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Review

Tower crane safety technologies: A synthesis of academic research and industry insights

Ali Hassan Ali *, Tarek Zayed, Roy Dong Wang, Matthew Yau Shun Kit

Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Tower cranes (TCs) are vital equipment highly sought after on construction sites due to their efficiency in handling and lifting heavy loads. Nevertheless, the use of TCs on construction sites is riddled with significant safety issues, resulting in numerous accidents across the globe. This study uniquely focuses on the emerging tower crane safety technologies (TCST) field and makes vital contributions by investigating and analyzing TCST research. It aims to explore knowledge gaps and propose future research directions through a systematic review. The uniqueness of this study is its comprehensive examination of TCST, which encompasses not only academic research but also industrial technologies and products. TCST has been categorized based on their purposes and specific aspects of crane management, leading to four key categories: (1) proactive preconstruction crane management technologies; (2) monitoring technologies during construction; (3) anti-collision technologies during construction; and (4) stability control technologies during construction. This study makes a threefold contribution. First, it identifies six crucial knowledge gaps, three in academia and three in the industrial sector. These gaps relate to data completeness, data scope, real-world application, post-construction dismantling, accuracy and data reliability, and data security. Second, it outlines future research opportunities in both academic and industrial contexts, providing a clear path to address these gaps and improve tower crane (TC) operation safety and efficiency. Lastly, it delivers valuable insights to industry practitioners by presenting the latest TCST applications in real-world scenarios, thereby promoting safer and more effective construction practices.

1. Introduction

The construction industry stands as one of the most pivotal contributors to economic growth, playing a vital role in shaping the infrastructural landscape of societies worldwide [1–3]. As an essential sector, it operates within intricate and perpetually evolving work environments [4]. These environments regularly bring forth new risks and hazards for workers, sometimes even hourly. Consequently, the construction sector bears a disproportionately high burden of injuries and fatalities when compared to other industries. One iconic emblem of construction sites is the TC, making it a cornerstone of modern construction equipment [5]. Its towering height, extensive jib reach, robust lifting capacity, and exceptional efficiency have rendered it indispensable for a multitude of construction tasks [6]. Regrettably, the rise in TC accidents appears to be closely correlated with the increasing prevalence of these towering structures on construction sites. Table 1 provides a comprehensive overview of accidents occurring across diverse continents, including Asia, the USA, and Europe. It summarizes both the causes and outcomes of each incident, offering insights into the occurrences within different contexts.

It is noteworthy that Hong Kong's construction industry reported the highest proportion of fatal injuries at 20.5% and nonfatal injuries at 9.4% in 2019 [20]. Similarly, China recorded nearly 125 TC accidents in a single year [21]. Highlighting the significance of crane-related incidents, it is crucial to note that cranes contribute to one-third of construction and maintenance fatalities and permanent disabilities in the United States [22]. Moreover, between 2011 and 2020, the USA witnessed 129 recorded construction crane accidents [20]. Additionally, crane accidents in Australia's construction sector claimed 47 lives between 2003 and 2015, representing 8.5% of all construction industry fatalities [20,23].

According to [24], which investigated crane accidents spanning from 1989 to 2012 across 36 countries, a total of 130 crane accidents occurred during this period. The data collected also includes the number of fatalities resulting from these accidents. Fig. 1 illustrates the distribution of both the number of accidents and the corresponding fatalities

* Corresponding author.
E-mail address: ali-hassan.hassan@connect.polyu.hk (A.H. Ali).

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reported by each country.

The incidents mentioned above highlight the importance of crane safety and the need for stringent operational standards and maintenance to prevent such tragic accidents. Consequently, the safety and efficiency of TCs have garnered significant attention from academia and industry. A multitude of approaches have been proposed to address this pressing issue. These encompass but are not limited to (1) Investigating the root causes of crane accidents [6,25,26]; (2) Developing advanced monitoring technologies to enhance crane safety [27,28]; (3) Optimizing crane layout and configuration [29,30]; (4) Strategically planning and managing crane operations [31,32]; and (5) Conducting structural and mechanical analyses to ensure crane safety [33,34]. These various approaches are vital in mitigating the risks and improving safety in the construction industry, particularly in crane operations.

Several recent literature reviews have attempted to analyze the fragmented body of crane research to establish a more comprehensive understanding of this subject. Table 2 provides a comprehensive comparison of these studies, outlining their review scopes, themes, methods, and findings. Each of these crane review studies has contributed to the understanding of crane-related topics, either by mapping general trends and exploring research trends [35] or by dissecting specific crane research problems to examine their formulation, development, and resolution, as observed in the cases of crane selection [36] and crane lift planning [37].

Nonetheless, it is essential to emphasize that these review works have overlooked the significance of industry-specific technologies and practices that are prevalent in the field. Their primary focus has been on academic research, which, while valuable, may not always seamlessly translate into practical, real-world applications. This narrow focus can be problematic, as it disregards the critical fact that academic findings do not always align perfectly with the complexities of practical, on-the-ground operations. Consequently, a noticeable gap persists in systematically investigating existing technologies and their applications within the industry, specifically aimed at enhancing crane safety.

In light of this gap, this paper aims to offer new and comprehensive insights by combining both industry-specific technologies and academic knowledge to enhance the safety of TCs on construction sites. This integrated approach effectively bridges the gap between theoretical knowledge and practical applicability. Using insights gathered from industry and academic perspectives enhances the overall research, rendering the findings more insightful and applicable in real-world scenarios.

2. Research methodology

With a clear objective of identifying and classifying existing technologies to enhance TC safety performance, the study has adopted a systematic review method. This study comprises three main stages for conducting a systematic review, which include: literature/product identification, literature/product results and discussion, and the exploration of research limitations and future opportunities, as demonstrated in Fig. 2.

2.1. Literature/product identification

The literature and product identification method is the initial step in the systematic review process [40]. It involves the collection of pertinent papers and products from academic publications and industry companies. The identification stage comprises three key components: the formulation of a search strategy, the application of a filtering process, and the evaluation of the quality of the gathered materials, as illustrated in Fig. 3.

2.1.1. Search strategy

Google Scholar, Web of Science, and Scopus are the three most often used databases in construction management research [41–44]. Scopus was chosen as the primary database due to its unique advantages over other databases, such as Web of Science (WOS) and other databases. According to [45], Scopus offers comprehensive coverage of social sciences literature and ranks first regarding recall, average citation count, and submission frequency to individual journal titles. Similar to WOS, Scopus provides functionalities for searching, analyzing, and processing cited references. Additionally, [35] argued that Scopus often includes more recent publications, indexing articles ahead of WOS. However, the latter might have greater historical depth in specific disciplines due to its extended indexing history.

Moreover, Scopus offers advanced search capabilities, enabling researchers to refine results based on specific criteria like publication date, document type, or author, streamlining the search process. For this research, the search query used was ("tower crane" AND "safety" AND "technology") to determine relevant academic studies, focusing on those conducted in the English language. The eligibility timeframe for the search was set from 2015 to October 2023.

On the contrary, the authors utilized four criteria to pinpoint safety products developed by the industry for TCs. Firstly, Google searches were conducted using keywords like "tower crane safety equipment," "industry leaders in crane safety," "top manufacturers of crane safety devices," or "tower crane safety product companies." Additionally, industry-specific directories, reports, or market analyses, such as **Future Market Insights**, were explored to highlight key companies involved in producing safety products for TCs. Furthermore, trade publications, industry journals, and magazines like Cranes Today Magazine were reviewed, focusing on construction, crane technology, and workplace safety. Finally, industry-related social media pages were followed, and

Table 1
Summary of crane accidents across different countries and years.

Country	Year	Reason of accidents	Result of accidents	References
		Asia		
India	2023	Crane instability	20 fatalities	[7]
China	2023	Improper control of TC	1 fatality	[8]
Hong Kong	2022	Poor quality in steel beam welding at the crane's base	3 fatalities	[9]
China	2019	Use of obsolete cranes, resulting in collapses	15 fatalities and 12 injuries	[10]
South Korea	2017	Communication issues	6 fatalities and 25 injuries	[11]
		United States		
US	2023	Engine fire	12 injuries	[12]
US	2023	Dropping of crane's counterweight	4 injuries and substantial damage to structural concrete	[13]
US	2021	The crane collapsed during dismantling operations	5 fatalities and substantial damage to nearby structures	[14]
US	2020	Improper control of TC	Explosion of power line and damage to nearby vehicles.	[15]
		Europe		
Switzerland	2023	Severe storm	40 injuries and damage to buildings	[16]
Austria	2023	Crane jib fell due to a remote-control malfunction	1 fatality	[17]
Germany	2022	Overturning of crane due to unstable ground	Damage to the crane and the building under construction	[18]
Germany	2022	Lack of inspection for TC parts	Significant destruction to the two top-floor apartments	[19]

company websites were visited directly. Companies often share updates or achievements related to their safety products through these channels.

The technologies developed by companies other than crane manufacturers are excluded from this study for several reasons: Firstly, the focus might primarily be on crane-specific technologies, which are often better understood and tested within the crane industry itself. These technologies are more directly tailored to crane operation and safety's unique demands and intricacies. Secondly, while other companies may develop safety technologies, these might not be specifically optimized or designed for crane operation. Crane manufacturers have an in-depth understanding of the engineering, dynamics, and operational challenges inherent to cranes, potentially resulting in more specialized and practical safety solutions. Finally, concentrating on crane manufacturer-based technologies stems from the need for seamless integration and compatibility with existing crane systems. Technologies developed in-house by crane manufacturers often ensure better compatibility and smoother implementation, enhancing overall safety measures. As a result of these efforts, a total of 32 papers and 21 products were gathered.

2.1.2. *Filtering process*

The filtering process involves four iterations of screening and selecting articles and products. In the first iteration, all unrelated studies and products were excluded by scanning their titles, abstracts, or brief introductions. In the second iteration, by checking the full text of the articles and the functions of the products, we applied three additional criteria to exclude items:

- Studies that were purely review works without the development of new technologies.
- Technologies that did not primarily address TC safety issues (e.g., where "safety" was only mentioned in the abstract but not addressed in the content).
- Cranes that were not used in the construction industry, such as gantry and overhead cranes in a factory.

The third iteration involves the snowballing process, which includes both backward snowballing (references) and forward snowballing (citations) to unveil additional related papers. Articles and products that met all the inclusion criteria were considered as target objects for further analysis.

2.1.3. *Quality evaluation*

To ensure publication quality in terms of rigor and credibility, the selected studies and products must follow the four criteria proposed by [36]: (1) The paper or product must have a clearly stated objective; (2) The content should involve tangible technologies, not just conceptual ideas without any prototype or real-world application for TC safety; (3) The method for data collection and analysis must be explicitly provided; (4) The findings or performance results should be clearly presented. In total, 32 academic studies and 21 industry products were collected for the systematic review.

2.2. *Systematic review*

Systematic reviews are crucial for research and evidence-based decision-making [46–48]. They compile and synthesize relevant studies on a specific topic, reducing bias through a systematic process [49]. Their role includes informing decision-making, predicting research opportunities, and uncovering knowledge gaps. By adhering to a predefined protocol, systematic reviews ensure transparency, accountability, and facilitate the advancement of knowledge by organizing existing research, thus enhancing understanding of the subject and its implications [50,51]. Table 3 illustrates the countries most actively involved in producing industrial products for TC safety.

Notably, Asia hosts the most significant number of countries offering industrial products related to TC safety, as demonstrated in Fig. 4.

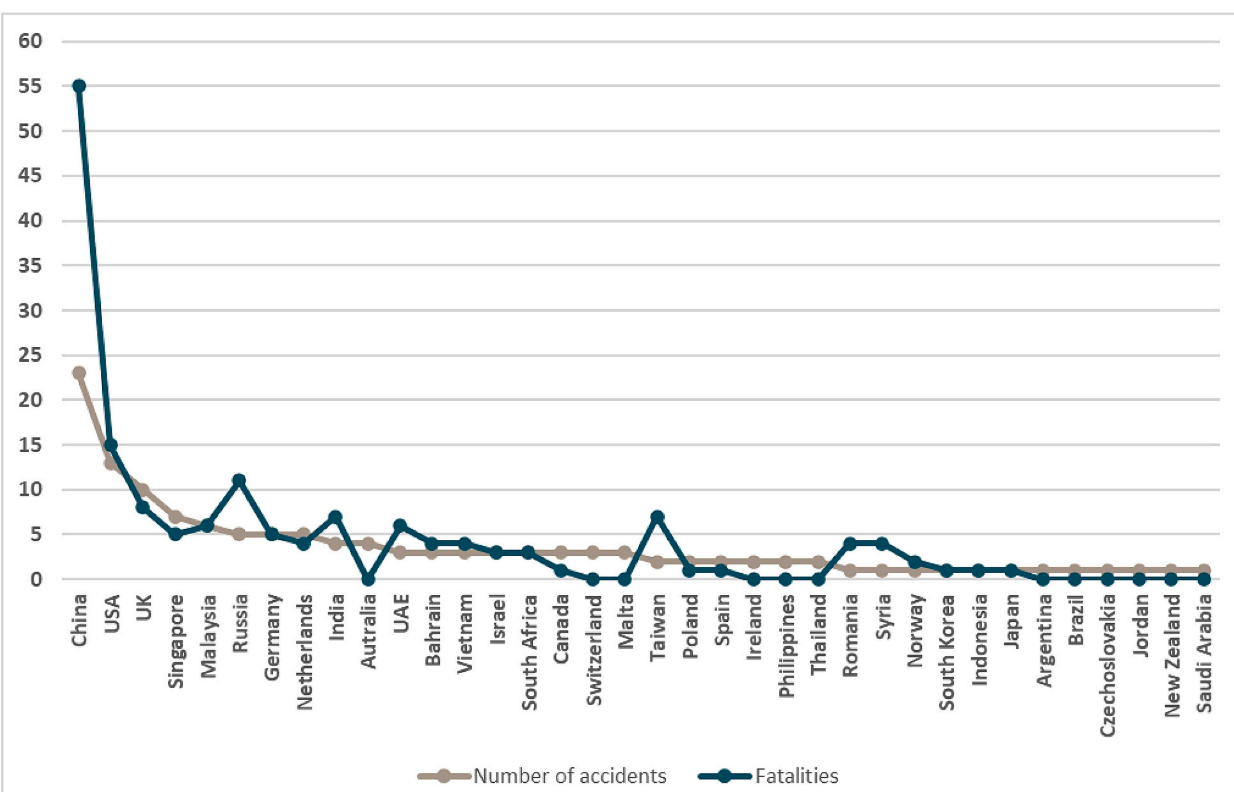

Fig. 1. Accidents and fatalities in 36 countries.

