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Review

Applying Systems Thinking to Research into Risk Factors Influencing Earthmoving Equipment Operation Safety in Construction Sites

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Abstract: Earthmoving operations in the construction process are complex environments that involve interactions between equipment, the workforce, and materials within an overarching construction plan. Over the past two decades, researchers in construction have focused on improving the safety of construction earthmoving equipment due to their omnipresence in the construction environment. Although previous studies have explored safety risks and the causes of accidents involving construction earthmoving equipment, their approaches were common and lacked a comprehensive perspective. Hence, this systematic literature review applies Rasmussen's (1997) risk management framework using a systems thinking approach to identify and classify the risk factors influencing earthmoving equipment operation safety in construction sites. Utilizing a multistep methodology, this research first identifies 38 risk factors pertinent to earthmoving equipment operations and then classifies them based on systems thinking. Social network analysis (SNA) is employed to analyze the data. The results show that most research on earthmoving equipment safety focuses on monitoring construction sites, but very little on government and regulatory roles. When considering the interdependencies of risk factors, safety training is the most important factor, followed by the largely overlooked earthmoving machinery characteristics and manufacturer's performance. The results of this review inform both the research community and industry practitioners regarding the less-understood aspects of earthmoving equipment operation safety and future research directions.

Keywords: earthmoving equipment; safety management; systems thinking; social network analysis (SNA)

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1. Introduction

Earthmoving equipment operation in the construction process is a major contributor to collisions [1–3], and workers are exposed to dangerous situations during operation [4]. The transitory nature and complexity of earthmoving equipment operations pose safety risks to workers and equipment [3,5]. Safety noncompliance related to earthmoving operations is common due to the tight workspace and the proximity of workers and equipment during operation [2,6–8]. In Australia, 15% of construction incidents involved contact between people and moving plant, in particular heavy plant, such as articulated haul trucks, excavators, front-end loaders, and dozers, which ranked second after manual handling incidents (17%), according to Woolley et al. [9].

Excavation is one of the high-risk construction tasks [10] and includes activities such as digging, hauling, dumping, swinging, moving, filling, and compaction [11]. It involves various types of earthmoving equipment including excavators, bulldozers, backhoes, forklifts, dozers, compactors, motor graders, loaders, concrete pumps, cherry pickers, scrapers, and trucks [12]. Earthmoving equipment operation safety can be regarded as a complex sociotechnical system consisting of two influential subsystems: the technical aspect of the system encompasses the technologies (techniques, machines, equipment, etc.) and the social aspect of the system encompasses humans (skills, attitudes, values, and needs) [13].

Some studies have identified major risk factors related to earthmoving equipment operation [2,14–17]. Despite a plethora of research on technological safety solutions [18] to improve the safe operation of earthmoving equipment in construction projects [19–23], many of them have focused on a narrow perspective of risk factors, offering solutions to isolated levels of risk factors. For example, research has been focused on technologies for safe and resilient earthmoving operations [24], earthmoving equipment automation [25], and management of construction plant and equipment [26]. While these are important, a systematic review of the literature on the safety of earthmoving equipment is needed to review what has been done and identify knowledge gaps for further research from a systems thinking perspective. There is a lack of understanding of whether the current directions of construction earthmoving equipment safety research are aligned with the systems thinking approach for the causation and prevention of accidents and the extent to which the identified risk factors are addressed or neglected.

This article aims to evaluate the current earthmoving equipment operation safety literature with a systems thinking perspective.

The objectives are: (1) Categorize the risk factors that have been identified from selected articles from a systems thinking perspective and (2) examine the interrelationships of the risk factors. Content analysis was conducted to extract the risk factors and map them to the well-established systems thinking Rasmussen risk management framework [27] for further analysis. Social network analysis (SNA) was then conducted to visualize the interrelationship patterns of the risk factors. This review contributes to the existing body of knowledge in several distinct aspects. It employs a holistic systems thinking perspective to analyze risk factors of earthmoving equipment operation safety, embracing a wide spectrum of risk factors in the Rasmussen risk management framework and revealing their interrelationships. The significance of this study lies in providing new insights for developing an integrated safety approach for earthmoving equipment operation that considers the interconnections of all risk factors. It also enhances safety solutions research by including various aspects of operation at different levels of the risk management framework. Most of the other studies focused only on technological and non-technological solutions in isolation, but this research showcases different research streams, from the identification of risk factors to different safety solutions methods for social and technical aspects of the system, which converge toward the ultimate goal of improving the safety of earthmoving equipment operation by taking incremental steps. The findings clarify further safety solutions development requirements for an integrated safety approach for earthmoving equipment operation in which all elements of the systems have interconnected actions.

2. Systems Thinking Framework

The systems thinking approach has been employed to examine the system's interconnections [28] and explore ways to improve safety performance in the sociotechnical systems [29]. It can recover the lost pieces of the puzzle of risk factors and accident analysis methodologies in a complex and interconnected system. In the risk management domain, systems thinking is a fertile ground for an understanding of being change-oriented, adaptable and improving the system's interconnections [28], and increasing the safety performance in sociotechnical systems [29]. The Rasmussen risk management framework [27], as commonly applied in the domain of risk management, has decomposed the system into six levels (i.e., authorities, lawmakers, company, management, personnel, and work), which interact with each other for safety decisions (Figure 1). In recent years, practical investigations and systematic literature reviews have supported the principle of systems thinking theory and the significance of various actions at different levels for the betterment of safety management for specific construction heavy equipment such as tower cranes [30–32]. Refs. [30,31] employed the systems thinking lens to capture and categorize the complex system of crane safety risk factors in a structured way and have a comprehensive detection strategy to consider all aspects of risk factors such as regulation, human, equipment, environment, and management.

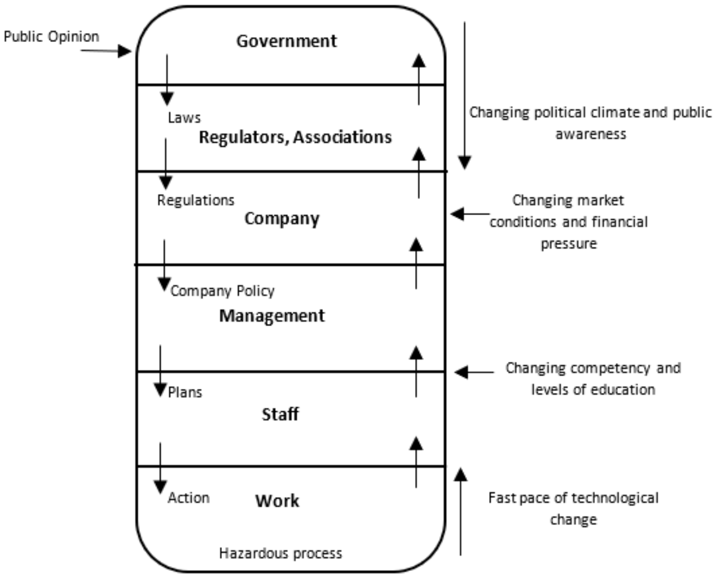

Figure 1. Rasmussen's risk management framework [27].

3. Research Method

This review aims to identify the trend and distribution of research efforts on enhancing earthmoving equipment safety in construction under the tenet of the systems thinking approach. Its primary objectives include categorizing risk factors and their interrelationships. This paper adopted a systematic literature review in which the process is objective, explicit, and replicable [33] and employed the PRISMA (preferred reporting items for systematic reviews and meta-analyses) workflow [34]. The paper selection process is depicted in Figure 2.

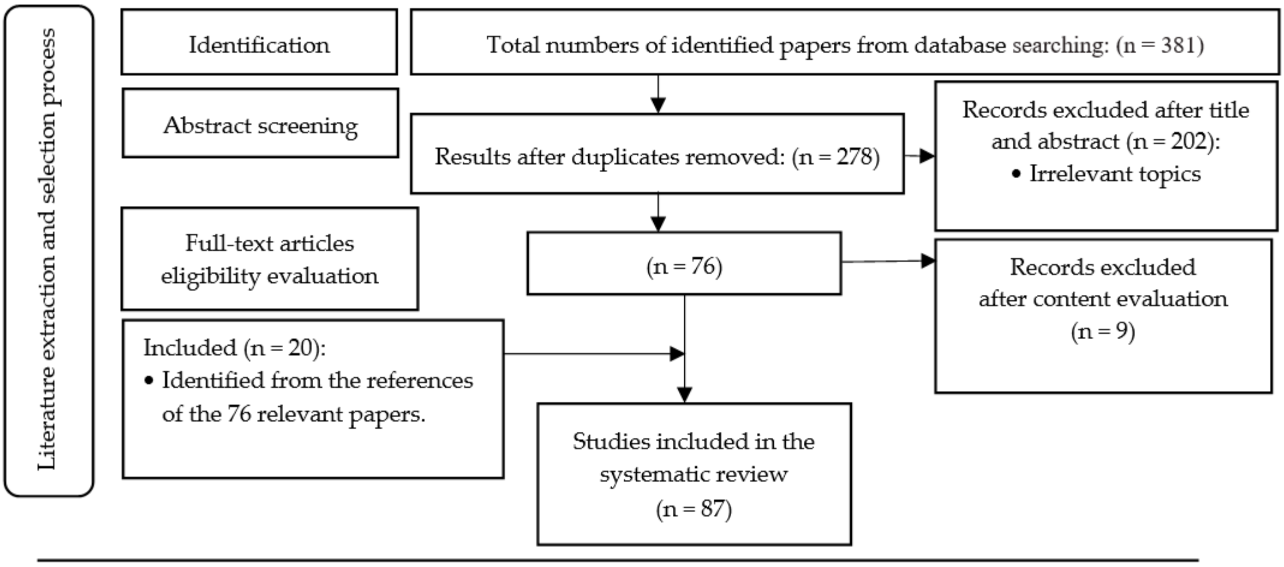

Figure 2. Literature extraction and selection process (PRISMA flow chart).

