleet Ballistic Missile program in the 1950s, as described by Touran (1986) and Williams (1999). In this initiative, the method Program Evaluation and Review Technique (PERT) was proposed by Malcolm et al. (1959) to introduce probabilistic input variables into the Critical Path Method (CPM), which is the most used technique for construction planning, but deterministic in nature. It is worth noting that CPM was idealized almost at the same time by Kelley and Walker (1959), who were inspired by the Gannt chart proposed by Clark in 1922 and later adapted with the predecessor network concept by Fondahl in 1962, but always maintaining its deterministic nature, as stated by Hadipriono (1988). Following the PERT/CPM method, other derived techniques for dealing with uncertainties emerged, such as the Graphical Evaluation and Review Technique (GERT) proposed by Moore and Clayton (1976). The predecessor network in this approach works with deterministic and probabilistic nodes with additional operators to the PERT technique. As a result, Kavanagh (1985) considered GERT to be a complex and refined methodology, whose use is challenging to planners who do not have experience with statistical analysis and derived topics.

Later, in 1988, Hadipriono proposed a deductive method based on fault tree analysis for considering uncertainties in construction planning, which is applicable to both deterministic and non-deterministic analyses. The Modified Fault Tree Networking (MFTN) method adds to CPM causal interrelationships between events that can cause scheduling problems. This approach follows the recommendation made by Caron et al. (1998) regarding the planning process flow, which is to begin at the end. For example, you can first establish the deadlines, and then define the deliverables and procurement processes based on those dates. Using this logic, Hadipriono (1988) argues that MFTN is a construction planning method useful for identifying activities and construction sequences that are most likely to contribute to schedule delays.

Many construction planning techniques were developed during the aforementioned periods to optimize the processes of repetitive construction and to deal with cost and risk estimation (Russell & Wong, 1993). Ock and Han (2010), for example, proposed a fuzzy-based method to calculate the risks associated with uncertainties in other methods. The Line of Balance (LOB) approach is another approach focused on repetitive construction that allows productivity and production rates to be considered alongside the PERT approach, but in a deterministic manner (Kavanagh, 1985). The problem with this deterministic analysis is that it normally results in optimistic estimations because it does not incorporate uncertainties and random variables into the construction plan (Touran, 1986). In fact, according to Bacon et al. (1996), when paired with inadequate risk analysis, this optimistic scenario can render huge projects unaffordable in infrastructure projects built in development countries.

Indeed, as stated by Lee et al. (2009), in infrastructure projects involving new technologies, project managers typically apply a large margin compared to building projects to cover many uncertainties that traditional planning methods do not take into account. As a result, for that scope of project, contingency estimation is critical (Tseng et al., 2009), and computer simulations are commonly used to overcome the drawbacks of traditional planning methods. In this context, it is important to mention Monte Carlo (MC) simulation, which according to Woolery and Crandall (1983), is an acceptable technique for performing stochastic analysis in network models of large and complex projects, and, thus, applicable for construction activities. However, Manik et al. (2008) emphasized that MC simulations necessitate a significant amount of computational time and power, and Lee (2005) claimed that these simulations are a useful supplement to traditional planning methods. Similarly, some stochastic methods are based on deterministic methods (e.g., CPM) as demonstrated by the work of Kokkaew and Chiara (2010). The authors proposed the Stochastic Critical Path Method (SCPM) in that study, which combines the critical path with MC simulations and enveloping analysis. By doing so, the authors argue that it is possible to account for the manager's subjectivism in schedule estimation. According to Tseng et al. (2009), another feature of MC simulation is the requirement for better data history and maintenance, which can include pre-processing and data mining techniques. Furthermore, according to Du et al. (2016), MC simulation maximizes the benefits of Markov chain models, which explains why many studies combine MC with stochastic analysis (Hassan et al., 2021; Hosny et al., 2022; Kammouh et al., 2022; Zhong et al., 2016).

It should be noted that simulation techniques are not limited to MC; for example, Halpin (1977) proposed the CYCLONE system, which is based on Discrete Event Simulation (DES), to study construction operations. Indeed, DES is an important technique that is being used by several studies in the construction planning area to integrate with building information models (Abbasi et al., 2020), fuzzy analysis (Szczesny & König, 2015), probabilistic approaches (Feng et al., 2022), among others.

Furthermore, construction planning methods frequently employ probabilistic analysis to estimate activity duration based on historical data. Naturally, there are inherent uncertainties in that historical database that can affect the estimation results. Probability Density Functions (PDF) are commonly used in this type of approach, as evidenced by the studies of AbouRizk and Halpin (1992) and Lee (2005). Although AbouRizk and Halpin (1992) suggested using the Beta distribution to estimate earth movement activity durations, PDFs are difficult to determine. Furthermore, as stated by Touran (1986), general users typically lack the necessary statistical analysis knowledge to incorporate probabilistic techniques into planning methods.

Indeed, according to Jaśkowski and Sobotka (2006), time and cost are the most used decision-making indicators, which explains why these two variables are frequently used in construction planning methods that account for uncertainties. Also, according to Ock and Han (2010), the success of a construction project is related to three factors: time, cost, and quality, but the “risk path”, as the authors refer to it, may comprehend activities that are not included in the critical path and are related to other areas. However, several authors (Kavanagh, 1985; Ock & Han, 2010; Ozdemir & Kumral, 2017; Yang & Chang, 2005) criticize traditional methods for ignoring resources or believing that resources are limitless. As a matter of fact, resources are the means to an end (Vaziri et al., 2007), which can be time and cost variables, but their omission in construction planning results in unrealistic scenarios. As a result, schedule estimates can be overly optimistic (Kavanagh, 1985), causing practical issues on the job site such as contractual schedule adjustments. Therefore, CPM, PERT, bar charts, and other traditional methods are insufficient to solve the problem of resource allocation on construction sites, and the subject is widely discussed in construction site planning studies, which propose everything from linear programming to genetic algorithms (Yang & Chang, 2005).