Table 2
Previous crane review studies.

Studies	Year	Scope	Database	Theme	Method	Finding
[38]	2018	Crane accident reports in China	n/a	Crane safety factors	Rasmussen's risk management framework & AcciMap model	56 tower crane safety factors from 5 levels and 9 categories
[37]	2020	108 journal articles	Scopus WoS	Crane lift planning and optimization (LPO)	Taxonomy and systematic analysis	5 IPO issues 6 IPO methods 4 IPO research directions
[39]	2021	134 journal articles	Scopus WoS IEEE	Crane lift planning (CLP)	Tri-axial evaluation diagram	4 CLP problems 6 CLP methods 11 assumptions 5 constraints
[35]	2021	129 journal articles	Scopus	Crane operations and planning (COP)	Bibliometric and systematic analysis	4 POC problems 6 POC technologies 4 POC research opportunities
[5]	2021	74 journal articles Crane operation risk directory	Scopus WoS	Crane safety requirements and risk factors	Step-by-step systematic review	59 crane safety factors from 6 categories
[36]	2021	73 articles	Scopus WoS ScienceDirect	Crane selection	System boundary review model	19 constraints, 71 criteria, 8 methods 4 research opportunities
This study	2024	32 journal articles 21 products	Scopus	Tower Crane Safety Technologies (TCST)	Systematic review	4 categories of technologies (TCST) 6 research gaps and opportunities from industry and academia

Regarding the regional distribution of companies, Fig. 5 shows that China has the highest representation of four companies, underscoring the significance of the Chinese market in the TC safety industry. The United States includes two companies that provide TC safety-related products. Other regions are represented by one company each, including France, Taiwan, Finland, Sweden, Malaysia, Hong Kong, Singapore, and the UK.

Concerning the products each company offers, Fig. 6 demonstrates that Weite is the most prominent company in terms of the number of products, offering six TC safety products. This extensive product range covers various aspects of TC safety. Weite's products constitute 29% of the total products, making it a major player in the market. Following Weite, AMCS Technologies, and Chengdu Hi-tech each contribute two TC safety products to the market. Collectively, these companies represent a respectable 10% of the total products on offer, indicating their substantial presence in the industry.

Concerning the aim of the introduced products, Fig. 7 illustrates that real-time monitoring systems, at 48%, are the most common, emphasizing their critical role in TC safety and operational efficiency. Stability control products, representing 19%, maintain balance during heavy loads. Anti-collision systems, at 14%, prevent crane accidents. Load moment indicators and AI technologies, each comprising 10%, address specific safety and technological needs, reflecting companies' multifaceted approach to TC safety.

Additionally, several reputable manufacturers are known for their expertise in producing these towering structures. These manufacturers prioritize safety as a core element in their crane designs and operational methods. They focus not only on enhancing crane performance but also on ensuring the highest level of safety for workers and the environment through the application of advanced technologies. Their steadfast commitment to safety underscores the significant role these towering structures play in upholding secure and efficient building practices within the industry. Based on [52,53], Table 4 demonstrates the leading TC manufacturers worldwide.

3. Findings and discussion of systematic review

The systematic review of the 32 academic articles is conducted by reviewing the introduction, methodology, and conclusion, with occasional readings of the entire paper to gather additional information. In contrast, reviewing the 21 industry products involves reading all available information about the systems, including their purpose and components. The main goal was to categorize these articles based on their purposes and specific aspects of crane management using a two-dimensional method. This method facilitated the identification of TC research trends and research gaps. Brainstorming and a literature review were utilized to classify 53 TC safety technologies. Brainstorming is a popular method for problem-solving and ideation that encourages creativity, cooperation, and information organizing. This method identified four categories: Proactive Preconstruction Crane Management Technologies (PPCMT); Monitoring Technologies During Construction (MTDC); Anti-collision Technologies During Construction (ATDC); and Stability Control Technologies During Construction (SCTDC).

Table 5 offers a comprehensive overview of various studies concentrating on TCST. Each study falls under specific categories that are previously mentioned. Within each category, the table systematically presents target variables, data sources, key indicators, methods/technologies employed, feedback mechanisms, and the timing of the function. This table not only facilitates a holistic understanding of the diverse studies but also provides a clear and organized snapshot of the essential components contributing to the advancement of TCST. Each study presented in this table is individually examined in the following sections, providing a detailed exploration to ensure a comprehensive understanding of each study's unique contributions, insights, and limitations.

3.1. Proactive preconstruction crane management technologies

The observation that 14 out of 32 academic papers discuss Proactive Preconstruction Crane Management Technologies, while none of the industry products address this, indicates a significant academic emphasis on this facet of crane management. This suggests that academia prioritizes innovation and exploring emerging technologies, whereas industry technology primarily centers on practical, established solutions for immediate needs. This category has two primary sub-categories: one focusing on accident prediction and the other on operational planning of crane activities. Fig. 8 illustrates the hierarchy of this category, including sub-categories.

3.1.1. Accident predictions

5 out of 14 academic papers specifically addressed accident predictions. Accident predictions in machine learning and algorithms involve using data-driven techniques to forecast the likelihood and severity of accidents. Machine learning algorithms analyze historical

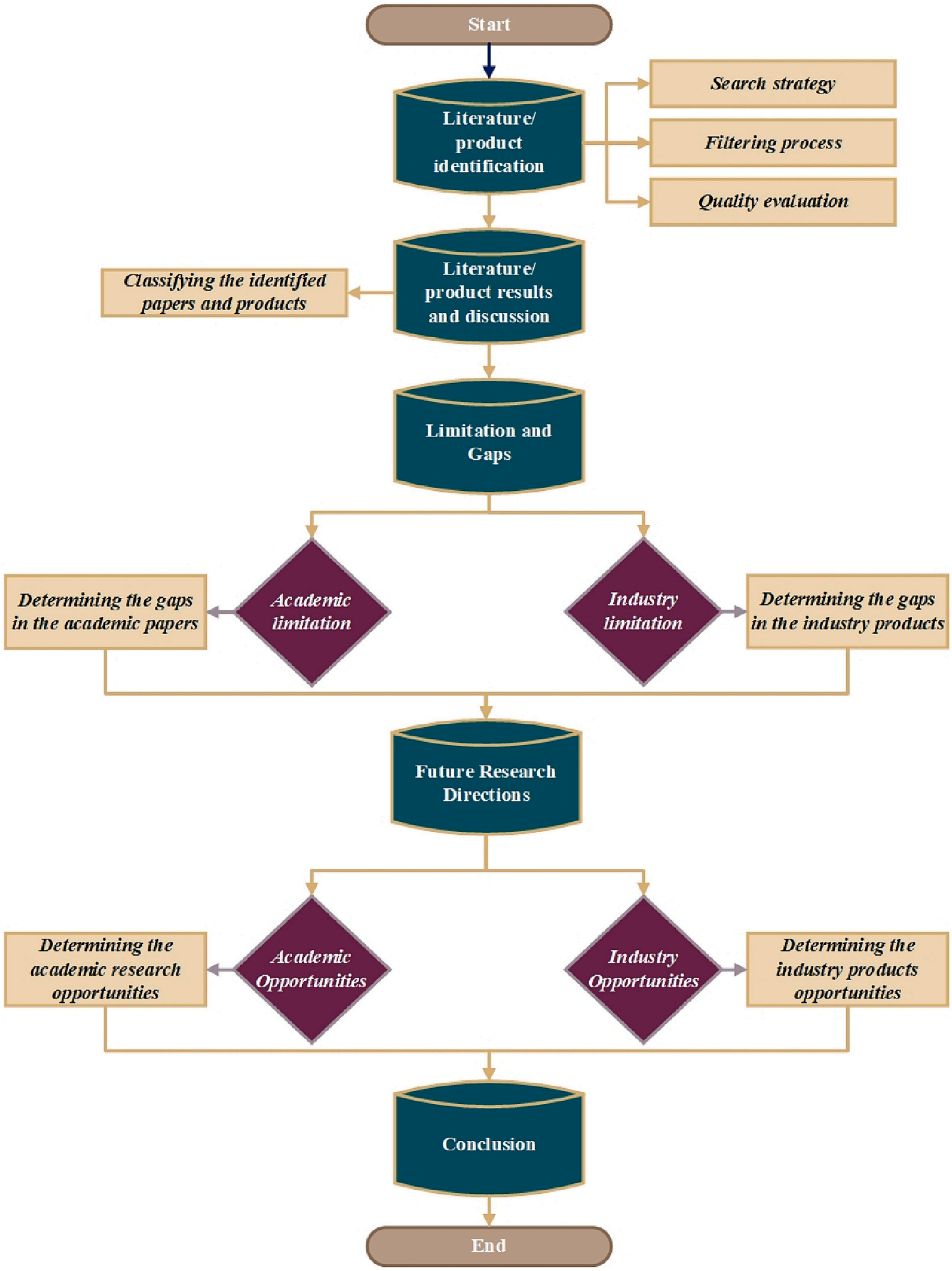

Fig. 2. Overall research methodology.

data to make predictions and identify contributing factors to accidents [54]. For instance, [55] introduced an IoT-based machine-learning model tailored to forecast TC reactions to intense winds, especially amidst typhoons. These algorithms harness real-time data from IoT sensors to gauge maximum tower displacement, showcasing their potential for field measurements. Notably, the model accurately predicted the maximum tower structure displacement during super typhoon In-fa, relying on on-site wind speed and IoT-monitored displacement data. However, the research solely delves into wind impacts on crane structures, overlooking variables like seismic activity or human errors. Validation in real-world projects is essential to assess its broader effectiveness, an aspect overlooked in this research. Additionally, the study confines its focus to a specific type of TC in a distinct coastal area of China, potentially limiting the transferability of its conclusions to other crane types or diverse geographic settings.

Additionally, [56] introduced a BPNN (Backpropagation Neural Network) model tailored to predict safety hazards associated with TCs in high-rise structures. This model replicates human brain processing, enabling it to discern intricate patterns and extract insights from a vast dataset. It considers crucial operational variables and accident probabilities when integrated into a TC construction safety assessment system. Validation using data from 90 TC accidents supports the model's accuracy, revealing a prediction deviation of <15%. However, the paper lacks a discussion on potential constraints or limitations in implementing the proposed safety evaluation system and neural network model in real-world construction settings, overlooking crucial factors like data

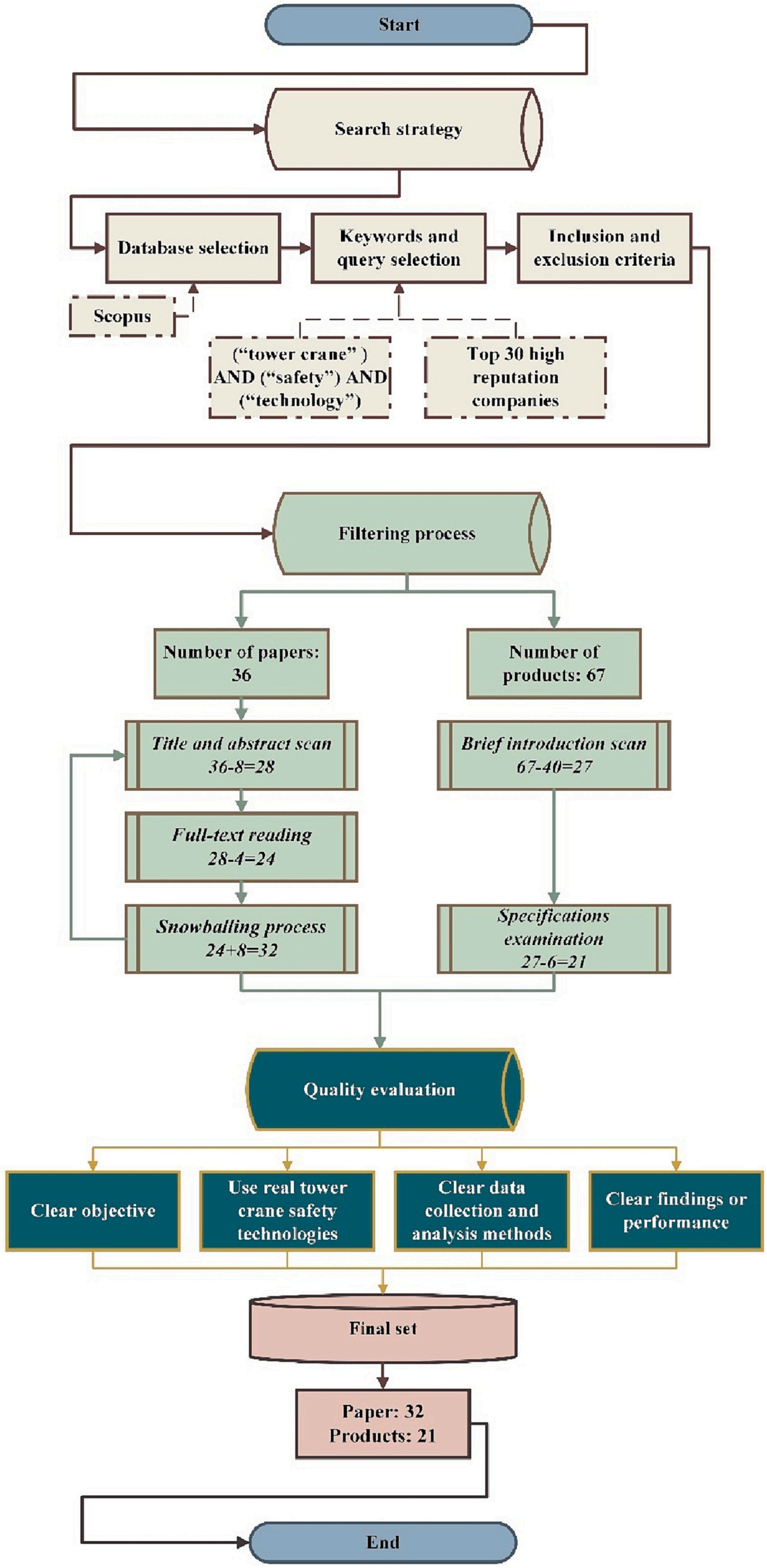

Fig. 3. PRISMA schematic for information retrieval.