Extraction of Relevant Publications

Search strategies were applied to filter the pertinent investigations from online digital libraries such as Scopus and Web of Science as the repositories of publications eligible for this review [35]. The timeframe for inclusion in publications was limited to between 2000 and February 2024, when the search was performed. In the current review, the search string comprised keywords that created Boolean operators such as “AND” and “OR” to connect the pertinent keywords. The search was restricted to TITLE-ABSTRACT-KEY and English peer-reviewed journal publications. Table 1 displays the relationship between the Boolean operators and the outcome of the search used to find relevant scientific articles. The total number of findings is 381, with 250 and 131 studies obtained from Scopus and Web of Science, respectively.

Table 1. The PRISMA identification stage results from searching the database (SCOPUS and Web of Science).

Boolean Operators (Searches Done in February 2024)	Results	
(“earthwork equipment” OR “heavy equipment operator” OR “construction earthmoving equipment” OR “mobile equipment” OR “construction equipment safety” OR “Equipment operators” OR “heavy construction equipment” OR “construction equipment operator” OR ”backhoe” OR “excavator” OR “dozer” OR “truck” OR “forklift” OR “bulldozer” OR “saw” OR “trailer” OR “compactor” OR “roller” OR “cherry picker” OR “loader” OR “concrete pump” OR ”grader” OR “auger”) AND (“construction site” OR ”construction jobsite” OR “construction work zone” OR “construction industry” OR “construction workplace” OR “construction work *” OR “construction professional” OR “construction labo *” OR “construction workforce” OR “construction staff” OR “construction personnel” OR “construction activit *”) AND (“safety” OR ”safety management” OR “risk” OR “risk management” OR “hazard” OR “accident” OR ”accident prediction” OR “accident prevention”)	S	W
	250	131
	Total: 381	

Once duplicate papers were removed, 278 papers remained. After reviewing the titles and abstracts, 202 papers were removed from the list because they were not relevant to the scope of the study. In the phase of the full-text review, two crucial criteria were considered to determine the selection of the papers: (1) the study should focus on the safety of earthmoving equipment in a construction context; (2) research focusing on the automated operations of autonomous earthmoving equipment that are still in the experimental phase and have yet to be validated in actual practice should be excluded [25]. Consequently, nine papers on the robotic teleoperation of construction machinery were eliminated from the list of papers. A manual examination of the references in the included papers was conducted to complement the electronic searches. Finally, 20 additional papers were identified as a result of reference tracking published within the same period (2000–February 2024). This brought the total number of papers included in the review to 87.

4. Data Analysis

4.1. Content Analysis

A total of 87 papers were subjected to content analysis to determine the risk factors of earthmoving equipment operation in the construction process. NVivo Qualitative Data Analysis software version 12 was employed to extract the themes and codes. To achieve objective 1, content analysis was conducted to categorize the textual data according to the systems thinking framework.

4.2. Social Network Analysis

To achieve objective 2, social network analysis (SNA) was employed to explore the patterns of interactions and relations using a combination of the network and graph theory [36]. SNA was conducted in Gephi (0.10.1 version), an open-source visualization software and computational tool for SNA to visualize the interrelationship patterns of risk factors [37]. After converting the collected data into the CSV format compatible with Gephi and importing it, we obtained a network matrix comprising 38 nodes and 92 directed edges within Gephi. Each node represents the risk factors extracted from 87 papers, while the edges denote the forwarding interdependencies of these risk factors as identified from the safety solutions research in 79 papers. The "Force Atlas" algorithm was first employed to arrange the nodes in Gephi, after which the Fruchterman and Reingold algorithm was applied to refine the node distribution. The virtue of gravity characteristic of this algorithm allows it to center the highly rated sources [38]. The subsequent sections provide detailed analysis information.

4.2.1. Degree Centrality

The degree centrality of a node, which determines the effect of existing edges on a certain node, is the sum of all linkages existing on a node in a network [39–41]. The in-degree and out-degree of various factors indicate the interdependency with other nodes. A higher out-degree signifies the number of times the node requires more content from other nodes. A node is considered central when it is more frequently forwarded by other nodes, has more connections, and holds greater interdependency with other nodes within the network.

4.2.2. Betweenness Centrality

Betweenness centrality is an essential indicator that evaluates the node's ties to various clusters or levels. It is calculated by identifying the shortest paths through the network and quantifying how frequently a node acts as an intermediary along these paths [42]. The betweenness centrality is more important than degree centrality because it underscores the node's strategic importance in the network, offering insights into its potential to influence the control of information or resources across different segments of the network [43,44].

4.2.3. PageRank Value Analysis

PageRank value analysis was employed to measure the importance of each node based on the number of incoming relationships and the rank of the related source nodes. PageRank value analysis output is a probability distribution that represents the likelihood of visiting any node by randomly traversing the graph. It can help identify important nodes that would have cascade effects on other nodes in the network [45]. To further assess and determine the impact of each node type within the earthmoving equipment safety network, Gephi (0.10.1 version) was used to calculate the PageRank value.

5. Results

5.1. Publication Distribution by Year

Figure 3 displays temporal trends in the volume of publications from 2001 to 2023, focusing on the risk factors associated with the operation of earthmoving equipment categorized according to different levels of Rasmussen's 1997 risk management framework. The research trends in the category of regulatory bodies and associations illustrate the relatively low frequency of publications that mentioned risk factors at this level. The frequency of publications at the construction site management level risk factors has an overall increasing trend, with some fluctuations, and it demonstrates a particularly strong research interest, with pronounced peaks in publication numbers around 2013, 2016, and 2018. The "Workforce" category, encompassing the human aspect of construction operations, exhibits the highest peaks of all the categories, especially in the years 2013, 2020, and 2022. Research in the "Environment and Equipment" sector varies, showing heightened activity in certain years like 2010, 2013, and 2016. Meanwhile, the "Company Management" level experienced significant upticks in years such as 2011 and 2013, reflecting the continuous evolution in managing the construction industry amidst economic shifts and emerging management practices related to the safe operation of earthmoving equipment.

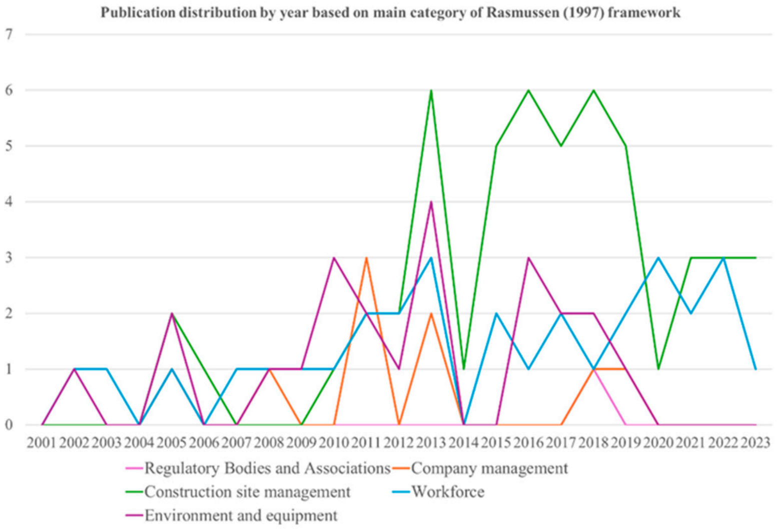

Figure 3. Publication distribution by year based on the main category of Rasmussen's (1997) risk management framework.

5.2. Publication Distribution by Journal

As shown in Figure 4, *Automation in Construction* and *Journal of Computing in Civil Engineering* are the top two journals, jointly making up 44% of total publications. *Automation in Construction* contributes 28% (21 publications), and *Journal of Computing in Civil Engineering* contributes 16% (12 publications), indicating a focus on automated safety solutions for risk factors related to earthmoving equipment operation in the construction process. Other notable journals include *Journal of Construction Engineering and Management*, with 11% (8 publications), *Advanced Engineering Informatics* with 8% (6 publications), and *Engineering, Construction and Architectural Management* with 7% (5 publications). Additionally, several journals contribute two publications each, constituting 3% of the total publications, while the remaining journals collectively contribute 3%, with one publication each.

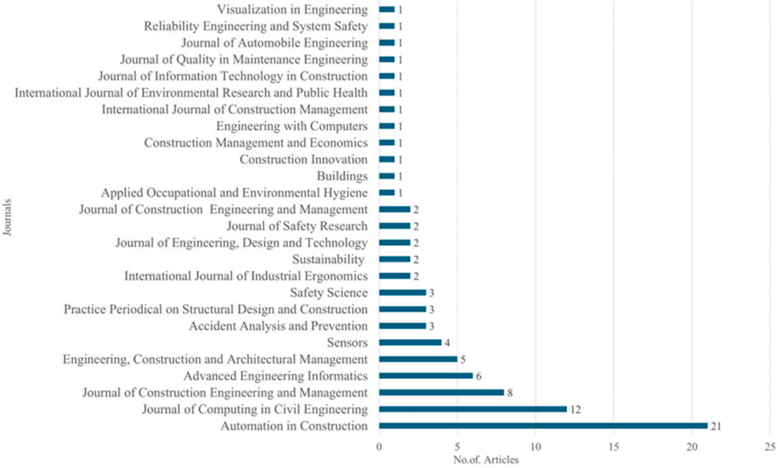

Figure 4. Publication distribution by journal.