In this line of reasoning, the worker or labor is introduced, which is regarded as the most critical type of resource by Vaziri et al. (2007) when compared to equipment and materials. However, labor sizing has traditionally been done by relying on past experiences rather than using specific tools or methods. Based on this finding, Elhakeem and Hegazy (2005) proposed the Distributed Scheduling Model (DSM), which is a model based on CPM concepts, progress rates and work crew estimation, and has as its goal the optimization of resource allocation in construction and maintenance operations. Unlike DSM, which employs abacus calculations and deterministic formulations, other authors propose more advanced methods, such as the study by Zahraie and Tavakolan (2009), which employs genetic algorithms associated with fuzzy logic to optimize time and cost while also allocating and placing labor. Similarly, Tomczak et al. (2019) proposed a conceptual mathematical model of multi-criteria optimization with nonlinear processes under deterministic conditions, with the goal of minimizing team downtime and total project duration.

Even more specific is the issue of workplace safety, which is frequently overlooked by construction planning methods but can undeniably interfere with the main indicators of time and cost. The impact of workplace safety on the duration of construction activities is investigated in the study developed by Francis (2019), and a method is proposed that considers both themes concurrently to avoid errors in decision making. It is worth noting that the simultaneous consideration of variables in construction planning methods has already been studied by several authors, including Isidore et al. (2001), who proposes the integration of time and cost simulations to understand the correlation between them.

When compared to vertical building projects, the concern with occupational safety and health issues is even more important in the realm of infrastructure works because they typically involve heavier equipment and a larger number of workers in the field. According to Elhakeem and Hegazy (2005), there are three key decisions in this type of construction: the number of available teams; the construction method used in each activity; and the order of execution of the activities in each space. Certainly, activity prioritization is a study that has piqued the interest of researchers such as Bruni et al. (2011), who propose new prioritization rules based on heuristic programming and statistical analysis, with the goal of taking uncertainties and resource constraints into account in construction planning. Unlike other planning methods with uncertainty, the authors' method was designed to have an easy-to-use and friendly graphical interface, which has aided in the spread of stochastic methods in the construction industry.

Moreover, logistics and equipment sizing can have a significant impact on the risk of accidents on the construction site in infrastructure projects. With this, fleet sizing is a problem that has drawn the attention of stochastic process scholars in construction planning. Ozdemir and Kumral (2017) proposed the use of stochastic processes in the deterministic Match Factor method to consider risks over time, as well as Monte Carlo simulations to understand equipment availability over time. The authors were able to demonstrate through case studies that traditional methods generate exaggerated or pessimistic estimates, whereas the proposed stochastic method generates more realistic, but not necessarily optimistic, scenarios.

To summarize, planners began to consider uncertainties in construction using variations of the CPM approach and were primarily concerned with the time issue (construction duration). The planning network model was then improved by logical methods, which enabled the creation of process maps to simulate the construction sequence. However, the simulation itself was only possible due to advances in computer processing power, which enabled Monte Carlo simulation models and, as a result, the consideration of multiple variables beyond time. Furthermore, specific challenges in construction projects, such as repetitive construction, prompted the development of new techniques that were not entirely based on CPM and were more closely related to statistical analysis. In doing so, the theoretical background revealed that there are many construction planning methods that originated over the last decades and due to technological evolution but understanding the different levels of uncertainty appears to keep this topic at a superficial level of implementation.

Literature Review Approaches

Following Denyer and Tranfield (2009), the Systematic Literature Review (SLR) is an approach to discovering findings and research gaps in scientific areas in an impartial and objective manner. Although the SLR method strives for objectivity, the researcher's parameters, such as search terms and filters, may be biased due to personal perspective, experience, and knowledge. As a result, this paper proposes the use of adapted systematic reviews, as suggested by He et al. (2017), including term cooccurrence analysis to better understand the topics covered by many papers without requiring a thorough reading and a snowballing analysis as an additional step. By doing so, it is possible to gain a better understanding of whether the search terms are correct and to obtain preliminary answers to the research questions.

Traditionally, according to Khan et al. (2003), the SLR follows a set of standardized steps: question formulation, study location, selection and evaluation, analysis and summary, and results and reporting. The first step is to properly describe the research topic under consideration, which will help direct the search for relevant papers. The following step is to do an article database search using previously defined search terms and filters. As a result, the researcher receives a list of studies that must be selected and reviewed using inclusion and exclusion criteria, which can include language, scope of study, and other relevant criteria to the literature review. The fourth step comprises thoroughly examining the final selection of studies to summarize each contribution, limitations, and subjects relevant to answering the SLR questions. Finally, the fifth stage is concerned with results and reporting, which includes graphs depicting the insights and tables summarizing the SLR results, among other outputs.

The snowballing analysis is another method for conducting a literature review. This method involves the researcher using a reference list or citations to well-known articles on the subject (Wohlin, 2014). So, it is essentially a thorough dive into a certain papers' references. The second and third steps of the snowballing analysis differ from those of the SLR. Instead of a structured search in databases, the snowballing approach focuses on the key articles in a given subject, and with these key papers, the researchers use inclusion and exclusion criteria to filter the reference list, and then begin the analysis, summary, results, and reports similarly to the SLR. Snowballing can be done in two ways: forward or backward. The references in the important publications are used in the former search. The citation to the key papers is used in the latter search.