Table 3
List of companies, their locations, and available products.

Company Name	Region	Products
Turner's Innovation	US	CraneView™ system
AMCS Technologies	France	DCS 61-S Site Supervisor
Scarlet Tech	Taiwan	Hercules crane camera
Epec	Finland	Cloud support system
AGC International	US	Suspended load system
ABB Robotics	Sweden	Specific programmable logic controller
Hicharm	Malaysia	Safety Monitoring System
viAct	Hong Kong	AI Video Analytics
Ailytics	Singapore	AI Video Analytics
Rika	UK	Anemometer
Zoomlion	China	Pilot 5G Tower Crane Remote Intelligent Control System
Hongdian	China	Tower Crane Wireless Management Platform
Chengdu Hi-tech	China	Load moment indicator Anti-collision and zone protection system
Weite	China	Hook Monitoring Wire Rope Nondestructive Testing Load Moment Indicator Real-time monitoring system Tower anti-collision system Overload limiter

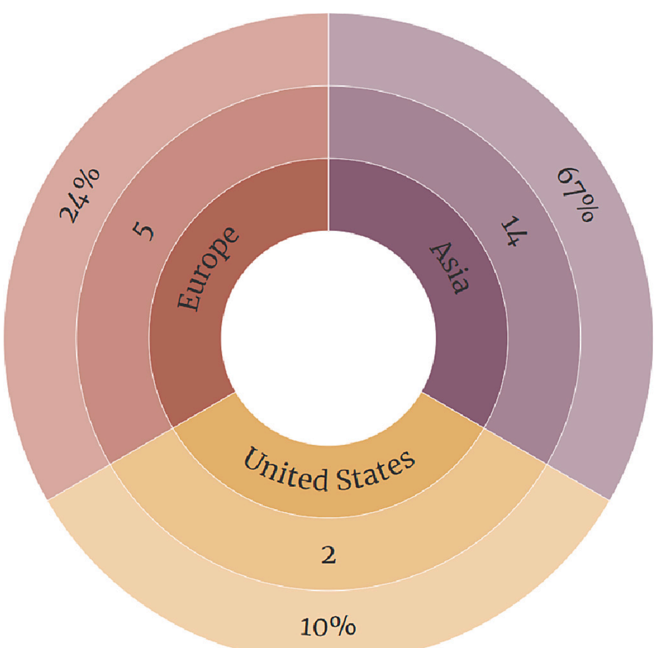

Fig. 4. Number and percentage of countries providing crane-related products on the same continent.

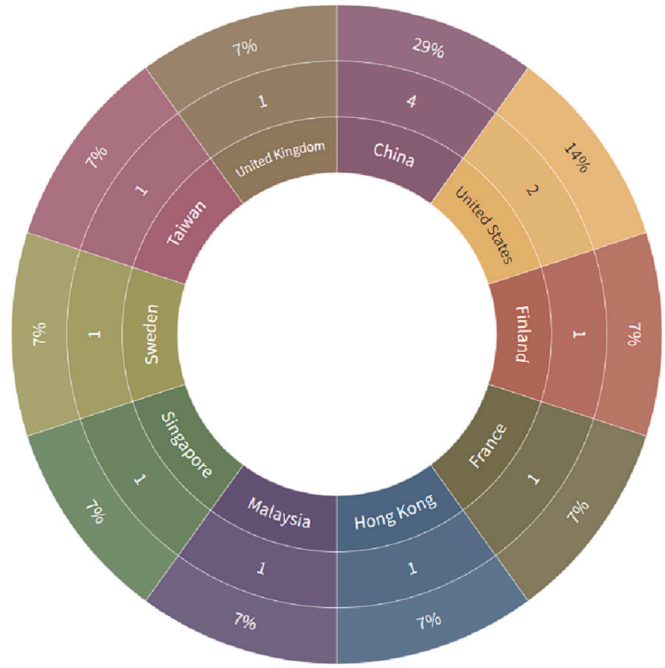

Fig. 5. Number and percentage of companies in each country.

availability and resource constraints.

[57,58] independently introduced BPNN models to predict safety risks, monitor TC operations, and forecast faults during construction. These models highlight the promise of artificial neural networks, specifically BPNN, in bolstering safety, reliability, and efficiency through real-time monitoring and fault anticipation. However, the papers lack discussion regarding the challenges associated with implementing BP neural networks in actual crane operations. It overlooks considerations such as potential limitations, external factors like environmental conditions or equipment malfunctions, and their potential impact on the accuracy and reliability of the models. Additionally, the papers fail to provide information on the size or diversity of the dataset used to train and test the BP neural network models. This information is critical in assessing their robustness and practicality.

[59] employed the Multiple Imputation Random Forest (MIRF) technique to develop a TC accident prediction model using historical accident data. The study showcases the MIRF model's effectiveness in handling incomplete data, a common occurrence in real construction settings. It delivers precise forecasts for various accident phases, maintaining robust prediction accuracy even when dealing with 20% missing data. Although the MIRF model exhibits impressive handling of incomplete data, its performance notably declines when missing data reaches the 40% mark. This decline in accuracy emphasizes the critical significance of comprehensive data collection for optimizing the model's performance, particularly under circumstances where crucial factors are absent.

3.1.2. Operation planning

9 out of 14 papers discuss the operational planning of TCs. Operation planning of cranes using machine learning and algorithms involves using data-driven techniques to optimize, enhance, and plan the operation of cranes. It focuses on making informed decisions to improve safety, efficiency, and productivity in crane operations [32]. For example, [23] presented an automated Prevention through Design (PtD) technique targeting Hazard Exposure (HE) from TC operations (TCO) within construction sites. This method employs a Practicality and Safety-aware RRT* (PSRRT*) to estimate and visualize the dynamic distribution of TCO hazards, generating safe lift paths. Integrating algorithm-based paths enhances accuracy, detail, and inclusiveness. Additionally, Building Information Modeling (BIM) aids in visualizing HE heatmaps and validates control measures by coordinating crane operations with on-site activities. However, the method overlooks crane-to-crane collisions in automated path planning and excludes TC anti-collision mechanisms from the Hazard Exposure Estimation Module. The study recognizes the ongoing need for administrative measures and safety devices like prioritizing crane heights and deploying anti-collision radars to ensure real-time protection for workers and operators.

[60] applied RRTs (Rapidly-exploring Random Trees) algorithms for crane motion planning and dynamic re-planning, operating almost in real-time. Their motion planning algorithm efficiently crafts secure and fluid paths, meticulously considering engineering constraints and path quality. Meanwhile, the dynamic motion re-planning algorithm ensures

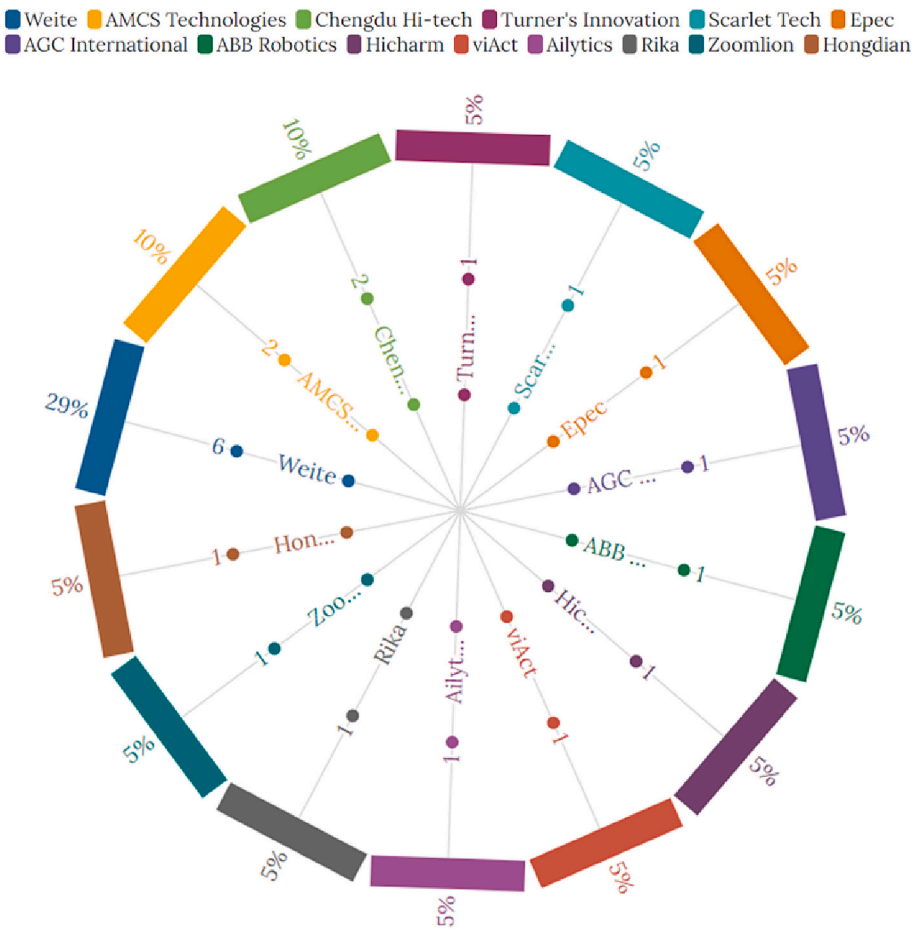

Fig. 6. Number and percentage of products introduced by each company.

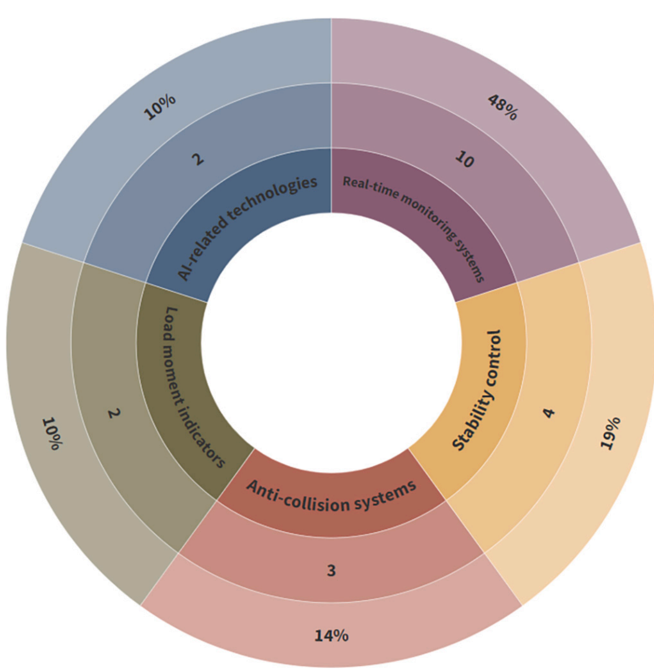

Fig. 7. Number and percentage of purposes and aims for various tower crane safety products.

safety during execution by adapting to and sidestepping potential collisions. The study showcases enhanced path quality, reduced execution time, and cost savings within crane operations. However, the paper lacks an in-depth analysis of the computational complexity of these algorithms, which is critical for assessing their scalability and feasibility in practical applications. While the evaluation measures planning and re-planning times and path costs, there is an absence of discussion on their performance concerning crucial factors like accuracy, robustness, or adaptability across diverse scenarios.

[61] introduced a constraints optimization service facilitated by SWP (Service-oriented Workflow Platform) for dynamically re-planning crane paths during on-site assembly of prefabricated housing production (PHP). This approach enhances planning efficiency by leveraging IoT-enabled BIM platforms and adapting paths based on cost-related values like distance and specific constraints. Their findings illustrate that the crane lifting task necessitates 66 movements, encountering between 1 and 5 dynamic constraints per movement. However, limitations arise concerning the scalability of this approach to larger or more complex construction sites. Effectiveness with 66 movements may not apply to scenarios with significantly more movements or dynamic constraints. Real-time adaptation reliant on IoT platforms could struggle to integrate data updates promptly, potentially affecting path re-planning efficiency. The method's generalizability to other construction settings is uncertain, requiring assessment of factors such as resource utilization, computational complexity, data accuracy, and testing environment relevance for broader applicability.

[62] introduced an optimization model that efficiently schedules multiple TCs operating in overlapping areas, emphasizing the minimization of makespan and collision prevention. Makespan denotes the

duration required to complete scheduled tasks. They proposed the CCGA (Crowding-based Cooperative Genetic Algorithm) as a solution and compared its performance with traditional genetic algorithm (TGA) and near neighbor algorithm (NNA) to evaluate efficiency and effectiveness. Results indicated CCGA's superiority, achieving an optimal makespan and requiring less CPU time. However, the paper solely focuses on the scheduling problem without addressing external factors impacting TC operations, like weather conditions, equipment breakdowns, or material availability. Furthermore, limitations or potential challenges regarding the algorithm's practical implementation in construction sites, such as data accuracy needs, potential conflicts with other activities, or scalability for larger projects, are not discussed.