5.3. Risk Factors

The analysis results show that there are two major types of earthmoving equipment operation safety research:

(1) Identification of the risk factors of earthmoving equipment operation safety (8 papers) (Category 1);

(2) Safety solutions for risk factors of earthmoving equipment operation safety (79 papers) (Category 2).

Eight papers focusing on identifying all risk factors related to the operation of earthmoving equipment were utilized to consolidate risk factors. Although introducing safety solutions is not the main focus of the paper, the 79 papers on safety solutions for these risk factors were further analyzed to identify the interrelationships among risk factors through the contributions, benefits, and recommendations of safety solutions. In the 87 total papers reviewed in this work, risk factors were mentioned a total of 174 times. Table 2 illustrates the mapping of the extracted risk factors for earthmoving equipment operation. Some categories of Rasmussen [27] risk management framework are named slightly differently to better reflect construction industry terminology.

There are eight studies (Category 1) related to the identification of risk factors related to earthmoving equipment operation in the construction process. Lingard et al. [14] applied the ConAC model to delve into the complex interplay of variables that contribute to safety incidents in earthmoving operations, advocating for a systemic analysis beyond immediate causes. The ConAC model uses a systems thinking approach through understanding the root causes and systemic factors that can significantly contribute to enhancing the safe operation of construction earthmoving equipment such as excavators [46]. Plant-related accidents such as earthmoving equipment operation incidents in the construction process result from a complex interplay of these factors rather than from simple and direct causes. It highlights the importance of looking beyond the immediate circumstances, to understand the shaping and originating influences that contribute to the risk of incidents and to develop more effective prevention strategies [14,46]. Ref. [15] found that the majority of struck-by accidents related to construction earthmoving equipment were due to variables such as technical, environmental, human, and safety culture characteristics, which are a reflection of some aspects of the systems thinking approach.

From the total of 79 papers in category 2, 65 studies (82%) addressed the risk factors of construction earthmoving operations through applying technological approaches for specific risk factors, with 16% suggesting automated solutions for site monitoring and warning systems. Furthermore, 14 scholarly works (18%) focused on the analysis of risk factors through non-technological solutions.

As shown in Table 2, the top three categories are construction site management, workforce, and environment and equipment. Construction site management factors accounted for 56% of the total research reviewed. This indicates that there is a focus on research at the operation level. The prevalent scholarly attention is directed toward site monitoring and warning systems (S1), as evidenced by the highest-frequency occurrences of 30 studies, of which 28 of them proposed safety solutions within this particular area. Utility problems (S6) are highlighted as a significant concern by 14 studies, of which 6 studies mention the risk factors and another 8 studies present safety solutions, indicating a proactive academic response to the identified risks. Regarding S11, which pertains to the lack of sufficient protective work clothing and equipment, five studies pinpoint this as an important risk factor. Despite the identification of this issue, there appears to be a dearth of safety-solution-focused research, with no studies offering safety measures specifically tailored to a variety of earthmoving equipment types and operations.

Research on the workforce level follows closely, representing 30% of the studies, underscoring the significant impact of human factors. A pronounced focus is observed in the realm of safety training (W7), which is identified in 13 studies. This concentration underscores agreement on the critical role of training, further emphasized by the presence of eight articles proposing related safety solutions in the context of earthmoving equipment operation. A considerable number of safety solutions studies emerged: five, four, and three articles addressed physiological conditions, mental conditions, and hazard perception of earthmoving equipment operators, respectively. This implies a recognition of their indirect impact on safety and a responsive effort to address potential problems.

Table 2. Mapping the extracted publications at the levels of the systems thinking classification scheme [27].

Level of Rasmussen [27] Framework	Risk Factors	Type 1	Type 2	Frequency Count
Government	0	0	0	0
Regulatory bodies and associations (R)	R1: Inadequate regulation	[2,47]	-	2
Company management (C)	C1: Stakeholder management	[14,47]	[48]	3
	C2: Manufacturer's performance	[46]	[49,50]	3
	C3: Procurement management	[47]	[50]	2
	C4: Economic climate; budget pressure	[14]	-	1
	C5: Risk management	[14]	-	1
	C6: Safety culture	[2,14]	-	2
	C7: Contractor management	[14,16,47]	-	3
	C8: Accident investigation	[16,46]	[51]	3
Construction site management (S)	S1: Site monitoring and warning system	[14,46]	[1,11,52–77]	30
	S2: Site isolation	[14,46]	[6]	1
	S3: Obstacles and congested work sites	[14,46]	[3,5,78]	5
	S4: Site layout/trajectory and path planning	[2,14,15,46]	[21,79]	6
	S5: Coordination and planning of multiple operations	[14,46]	[22,80]	4
	S6: Utility problems	[2,14–17,47]	[23,81–87]	14
	S7: Traffic management	[47]	[51]	2
	S8: Insufficient or lack of housekeeping program	[2,14,17,46]	-	4
	S9: Insufficient or lack of written work practices	[17]	-	1
	S10: Work schedules	[14,46]	-	2
	S11: Insufficient protective work clothing and equipment	[2,15–17,46]	-	5
Workforce (W)	W1: Operation communication	[2,14,15,46]	[51,88,89]	7
	W2: Situational awareness	[26]	[90,91]	3
	W3: Mental condition of the operator	-	[92–95]	4
	W4: Physiological condition of the operator	-	[96–100]	5
	W5: Operator proficiency	[26]	[51,101]	3
	W6: Safety behavior	[14–16,46]	[102,103]	6
	W7: Safety training	[2,14,15,46,47]	[48,51,61,90, 91,103–105]	13
	W8: Supervisory factor	[2,14,47]	-	3
	W9: Worker knowledge and experience	[47]	-	1
	W10: Hazard perception of the operator	-	[106–108]	3
Environment and equipment (E)	E1: Plant inspection and maintenance	[2,14,15,17,26,46,47]	[101,109]	9
	E2: Earthmoving machinery characteristics (types, stability, and reliability of attachment)	[2]	[48–50,110]	5
	E3: Structural reliability of machinery	-	[111]	1
	E4: Blind spot	[2,14–16,46]	[8,19,20,105, 112–115]	13
	E5: Soil and ground condition	[17,46,47]	-	3
	E6: Weather condition	[14,46,47]	-	3
	E7: Inappropriate application of equipment for tasks being performed	[2,17]	[111]	3
	E8: Task-related malfunction	[2,17]	-	2

Environment and equipment research accounted for 18.9%, reflecting the attention given to the solutions to the risk factors related to the equipment and environment level. Blind spots (E4) in earthmoving equipment operation safety are a significant academic concern, with five studies identifying the issue and eight studies proposing solutions, reflecting a concerted effort to both understand and mitigate this safety challenge. Plant inspection and maintenance (E1), while covered in nine studies in total, split focus between identifying risks and providing solutions, with seven and two studies, respectively, showing a significant inclination toward proactive solutions. Soil and ground conditions (E5) and weather conditions (E6) each present three studies contributing to the understanding of these risk factors. While structural reliability of machinery (E3) has yet to be identified as a risk factor in earthmoving equipment safety literature, task-related malfunction (E8) is acknowledged in two studies, yet without accompanying articles offering safety solutions.

Company management, with a 5% share, suggests a relatively smaller focus, pointing to potential areas for expanding research to bolster managerial effectiveness within the safety of earthmoving equipment operation in the construction process. The scholarly focus addresses the solution of risks associated with manufacturer’s performance (C2), as indicated by two studies dedicated to devising safety solutions. This contrasts with the identification of risks in contractor management (C7), which, despite being the subject of three articles in the Type 1 group, suggests a disparity between the identification of risk factors and the pursuit of corresponding safety measures in the literature.

5.4. Interrelationships of Risk Factors

Figure 5 presents a network graph that visually maps the interconnected risk factors pertinent to earthmoving equipment operation safety across five distinct categories: Regulatory Bodies and Associations (R), Company Management (C), Construction Site Management (S), Workforce (W), and Environment and Equipment (E). The lines between the nodes depict the complex web of interactions and dependencies among the risks, illustrating the multifactorial challenges in ensuring earthmoving equipment operation safety. This graphical representation underscores the interrelated nature of risk factors, necessitating a comprehensive and systematic approach to risk management in the field of earthmoving equipment operation. The interrelationships among the risk factors, as documented in referenced publications, are available in the Supplementary Materials, Table S1.