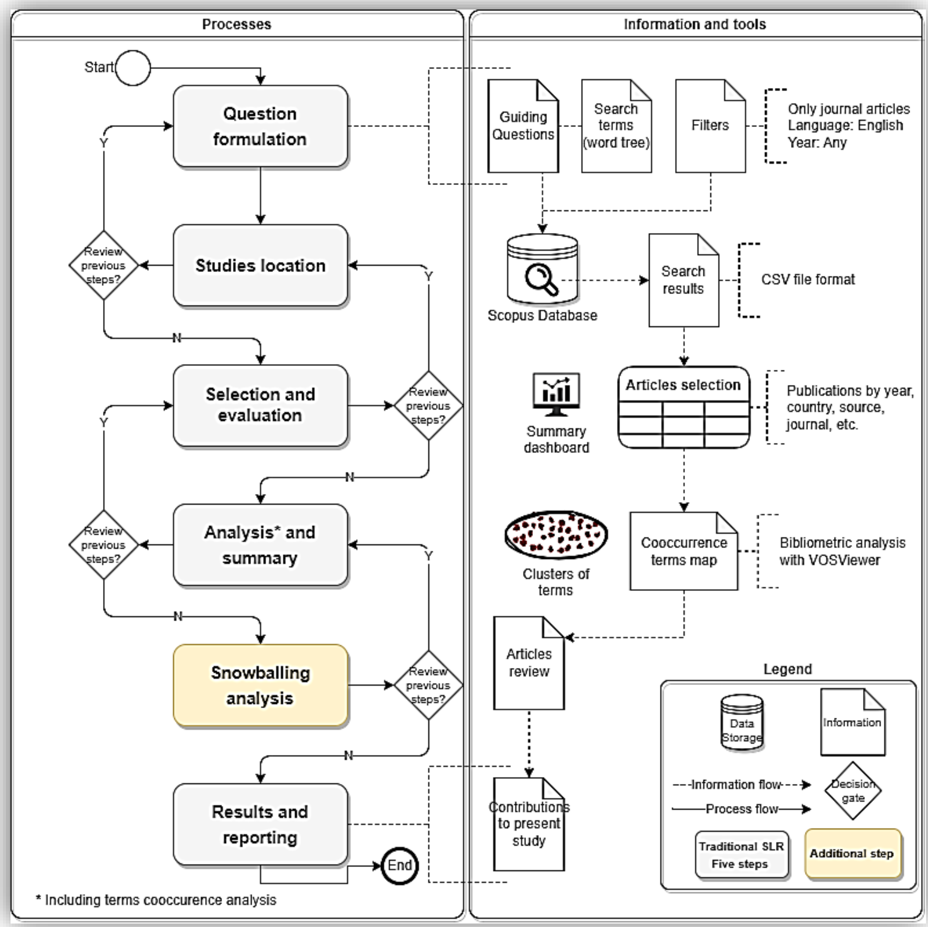
The quality of the final list of studies, however, can be influenced by the researcher's experience, as they may not completely comprehend what the significant publications in a specific area are. Furthermore, according to Jalali and Wohlin (2012), the snowballing analysis is simple to understand and replicate, as opposed to the SLR, which contains more difficult procedures for a rookie researcher. However, as a disadvantage, "the lack of randomized representativeness" in the snowballing study can result in biased conclusions, according to Geissdoerfer et al. (2017).

It should be noted that the snowballing technique is intended to be complementing rather than a replacement for SLR (Wohlin, 2014).

METHODOLOGY

In this section, an adapted systematic literature review is proposed, combining SLR and snowballing analysis, using the following sets: question formulation, study location, selection and evaluation, analysis and summary, snowballing analysis, and results and reporting. All steps and information used and extracted during the adapted SLR processes are summarized in Figure 1.

Figure 1. Workflow that represents the adapted SLR used in the methodology.



Source: Authors (2023).

The SLR questions in this study are:

- How do construction planning methods handle uncertainties?
- What kinds of uncertainties are taken into account in construction planning methods?

Following that, a comprehensive literature search was conducted, in which Scopus database was used to identify relevant studies by using inclusion and exclusion criteria. Basically, the search engine was configured to find only journal articles written in English without period limit and with the search terms, derived from the initial questions, occurring in the title, abstract, or keywords. The search terms involved words related to construction planning methods (e.g., “construction plan*” and “construction schedule*”) and uncertainties (e.g., “uncertain*” and “risk*”).

Thus, 444 studies were discovered using the database’s search terms and filters. It is worth noting that 67% of the found papers were taken with the search term “risk*” and 33% with “uncertain*”. This distinction indicates that the studies are more concerned with variability and controlled scenarios than with completely unknown scenarios. It is also worth noting that some authors may not have the same understanding of the distinctions between risk and uncertainty, as suggested by (Feng et al., 2022). The current study concentrated on uncertainty scenarios that are considered in construction planning methods.

All article titles from the search results were read to determine whether or not they fit the scope of the current work. To avoid mistakes, this evaluation was repeated twice, and 226 articles were removed. The remaining 226 studies' abstracts were then read using the same logic and process as the title reading. The sample was reduced to 103 papers after the second evaluation, which means approximately 23% of the initial sample.

The fourth step in the proposed SLR involved extracting data, such as authors and publication year, from the chosen studies, to develop classification criteria and organize the articles in a logical manner. So, a bibliometric analysis was performed using the ‘VOSViewer’ tool (van Eck and Waltman, 2010) to better understand the study clusters, categorize similar studies, and identify potential scientific gaps. To that end, it is necessary to define some configurations. To begin, it was established that only the terms presented in the abstract and title would be examined, with structured abstracts and copyright statements being excluded. Second, the terms were counted using binary logic, which means that even if a term appears multiple times in the field, the tool will count each occurrence as one. Third, it was determined which terms should be dropped (generic terms such as contribution, example, and so on) and which should be synonymized. Fourth, the analysis was set up to include only terms that appeared at least three times.

As a result, the analysis yielded six clusters, which are denoted by different colors in Figure 2. The higher the text font, the more frequent the term appears, and the closer the terms, the more they appear together (cooccurrence).