[63] devised an Agent-Based Model (ABM) simulation tool to scrutinize the impact of dynamic supply selection on crane efficiency. This tool navigates diverse scenarios, pinpointing optimal tasks, crane, and supply location connections to enhance efficiency. It factors in idle time, aiming for the shortest total scheduled time. Results showcased notable improvements in overall scheduling time by considering intricate interactions among supply, demand, cranes, and tasks, leading to around a 15% enhancement in approximately 78.84% of scenarios. However, the paper lacks a comprehensive analysis encompassing all possible crane operation variations and scenarios. Notably, the results stem from a specific case study and may not universally apply to all construction projects. Moreover, the paper overlooks discussing potential constraints or limitations regarding implementing this method in real-world construction, such as data availability, computational demands, and practical feasibility.

[64,65] utilized BIM-based models for TC layout visualization and operation simulation, aiding in detecting spatial conflicts within TC operations and automating plan reviews. Employing a Facility Layout Optimization algorithm and 4D-BIM modeling, respectively, these methods streamline TC planning, minimizing manual input requirements and ensuring consistent reviews across multiple options. As a result, these models exhibit efficiency, safety improvements, and cost-effectiveness. However, the papers fail to address potential challenges or limitations in practically implementing these approaches within real-world construction projects.

[66] employed 4D-BIM to devise an optimized assembly sequence and lifting path for precast elements, emphasizing efficiency and safety in lifting operations. The study emphasizes collision-free lifting paths as pivotal for determining the optimal sequence, thereby enhancing safety in TC operations. Results suggest that integrating lifting and assembly processes in precast construction holds promise for achieving collision-free, safe, and efficient lifting of wall elements. However, the research focuses solely on assembly scheduling and lifting path planning for wall elements in precast construction, omitting consideration for other precast elements like columns and beams. Moreover, the presented case study pertains only to a residential building, potentially limiting the generalizability of findings to other construction projects. Critically, the paper overlooks discussing potential challenges or limitations in implementing the proposed BIM4D-based Intelligent Assembly Scheduler (BIAS) in real-world construction scenarios. Furthermore, the research does not address external factors such as weather conditions or site-specific constraints on assembly scheduling and lifting operations.

[67] developed an automatic re-planning module within the Computer-Aided Lift Planning (CALP) system, utilizing GPU-based parallelization for collision detection and path planning. This system incorporates BIM and Single-level Depth Map (SDM) representation to condense datasets effectively. Introducing a novel re-planning decision-making algorithm utilizing multilevel Oriented Bounding Boxes (OBBs) within the Decision Support System (DSS), the study showcases how critical obstacles are identified, guiding re-planning decisions based on collision checks with the environment's SDM points. Additionally, the Path *Re*-planner (PRP) selects initial configurations for local re-planning, yielding locally optimized paths. However, the paper lacks discussion regarding potential limitations or challenges in implementing the re-planning module within real-world construction environments. Furthermore, insights into the scalability or adaptability of the CALP system across various construction project types or crane operations are notably absent from the research.

3.2. Monitoring technologies during construction

The numbers show that 3 of 32 academic studies and 13 of 21 industry products are centered around monitoring technologies during construction. This indicates a significant emphasis on monitoring technologies in practical industry products, while academia focuses less on this specific aspect. Monitoring technologies in crane operations encompass a range of systems and methods employed to oversee and control the operation of cranes within industrial and construction environments. These technologies are critical for ensuring safety, optimizing performance, and minimizing downtime. They can be sub-

Table 4
List of tower crane manufacturers, their locations, and their safety efforts.

Manufacturer	Region	Safety Efforts
Potain (by Manitowoc)	France	Focuses on safety features like remote monitoring, overload protection, and advanced jib configurations to ensure safe and efficient operations.
Liebherr	Switzerland	Implements safety features such as advanced control systems, anti-collision technology, and precise monitoring systems to enhance safe operations.
Jaso	Spain	Implements safety features such as anti-sway technology, overload prevention systems, and user-friendly control interfaces to ensure safe and efficient crane operation.
Terex	United States	Focuses on safety with advanced control systems, limit switches, and safety devices incorporated into their TC designs to prevent accidents and ensure safe operations.
Wolffkran	United States	Known for innovative safety features like their "WolffBoost" system, which enhances crane performance while maintaining safety, as well as their advanced control technology.
Comansa	Spain	Prioritizes safety through features like precise load control, anti-collision systems, and ergonomic designs for the operator's safety and comfort.
Saez	Spain	Emphasizes safety by integrating features such as precise load control systems, anti-collision technology, and operator safety training programs.
Zoomlion	China	Implements safety features like automatic safe load control, precise positioning systems, and rigorous safety monitoring mechanisms to enhance overall safety.
FMGru	Italy	Known for their commitment to safety by incorporating features like automatic brakes, overload protection, and advanced control systems in their TC designs.
Favelle Favco	Malaysia	Known for their focus on safety through advanced control systems, high-quality materials, and compliance with global safety standards in their TC manufacturing.
Hankook Tower Crane (HKTC)	Korea	Implements advanced safety technologies such as anti-collision systems, load monitoring sensors, emergency braking systems, overload protection, anti-tipping devices, and intelligent control mechanisms in their TC designs.
Action Construction Equipment (ACE)	India	Utilizes remote operation capabilities and a proactive approach to understanding and mitigating hazards to promote safer TC operations.

Table 5
Comparison of crucial elements of different tower crane technologies.

Studies	Category	Target variable	Data source	Key indicator	Methods/ Technologies	Feedback	Timing of the function
[47–50,52–61]	PPCMT	• Cranes	• Accidents Reports • Sensors	Risk probability	• Machine learning • Optimization algorithms • Simulation	Warning	Beforehand
[62–69,70–77]	MTDC	• Cranes • Site equipment • People	• Cameras • Sensors	Threshold value of the sensor	• IoT • AI	Warning	Real-time
[21,78–86]	ATDC	• Cranes • Surrounding environment	• Cameras • Sensors	Distance between the crane and other objects (e.g., nearby structures)	• Computer vision • Simulation • Optimization algorithms • IoT	Warning + control	Real-time
[87–98]	SCTDC	• Cranes • Crane parts (e.g., base and jib)	• Cameras • Sensors	Stability indicators	• Machine learning • Computer vision • Optimization algorithms • Digital Twin	Warning + control	Beforehand/ Real-time

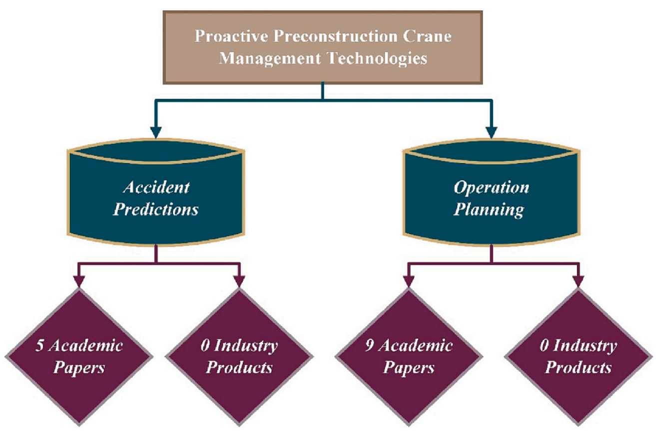

Fig. 8. The hierarchy of the proactive preconstruction crane management technologies category.

categorized into two primary approaches: onsite monitoring and remote monitoring. Fig. 9 shows the category hierarchy and its sub-categories.

3.2.1. *On-site monitoring*

In this sub-category, 1 out of 3 academic papers investigated onsite monitoring. In contrast, 7 out of 13 industry products delve into onsite monitoring. On-site monitoring for crane operation involves real-time observation and supervision of crane activities in construction sites. Technology, sensors, and data collection methods ensure safety, efficiency, and regulatory compliance. It identifies potential hazards and offers immediate feedback to operators for smoother and safer operations. For instance,

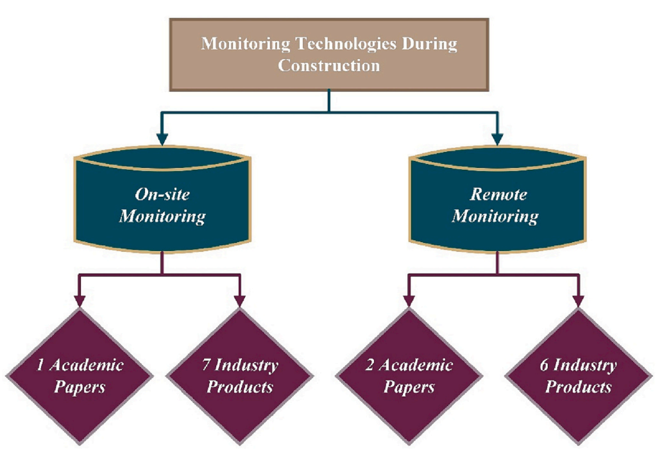

Fig. 9. The hierarchy of the monitoring technologies during construction category.

[68] introduced an Autonomous Jobsite Safety Monitoring System integrating various sensors like RFID, localization sensors, accelerometers, load cell sensors, and BIM data. This system comprehensively analyzes load dimensions, clearance distances, and worker movements, employing a yellow-green safety zone to alert workers to potential risks during transitions. Results highlight a consistently higher recall and capture rate compared to traditional methods, validating the system's efficacy in pinpointing worker locations on construction sites. However, the paper lacks an extensive exploration of potential impacts stemming from data errors on decisions within autonomous job site safety monitoring systems. Similarly, it does not delve into potential strategies or solutions to mitigate the effects of data errors on the performance of safety monitoring systems. Additionally, there is a lack of discussion regarding the scalability or applicability of the findings to different construction sites or various types of safety monitoring systems.

[69,99] introduced AI Video Analytics for construction site monitoring, utilizing IP cameras to oversee critical zones. This technology allows for safety trend tracking and proactive measures, monitoring workers near TCs and machinery operations via GPS within a 5-m horizontal and 6-m vertical range. It triggers immediate sound alerts for crane operators and activates light and sound alarms for on-site workers in potential danger zones. However, further investigation is necessary to ensure its efficacy regarding the system's precision in tracking movements, the effectiveness of alerts in accident prevention, adaptability to varied conditions, integration into safety protocols, and ethical considerations related to constant surveillance. Furthermore, the system does not mention any data security procedures to protect information collected from potential vulnerabilities. This raises significant concerns about the safety of both the collected data and the personal information of individuals.

[70] presented a hook monitoring system, incorporating an automatic video navigator within the crane's cabin alongside an HD Hook Camera situated atop the TC's hook. This innovative setup captures real-time video footage of the hook's position and its immediate surroundings, empowering crane operators with direct visual monitoring during lifting operations. This immediate visual insight enables operators to autonomously address potential load irregularities, minimizing reliance on external communication and reducing miscommunication risks. However, a comprehensive examination of the system's reliability, response time in detecting anomalies, and its integration within broader

safety protocols remains essential for validating its effectiveness in enhancing crane operation safety. Additionally, considerations regarding system maintenance, adaptability in various environmental conditions, and potential technological limitations warrant further exploration for a more robust implementation of this technology.

[71] launched the WTL-A220 Load Moment Indicator, specifically designed to avert overloading. This system comprises sensors, cables, and a microcomputer host. An intelligent weight sensor consistently measures fluctuations in the load weight. Upon reaching the predetermined limit, it triggers an acoustic-optic alarm, alerting operators to potential overloading risks. Remarkably, this device accommodates a wide weight range, from 0 T to 400 T, and boasts minimal synthetic errors of $\leq$5%, ensuring dependable protection throughout operations. However, further scrutiny is required to comprehensively evaluate its efficacy regarding its accuracy under diverse operational conditions, potential false alarms, integration into existing safety protocols, and adaptability to varying environmental factors impacting load measurements. A detailed assessment of these aspects would ascertain the device's reliability and practical utility in preventing overloading incidents across different operational scenarios.

[72] introduced a Wire Rope Nondestructive Testing and Monitoring system aimed at detecting changes in the stray magnetic field of wire ropes. This technology can determine various issues such as wear, broken wires, corrosion, and deformation. By recording magnetic field intensity components, it evaluates stress concentration, micro-defects, and internal stress. Changes in the magnetic field precisely determine the location and severity of damage. The system showcases remarkable precision, boasting a mere $\pm$1% error in diameter measurement and over 95% accuracy in pinpointing damage locations, thereby enabling prompt maintenance for worn ropes. Nevertheless, a comprehensive evaluation encompassing its performance in diverse environmental conditions, potential limitations in detecting certain types of damage, integration into maintenance protocols, and its cost-effectiveness in routine inspections is necessary to gauge its practical utility in ensuring ongoing safety and reliability in crane operations.

[73] introduced the HICHARM TSM system for TC Safety Monitoring, which utilizes IoT and Sensor Detection Technology to enhance crane operator safety. The system incorporates the HICHARM cloud, enabling the uploading of critical data such as load, moment, height, trolley slewing, swing direction, wind speed, and luffing angle to prevent overloading. Additionally, it includes an anti-collision and zoning system to detect potential TC collisions with structures or obstacles, offering TC operators valuable operational assistance through a digital display. However, it is essential to conduct a comprehensive analysis of the system's reliability under various operational conditions, its response time in detecting collisions or potential overloading, its adaptability to diverse construction environments, and its integration into existing safety protocols. Additionally, there are concerns about the security features within the system itself, such as authentication protocols for accessing data, implementation of secure communication channels, and regular system updates to patch any identified security loopholes. These concerns raise doubts about the system's security and data protection.