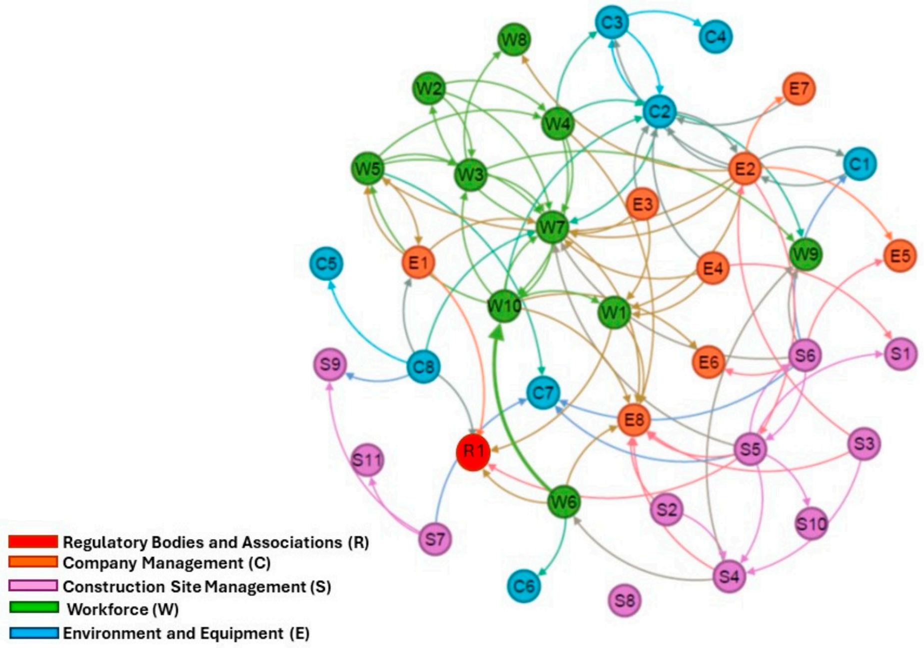

Figure 5. Interdependency of factors affecting construction earthmoving equipment safety. Note: Refer to Table 2 for the corresponding names of the risk factors depicted in the graph.

5.4.1. Degree Centrality Analysis

Table 3 demonstrates the degree of centrality of each node. The attribute in Table 3 indicates to which level of Rasmussen’s framework a node belongs. Degree centrality analysis reveals the following:

(1) The nodes that were forwarded more (high in-degrees) were concentrated more in the workforce level (W), safety training (W7); company management level (C), manufacturer’s performance (C2); and environment and equipment level (E), task-related malfunction (E8).

(2) The nodes that forwarded others with high frequency (high out-degrees) were concentrated at the environment and equipment (E) level, earthmoving machinery character-

istics (types, stability, and reliability of attachment) (E2); construction site management (S) level, coordination and planning of multiple operations (S5) and utility problems (S6); and workforce (W) level, hazard perception of the operator (W10).

As shown in Table 3, the node representing safety training (W7), characterized by the first highest in-degree, illustrates that a significant number of publications focusing on safety solutions underscore the critical role of safety training (W7) in conjunction with their approaches to mitigating specific risk factors [23,48,51,80,85,89,93,98]. The task-related malfunction (E8) has the second highest in-degree primarily because the operation of earthmoving equipment involves a complex interplay of various repetitive tasks and subtasks, each with its unique set of potential hazards. It is imperative to consider the detailed knowledge components of these tasks (cleaning and grubbing, excavation and hauling, compaction, and grading) along with the subtasks (digging, dumping, and relocating) [12]. Each task has inherent risks, and the safety solutions should be sophisticated enough to recognize and navigate the specific challenges presented by these activities to mitigate the risks effectively.

The prominence of manufacturer performance (C2) as the node with the third highest in-degree within the network in the context of preventing earthmoving equipment overturns, such as excavators during lifting operations, reflects the need for more comprehensive information from original equipment manufacturers (OEMs) [49]. Manufacturers also play a crucial role in safety by ensuring lifting points on equipment like quick hitches are of the "closed eye" type and rated for safe working load (SWL). This helps prevent accidents by guiding operators on how much weight can be safely lifted [111].

Earthmoving machinery characteristics (E2), site layout/trajectory and path planning (S5), hazard perception of the operator (W10), and traffic management within the construction site (S6) have the highest out-degree, which indicates their safety enhancement depends on improvements in other interconnected factors. Insufficient or lack of housekeeping program (S8) has no in-degree or out-degree with other nodes.

Table 3. Degree centrality ranking.

Order	Risk Factors	In-Degree	Out-Degree	Degree	Attribute
1	W7	13	3	16	Workforce
2	E2	3	10	13	Environment and equipment
3	C2	7	4	11	Company management
4	S5	2	8	10	Construction site management
5	W10	3	7	10	Workforce
6	E8	9	0	9	Environment and equipment
7	W5	3	5	8	Workforce
8	S6	1	7	8	Construction site management
9	W4	2	5	7	Workforce
10	S4	3	3	6	Construction site management
11	W3	3	3	6	Workforce
12	W1	4	2	6	Workforce
13	W6	1	4	5	Workforce
14	C3	3	2	5	Company management
15	E1	2	3	5	Environment and equipment
16	R1	5	0	5	Regulatory bodies and associations
17	C8	0	5	5	Company management

Table 3. *Cont.*

Order	Risk Factors	In-Degree	Out-Degree	Degree	Attribute
18	W2	1	3	4	Workforce
19	C7	4	0	4	Company management
20	W9	4	0	4	Workforce
21	E4	0	4	4	Workforce
22	C1	2	1	3	Company management
23	S3	0	3	3	Construction site management
24	S7	0	3	3	Construction site management
25	E3	0	3	3	Environment and equipment
26	S1	2	0	2	Construction site management
27	S2	0	2	2	Construction site management
28	S9	2	0	2	Construction site management
29	W8	2	0	2	Workforce
30	E5	2	0	2	Environment and equipment
31	E6	2	0	2	Environment and equipment
32	E7	1	1	1	Environment and equipment
33	C4	1	0	1	Company management
34	C5	1	0	1	Company management
35	C6	1	0	1	Company management
36	S10	1	0	1	Construction site management
37	S11	1	0	1	Construction site management
38	S8	0	0	0	Construction site management

5.4.2. Betweenness Centrality

As shown in Table 4, the characteristics of the machinery (E2) have the highest betweenness centrality of the network. This indicates that they play an important role as intermediaries in the flow of safety-related information. This central positioning suggests that earthmoving machinery characteristics (types, stability, and reliability of attachment) (E2) act as a bridge connecting various Rasmussen risk management levels, and improvements or changes to E2 could significantly influence the other risk factors. Reflecting on E2's connections, as depicted in Figure 5, to a range of nodes across different categories—workforce (W7, W5, W8, W1), company management (C1, C2, C3), environment and equipment (E5, E7), and construction site management (S5)—it acts as a central hub influencing multiple facets of earthmoving equipment operation safety. For example, because E2 is connected to safety training (W7), this implies that any protocols or policies related to safety training may need to consider the specifications or limitations of the machinery. In essence, E2's high betweenness centrality suggests that it not only impacts but also potentially dictates the nature of safety training, indicating that an understanding of E2 is crucial for the effective design and implementation of safety training programs (W7). The same principle applies to E2′s connections to other nodes, which indicates that it might serve as a critical factor in shaping or influencing safety considerations across different levels of the Rasmussen framework.

With the second-highest betweenness centrality, the manufacturer's performance (C2) shapes the earthmoving equipment operation safety. It affects safety training (W7) by aligning it with equipment performance, driving procurement management (C3) toward high-quality machinery and impacting the machinery's design and safety (E2).

The third highest betweenness centrality belongs to the hazard perception of the earthmoving equipment operator (W10). This indicates how operators' ability to perceive and react to hazards is influenced by, and influences, a variety of elements, such as their mental condition (W3), proficiency (W5), knowledge, and experience (W9).

Table 4. Betweenness centrality ranking.

Order	Risk Factors	Betweenness Centrality	Attribute
1	E2	231.16	Environment and equipment
2	C2	212.75	Company management
3	W10	163.33	Workforce
4	W7	121.083	Workforce
5	S5	117.0	Construction site management
6	W6	67.16	Workforce
7	S4	64.66	Construction site management
8	W5	58.91	Workforce
9	W4	46.0	Workforce
10	C3	20.0	Workforce

5.4.3. PageRank Value Analysis

The high PageRank of a node suggests that it is not merely receiving numerous in-links but is also being referenced by other nodes of significant importance within the system. Table 5 reveals that safety training (W7) not only holds the highest in-degree, being the most referenced by other nodes, but also carries the highest PageRank. This underscores its status as a central node, frequently cited by other key nodes with high in-degrees, including manufacturer's performance (C2). Task-related malfunction (E8) and manufacturer's performance (C2) also boast high in-degrees, indicating they are significant points of reference within the network and are cited by pivotal nodes like safety training (W7). Manufacturer's insights into equipment capabilities and limitations are essential for developing task-specific training programs that address real-world applications and hazards.

Table 5. PageRank ranking.

Order	Risk Factors	PageRank Value Analysis	Attribute
1	W7	0.080	Workforce
2	E8	0.078	Environment and equipment
3	C2	0.060	Company management
4	E2	0.044	Environment and equipment
5	W10	0.043	Workforce
6	W9	0.042	Workforce
7	R1	0.037	Regulatory bodies and associations
8	W2	0.035	Workforce
9	C3	0.033	Company management
10	W3	0.032	Workforce

6. Discussion

The objectives of this article are to map earthmoving equipment operation risk factors through the lens of systems thinking, leveraging Rasmussen's (1997) risk management framework and then to identify the interconnections among these risk factors.

6.1. Key Categories of Risk Factors

Some factors at various levels of Rasmussen's risk management framework, presented in Table 2, are unexplored areas where no scholarly papers were identified within the databases we searched. These areas in Table 2 should be subjected to empirical investigation before defining new research related to those risk factors. No research in these areas may also simply demonstrate that the current status quo is deemed satisfactory, suggesting that additional research in these areas might not yield significant contributions to the existing body of knowledge. Nonetheless, the explicit identification of these risk factors in prior publications stands as strong evidence of the merit of investigating factors that have received no attention.