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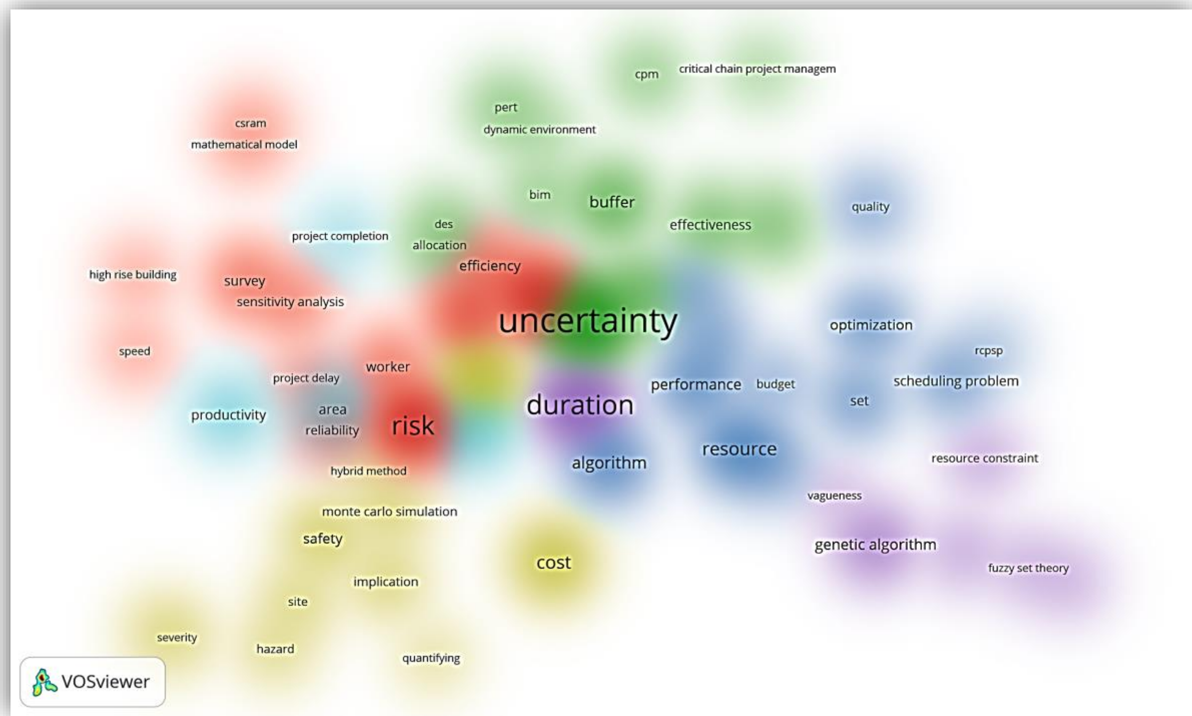
Figure 2. Cooccurrence terms mapping and clustering resulted from the selected papers.



Source: Authors (2023).

As expected, the term "uncertainty" has the highest occurrence and is in the center due to the SLR objectives and search terms. The terms "PERT", "CPM", and "buffer" are also included in the same "uncertainty" cluster. Close to "uncertainty", "duration" is the second most cited term, as expected given that planning methods typically deal with activity and project duration. Terms such as "duration", "genetic algorithm", and "resource constraint" are included in the cluster identified for "duration", and can indicate possible techniques used to consider multiple types of uncertainties in the planning method. The third most frequently used term is "risk", which can be attributed to possible misunderstandings on the distinction between uncertainty and risk, as discussed in the introduction section. Terms like "risk", "worker", "efficiency", and "survey" were grouped together in the same cluster. There is a cluster involving the terms "productivity" and "project completion", almost mixed with the previous cluster, with no clear conclusion. On the other hand, there is a cluster with terms like "resource", "optimization", and "algorithm", which again indicates possible techniques and construction planning methods purposes that take uncertainties into account. The final cluster that was discovered was associated with "cost", "safety", and "Monte Carlo simulation", which is more closely related to the risk cluster than the duration and resource clusters.

The final sample was then thoroughly read to answer the SLR questions. This step included a sensitivity analysis to classify the studies based on the types of uncertainties being considered (cost, environmental impact, safety, resources, site layout, weather, quality, and others) and the techniques used (fuzzy logic, machine learning, discrete event simulation, probabilistic analysis, Monte Carlo simulation, stochastic processes, information modelling, and others) while considering, but not limited to, the clusters suggested by the bibliometric analysis.

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Then, a forward snowballing analysis was carried out to collect papers that were not found by the SLR mechanism but were included in references and were related with the scope of this work. This approach was applied in the key papers observed in the SLR results.

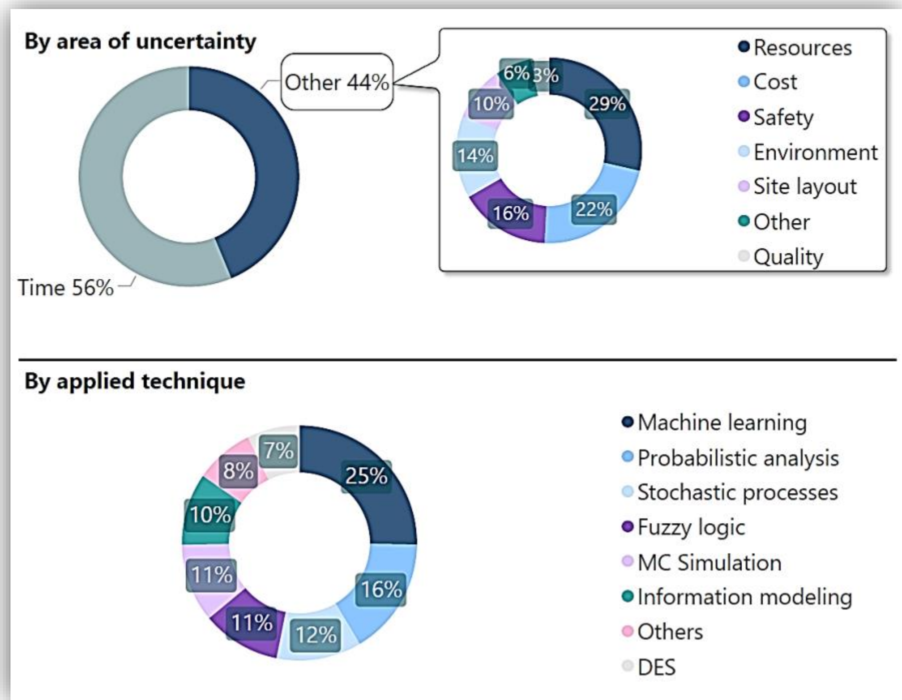
In the final step of the SLR, the authors synthesized the findings of the selected studies to identify interesting discussions and conclusions related to the question formulation. Also, the authors also propose the creation of a summary table resuming all main suggestions for future work described in the SLR. This step is critical for understanding the overall scenario of the topic in the context of the guide questions. It is intended to answer, even partially, the SLR questions and to provide substantial material to orient new studies that aim to reinforce the main works identified or fill scientific gaps.