[74] launched the CXT-90IIA, a Multi-Function Indicator system that offers real-time status updates for single or multiple TCs. It is equipped with height, traveling, slewing, and wind speed sensors, which gather critical data and store work records. It has the ability to connect to up to 30 TCs. The safety features encompass three levels: a warning at 90% of capacity, an alarm at 100%, and an automatic stop at 105% to prevent unsafe operations. Despite its advertised connectivity for up to 30 TCs, concerns arise about its efficacy and performance under heavy network loads. Questions persist regarding the effectiveness of safety features, particularly the automatic operation stoppage at 105% capacity, raising concerns about abrupt crane function cessation during critical construction scenarios. Furthermore, the precision and reliability of the integral sensors, crucial for ensuring safe crane operations, lack detailed information, creating ambiguity about their accuracy and calibration. Additionally, essential factors like maintenance requirements, susceptibility to environmental conditions, and potential system malfunctions are notably absent.

3.2.2. Remote monitoring

2 of 3 academic papers and 6 of 13 industry products discuss remote monitoring. Remote monitoring for crane operation involves using technology and communication systems to observe and control crane activities at construction or industrial sites from a distance. It replaces on-site personnel, allowing operators and supervisors to oversee crane operations via the internet or dedicated networks. This enhances safety by continuously monitoring crane performance, load management, and operator behavior, offering real-time alerts for swift issue resolution [75]. For instance, [76] developed a mobile monitoring system to optimize remote communication protocols for assembly TCs through IoT technology. This study targeted various challenges, such as driver vision blind spots, difficulties in communicating with signal flag bearers, and high data loss rates in existing systems. The findings indicate that integrating IoT technology enhanced the average data loss rate in the mobile monitoring system for TCs. However, the experimental results solely focused on comparing the average packet loss rates of the designed system with other methods, neglecting discussion on other performance metrics or potential limitations. Furthermore, the paper omitted any exploration of the system's scalability or adaptability across diverse construction sites or scenarios. Notably absent was any discussion regarding potential security or privacy concerns associated with the mobile monitoring system.

[77] introduced a remote monitoring and alarming system for TCs that relies on data-driven approaches and 3D simulation integration. Their system integrates field data with 3D simulation, employing a smart Controller Area Network (CAN) Bus-based data acquisition and transmission system. This system aims to enhance the flexibility and volume of information acquired. They implemented the Module-Position-Attitude-Scale (MPAS) method, enabling easier construction of a virtual crane through parameterization and modularization techniques. However, the fusion of field data and 3D simulation might demand considerable computational resources, potentially leading to limitations in real-time processing and system responsiveness. Moreover, implementing and popularizing this system might encounter hurdles related to user acceptance, training, and ongoing maintenance, impacting its practical adoption. Additionally, the system's setup and calibration requirements could pose limitations, especially in time-sensitive scenarios where quick deployment is essential.

[100] introduced the CraneView™ system, which utilizes IoT sensors attached to the crane hook. These sensors leverage AI to categorize lifted objects, record weights, and measure lift cycle durations. The collected data is accessible through an online and mobile dashboard, empowering site teams to evaluate crane performance, set alerts, and generate detailed reports. This facilitates improved crane planning and task sequencing. Notably, the CraneView™ system showcased its reliability during its implementation in the Manchester Pacific Gateway project in San Diego. It oversaw over 2113 crane lifts with zero under-the-hook safety incidents and misses. Nevertheless, relying solely on IoT sensors raises concerns regarding robustness in adverse conditions and potential calibration issues impacting data accuracy. Success in one project might not universally apply due to diverse construction site challenges. Moreover, crucial details like integration into existing infrastructure, compatibility, maintenance expertise, and scalability were omitted. Although the system highlights object categorization and weight recording, the precision and reliability of these functionalities remain unexplored, leaving uncertainties about their accuracy.

[78] introduced a real-time monitoring system designed to continuously track crane statuses and mitigate risks. This system integrates a built-in remote module designed for swift defect diagnosis and repairs. It enables remote monitoring across multiple operations by providing real-

time GPS positioning and movement tracking. It boasts high accuracy, with error rates of ≤5% and motion errors of ≤ ± 3%, allowing precise location monitoring to adhere to planned schedules. While the system claims high accuracy rates, the crucial context regarding the conditions under which these error rates were measured is absent. This absence raises uncertainties about its reliability in real-world conditions. Moreover, the efficacy of the remote module for defect diagnosis and repairs lacks explanation, leaving doubts about its capacity for on-site intervention. The precision and reliability of the GPS positioning and movement tracking functionalities remain unexplored, raising concerns about its performance in dynamic construction environments. Furthermore, crucial details regarding scalability, compatibility, integration, and maintenance are missing, hindering a comprehensive evaluation of its suitability for diverse settings.

[79] introduced the Hercules Crane Camera, an IoT-integrated camera designed for long-range capture of high-quality 2 k video feeds from cranes and construction sites. It offers 24/7 remote live viewing and video backup, supported by a sustainable solar battery lasting up to 35 h. The camera allows software customization, including integration with network video recorders tailored to client-specific systems. Equipped with a defogging feature for low-visibility environments and ultra-long wireless communication to eliminate blind spots during crane operation. However, critical details regarding the test conditions validating claims about video quality and battery life, potential performance limitations in adverse weather or lighting conditions, and the reliability of continuous streaming via wireless communication remain undisclosed. These omissions raise concerns about potential disruptions in data transmission. Furthermore, the effectiveness of the defogging feature in real-world scenarios and its impact on video clarity under different environmental conditions are uncertain. Additionally, the system's security measures are not discussed, which raises concerns about exposing the system to cyber threats.

[80] introduced the Site Supervisor Sup 61 system, featuring a radio connection for crane communication and data exchange. It records data for every crane, providing real-time updates on positions, movements, and weather conditions, including wind speed. The processed data is available for download, and multiple workstations can access it simultaneously for efficient crane operation management. Notably, the system's deployment at the Vinci HQ job site with 11 flat-top cranes resulted in zero TC accidents. Although the system claims to offer real-time updates on various parameters, there is a lack of specificity regarding the frequency of data updates and the potential impact of latency in communication, particularly in scenarios where instantaneous data transmission is critical for crane operation safety. Additionally, details concerning the system's adaptability to diverse crane models, potential vulnerabilities to signal interference, or the system's performance under adverse weather conditions are notably absent. These factors hinder a comprehensive understanding of its reliability and effectiveness across various construction settings.

[81] unveiled a cloud support system that seamlessly integrates IoT, edge computing, and remote diagnostics. The central unit controllers ensure real-time data collection with 4G/LTE/GNSS/WLAN connectivity. This data is used to optimize lifting routes for TCs, relieving operators of decision-making responsibilities. Construction progress can be monitored through a web browser and shared with relevant stakeholders. However, while the system claims to optimize lifting routes and reduce operator decision-making, there is a lack of clarity regarding how it determines these optimal routes. This absence raises concerns about its adaptability to complex construction scenarios or unforeseen site-specific challenges. Additionally, the system emphasizes real-time data collection but lacks crucial specifics such as update frequency, potential data transmission delays, and performance in varied network conditions. These uncertainties cast doubt on its reliability in critical operational situations. Furthermore, the system lacks explicit details about data protection measures and strategies for ensuring data security, prompting questions about the safeguarding of collected information.

Finally, [82] unveiled Pilot 5G Tower Crane Remote Intelligent Control System, a revolutionary technology that combines 5G connectivity with intelligent control to manage TCs remotely. This system comprises four cutting-edge subsystems: video surveillance, intelligent hook tracking, digital status monitoring, and anti-collision and dispatch systems. This technology restored TCs, changed construction methods, enhanced operator conditions, and reduced labor intensity to ensure safety. Despite emphasizing cutting-edge subsystems like video surveillance, intelligent hook tracking, digital status monitoring, and anti-collision systems, the system lacks explicit details about their comprehensive functionality, precision, and adaptability across diverse operational conditions and construction environments. Deeper exploration is needed to assess robustness in adverse weather conditions, vulnerabilities to cyber threats, and the accuracy of control mechanisms for ensuring precise crane operations, which is crucial for a comprehensive reliability assessment. Moreover, the absence of information regarding integration, compatibility with existing crane models, operator training requirements, limitations in remote management, and emergency response strategies impedes understanding its scalability and adaptability in various construction settings.

3.3. Anti-collision technologies during construction

Out of the 32 academic papers, 7 discuss anticollision technologies. In contrast, 3 out of 21 industry products focused on anti-collision technologies during construction. This indicates a shared emphasis on safety in both academia and the industry, with the potential for collaborative efforts to improve construction site safety through technology and research. Anti-collision technologies aim to prevent physical collisions or interference among objects, vehicles, or machinery. These technologies use sensors, algorithms, and communication systems to detect object proximity and take preventive actions, like issuing warnings, altering trajectories, or stopping movement to avert collisions. They can be sub-categorized into two approaches: Collision of Cranes with Surrounding Environment and Collision of Cranes with Other Cranes. Fig. 10 presents the hierarchical structure of this category, including its corresponding subcategories.

3.3.1. Collision of cranes with surrounding environment

In this sub-category, 3 of 7 academic papers and 2 of 3 industry products discuss crane collisions with the surrounding environment. Collision of Cranes with Surrounding Environment is a significant safety issue in construction settings where cranes are employed. It transpires when a crane in operation contacts nearby structures, equipment, or objects. Collisions of this nature can result in extensive damage to the crane itself and adjacent structures, posing a threat to the safety of both

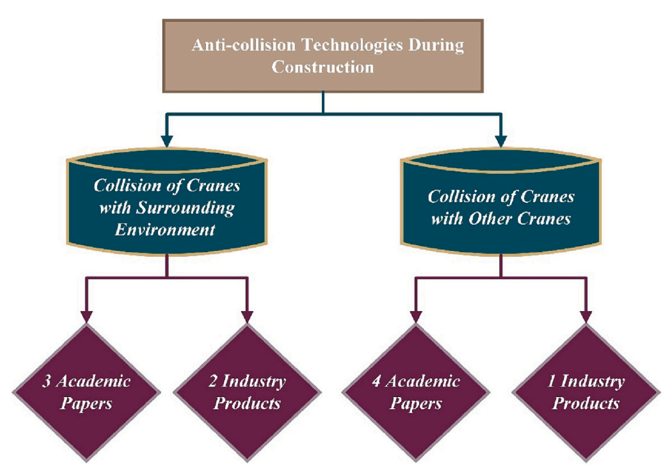

Fig. 10. The hierarchy of the anti-collision technologies during construction category.

crane operators and on-site personnel [83].

For instance, [28] developed an automatic collection, analysis, and early-warning system integrated with workers on construction sites. Utilizing TC camera footage and employing the MASK R-CNN method, the system achieved remarkable image recognition accuracy with a mean average precision of 0.986, enabling meticulous monitoring of TC operations for safety and efficiency. However, while the system exhibited high accuracy in image recognition, specific details regarding its performance in varying lighting conditions, cluttered environments, or scenarios with obstructed views remain undisclosed. Additionally, aspects such as practical implementation in dynamic construction environments, potential false positives or negatives in hazard identification, and adaptability to different construction sites or crane models necessitate further exploration for a comprehensive assessment. Additionally, the paper fails to address potential security or privacy concerns associated with the mobile monitoring system, which are critical considerations for real-world applications.

[84] introduced a pioneering dynamic collision prewarning system for TC construction, integrating vision and trajectory analysis. This innovative approach harnesses computer vision and on-site cameras to predict real-time collision risks, specifically anticipating potential worker-load collisions and elevating safety standards in TC operations. However, the paper primarily concentrates on developing and evaluating the mechanism without delving into potential challenges or limitations in its practical implementation or real-world application. Crucially, the discussion lacks mention of potential limitations in the data collection process, such as data availability or quality used for training and testing the models. Additionally, the study overlooks addressing potential computational or resource limitations that might arise when deploying the proposed mechanism in real-time scenarios, an aspect crucial for assessing its practical feasibility.

[85] presented a point cloud segmentation algorithm employing Dynamic Graph CNN (DGCNN) to detect crane parts within construction yards. The segmentation data was obtained using LIDAR sensors. Their findings indicated that DGCNN outperformed PointNet, demonstrating higher recall and precision values. This superiority in segmentation accuracy for both crane parts and the background highlights its potential suitability for collision avoidance systems. However, the algorithm's evaluation was limited to a maximum distance of 50 m, requiring further assessment across longer distances for broader effectiveness. Additionally, the absence of comparative analysis with other crane collision avoidance systems impedes understanding its performance. Lastly, the manual labeling of point cloud data introduces potential inaccuracies, risking compromised functionality, particularly for DGCNN relying on local features.

[86] developed the DCS 61-S system to enhance safety and efficiency in crane operations, especially in environments with multiple cranes in close proximity, such as the construction industry. This system includes anti-collision measures, real-time monitoring, data logging, inter-crane communication, and zoning capabilities. It continuously calculates 3D distances between crane components to prevent collisions, monitors movements, and identifies collision risks. It triggers alarms or slows and immobilizes crane movement when nearing obstacles. While touted as comprehensive and effective in collision prevention, specific details are required regarding its reliability across diverse environmental conditions or scenarios, potential blind spots, and limitations in accurately detecting obstacles. Moreover, the operational efficiency of its preventive actions, such as slowing or immobilizing crane movements, may pose challenges impacting construction schedules, warranting a more nuanced explanation.

[101] presented the CXT-90IIB anti-collision and zone protection system designed for TCs. This system utilizes Amplitude Traveling and Slewing Sensors to continuously monitor crane operations, promptly triggering pre-alarms or alarms upon detecting potential threats. Notably, it offers flexible zone protection, allowing for up to 10 prohibited zones and 30 boundary protection points. Its crucial feature involves simplified configuration through wireless parameter adjustments via computers, eliminating the need for manual TC adjustments and enhancing safety and operational efficiency. Nonetheless, the effectiveness of real-time wireless adjustments and the system's adaptability to dynamic site conditions lack specific details. Although it emphasizes its capabilities in threat detection and alarming, further clarification is necessary regarding detection precision, the possibility of false alarms, and potential limitations in detecting specific hazards.