An overview of earthmoving equipment operation risk factors indicates that the risk profile of earthmoving equipment research has not extended beyond the organizational level. Specifically, there is a lack of comprehensive insight into the impact of decisions and actions taken by government and regulatory bodies on behavior and their contribution to accident causation. Without extending attention beyond the organizational level, the chance to address and revise inefficient laws and regulations becomes slim, and important risks might remain unidentified [116]. Although there is stringent implementation of safety standards and legislative mandates, which require consistent checks and certifications of machinery and the competency of operators [51,117], there is no research on how risk factors can be derived from improvement through engaging government actors and regulatory bodies. The results at this level reflect intrinsic limitations within current methodologies and underscore the importance of augmenting research approaches with comprehensive system-wide evaluations.

For instance, within the domain of company management (C), areas such as economic climate and budget pressure (C4), risk management (C5), safety culture (C6), and contractor management (C7) in the health and safety management of earthmoving equipment represent overlooked areas in research.

At the construction site management (S) level, approximately 35% of the 79 safety solutions studies related to earthmoving equipment operations are site monitoring and warning systems (S1); 19% of them emphasize the dual importance of productivity alongside safety through computer vision technology [68,73,74]. Maintaining a high level of productivity should not come at the expense of safety. Efficient operations must incorporate safe practices to prevent accidents, thus avoiding the indirect costs and delays associated with safety incidents. At the workforce level (W), more than 55% of 22 safety solutions publications are related to cognitive research, representing the relatively nascent field of study. For example, the workforce in earthmoving operations often experiences challenges in maintaining situational awareness due to the dynamic and stressful nature of the job site. It is difficult for them to perceive and process all safety-related elements continuously, which can lead to losing track of critical information. This underscores the need for cognitive research to concentrate on comprehending and mitigating the limitations of human cognition in dynamic and stressful earthmoving operations. It also highlights the potential of technologies to enhance situational awareness by presenting information in cognitively manageable ways, thereby aiding in decision making and risk awareness [118]. The development of a cognitive framework of hazard perception and safety behavior offers a structured approach to understanding the complex interplay between cognition and behavior in safety-critical situations, ultimately leading to more effective safety interventions and improved overall safety outcomes in high-risk industries [118]. At the environment and equipment (E) level, the impact of soil and ground conditions (E5), weather conditions (E6), and task-related malfunction (E8) in earthmoving equipment operation safety are unexplored in current research.

6.2. Interrelationships of Risk Factors

Earthmoving equipment safety in construction operations can be regarded as a complex sociotechnical system [24] in which projects, operations, processes, tasks, microtasks, products, resources, and actors are considered knowledge components of the system [12]. The review revealed that when safety solutions are applied to improve one element of the system, the impact on other factors, or how other factors are interrelated, has been overlooked. Understanding this connection is crucial for seeing how safety measures affect the entire system's safety performance [116].

Despite the lack of direct research on inadequate regulation (R1) at the regulatory bodies and associations level, it stands out with a notably high in-degree compared with other nodes without research around them. This contrasts with the general oversight of such nodes, underscoring the unique position of regulatory influences in safety practices as a critical yet unexamined area. At the company management level, manufacturer performance (C2) is an important company-level factor that should remain informed, with continual updates regarding prior operational problems and innovative construction machinery health and safety solutions [49]. There is no identified research on how manufacturers update their information based on the mechanism of accidents in the construction process related to different types of earthmoving equipment. Contractor management (C7) has the second highest in-degree within the network, highlighting the responsibility of contractors, as key stakeholders, in securing health and safety on construction sites. Their responsibility entails gathering comprehensive health and safety information about the proposed project before work begins [48,51]. In some research, a key takeaway for stakeholders involved in earthmoving operations is the need to adopt a multifaceted approach to safety, considering not only the technical aspects of machinery operation but also the human and organizational factors [48,49,109]. This involves interdependencies of rigorous training, adherence to safety protocols, effective communication among stakeholders, and the adoption of innovative technologies to predict and mitigate risks [51]. Accident investigation (C8) has also the highest out-degree within the network, signifying the role of this factor in disseminating information about other risk factors such as W7, E1, R1, C5, and S9 in various levels of management. Plant inspections and risk assessments form a vital part of the accident investigation process, entailing a systematic cycle of documenting and reporting incidents in accordance with health and safety executive (HSE) regulations. The findings from these investigations feed into evaluations of the site and corporate policies, prompting safety alerts and preventive measures that influence company-wide policy decisions and project planning. Training records and statuses, as well as compliance with approved safe method statements, are factored into this process to ensure continuous improvement in safety management and legislative adherence [51]. However, the literature reveals a paucity of studies focusing on contractor management, budget allocations, and accident investigations within the domain of earthmoving equipment safety operations.

At the construction site management level, the most important node is site layout/trajectory and path planning (S4), marked by a leading in-degree count of 4. This node is linked to types of equipment activities and plays a key role in finding the pattern of safe behavior (W6) within the operational confines of the equipment [21]. The coordination of multiple operations (S5), with the highest out-degree at this level, is interconnected with utility management (S6), equipment task malfunction (E8), safety regulation (R1), and project scheduling (S10). These elements influence site layout decisions (S4) and necessitate effective safety training (W7), ensuring safe earthmoving operations [22,80]. Both site isolation (S2) and obstacles in congested work sites (S3) have interdependencies with site planning and layout (S4), as well as equipment characteristics (E2) such as footprint and the cyclic pattern of task of equipment (E8) [6]. These elements are closely linked to the characteristics of the equipment (E2), including its pose (orientation and position), state (operational condition), geometry (physical dimensions), and speed [3,5].

Despite the high frequency of publications in site monitoring and warning systems (S1), interdependencies with other risk factors are not identified unless there is a focus on advancing technology for developing warning systems [1,54,57] and automated collision monitoring of earthmoving operation resources (human–equipment) [66] through computer vision [11,63,65,67–70]. Resilience engineering through the application of these kinds of technologies focuses on creating systems that are capable of anticipating, absorbing, and adapting to potential accidents. This approach goes beyond the traditional safety protocols, which often react to accidents after they occur [24]. Additionally, they apply one technique for automated tracking of workers and equipment. Although this has merits, it cannot address all the complexities of construction sites or guarantee success in every situation. Therefore, developing mixed methods that combine various approaches to improve results could be very advantageous [119]. Establishing mechanisms for continuous feedback and learning from both successful operations and near-misses promotes ongoing improvement in safety practices, which directly contributes to enhanced productivity.

At the workforce level, safety training (W7) stands out as the factor most referenced in high interdependency to other risk factors, representing 7% of all safety solutions. There is a lack of effective safety measures and training methods centered on attentional guidance of the workforce involved in earthmoving operations based on task and subtask breakdown [91] to reduce accidents on construction sites [93]. Safety training based on the characteristics of various earthmoving equipment (technical standards), tasks' steps definition, and hazard identification based on elementary activity are other overlooked research areas [103]. Operation communication (W1) and worker knowledge and experience (W9) are both the second highest in-degree in this level. Effective communication enhances the safety climate and safety outcomes in earthmoving operations such as excavation [89]. However, there is a lack of research on communication and task analysis to find the patterns of movement of humans during their interaction. Additionally, worker knowledge and experience (W9) is also an overlooked investigation area that has interdependency with critical factors such as manufacturer's performance (C2). Hazard perception of the operator (W10) and mental condition of the operator (W3) are the third highest in-degree at the workforce level. In long-term continuous earthmoving operation tasks (W10), the hazard perception of the operator (W10) has interdependences with mental workload/mental fatigue (W3), manufacturer performance (C2) in designing more ergonomic and safe equipment, and other factors outside the framework, including controlling the attention allocation, cognitive failure, time of day, temperature, operation skill, personality, emotion, safety attitude, etc. [106,107]. These factors are crucial, but research and understanding of them in the construction industry is lacking [106].

Safety behavior (W6) also acts as a key indicator of an organization's safety culture (C6), playing a critical role in its overall safety outcomes [102]. Task-based (E8) safety behavior is a prerequisite for achieving higher safety levels from both project and operational standpoints. For example, the behavior of concrete mixer trucks' operators should be evaluated when performing various tasks like driving in the construction site, getting into/out of the cabin, parking and setting at the working place, concrete direct discharge, concrete discharge into a pump, concrete discharge into a bucket, cleaning the drum, maintenance, and final setting [103]. Leveraging predicted levels of mental fatigue (W3) aids safety managers (W8) in notifying operators of earthmoving equipment about possible health dangers in their ongoing tasks [95].

One of the physiological challenges to the operator (W4) is related to whole-body vibration (WBV) during the operation of earthmoving equipment [96,97,99]. Ref. [96] measured whole-body vibration of front-end loader operators and assessed the impact of traction chains and work tasks on their WBV exposures.

At the environment equipment (E) level, a significant amount of research (16%) focused on tackling the problem related to blind spots (E4) of equipment, which has interdependencies with proactive decisions regarding stakeholder management (C1) and manufacturer performance (C2) [114,115]. For example, providing tailored courses and safety training (W7) addresses the risks related to the operation of or proximity to earthmoving machinery to frontline stakeholders engaged at the construction site. This includes the construction safety manager, the equipment operators, and the ground workers [115]. However, there is no research directly related to task-related malfunctions (E8) that has the highest in-degree and page rank value at this level due to its interdependencies with other critical risk factors.