RESULTS AND DISCUSSIONS

The categorization revealed that the majority of articles (56%) deal with uncertainties through time variables, which was expected given that construction planning methods typically work with deadlines and activity duration. When the papers that are not focusing on time were examined, four main areas represent 81% of the other topics studied as uncertainties in construction planning methods: resources (29%), cost (22%), environment (14%), and safety (16%). It is also worth noting that many works combine those areas, such as the construction duration estimation model proposed by Lee et al. (2009), which considers both weather conditions (environmental issue) and work cycles (time issue). These groupings follow a nearly identical division as shown in Fig.3, with a high occurrence for the four areas mentioned.

Moreover, the Table 1 shows specifically the related uncertainty, the solution method, and the use or not of Artificial Intelligence (AI) adopted in the selected papers from the last 6 years.

Figure 3. Papers divided by area of uncertainty and applied technique.



Source: Authors (2023).

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Table 1. Selected papers published since 2018: Related uncertainties, adopted solutions, and AI use.

Articles	Related uncertainties							Solution methods								AI used?
	Cost	Envir.	Resour.	Safety	Time	Quality	Other	BIM	DES	FL	MC	ML	Probab.	Stoch.	Other	
Hu et al. (2023)				•				•				•				•
Zhang et al. (2023)				•											•	
Chen et al. (2023)					•						•	•				•
Adedokun et al. (2023)							•					•				•
Wang et al. (2023)					•				•	•		•				•
AlJassmi et al. (2023)					•							•				•
Hosny et al. (2022)							•	•			•			•		
Kammouh et al. (2022)					•										•	
Hong et al. (2022)					•										•	
Sharma et al. (2022)	•	•	•		•							•			•	
Kedir et al. (2022)			•		•							•			•	•
Kammouh et al. (2022)					•						•		•	•		
Feng et al. (2022)					•				•						•	•
Milat et al. (2022)					•							•				•
Canca et al. (2022)					•		•							•	•	•
Ramani et al. (2022)				•	•										•	
Fitzsimmons et al. (2022)					•						•	•			•	•
Alhussein et al. (2022)							•								•	
Chen et al. (2021)							•				•	•	•			
Sarkar et al. (2021)					•										•	
Abadi et al. (2021)								•							•	
Cheng et al. (2021)					•							•			•	•
Kulejewski et al. (2021)					•										•	
Plebankiewicz et al. (2021)	•				•					•						•
Isah et al. (2021)			•		•									•	•	
Taghaddos et al. (2021)							•		•						•	
Mohamed et al. (2021)		•			•										•	
Liu et al. (2021)					•										•	
Biruk et al. (2021)					•										•	
Ansari et al. (2021)					•	•						•			•	•
Kaveh et al. (2021)	•	•	•	•	•	•						•			•	•
Zhang et al. (2021)					•							•	•			
Hassan et al. (2021)	•				•						•	•		•		•
Chakraborty et al. (2020)	•											•	•			
Abbasi et al. (2020)					•			•	•						•	
Hosny et al. (2020)			•				•	•								
Jaśkowski et al. (2020)					•				•				•			
Zohrehvandi et al. (2019)					•										•	
Maronati et al. (2019)	•				•						•		•	•		
Wang et al. (2019)			•												•	
Husin et al. (2019)					•			•								
Tran et al. (2018)	•				•							•			•	•
Rahman et al. (2018)	•				•				•						•	
Li et al. (2018)			•									•			•	•

Source: Authors (2023).

A division by technique was performed besides the area grouping, as shown in Fig.3. This chart shows that some procedures, such as Machine Learning (ML), probabilistic analysis, stochastic processes, Fuzzy Logic (FL), Monte Carlo (MC) and Discrete Event Simulation (DES), and information modelling are frequently used in uncertainty analyses for construction planning. It should be noted that traditional techniques such as probabilistic analysis, stochastic processes, and MC simulation are losing ground to ML algorithms, which gained popularity in

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the 2000s because of technological advances, primarily in processing hardware solutions. However, some of these algorithms are internally based on traditional techniques, such as the Genetic Algorithm (GA) proposed by Leu and Hung (2002), which searches for probability distributions that best describe project duration under resource constraints.

A more detailed discussion about the areas and techniques identified in the selected papers is presented in the following sections.

Uncertainties Related to Time, Cost, and Resources

A common approach used to address time issues as uncertainties in construction planning methods is to draw on previous experiences and user subjectivism. For example, Mulholland and Christian (1999) developed a study that involved quantifying uncertainties in a construction chronogram using expert knowledge and experience, lessons learned, and project information. Similarly, understanding that there is subjectivism in the information provided to estimate construction duration, AbouRizk and Sawhney (1993) proposed a system to assess uncertainties caused by planner subjectivism using FL.

Another common subset of time uncertainties is the time buffer, which is essential for simulating both optimistic and pessimistic scenarios in activity duration. In fact, Nasir et al. (2003) claim that the definition of upper and lower duration values can have an impact on risk management. For that reason, Sarkar et al. (2021) proposed a Critical Chain Project Management by improving the buffer sizing through the integration of multiple uncertainties that affects the construction schedule, such as environmental disasters and resources restrictions.