3.3.2. *Collision of cranes with other cranes*

4 out of 7 academic papers and 1 out of 3 industry products delve into crane collisions with other cranes. Collision of Cranes with Other Cranes is a significant safety concern in construction settings where multiple cranes operate closely. It occurs when two or more cranes unintentionally collide during their lifting and movement operations. These collisions can lead to substantial crane damage, operator risks, and work schedule disruptions [87]. For instance, [88] utilized AnyLogic software to develop a 4D simulation model to prevent crane collisions in construction sites with overlapping crane operations. The model features a user-friendly interface accessible from the crane operator's cabin, providing essential data on crane positioning, movement, proximity to other cranes, and obstacles. Successfully deployed in Lebanon, it effectively issued warnings near safety thresholds, significantly improving safety and operational efficiency. However, the study overlooks potential challenges associated with integrating additional sensors for measuring velocities and accelerations, potentially impacting the effectiveness of the anti-collision system. Furthermore, there is no mention of challenges related to designing a load-stabilizing controller or a clash avoidance system based on the collected data, creating gaps in understanding potential limitations.

[89] developed a real-time location system using computer vision-based (CVB) technology for precise 3D localization of TCs and hooks. This system aims to improve construction site safety by estimating jib orientation and hook positions. Far-field surveillance cameras enable geometric feature reconstruction accuracy of $<2.0\%$ and identification prediction errors of $<5.0\%$. This precision enhances data accuracy, reduces accident risks, and enhances overall construction site safety. However, potential limitations lie in environmental susceptibility, coverage over longer distances, adaptability to dynamic conditions, data processing speed, error tolerance, and seamless integration within existing construction operations. Addressing these limitations through comprehensive testing under varied conditions is crucial for validating the system's reliability and applicability in real-world construction environments.

[90] introduced a Mixed Integer Linear Programming (MILP) model to optimize service schedules for multiple overlapping TCs, prioritizing transportation efficiency and operational safety. Their findings demonstrated a notable 6.54%–18.07% reduction in total operational costs and enhanced operational safety by preventing collisions between cranes. This innovation significantly improves the real-life scheduling of multiple TCs, positively impacting efficiency and safety. However, the paper does not address potential limitations or challenges in implementing the MILP model in real-life construction scenarios nor discusses the model's scalability or adaptability to different construction projects. Additionally, it does not explore potential limitations or drawbacks of the anti-collision systems mentioned, such as Ultra-Wide Band (UWB), Radio Frequency Identifications (RFID), Global Positioning System (GPS), Encoder, and Inertial Measurement Unit (IMU).

[91] introduced the Safety Management System for TC Groups (SMS-TC), aiming to bolster individual TC safety during construction by integrating Wireless Sensor Networks (WSN) and Internet of Things (IoT) technologies. The proposed anti-collision algorithm draws upon collective status data from the entire crane group to protect each TC. However, despite its potential advantages, several limitations are evident. The wireless communication system using Zigbee networks might encounter constraints related to range and susceptibility to

interference. Additionally, initial implementation may necessitate a significant investment in specialized sensors and infrastructure. Concerns regarding data security and privacy arise due to the transmission and storage of sensitive information. Despite undergoing testing in simulated environments, the system's performance in real-world scenarios remains unverified, potentially casting doubt on its practical efficacy.

[92] introduced the WTAU WT-W660V2 tower anti-collision system, integrating advanced millimeter-wave radar sensors to detect obstacles surrounding cranes actively. The system transmits data to alert crane operators when obstacles are detected on both sides of the crane's boom, enhancing safety and preventing potential collisions. The radar sensor is sensitive and capable of detecting objects as small as 15 mm wire ropes within a range of 0.5 m to 8 m, and larger obstacles within a range of 0.5 m to 30 m. This sensitivity enables early hazard detection at construction sites with multiple TCs. However, the effectiveness of the system in various environmental conditions, including inclement weather, dust, or other obstructions potentially affecting sensor accuracy, remains unexplored. Additionally, while the system highlights its capacity to detect small objects like wire ropes, further clarification is needed regarding the reliability of this detection in dynamic construction environments characterized by varying clutter and movement.

3.4. Stability control technologies during construction

8 of 32 academic papers and 4 of 21 industrial products discuss Stability Control Technologies in construction. This highlights the shared interest in these technologies between academia and industry, with a slightly stronger focus on academics. This alignment recognizes the importance of safety in construction and the potential for collaboration to enhance technology utilization. Stability Control Technologies refer to a set of advanced systems and features implemented in cranes to ensure the stability and safety of the crane during lifting and material handling operations. These technologies are crucial for preventing accidents and ensuring efficient and precise crane operation. They can be further categorized into two approaches: Crane Stability Technologies and Load Stability Technologies. Fig. 11 shows the category hierarchy with its subcategories.

3.4.1. Crane stability technologies

It is noteworthy that 5 out of the 8 academic papers and 1 out of the 4 industry products are dedicated to the discussion of crane stability technologies. TC stability in safety operation is its capacity to maintain balance, structural integrity, and safety while lifting and handling materials. It encompasses multiple factors and precautions to prevent

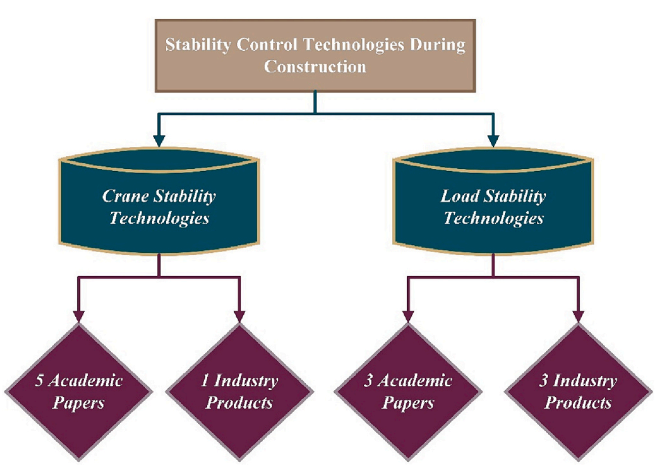

Fig. 11. The hierarchy of the stability control technologies during construction category.

accidents and ensure secure crane operation [93]. For instance, [94] proposed an enhanced back-stepping controller with a fixed-time disturbance observer to manage external disruptions, particularly wind mismatches impacting TC efficiency and safety. The system incorporates the fixed-time disturbance observer, cascade form-based observer, and controller. These observers continuously monitor the crane's status, collecting data on stability-affecting disturbances via dynamic responses and path deviations. Upon detecting such disruptions, they send stabilization signals to the controller, ensuring stability and mitigating their impact on the crane system. However, the linearization of the crane system model while studying unmatched disturbances may introduce inaccuracies compared to the actual crane system. Moreover, the specific parameters and experimental setup utilized in the paper might not comprehensively represent all real-world scenarios and variations in TC operations. Additionally, the paper doesn't discuss potential limitations or challenges associated with implementing the proposed controller in practical applications or real-world TC systems.

[95] introduced a TC security system utilizing an advanced neural network algorithm to autonomously ensure stability and prevent crane overturning, particularly from strong winds. The system relies on wind sensors to continually monitor and predict hazardous wind gusts, enabling preemptive protective measures. Their findings illustrate the system's capability to detect perilous wind gusts and automatically engage the drive control, preventing overturning and maintaining stability. However, the paper lacks discussion on the practical implementation and feasibility of the proposed stability system within real-world construction sites. Additionally, it does not address potential challenges or limitations in integrating the proposed system with existing TC control algorithms. Moreover, there is no exploration of the potential costs or resources required for implementing and maintaining the proposed stability system.

[96] proposed an automated system designed for TC stability analysis, mainly focusing on wind conditions. This system aids in selecting the appropriate crane and foundation dimensions, aiming to minimize lifting stress and travel time while ensuring heightened stability. It considers various factors such as crane type, configuration, spatial limitations, and trajectories to further enhance stability. Their findings demonstrate that integrating crane support analysis with crane selection significantly improves crane stability. However, the paper does not directly incorporate wind effects into TC stability analysis or in selecting a TC and its location. Additionally, the study focuses solely on anchored foundations, neglecting other types of foundations, which limits the generalizability of the findings.

[97] presented a digital twin framework focusing on human-machine interaction in construction. Their objective was to simulate a range of hoisting behaviors realistically and analyze their dynamic effects on TCs. They developed a methodology to assess the collapse potential of components based on their structural composition. The findings emphasize tilt hoisting as significantly hazardous, substantially impacting crane stability. Additionally, the study identifies TC foundations and masts as particularly susceptible to disruption caused by unsafe hoisting behaviors. However, the research's reliance on a scale model might limit its ability to fully encompass the complexities and dynamics inherent in real-world TC hoisting operations. The results are obtained through a specific collapse probability level function, which may have limitations in accurately representing the actual stability change law of TCs. Furthermore, the feasibility and cost-effectiveness of implementing this proposed digital twin framework on actual construction sites lack detailed discussion within the study.

[98] developed spatio-temporal computational fluid dynamics (CFD) models focusing on the safety of TCs that are externally attached to super high-rise buildings in tornado wind fields. The study adopted the modified generalized flexural-shear model (FSM-MS) to estimate the along-wind and across-wind displacement response of the main building and the response at the connection support of the TC, thereby assessing the safety status of TCs. However, the study does not consider other

potential factors that could affect TC safety, such as human error or equipment malfunction. The safety assessment procedure and safety envelopes generated in the study are based on specific and simplified assumptions and scenarios. They may not fully capture all possible failure modes and scenarios that could occur in practice. Additionally, the study is limited to TCs attached to super high-rise buildings in tornado wind fields, and its findings may not be directly applicable to other types of cranes or construction scenarios.

[102] introduced a specialized programmable logic controller (PLC) designed to ensure maximum structural load management during crane operations. This PLC seamlessly integrates with variable speed drives, facilitating efficient crane communication and control. The system establishes a network that connects the safety PLC in the control room with those installed on the cranes, enabling remote emergency stop control. In critical situations, operators can activate the stop button from a remote station and select the specific crane to halt. Notably, the PLC and speed drives are recognized for their durability, featuring replaceable memory cards to sustain operation in extreme conditions. Nevertheless, while the system offers maximum structural load capacity and remote emergency stop control, it lacks details on emergency response times, communication latency, and reliability in different networks. Despite durability and replaceable memory cards being touted for extreme conditions, their precise impact on system reliability needs clarification. Moreover, the complexities of integrating remote emergency stop control across diverse crane models or larger construction sites remain unspecified.

3.4.2. Load stability technologies

Among the 8 academic papers and 4 industry products, 3 and 3 are devoted to discussing load stability technologies. Load stability in TC safety operations is crucial for maintaining the safe and secure positioning and movement of the load during lifting operations. It is vital for preventing accidents, protecting workers, and safeguarding the construction site [97]. For instance, [103] introduced a vision-based control system tailored for a 3 degrees of freedom crane system, integrating analytical and experimental models alongside adaptive optimization algorithms. This system accurately estimates the crane's displacement during operations and provides precise measurements of jib angle, cart position, and hook position parameters. Notably, it performs real-time adjustments to counteract swinging motions, ensuring stability during lifting operations within an absolute error range of −0.5 to +0.5. This level of precision significantly enhances safety during lifting. However, the performance of the proposed system in varied lighting conditions or with different types of cranes remains uncertain, as the paper does not address these aspects. Additionally, implementing the system may necessitate a skilled operator for setup and calibration, potentially limiting its practicality in certain situations.

[104] presented a novel force-feedback control system aimed at mitigating sway in TC operations. This innovative approach utilizes haptic devices connected via a 3D-printed pole to convey real-time feedback on the payload's balance status, enabling operators to make precise adjustments by applying counterbalance force. The system's implementation of real-time feedback significantly improves control, reducing human errors and leading to notably fewer collisions compared to traditional methods. This highlights the system's efficacy in enhancing safety and operational accuracy. However, the study's reliance on a human-subject experiment with a relatively small sample size of 34 participants might restrict the findings' statistical power and general applicability. Furthermore, the paper does not explore potential limitations or challenges associated with implementing the proposed haptics-based force balance controller in real-world TC operations. Lastly, a comprehensive comparison of the proposed method with other existing anti-sway control methods is absent, which could hinder a thorough understanding of its relative advantages and disadvantages.

[105] introduced a computer vision (CV)-based method for load sway monitoring, demonstrating its superiority over IMU-based techniques in crane operations. The research validated the accuracy and reliability of this approach through lab and field experiments, showcasing its effectiveness in diverse scenarios. The CV-based monitoring showed real-time capabilities in accurately tracking crane states, aiding operators in recognizing and mitigating unsafe conditions, especially during blind lifts. Despite its strengths, limitations were observed: the color segmentation struggled with similar foreground and background colors, causing inconsistencies in object tracking, especially during rapid movements or background color changes. This might lead to significant errors, particularly in complex backgrounds. Additionally, relying solely on 2D images without depth perception made it challenging for operators to assess load sway magnitude and judge clearances from the load to surrounding objects in both vertical and horizontal dimensions.

[106] introduced the WTZ-A100N overload limiter system to enhance TC safety. Comprising a load sensor, connecting cable, and a microcomputer host, this system works cohesively to prevent overloading incidents. The load sensor measures the load's weight and converts it into an electrical signal processed by the microcomputer host, displaying precise weight on the screen for crane safety. Additionally, the system issues a warning to the operator when the load reaches 90% of the rated weight and automatically cuts off the crane's power source if the load exceeds the rated weight, effectively preventing overloading. However, the system lacks specific details about the response time in critical situations, potential errors in load measurement, or the reliability of the automatic power cut-off feature under varying operational conditions. Furthermore, the system's adaptability to different load types, potential calibration issues, and the impact of environmental factors on load measurement accuracy require further clarification for a comprehensive assessment of its functionality.