Earthmoving machinery characteristics (types, stability, and reliability of attachments) (E2) is marked by the highest out-degree and betweenness centrality, acting as the starting points for safety decisions for various other risk factors at different levels of management, such as manufacturer performance (C2) and safety training (W7) [48–50,110]. Moreover, site-specific challenges, such as soil types (E5) [14], irregular terrain, and weather conditions (E6) are the neglected areas that should be considered as risk factors related to earthmoving operations in the construction process.

7. Future Research Directions

After reviewing various studies, we have pinpointed some areas that still need more attention and warrant further investigation.

In earthmoving operations, understanding the interplay between the characteristics of the equipment and the tasks it performs is essential. Systems thinking (ST) is necessary in this context because it provides a comprehensive perspective that encompasses all facets of the operation, including human behavior, technological interfaces, organizational culture, and external environmental factors. The event analysis of systemic teamwork (EAST) framework is designed to analyze the task network, social network, and information network [120]. Earthmoving machinery's (E2) diverse functionalities, ranging from specific equipment types like hoes and dozers to their use in composite operations like earthmoving, which combines tasks such as excavation and hauling [12], highlight its critical role in information distribution for other nodes of the network and decision making for safety at different levels of management. By bridging objectives one and two for future research directions, earthmoving equipment operations could entail social interaction patterns between operators, manufacturers, and frontline ground workers and involve understanding how tasks are distributed, interconnected, and managed within the system. Task analysis involves breaking down each operation into smaller tasks and microtasks to understand the workflow, the resources needed, and potential safety hazards. Understanding the steps of each task allows for the identification of potential risks. For example, excavating a trench involves different steps and precautions than grading a slope [47]. The information network covers how information flows through the system, which is crucial for decision making and coordination. In earthmoving, this could include the transmission of safety alerts, operational updates, and performance data. For example, with safety training (W7) as one of the important factors in the network, research could focus on designing training programs that specifically target the understanding and mitigation of task-related malfunctions (E8) and improve familiarity with machinery (E2). Such training could also be developed in collaboration with manufacturers (C2) to ensure it is grounded in the latest equipment specifications and performance standards. This necessitates a detailed task analysis and an effective flow of information, incorporating social interactions among various stakeholders. Frameworks like AcciMap, Human Factor Analysis Classification System (HFACS), and Functional Resonance Analysis Method (FRAM) are examples cited in the literature as sociotechnical system (STS)-based analytical tools [120–122]. Systems thinking in accident investigations can uncover root causes beyond the immediate factors, and interviewing the involved workforce enriches data for prevention measures [9].

Most safety solutions are predominantly based on technological interventions. Real-world testing is crucial for the effectiveness of construction site safety technologies, focusing on resolving challenges like data accuracy, user resistance, and ensuring scalability and cost effectiveness. Emphasizing technologies as supplements to human factors, rather than the primary focus, is key to improving safety outcomes [18,122–124]. Future studies should explore technological solutions, like advanced monitoring and predictive systems, to predict and prevent task-related malfunctions (E8) in earthmoving equipment operations. Focus on human factors research includes studying the hazard perception of operators (W10), which includes the mental (W3), physical (W4) (e.g., whole-body vibration (WBV)), and cognitive demands in operating earthmoving equipment. Develop and validate a comprehensive cognitive model of the operator and worker in earthmoving equipment operation, hazard identification, integrating attention, and the role of technology [118].

8. Conclusions

In this research, we have presented state-of-the-art research on earthmoving equipment operation safety and have covered 87 pertinent publications. The work provides an overview of the current literature on earthmoving equipment operation safety, shedding light on how researchers are mostly focusing on which aspects of mitigating hazards in this field. This research conducted a multistep approach, firstly, to identifying 38 risk factors associated with earthmoving equipment operation according to systems-thinking-based classifications, and the social network analysis (SNA) approach applied as a novel approach for the content analysis of the literature, by using Gephi for finding the interdependencies of risk factors from the safety solutions literature. Safety training (W7), task-related malfunction (E8), and manufacturer performance (C2) are identified as having both the highest in-degree centrality and PageRank values in the network of risk factors, emphasizing their considerable influence in the network of interdependencies. Hazard perception of the operator (W10), earthmoving machinery characteristics (types, stability, and reliability of attachment) (E2), and manufacturer performance (C2), with the highest betweenness centrality, indicate their critical roles as key connectors within the network of risk factors. Finally, this study reveals paths for future research in the area of earthmoving equipment operation safety in the construction process. This study contributes to providing a holistic picture of risk factors affecting earthmoving equipment operation safety and highlighting portfolios of interconnected risk factors, which, if addressed properly, would bring about cascading effects on improving earthmoving equipment operation safety.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14071978/s1, Table S1 illustrates the interrelationships among risk factors as documented in the referenced publications.

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References

1. Chae, S.; Yoshida, T. Application of RFID technology to prevention of collision accident with heavy equipment. *Autom. Constr.* **2010**, *19*, 368–374. [CrossRef]
2. Kazan, E.; Usmen, M.A. Worker safety and injury severity analysis of earthmoving equipment accidents. *J. Saf. Res.* **2018**, *65*, 73–81. [CrossRef] [PubMed]
3. Vahdatikhaki, F.; Hammad, A. Risk-based look-ahead workspace generation for earthwork equipment using near real-time simulation. *Autom. Constr.* **2015**, *58*, 207–220. [CrossRef]
4. Chinniah, Y. Analysis and prevention of serious and fatal accidents related to moving parts of machinery. *Saf. Sci.* **2015**, *75*, 163–173. [CrossRef]
5. Vahdatikhaki, F.; Hammad, A. Dynamic equipment workspace generation for improving earthwork safety using real-time location system. *Adv. Eng. Inform.* **2015**, *29*, 459–471. [CrossRef]
6. Shen, X.; Marks, E.; Pradhananga, N.; Cheng, T. Hazardous proximity zone design for heavy construction excavation equipment. *J. Constr. Eng. Manag.* **2016**, *142*, 05016001. [CrossRef]
7. Lingard, H.; Cooke, T.; Zelic, G.; Harley, J. A qualitative analysis of crane safety incident causation in the Australian construction industry. *Saf. Sci.* **2021**, *133*, 105028. [CrossRef]
8. Marks, E.D.; Cheng, T.; Teizer, J. Laser scanning for safe equipment design that increases operator visibility by measuring blind spots. *J. Constr. Eng. Manag.* **2013**, *139*, 1006–1014. [CrossRef]
9. Woolley, M.J.; Goode, N.; Read, G.J.; Salmon, P.M. Moving beyond the organizational ceiling: Do construction accident investigations align with systems thinking? *Hum. Factors Ergon. Manuf. Serv. Ind.* **2018**, *28*, 297–308. [CrossRef]