Note that uncertainties are typically treated as risks, especially when they are time related. Consider the study of Chen et al. (2023), who investigated the interdependence of risks in building construction schedule using Bayesian networks and MC simulation. They suggested a planning strategy that, when compared to standard methods (CPM and PERT), resulted in more accurate construction time due to its ability to foresee the sequence of risks. An interesting aspect of the study performed by Chen et al. (2023) is that they suggested that the literature is limited in approaches that include risk interdependence, which could be interpreted as a lack of understanding on deeper uncertainties.

Returning to the discussion on time buffers, Ma et al. (2014) proposed a framework to size buffers and allocate resources based on the critical chain concept, similarly with the study of Sarkar et al. (2021). Furthermore, they emphasized that improving information flow can reduce uncertainties in construction activities, which is the what the study by Abbasi et al. (2020) addresses. The authors proposed a construction planning method that uses information extracted from a Building Information Modelling (BIM) model and DES searches for optimal activity durations that represent realistic scenarios.

The complete reading of the selected papers revealed that information modelling, primarily related to BIM and Virtual Design and Construction (VDC), is widely used in construction planning method proposals, such as the work developed by H. Li et al. (2009). The authors investigated virtual construction prototypes created with BIM and VDC to analyze and optimize the schedule through the visualization of "what-if" scenarios. It is worth noting that the solution in this case is influenced in part by the planner's subjectivism regarding the virtual model, bringing back the importance of studies like Mulholland and Christian (1999) and AbouRizk and Sawhney (1993).

To summarize, some light can be shed on current planning methods that account for uncertainties for time issues. First, the duration of the activity is considered in different scenarios, ranging from pessimistic to optimistic. It is already a result of the PERT implementation and its use as a model for new approaches. Second, the time buffer is essential not only for covering uncertainties during construction, but also for carrying out meaningful risk management. Third, model visualization is a feature that has been investigated to help with the search for better solutions and the impact of subjectivism on the schedule.

Another major point of discussion is resource constraints. Construction planning methods have traditionally assumed that resources are limitless and, thus, always available during the construction phase, but this is not the case. To solve this issue, many studies are using AI algorithms. Li et al. (2018), for example, used multi-objective optimization algorithms and metaheuristics; Kim and Ellis (2009) presented a hybrid and adaptative GA; and Leu et al. (1999b), Leu and Hung (2002), and Leu et al. (1999a) proposed a GA to find optimal solutions in resource allocation problems.

However, due to their multidimensionality, resources can be abstract and difficult to plan. The term "resources" refers to the equipment, workers, materials, and other auxiliary products required to carry out construction activities. As a result, Hosny et al. (2020, 2022) proposed a tool to model workspaces and detect interferences between them to gain a better understanding of some uncertainties that can be assessed before construction begins. Nonetheless, other studies deal with resources during the construction process, suggesting "live" planning methods, such as the work done by AlJassmi et al. (2023). Their work comprises of a neural network-based planning system that self-recovers the construction schedule by collecting and analyzing worker productivity rate on a regular (daily or weekly) basis.

When looking at studies that discuss cost uncertainties, two sub-areas were identified: cost estimate and cash flow. Cheng et al. (2013) proposed an inference model based on Support Vector Machine (SVM) and time series, in which FL is used to work with cash flow problems and construction estimates. In relation to cost estimation, Chakraborty et al. (2020) highlighted, after comparing multiple ML algorithms, that the use of a hybrid ML model to deal with uncertainties in the cost issue, associated with a probabilistic approach, is recommended.

It is important to note that many studies combine cost with other categories of uncertainty, such as time (Hassan et al., 2021), environmental impacts (Sharma et al., 2021), and so on. One of these categories, safety, is regarded by the authors as the one for which uncertainties are most difficult to estimate, since it is associated with human factors such as emotions, health, and a plethora of random variables that extend beyond a number or a historical data set.

Uncertainties Related to Other Variables

In relation to the safety issue, due to the high level of uncertainty that is involved, from a heart attack to an explosion that can result in a construction accident, many authors carry out questionnaire surveys to assess the uncertainties. For instance, Zolfagharian et al. (2014) proposed an automatic tool for safety planning based on a risk matrix calibrated with a survey applied to safety and construction managers.

Information modeling and simulations are also commonly used in studies related to safety uncertainties. Benjaoran and Bhokha (2010) proposed a rule-based integrated system that allows the user assessing and reviewing construction planning through model visualization and, thus, viewing potential work-related accidents. Goh and Askar Ali (2016) presented a hybrid simulation framework to facilitate the integration of safety uncertainties and construction activity sequence. They used DES, system dynamics, and agent-based simulation to achieve this goal.

Sometimes, however, uncertainties related to safety require spatiotemporal analysis. Hu et al. (2023), for example, presented a strategy for dealing with safety accidents induced by crane operations, based on a spatiotemporal analysis that was based on a BIM model. They collected data using the BIM methodology, applied AI algorithms to perform path analysis (connected to the crane's position), and visualized the results using a hazard exposure heatmap.

Uncertainties related to cognitive aspects were also identified in the SLR results. For example, Alhussein et al. (2022) utilized agent-based methods to investigate improvisational behavior in construction planning that emerges from unanticipated uncertainty. They discovered that improvised solutions are produced more frequently by managers than by laborers. It should be noted that agent-based techniques to deal with uncertainties are common in recent literature, with numerous research works such as those by Zhang and Lin (2022), Goh and Askar (2016), Abadi et al. (2021), Kedir et al. (2022).

Weather is other issue that is commonly studied in planning methods. For instance, Pan (2005) addresses rainfall uncertainty by proposing a construction planning approach that assesses the impact of rainfall on construction duration by using historical rainfall data and expert knowledge.

Other studies go beyond the specific category of uncertainties, but rather about risk inference in infrastructure project construction planning. Chen et al. (2021) created a method that does not require observed data and can be useful in cases where historical data is unavailable. The authors employed MC simulation with Bayesian networks to infer risks in infrastructure building scheduling.