[107] introduced the Vita Load Pilot, a suspended load system to enhance crane operation safety by preventing load swinging and spinning through remote user-controlled positioning for precise load movement. This system integrates position-hold and continuous load calibration features, eliminating the need for taglines and ensuring load stability. Notably, it demonstrates adaptability to challenging conditions, such as high winds, to ensure accurate lifts, showcasing a 31% reduction in project risk in practical testing, thereby enhancing safety. However, there is a lack of specific details about the system's response time in dynamic operational scenarios or its reliability in maintaining load stability under varying environmental conditions. Additionally, while the system's adaptability to high winds is mentioned, further exploration is needed to understand how effectively it compensates for wind-related factors impacting load stability, its limitations in extreme weather conditions, and its performance across different terrains for a more comprehensive assessment.

[108] introduced the Anemometer RK150–01 wind speed sensor, specifically designed for wind load detection. It provides exact wind speed measurements with a deviation of just ±1 m/s, facilitating early detection of high winds. Equipped with a programmable alarm system, it promptly alerts operators to hazardous wind conditions using both audible alarms and visual signals. Highlighting a rapid response time of under 100 ms and an impressive 1 km transmission range, this sensor enables centralized monitoring of multiple TCs at construction sites. However, the paper lacks details about the sensor's performance in diverse weather conditions, susceptibility to false readings, and reliability in triggering alarms amidst dynamic environmental changes. While emphasizing its rapid response time and transmission range for centralized monitoring, further clarification is needed regarding their practicality in large construction sites with varied topographies and potential interference sources for a comprehensive assessment of its effectiveness.

3.5. Summarizing industrial technologies and their workflow processes

It is not an exaggeration to conclude that the majority, if not all, of the industrial technologies rely on IoT sensors, online cloud services, and AI. The convergence of AI and IoT has given rise to various innovative industrial products. This integration may be called AIoT, which plays a pivotal role in the field of TCST. These technologies are harnessed for various applications, including predictive maintenance, load monitoring, environmental sensing, real-time monitoring, collision avoidance, remote operation, and data analytics. AIoT ensures crane safety by providing real-time data analysis, early warning systems, and remote-control options, ultimately reducing accidents, increasing productivity, and enhancing crane operations' overall safety and efficiency.

AIoT platforms possess the flexibility to accommodate technologies with diverse maturity levels. They evolve continuously, integrating both less mature and advanced technologies as they progress [109]. This progression involves several strategic approaches. According to [110], AIoT platforms create synergies between AI and IoT, leveraging their combined strengths. This collaboration fosters an environment where technologies complement each other, enabling seamless integration despite differences in maturity. [111] emphasize the significance of adaptable communication protocols that facilitate effective interaction among technologies at different maturity levels, ensuring seamless data exchange and enhancing interoperability. Additionally, [112] proposes employing a modular architecture approach, allowing AIoT platforms to accommodate technologies at various maturity stages, thereby enabling smooth integration and adaptability to emerging technologies. Fig. 12 displays the names and locations of IoT sensors and other components in the TC. In contrast, Fig. *13* provides a visual representation delineating a clear overview of the diverse functions and objectives of all technological products employed within the industry.

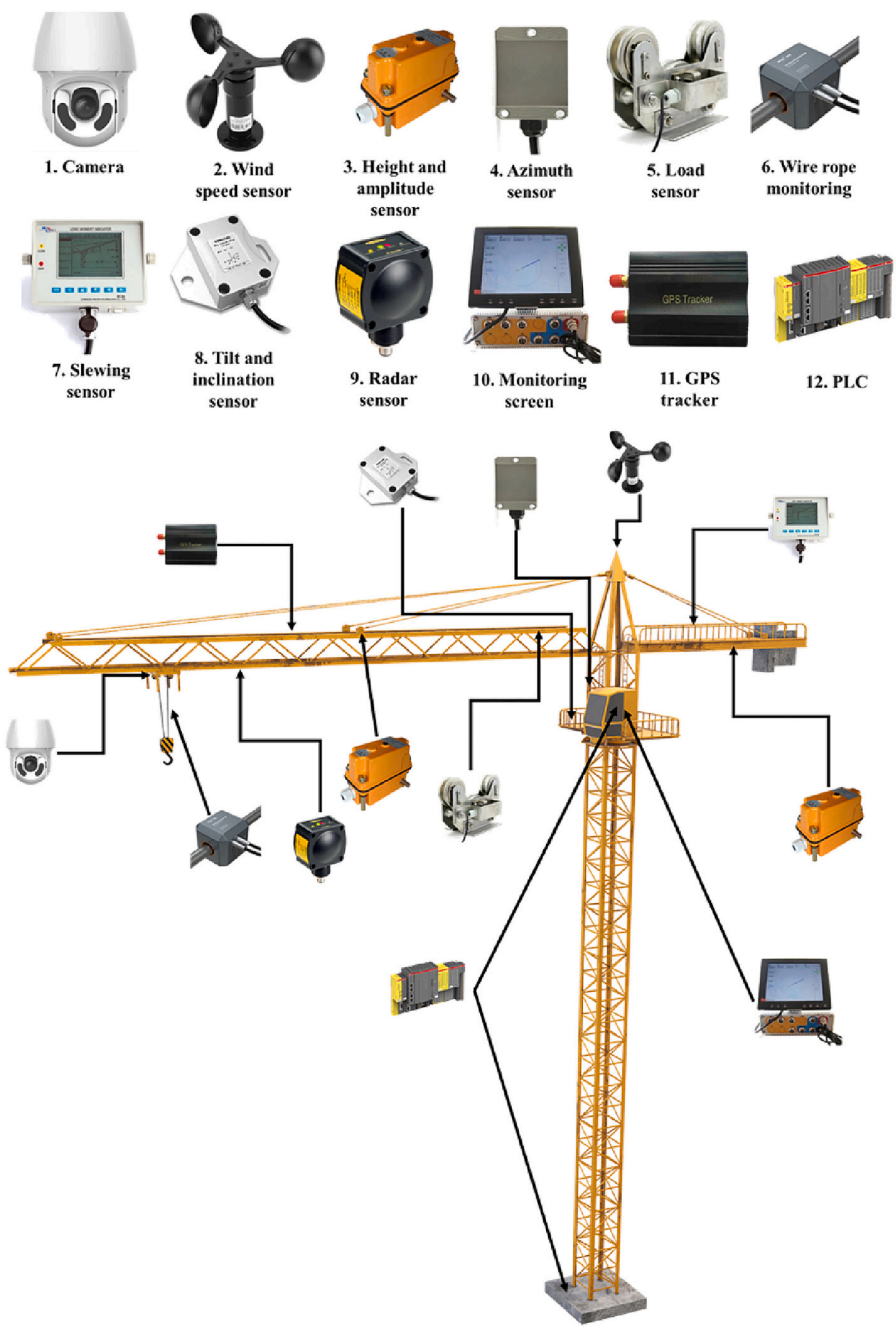

Fig. 12. Names and location of IoT sensors and other components in tower crane.

3.6. Potential technology for tower crane products

After conducting an extensive review of TCST in both industrial and academic domains, a noteworthy observation has emerged. It has come to our attention that within the current landscape, there is a distinct absence of industrial products incorporating predictions and operational planning, including path planning and layout planning using machine learning (ML). Furthermore, virtual reality (VR) and augmented reality (AR) technologies are lacking in industry products. Additionally, there appears to be a notable dearth of products striving to enable semi or fully autonomous operations for TCs. This is despite the fact that these technologies are already in use in the academic sector and have the potential to significantly impact industrial products.

ML can be employed for predictions and operational planning, offering several advantages for the industry. Firstly, it improves efficiency by quickly analyzing large datasets and making predictions based on historical or collected data, thus optimizing processes. This can lead to more efficient operations, ensuring safety and improved resource allocation [85,113]. Additionally, it reduces costs by optimizing operational planning and layouts, enabling organizations to save money on resources, labor, and energy consumption. Predictive maintenance can also reduce equipment downtime and repair costs [114]. Lastly, it enhances accuracy by providing highly precise predictions and recommendations, reducing human error, and improving decision-making in planning and execution [57,58,115].

Despite the myriad advantages of leveraging ML, it is essential to acknowledge its limitations, one of the most significant being its strong dependence on data quality and relevance. ML heavily relies on the input data used for training. If this data is incomplete, biased, or outdated, it can lead to inaccurate predictions and plans. Inaccurate or biased training data can result in models that perpetuate the same biases or make unreliable decisions, which can have significant real-world consequences [116]. Furthermore, ML is not a one-time, set-and-forget solution. It requires ongoing modifications and updates to remain effective. Data distributions and patterns can evolve over time, reflecting changes in the underlying processes or environmental factors. Consequently, models may lose their predictive accuracy if not regularly retrained and adapted to the evolving data landscape. Failure to do so can lead to reduced performance and, in some cases, even render the models obsolete [117].

VR and AR can be used to provide operators with immersive experiences and additional information during crane operations. Using VR and AR in TC operations can provide several advantages for the industry. For instance, VR provides a 3D visualization environment, allowing users to have a realistic and immersive experience in TC layout planning. Through VR, users can generate crane layouts with real-time feasibility checking, ensuring safety and efficiency [118]. Additionally, VR allows for creating immersive environments that closely resemble real construction sites, providing a realistic training experience for crane operators [119]. In contrast, AR can overlay real-time data or instructions on a crane's controls, which helps operators with lower knowledge and experience levels comprehend data and interact with the device. This enables them to make informed and precise decisions during processes such as maintenance and production [120].

Although there are advantages to using VR and AR, they also come with certain limitations. Firstly, cost can be a significant hurdle, as

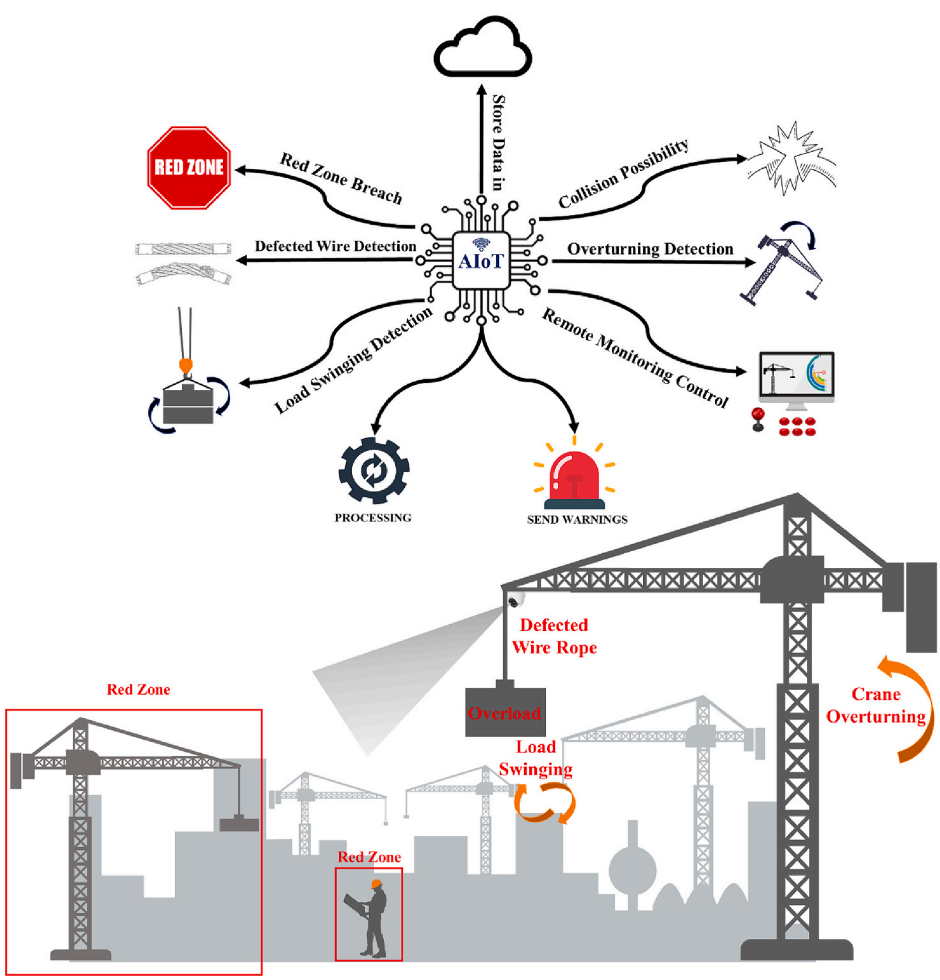

Fig. 13. Industry products functions.

implementing VR and AR systems can be expensive, including hardware, software development, and operator training. Small or resource-constrained organizations may find it challenging to adopt these technologies [121,122]. Secondly, user acceptance is a concern, as many people and organizations may resist change or be reluctant to adopt new technologies, potentially hindering the successful implementation of VR and AR in crane operations [123].

Unfortunately, neither academic nor industrial contexts have yet achieved fully autonomous TC operation. However, the academic sector has made progress in some aspects, such as automation in lifting operations, layout planning, 3D path planning, and the optimization of path points [32,65,124]. The integration of semi or fully autonomous operations in TCs holds the potential to revolutionize the industry, offering a diverse array of advantages. This transformative approach is widely regarded as the future of TCST. Firstly, automation enhances overall safety by reducing the need for human intervention in critical crane operations, minimizing the risk of accidents caused by human error [124]. Secondly, autonomous TC can operate around the clock without the need for rest breaks or shift changes, which can accelerate project timelines and improve productivity [125]. Finally, automated cranes provide precise and controlled movements, reducing the chances of load misplacement, collisions, spills, or accidents, thereby improving load placement accuracy.

While there are numerous benefits to utilizing automation for TC, its limitations must not be overlooked. Among these limitations, the initial investment is one of the most paramount constraints. The process of implementing semi or fully autonomous systems in TCs can prove to be financially demanding. This encompasses expenses such as the procurement of specialized equipment, the undertaking of extensive software development, and the intricate integration of these systems into existing operational frameworks [126]. The second significant limitation pertains to limited adaptability, as autonomous TCs may lack the flexibility and decision-making capabilities demonstrated by human operators when navigating unexpected or intricate scenarios, potentially resulting in erroneous decisions [126].