10. Safe Work Australia. *Model Work Health and Safety Regulations*; Safe Work Australia: Canberra, Australia, 2019.
11. Rezazadeh Azar, E.; McCabe, B. Automated visual recognition of dump trucks in construction videos. *J. Comput. Civ. Eng.* **2012**, *26*, 769–781. [CrossRef]
12. Taher, A.; Vahdatikhaki, F.; Hammad, A. Formalizing knowledge representation in earthwork operations through development of domain ontology. *Eng. Constr. Archit. Manag.* **2022**, *29*, 2382–2414. [CrossRef]
13. Bostrom, R.; Gupta, S.; Thomas, D. A meta-theory for understanding information systems within sociotechnical systems. *J. Manag. Inf. Syst.* **2009**, *26*, 17–48. [CrossRef]
14. Lingard, H.; Cooke, T.; Gharaie, E. The how and why of plant-related fatalities in the Australian construction industry. *Eng. Constr. Archit. Manag.* **2013**, *20*, 365–380. [CrossRef]
15. Hinze, J.; Olbina, S.; Orozco, J.; Beaumont, K. Earthmoving Equipment Fatalities in the Construction Industry. *Pract. Period. Struct. Des. Constr.* **2017**, *22*, 04017015. [CrossRef]
16. Hinze, J.W.; Teizer, J. Visibility-related fatalities related to construction equipment. *Saf. Sci.* **2011**, *49*, 709–718. [CrossRef]
17. Hinze, J.; Huang, X.; Terry, L. The nature of struck-by accidents. *J. Constr. Eng. Manag.* **2005**, *131*, 262–268. [CrossRef]
18. Soltanmohammadlou, N.; Sadeghi, S.; Hon, C.K.H.; Mokhtarpour-Khanghah, F. Real-time locating systems and safety in construction sites: A literature review. *Saf. Sci.* **2019**, *117*, 229–242. [CrossRef]
19. Ray, S.J.; Teizer, J. Coarse head pose estimation of construction equipment operators to formulate dynamic blind spots. *Adv. Eng. Inform.* **2012**, *26*, 117–130. [CrossRef]
20. Ray, S.J.; Teizer, J. Dynamic blindspots measurement for construction equipment operators. *Saf. Sci.* **2016**, *85*, 139–151. [CrossRef]
21. Cheng, T.; Mantripragada, U.; Teizer, J.; Vela, P.A. Automated trajectory and path planning analysis based on ultra wideband data. *J. Comput. Civ. Eng.* **2012**, *26*, 151–160. [CrossRef]
22. Vahdatikhaki, F.; Langari, S.M.; Taher, A.; El Ammari, K.; Hammad, A. Enhancing coordination and safety of earthwork equipment operations using Multi-Agent System. *Autom. Constr.* **2017**, *81*, 267–285. [CrossRef]
23. Tanoli, W.A.; Sharafat, A.; Park, J.; Seo, J.W. Damage Prevention for underground utilities using machine guidance. *Autom. Constr.* **2019**, *107*, 102893. [CrossRef]
24. Naghshbandi, S.N.; Varga, L.; Hu, Y. Technologies for safe and resilient earthmoving operations: A systematic literature review. *Autom. Constr.* **2021**, *125*, 103632. [CrossRef]
25. Azar, E.R.; Kamat, V.R. Earthmoving equipment automation: A review of technical advances and future outlook. *J. Inf. Technol. Constr.* **2017**, *22*, 247–265.
26. Edwards, D.J.; Holt, G.D. Construction plant and equipment management research: Thematic review. *J. Eng. Des. Technol.* **2009**, *7*, 186–206. [CrossRef]
27. Rasmussen, J. Risk management in a dynamic society: A modelling problem. *Saf. Sci.* **1997**, *27*, 183–213. [CrossRef]
28. Loosemore, M.; Cheung, E. Implementing systems thinking to manage risk in public private partnership projects. *Int. J. Proj. Manag.* **2015**, *33*, 1325–1334. [CrossRef]
29. Leveson, N. A new accident model for engineering safer systems. *Saf. Sci.* **2004**, *42*, 237–270. [CrossRef]
30. Zhou, W.; Zhao, T.; Liu, W.; Tang, J. Tower crane safety on construction sites: A complex sociotechnical system perspective. *Saf. Sci.* **2018**, *109*, 95–108. [CrossRef]
31. Zhang, W.; Xue, N.N.; Zhang, J.R.; Zhang, X. Identification of Critical Causal Factors and Paths of Tower-Crane Accidents in China through System Thinking and Complex Networks. *J. Constr. Eng. Manag.* **2021**, *147*, 04021174. [CrossRef]
32. Zhang, X.; Zhang, W.; Jiang, L.; Zhao, T.S. Identification of Critical Causes of Tower-Crane Accidents through System Thinking and Case Analysis. *J. Constr. Eng. Manag.* **2020**, *146*, 04020071. [CrossRef]
33. Fink, A. *Conducting Research Literature Reviews: From the Internet to Paper*; Sage Publications: Thousand Oaks, CA, USA, 2019.
34. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Ann. Intern. Med.* **2009**, *151*, 264–269. [CrossRef] [PubMed]
35. Çevikbaş, M.; Işık, Z. An overarching review on delay analyses in construction projects. *Buildings* **2021**, *11*, 109. [CrossRef]
36. Otte, E.; Rousseau, R. Analyse af sociale netværk: En stærk strategi, også for informationsvidenskaberne. *J. Inf. Sci.* **2002**, *28*, 441–453. [CrossRef]
37. Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. Science mapping software tools: Review, analysis, and cooperative study among tools. *J. Am. Soc. Inf. Sci. Technol.* **2011**, *62*, 1382–1402. [CrossRef]
38. Cherven, K. *Mastering Gephi Network Visualization*; Packt Publishing Ltd.: Birmingham, UK, 2015.
39. Antoniou, I.E.; Tsompa, E. Statistical analysis of weighted networks. *Discret. Dyn. Nat. Soc.* **2008**, *2008*, 375452. [CrossRef]
40. Kapoor, K.; Sharma, D.; Srivastava, J. Weighted node degree centrality for hypergraphs. In Proceedings of the 2013 IEEE 2nd Network Science Workshop (NSW), West Point, NY, USA, 29 April–1 May 2013; pp. 152–155.
41. Hickethier, G.; Tommelein, I.D.; Lostuvali, B. Social network analysis of information flow in an IPD-project design organization. In Proceedings of the International Group for Lean Construction, Fortaleza, Brazil, 29 July–2 August 2013.
42. Freeman, L.C. A set of measures of centrality based on betweenness. *Sociometry* **1977**, *40*, 35–41. [CrossRef]
43. Borgatti, S.P.; Everett, M.G.; Johnson, J.C.; Agneessens, F. *Analyzing Social Networks*; SAGE Publications Limited: Thousand Oaks, CA, USA, 2024.
44. Gould, R.V.; Fernandez, R.M. Structures of mediation: A formal approach to brokerage in transaction networks. *Sociol. Methodol.* **1989**, *19*, 89–126. [CrossRef]

45. Pavicic, V. PageRank Algorithm for Graph Databases. *Memgraph*, 1 February 2023. Available online: https://memgraph.com/blog/pagerank-algorithm-for-graph-databases (accessed on 2 May 2024).
46. Lingard, H.; Cooke, T.; Gharaie, E. A case study analysis of fatal incidents involving excavators in the Australian construction industry. *Eng. Constr. Archit. Manag.* **2013**, *20*, 488–504. [CrossRef]
47. Hinze, J. Use of trench boxes for worker protection. *J. Constr. Eng. Manag.* **2005**, *131*, 494–500. [CrossRef]
48. Edwards, D.J.; Holt, G.D. Health and safety issues relating to construction excavators and their attachments. *Eng. Constr. Archit. Manag.* **2008**, *15*, 321–335. [CrossRef]
49. Edwards, D.; Parn, E.A.; Sing, M.C.P.; Thwala, W.D. Risk of excavators overturning: Determining horizontal centrifugal force when slewing freely suspended loads. *Eng. Constr. Archit. Manag.* **2019**, *26*, 479–498. [CrossRef]
50. Edwards, D.J.; Holt, G.D. Mini-excavator safety: Toward innovative stability testing, procurement, and manufacture. *J. Constr. Eng. Manag.* **2011**, *137*, 1125–1133. [CrossRef]
51. Riaz, Z.; Edwards, D.J.; Holt, G.D.; Thorpe, T. Data flow analysis of plant and equipment health and safety management. *J. Eng. Des. Technol.* **2011**, *9*, 178–203. [CrossRef]
52. Elelu, K.; Le, T.; Le, C. Collision Hazard Detection for Construction Worker Safety Using Audio Surveillance. *J. Constr. Eng. Manag.* **2023**, *149*, 04022159. [CrossRef]
53. Jo, B.W.; Lee, Y.S.; Khan, R.M.A.; Kim, J.H.; Kim, D.K. Robust Construction Safety System (RCSS) for collision accidents prevention on construction sites. *Sensors* **2019**, *19*, 932. [CrossRef] [PubMed]
54. Jo, B.W.; Lee, Y.S.; Kim, J.H.; Kim, D.K.; Choi, P.H. Proximity warning and excavator control system for prevention of collision accidents. *Sustainability* **2017**, *9*, 1488. [CrossRef]
55. Kim, K.; Jeong, I.; Cho, Y.K. Signal Processing and Alert Logic Evaluation for IoT-Based Work Zone Proximity Safety System. *J. Constr. Eng. Manag.* **2023**, *149*, 05022018. [CrossRef]
56. Kim, Y.; Choi, Y. Smart Helmet-Based Proximity Warning System to Improve Occupational Safety on the Road Using Image Sensor and Artificial Intelligence. *Int. J. Environ. Res. Public Health* **2022**, *19*, 16312. [CrossRef] [PubMed]
57. Marks, E.D.; Teizer, J. Method for testing proximity detection and alert technology for safe construction equipment operation. *Constr. Manag. Econ.* **2013**, *31*, 636–646. [CrossRef]
58. Park, J.; Marks, E.; Cho, Y.K.; Suryanto, W. Performance test of wireless technologies for personnel and equipment proximity sensing in work zones. *J. Constr. Eng. Manag.* **2016**, *142*, 04015049. [CrossRef]
59. Park, J.; Yang, X.; Cho, Y.K.; Seo, J. Improving dynamic proximity sensing and processing for smart work-zone safety. *Autom. Constr.* **2017**, *84*, 111–120. [CrossRef]
60. Son, H.; Seong, H.; Choi, H.; Kim, C. Real-Time Vision-Based Warning System for Prevention of Collisions between Workers and Heavy Equipment. *J. Comput. Civ. Eng.* **2019**, *33*, 04019029. [CrossRef]
61. Teizer, J. Wearable, wireless identification sensing platform: Self-Monitoring Alert and Reporting Technology for Hazard Avoidance and Training (SmartHat). *J. Inf. Technol. Constr.* **2015**, *20*, 295–312.
62. Wang, J.; Razavi, S.N. Low False Alarm Rate Model for Unsafe-Proximity Detection in Construction. *J. Comput. Civ. Eng.* **2016**, *30*, 04015005. [CrossRef]
63. Fang, W.; Ding, L.; Zhong, B.; Love, P.E.D.; Luo, H. Automated detection of workers and heavy equipment on construction sites: A convolutional neural network approach. *Adv. Eng. Inform.* **2018**, *37*, 139–149. [CrossRef]
64. Kim, H.; Kim, H. 3D reconstruction of a concrete mixer truck for training object detectors. *Autom. Constr.* **2018**, *88*, 23–30. [CrossRef]
65. Shin, Y.S.; Kim, J. A Vision-Based Collision Monitoring System for Proximity of Construction Workers to Trucks Enhanced by Posture-Dependent Perception and Truck Bodies' Occupied Space. *Sustainability* **2022**, *14*, 7934. [CrossRef]
66. Son, H.; Kim, C. Integrated worker detection and tracking for the safe operation of construction machinery. *Autom. Constr.* **2021**, *126*, 103670. [CrossRef]
67. Xiao, B.; Kang, S.C. Vision-Based Method Integrating Deep Learning Detection for Tracking Multiple Construction Machines. *J. Comput. Civ. Eng.* **2021**, *35*, 04020071. [CrossRef]
68. Xiao, B.; Zhu, Z. Two-Dimensional Visual Tracking in Construction Scenarios: A Comparative Study. *J. Comput. Civ. Eng.* **2018**, *32*, 04018006. [CrossRef]
69. Zhu, Z.; Ren, X.; Chen, Z. Visual Tracking of Construction Jobsite Workforce and Equipment with Particle Filtering. *J. Comput. Civ. Eng.* **2016**, *30*, 04016023. [CrossRef]
70. Zhu, Z.; Park, M.W.; Koch, C.; Soltani, M.; Hammad, A.; Davari, K. Predicting movements of onsite workers and mobile equipment for enhancing construction site safety. *Autom. Constr.* **2016**, *68*, 95–101. [CrossRef]
71. Kim, H.; Kim, H.; Hong, Y.W.; Byun, H. Detecting Construction Equipment Using a Region-Based Fully Convolutional Network and Transfer Learning. *J. Comput. Civ. Eng.* **2018**, *32*, 04017082. [CrossRef]
72. Luo, H.; Wang, M.; Wong, P.K.Y.; Cheng, J.C.P. Full body pose estimation of construction equipment using computer vision and deep learning techniques. *Autom. Constr.* **2020**, *110*, 103016. [CrossRef]
73. Soltani, M.M.; Zhu, Z.; Hammad, A. Skeleton estimation of excavator by detecting its parts. *Autom. Constr.* **2017**, *82*, 1–15. [CrossRef]
74. Soltani, M.M.; Zhu, Z.; Hammad, A. Framework for Location Data Fusion and Pose Estimation of Excavators Using Stereo Vision. *J. Comput. Civ. Eng.* **2018**, *32*, 04018045. [CrossRef]
75. Wen, L.; Kim, D.; Liu, M.; Lee, S. 3D Excavator Pose Estimation Using Projection-Based Pose Optimization for Contact-Driven Hazard Monitoring. *J. Comput. Civ. Eng.* **2023**, *37*, 04022048. [CrossRef]