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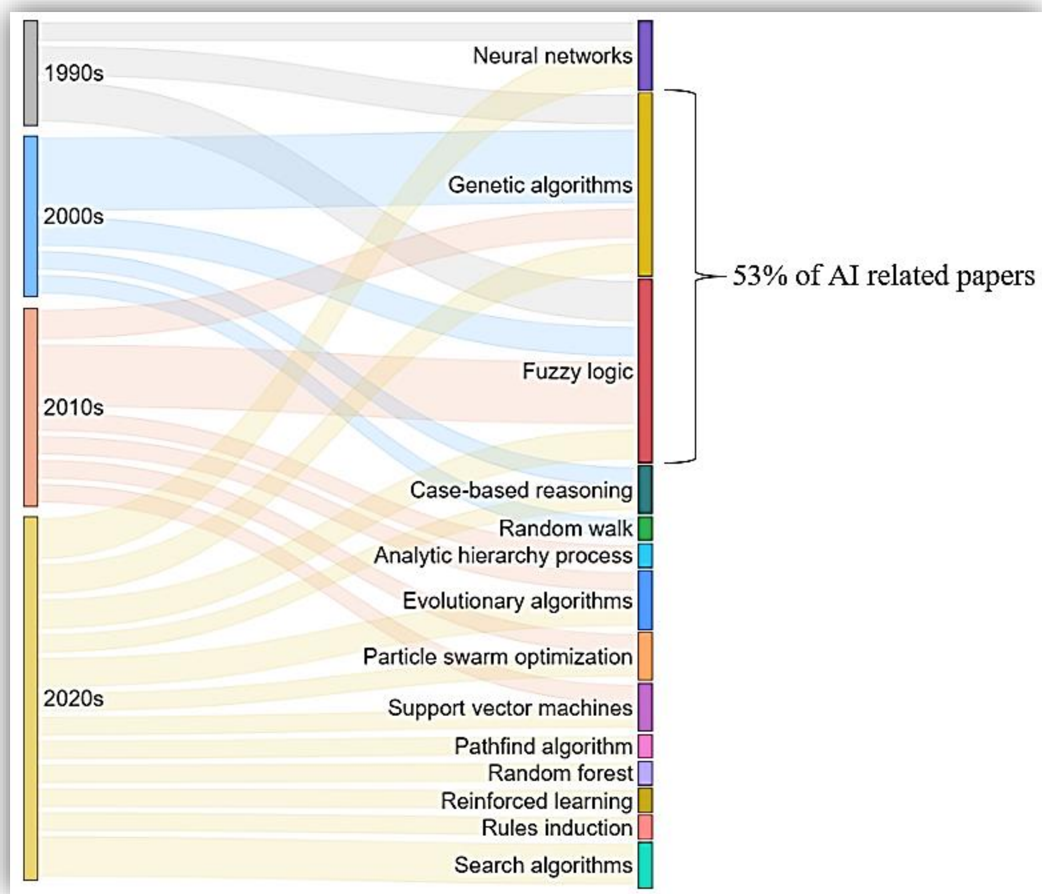
The growth of AI techniques

Aside from the types of uncertainties covered by the present SLR, certain discussions are necessary about the strategies used in these planning methods. Historically, the SLR indicated that uncertainties were frequently evaluated using statistical analysis (Touran, 1986), mathematical formulations (Woolery and Crandall, 1983), and simulation - typically DES (Sawhney et al., 1998) and MC (Sukumaran et al., 2006). In fact, Fig.3 shows that almost 50% of the planning methods found in the SLR are related to these traditional techniques.

However, more recent studies found in the SLR revealed that AI methods are commonly utilized. Some construction planning methods use evolutionary algorithms to deal with multi-objective optimization (Tran and Long, 2018; Milat et al., 2022; Hassan et al., 2021), FL to deal with uncertain data (Pawan & Lorterapong, 2015; Szczesny & König, 2015; Plebankiewicz et al., 2021), neural networks to forecast schedules in real-time (AlJassmi et al., 2023), rules induction methods to interpret and assess construction scenarios (Feng et al., 2022), among others. Fig.4 depicts a summary of the AI techniques revealed in the SLR. The widespread usage of FL and GA (53%) may indicate that they are the most promising methodologies to account for uncertainty in building planning procedures. However, the other part (47%) of the AI methods uses other ways that could also be seen as a promise for portraying random events in construction plan.

Figure 4. AI techniques utilized over the time in the construction planning methods.



Source: Authors (2023).

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Also, it is important to note that many studies propose hybrid planning methods that combine traditional and contemporary techniques, such as the work done by Fitzsimmons et al. (2022), who combined MC simulations with support vector machines, a well-known AI technique, to predict project delays while accounting for uncertainty. Furthermore, the integration of FL with GA has been reported by Moon et al. (2015) and Cheng et al. (2013). The former was used to consider the random variables, while the latter was utilized to optimize the outcomes. Indeed, some studies have already assessed AI approaches applied in certain themes of planning with uncertainties, such as Chakraborty et al. (2020), who analyzed six AI algorithms to anticipate cost and discovered that a hybrid solution produces better estimates.

Perspectives for Future Works

The present work suggests that new studies may consider unusual uncertainties (not just time, for example) and hybrid solutions, that combine traditional methods with advanced algorithms, in the developing of new construction planning methods. But it is important to highlight the recommendations for future work that are provided in the selected studies. Researchers can use these suggestions to direct their studies to fill scientific gaps completely or partially and, as a result, improve this research field.

In the current work, twenty suggestions from the reviewed articles. Many authors suggested as future works the expansion of their methods to other countries, industries, and more detailed data, aiming to validate their approaches with different test environments. Moreover, it was identified that some studies recommend dynamic approaches to deal with actual and field data, to create a kind of "live planning". Certainly, to make it viable, a user-friendly interface and advanced algorithms are needed, which are other two recommendation given by some authors. Finally, some authors proposed cognitive studies to better understand human behavior and planner attitudes toward construction planning (Table 2).