Another critical limitation is the vulnerability to both communication issues and cybersecurity risks. As autonomous systems become more reliant on internet connectivity, they are exposed to potential communication disruptions and the looming threat of cyberattacks. Ensuring the security and reliability of these systems is paramount to protect against unauthorized access and data breaches [127].

4. Limitation and gaps

In this study, several critical limitations and research gaps have emerged across various facets of TC management technologies. This section will be divided into two parts based on the gaps identified in academic research and those observed in the industry:

4.1. Academic limitation

- **Data Completeness:** Several studies, such as [58,59,68,84], have used machine learning technologies, demonstrating their promise in predictive tasks. Nonetheless, these models excel when handling complete datasets, but their efficiency diminishes as the quantity of missing data escalates. This decline in performance could impact the effectiveness of the proposed machine learning models.
- **Generalization:** Many studies such as [28,55,57,60,62,63,66–68,76,77,85,94,96–98] tend to narrow their focus to specific regions, a single facet of environmental factors, like winds, or a particular type of TC foundation, such as the ballast base foundation. This gap raises concerns about the generalizability of their findings to broader contexts.
- **Real-World Application:** Numerous studies such as [56,57,60–64,66,67,76,77,84,88,91,94–98] have encountered a common challenge, a lack of sufficient real-world application for their proposed technologies. This limitation significantly hampers the ability to assess these techniques' practicality, effectiveness, and reliability in real-world scenarios.

4.2. Industry limitation

- **Post-construction dismantling of TCs:** The construction industry faces a notable gap in technology and applications for the post-construction dismantling of TCs. While the sector has seen significant advancements in crane construction and operation, the dismantling phase continues to rely on traditional, often manual methods. This presents several challenges, including safety concerns, inefficiency, and the potential for increased costs.
- **Accuracy and Data Reliability:** Many systems, particularly those reliant on AI, cameras, and sensor-based technologies [69–74,99,78–82,100,86,101,92,102,106,108], often lack information regarding their data accuracy and reliability. AI systems heavily rely on an intricate network of cameras, sensors, and hardware components for data acquisition and processing. However, external factors like extreme weather, dust, moisture, and interference can significantly impact data accuracy and reliability. Consequently, technical glitches, sensor malfunctions, or connectivity disruptions can introduce inaccuracies. It is vital to recognize that data is the lifeblood of AI systems, and unreliable or erroneous input data can result in inaccurate outputs.
- **Data Security:** Some systems, including those that rely on cloud and online data storage [69,99,73,100,79,81], fail to mention how they ensure the security of their information. This underscores the paramount importance of data security. Security breaches in data can lead to substantial consequences, spanning from misguided operational decisions to privacy concerns and the misuse of sensitive information.

5. Future research directions

Identifying future research directions often stems from synthesizing existing knowledge, industry trends, and identified gaps in the literature, rather than solely referencing specific studies. Authors arrive at these directions through diverse approaches. Firstly, by scrutinizing research limitations and identified gaps, authors may propose future research to address limitations encountered in the studied papers. Additionally, insights from industry practices, emerging technologies, and evolving challenges provide indications for potential research directions. Lastly, authors also shape directions by uncovering unexplored areas or opportunities within their study or broader domains, often pointing toward avenues yet to be thoroughly explored. Fig. 14 depicts the academic and industry research directions and gaps, encompassing both academic and industrial domains.

5.1. Academic research opportunities

5.1.1. Data completeness

Investigating methods to enhance the efficiency of machine learning models when dealing with incomplete datasets is crucial. This could involve developing new imputation techniques, leveraging generative models, or enhancing model robustness to missing data. Additionally, exploring the use of data augmentation and data synthesis techniques can compensate for missing data in TC safety applications.

[128] argued that innovations in imputation methods aim to effectively fill missing data, thereby refining predictive models. According to [129], integrating generative models and reinforcing model robustness enhances the comprehension of underlying data distributions. This approach assists in data generation and potentially tackles the challenges posed by missing data, strengthening models to handle and adapt to incomplete datasets. Based on [130], data augmentation or synthesis strategies can address missing data issues. These methods aim to

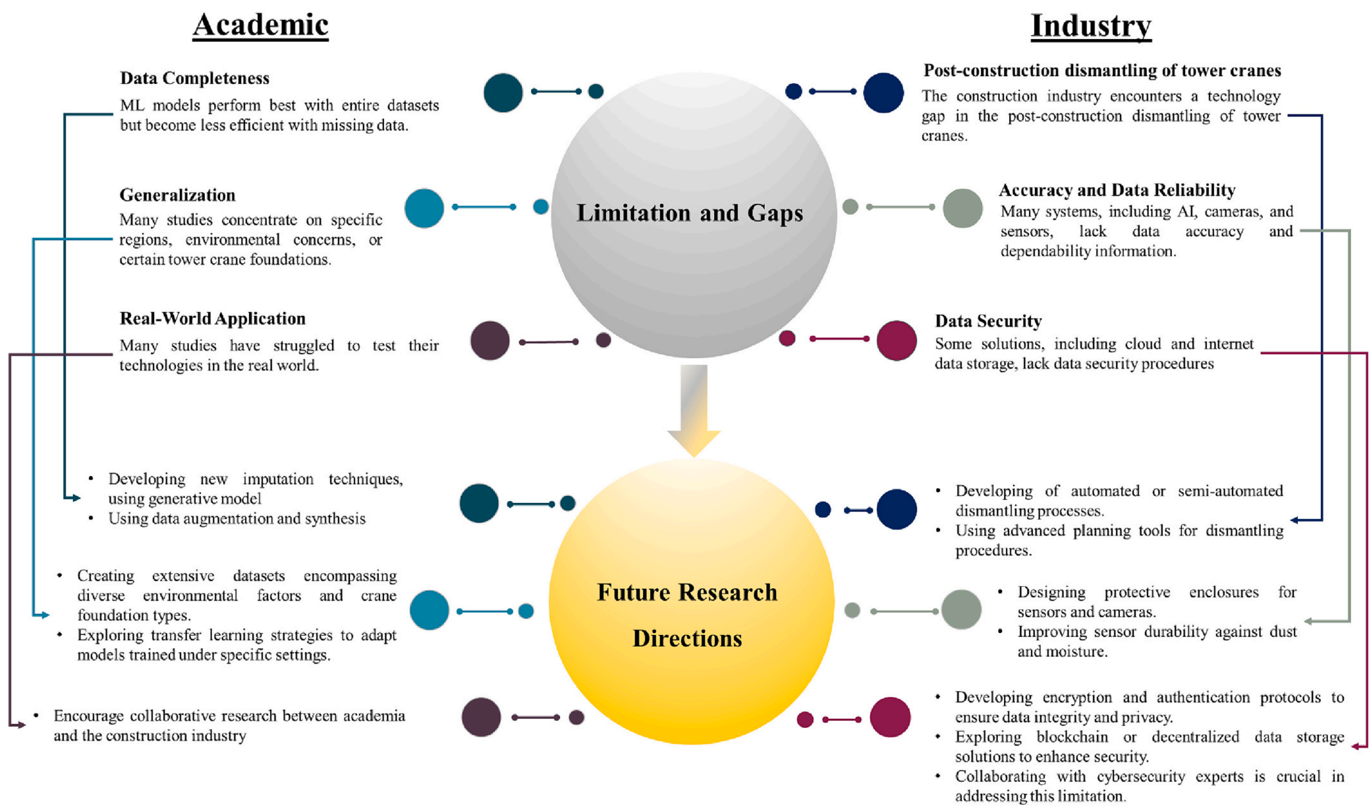

Fig. 14. Research directions and gaps for academia and industry.

mitigate the impact of incomplete information by generating more data or enhancing existing datasets.

5.1.2. Generalization

Conduct studies that aim to enhance the generalizability of findings from specific regions or contexts. This could involve creating comprehensive datasets that cover a wider range of environmental factors and crane foundation types. Investigate transfer learning techniques that allow models trained on one set of conditions to adapt to others.

[131,132] argued that exploring transfer learning methods is crucial for enabling models trained under specific conditions to adapt effectively across diverse contexts. These methodologies facilitate the adaptation of pre-trained models by leveraging their learned features and knowledge to excel in different scenarios or domains. By reusing and fine-tuning these models, researchers can expedite the learning process in new environments, saving computational resources and time while enhancing the model's performance.

5.1.3. Real-world application

Encourage collaborative research between academia and the construction industry to bridge the gap between theoretical models and practical applications. Implement pilot projects that showcase the feasibility and effectiveness of proposed technologies in real-world scenarios. This could involve partnering with construction companies for field trials and case studies. [133] highlights the significance of executing pilot projects that demonstrate the feasibility and effectiveness of proposed technologies in real-world scenarios. These initiatives serve to validate the practical application of these technologies.

5.2. Industry application opportunities

5.2.1. Post-construction dismantling of TCs

Explore innovative technologies and methods to ensure the safe and efficient dismantling of TCs after construction. This may include the development of automated or semi-automated dismantling processes, the utilization of robotics, virtual reality-based dismantling training, and implementing advanced planning tools for dismantling procedures. Emphasizing safety considerations is crucial as a primary focus. [134] advocated for virtual reality-based dismantling training, enabling trainees to simulate the complete dismantling procedure in a risk-free environment. This platform provides comprehensive training to workers before their on-site involvement, thereby enhancing the learning process and improving the safety performance of the trainees.

5.2.2. Accuracy and data reliability

Developing standards and certification processes for data accuracy and reliability in TC safety systems. Explore advanced sensor technologies, redundancy systems, and diagnostic tools to detect and mitigate technical glitches and sensor malfunctions. This may involve designing protective enclosures for sensors and cameras, improving sensor durability against dust and moisture, and conducting a thorough study on environmental influences on data accuracy. Additionally, research advanced sensor calibration and maintenance practices for reliability in challenging conditions and investigate resilient data communication methods to minimize connectivity disruptions.

According to [135], metrology and sensor calibration are crucial for reliable measurements, preventing measurement errors and unreliable data that could lead to uncontrollable risks and costs and the loss of market confidence. Moreover, [136] emphasized the criticality of data quality and accuracy obtained from sensors. They underscored the significance of redundancy systems and diagnostic tools to detect and mitigate technical glitches and sensor malfunctions.

5.2.3. Data security

Investigate secure data storage and communication methods for TC safety systems. Develop encryption and authentication protocols to ensure data integrity and privacy. Explore blockchain or decentralized data storage solutions to enhance security. Collaboration with cybersecurity experts is crucial in addressing this limitation.

As per [137], ensuring secure data storage and communication requires the implementation of robust encryption methodologies and authentication protocols, including blockchain technology. These measures are critical in upholding both data integrity and privacy. Furthermore, according to [138], establishing collaboration with cybersecurity experts is essential for successfully implementing robust encryption, authentication, and secure communication methods.

6. Conclusion

TCs, some of the heaviest machines on construction sites, pose significant risks when safety is compromised. Fatalities and substantial economic losses underscore the imperative to develop safety technologies. This study analyzes TCST by assessing the importance of TC safety reviewing various academic studies and industry products. A systematic review method meticulously examined 32 academic papers and 21 industry products. The systematic review offers a comprehensive analysis of the current state of TCST research, categorizes findings, identifies research gaps and limitations, and suggests future study opportunities. Categorization involved brainstorming and literature review techniques, revealing four main categories related to their purposes: (1) proactive preconstruction crane management technologies; (2) monitoring technologies during construction; (3) anti-collision technologies during construction; and (4) stability control technologies during construction. Each category includes subcategories based on specific aspects of crane management, such as accident predictions and operation planning in the first category, onsite and remote monitoring in the second category, collision prevention with the environment and with other cranes in the third category, and crane and load stability technologies in the fourth category.

A total of six critical knowledge gaps have been discerned, with three arising within the academic context and three within the industrial domain. Within the academic context, these gaps revolve around issues of data completeness, data scope, and the practical application of research findings. In contrast, the gaps identified within the industrial sector pertain to post-construction dismantling practices, the accuracy and reliability of data, and the paramount concern of data security.

Six future opportunities were suggested to bridge those gaps. New imputation techniques should be developed for the data completeness gap, using generative models or enhancing model robustness to missing data. Generate extensive datasets beyond specific regions, contexts, environmental factors, and crane foundation types for the generalization gap. Enhance collaborative research between academia and the construction industry to bridge the gap between theoretical models and practical applications for real-world application gaps.

For the post-construction dismantling gap, investigate innovative technologies and methods for the safe and efficient dismantling of TCs. Explore advanced sensors, redundancy systems, and diagnostic tools to detect and address technical glitches and sensor malfunctions, ensuring accuracy and data reliability. Additionally, encryption and authentication protocols for data security should be developed to ensure data integrity and privacy. Finally, consider exploring blockchain or decentralized data storage solutions to enhance security further.

Even though this research makes substantial contributions to both knowledge and practice, certain limitations must be acknowledged. Notwithstanding these limitations, the study satiated its objectives and surpassed all anticipations. Firstly, the categorization of papers according to purpose and crane management aspects depends on the subjective judgments of the authors. Secondly, despite diligent search strategies, there is a possibility that some TCST studies were unintentionally omitted.

This paper offers advantages to researchers and industry practitioners involved in construction safety. Researchers can acquire valuable insights and discover research directions for advancing the current knowledge base on TCST in construction. On the other hand, industry practitioners can become informed about TCST challenges within existing products, facilitating collaboration between practitioners and researchers and thereby promoting innovation in the field.

CRediT authorship contribution statement

Ali Hassan Ali: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Tarek Zayed:** Supervision. **Roy Dong Wang:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Matthew Yau Shun Kit:** Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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