Table 2. Suggestions for future works identified in the SLR.

#	Suggestions for future studies	Number of related studies
1	Context expansion (application in other industries or contexts)	10
2	Increasing sample data (application in more details)	6
3	Algorithms improvements	6
4	Development of dynamic approaches to deal with real-time data	6
5	Capturing field data with monitoring technologies and use of actual data	6
6	Geographical expansion (methods implementation in other countries)	4
7	Consideration of multiple variables	4
8	User friendly interface	4
9	Better understanding of variables and parameters	3
10	Development of microsimulation and micro modelling to deal with more details	3
11	Processes automatization	3
12	More case studies applying existing methods	3
13	Better computational performance	2
14	Cognitive studies to better understand people behavior and resilience	2
15	Creation of knowledge database based on field data and/or past experiences	2
16	Creation of specific databases to support similar studies	2

17	Investigation of hybrid simulation	1
18	Improvements in math formulations	1
19	Consideration of constraint conditions.	1
20	Deeper understanding of uncertainties	1

Source: Authors (2023).

The answers to the SLR questions

- How do construction planning methods handle uncertainties?

There are several ways that construction planning methods deal with uncertainties, and some commonly used strategies have been identified. First, as observed in Hossen et al. (2015); Mulholland & Christian (1999); Nasir et al. (2003); Rozenfeld et al. (2009), planners use risk assessment techniques to identify potential sources of uncertainty and to evaluate the likelihood and impact of these risks during construction project. They investigated methods for mitigating or managing these risks, such as developing contingency plans and acquiring additional resources. Second, it was discovered in some studies (Ansari, 2021; Chen et al., 2021; Ford et al., 2002; Tran & Long, 2018) that planning methods handle uncertainties by relying on flexibility and adaptability. Flexibility allows for adjustments to be made in response to changing circumstances caused by uncertain factors. Building in contingencies allows for scope changes, and being open to alternative approaches are all examples of this. Third, many of the proposed methods make use of computational resources and simulations to better understand various scenarios and critical sequences that may occur during the construction phase. Following the studies developed by Woolery & Crandall (1983), Zhong et al. (2016), MC is one of the most used techniques for simulation purposes. However, methods that use DES, such as Abbasi et al. (2020); Goh & Askar Ali (2016); Szczesny & König (2015), should be mentioned as an approach to understanding construction scenarios with uncertainties. Finally, a brief discussion on construction monitoring and lessons learned is provided next. Some planning methods (Bi et al., 2015; Kammouh et al., 2022; Szczesny & König, 2015) establish systems for ongoing monitoring of the project to identify potential issues early on and make necessary adjustments. There are also studies focused on the creation of knowledge bases, such as Pan (2005), which assesses the impact of rain on project completion based on historical data and expert experiences. Overall, the key to dealing with uncertainties in construction planning methods involves identifying uncertainty sources, strategies for collecting and modelling construction data, flexibility to work with many possible scenarios, and computational solutions, such as simulations, to capture multiple solutions and outcomes caused by uncertainties.

- What kinds of uncertainties are taken into account in construction planning methods?

According to the SLR results, uncertainties related to time (construction duration, project delay, productivity rates, and so on) are the most used in construction planning methods, followed by resource and cost issues. The reason for this is most likely because construction management has traditionally been based on three pillars: time, cost, and resources. However, after thoroughly reading the selected articles, it was discovered that many methods deal with multiple variables at the same time, such as the study carried out by Leu et al. (2001)

to optimize time and cost in construction trade-off subject to uncertainties. Furthermore, the findings point to other issues that have been investigated by numerous studies, such as quality, environmental impacts, and safety. In terms of safety issues, simulation techniques are typically used, such as the work done by Wang et al. (2016), and historic databases support planning methods by providing previous knowledge to draw future possible scenarios, such as the CHASTE approach (Rozenfeld et al., 2009). Similarly, in terms of environmental impacts, historical data is frequently used in planning methods associated with ML algorithms and fuzzy analysis, such as the work developed by Pan (2005). Furthermore, the most used techniques are ML algorithms and probabilistic analysis, with stochastic analysis coming in third with some studies relating to time, cost, resources, environmental impacts, and/or site layout. It is also worth mentioning the use of MC simulation in conjunction with stochastic processes, which is present in at least seven studies.

CONCLUSIONS

The authors used an adapted SLR to examine the state of the art in construction planning methods with uncertainties. The results revealed that most approaches consider time issues as a variable to consider uncertainty, but they also exposed that there are many methods that consider multiple variables at the same time. Furthermore, the findings showed that there is currently no common system in use, and that a combination of traditional techniques and advanced algorithms is being used to estimate uncertainties during the construction phase.

These findings have important implications for the understanding of this research area, which requires more studies not only consolidating existing methods, but also validating new methods with benchmarking data. As indicated by the summary of suggestions for future works, there is a need for universalization and dynamization of current methods, extending the application to other project contexts, countries, etc., and bringing actual data to create a "live planning".

This paper encourages construction planners to use methods that account for uncertainties and do not overlook out-of-the-ordinary planning variables that may have a significant impact on the project because of crisis events. Likewise, the review suggests that new research on construction planning methods should take those uncertainties into account while exploring different approaches that have already been discussed in the literature. Moreover, the authors suggest that new studies can be oriented to construction planning methods that deals with higher level of uncertainties, being able to capture unusual random events commonly observed in infrastructure project.

Finally, it is critical to emphasize that there is no close answer for considering uncertainties in construction planning approaches. On the contrary, some studies suggest that hybrid methods may be the best option for dealing with some sorts of uncertainties. Rather than repeating failing planning methods, that do not consider uncertainties during crisis events, academics and industry practitioners could dive into AI growth and strive to uncover atypical uncertainties with atypical strategies that can help anticipate the future of construction planning.

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