76. Yuan, C.; Li, S.; Cai, H. Vision-based excavator detection and tracking using hybrid kinematic shapes and key nodes. *J. Comput. Civ. Eng.* **2016**, *31*, 04016038. [CrossRef]
77. Zhao, J.; Hu, Y.; Tian, M. Pose estimation of excavator manipulator based on monocular vision marker system. *Sensors* **2021**, *21*, 4478. [CrossRef] [PubMed]
78. Oh, K.; Park, S.; Seo, J.; Kim, J.G.; Park, J.; Lee, G.; Yi, K. Development of a predictive safety control algorithm using laser scanners for excavators on construction sites. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2019**, *233*, 2007–2029. [CrossRef]
79. Lin, J.J.C.; Yang, C.E.; Hung, W.H.; Kang, S.C. Accessibility evaluation system for site layout planning—A tractor trailer example. *Vis. Eng.* **2013**, *1*, 12. [CrossRef]
80. Pradhananga, N.; Teizer, J. Automatic spatio-temporal analysis of construction site equipment operations using GPS data. *Autom. Constr.* **2013**, *29*, 107–122. [CrossRef]
81. Al-Bayati, A.J.; Panzer, L. Reducing Damage to Underground Utilities: Lessons Learned from Damage Data and Excavators in North Carolina. *J. Constr. Eng. Manag.* **2019**, *145*, 04019078. [CrossRef]
82. Talmaki, S.; Kamat, V.R. Real-time hybrid virtuality for prevention of excavation related utility strikes. *J. Comput. Civ. Eng.* **2014**, *28*, 04014001. [CrossRef]
83. Talmaki, S.; Kamat, V.R.; Cai, H. Geometric modeling of geospatial data for visualization-assisted excavation. *Adv. Eng. Inform.* **2013**, *27*, 283–298. [CrossRef]
84. Li, S.; Cai, H.; Kamat, V.R. Uncertainty-aware geospatial system for mapping and visualizing underground utilities. *Autom. Constr.* **2015**, *53*, 105–119. [CrossRef]
85. Talmaki, S.A.; Kamat, V.R. Sensor Acquisition and Allocation for Real-Time Monitoring of Articulated Construction Equipment in Digital Twins. *Sensors* **2022**, *22*, 7635. [CrossRef]
86. Kolera, B.T.; Bernold, L.E. Intelligent utility locating tool for excavators. *J. Constr. Eng. Manag.* **2006**, *132*, 919–927. [CrossRef]
87. Talmaki, S.; Kamat, V.R.; Saidi, K. Feasibility of real-time graphical simulation for active monitoring of visibility-constrained construction processes. *Eng. Comput.* **2015**, *31*, 29–49. [CrossRef]
88. Mahdi, H.S.; Afshar, E. Performance of electronic devices for bridging existing information gaps at construction sites: The case of a developing country. *Int. J. Constr. Manag.* **2022**, 1–11. [CrossRef]
89. Zamani, V.; Banihashemi, S.Y.; Abbasi, A. How can communication networks among excavator crew members in construction projects affect the relationship between safety climate and safety outcomes? *Saf. Sci.* **2020**, *128*, 104737. [CrossRef]
90. Cheng, T.; Teizer, J. Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications. *Autom. Constr.* **2013**, *34*, 3–15. [CrossRef]
91. Choi, M.; Ahn, S.; Seo, J. VR-Based investigation of forklift operator situation awareness for preventing collision accidents. *Accid. Anal. Prev.* **2020**, *136*, 105404. [CrossRef] [PubMed]
92. Li, J.; Li, H.; Umer, W.; Wang, H.; Xing, X.; Zhao, S.; Hou, J. Identification and classification of construction equipment operators' mental fatigue using wearable eye-tracking technology. *Autom. Constr.* **2020**, *109*, 103000. [CrossRef]
93. Li, J.; Li, H.; Wang, H.; Umer, W.; Fu, H.; Xing, X. Evaluating the impact of mental fatigue on construction equipment operators' ability to detect hazards using wearable eye-tracking technology. *Autom. Constr.* **2019**, *105*, 102835. [CrossRef]
94. Mehmood, I.; Li, H.; Umer, W.; Arsalan, A.; Saad Shakeel, M.; Anwer, S. Validity of facial features' geometric measurements for real-time assessment of mental fatigue in construction equipment operators. *Adv. Eng. Inform.* **2022**, *54*, 101777. [CrossRef]
95. Wang, L.; Li, H.; Yao, Y.; Han, D.; Yu, C.; Lyu, W.; Wu, H. Smart cushion-based non-invasive mental fatigue assessment of construction equipment operators: A feasible study. *Adv. Eng. Inform.* **2023**, *58*, 102134. [CrossRef]
96. Blood, R.P.; Rynell, P.W.; Johnson, P.W. Whole-body vibration in heavy equipment operators of a front-end loader: Role of task exposure and tire configuration with and without traction chains. *J. Saf. Res.* **2012**, *43*, 357–364. [CrossRef] [PubMed]
97. Cann, A.P.; Salmoni, A.W.; Vi, P.; Eger, T.R. An exploratory study of whole-body vibration exposure and dose while operating heavy equipment in the construction industry. *Appl. Occup. Environ. Hyg.* **2003**, *18*, 999–1005. [CrossRef] [PubMed]
98. Edwards, D.J.; Holt, G.D. Perceptions of workplace vibration hazards among a small sample of UK construction professionals. *Eng. Constr. Archit. Manag.* **2007**, *14*, 261–276. [CrossRef]
99. Langer, T.H.; Iversen, T.K.; Andersen, N.K.; Mouritsen, O.Ø.; Hansen, M.R. Reducing whole-body vibration exposure in backhoe loaders by education of operators. *Int. J. Ind. Ergon.* **2012**, *42*, 304–311. [CrossRef]
100. Shen, X.; Awolusi, I.; Marks, E. Construction Equipment Operator Physiological Data Assessment and Tracking. *Pract. Period. Struct. Des. Constr.* **2017**, *22*, 04017006. [CrossRef]
101. Edwards, D.J.; Holt, G.D.; Robinson, B. An artificial intelligence approach for improving plant operator maintenance proficiency. *J. Qual. Maint. Eng.* **2002**, *8*, 239–252. [CrossRef]
102. Goh, Y.M.; Ali, M.J.A. A hybrid simulation approach for integrating safety behavior into construction planning: An earthmoving case study. *Accid. Anal. Prev.* **2016**, *93*, 310–318. [CrossRef] [PubMed]
103. Fargnoli, M.; Lombardi, M. Preliminary human safety assessment (PHSA) for the improvement of the behavioral aspects of safety climate in the construction industry. *Buildings* **2019**, *9*, 69. [CrossRef]
104. Abdeen, F.N.; Gunatilaka, R.N.; Sepasgozar, S.M.E.; Edwards, D.J. The usability of a novel mobile augmented reality application for excavation process considering safety and productivity in construction. *Constr. Innov.* **2022**, *24*, 892–911. [CrossRef]
105. Teizer, J.; Allread, B.S.; Fullerton, C.E.; Hinze, J. Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. *Autom. Constr.* **2010**, *19*, 630–640. [CrossRef]

106. Li, J.; Li, H.; Wang, F.; Cheng, A.S.K.; Yang, X.; Wang, H. Proactive analysis of construction equipment operators' hazard perception error based on cognitive modeling and a dynamic Bayesian network. *Reliab. Eng. Syst. Saf.* **2021**, *205*, 107203. [CrossRef]
107. Gürcanli, G.E.; Baradan, S.; Uzun, M. Risk perception of construction equipment operators on construction sites of Turkey. *Int. J. Ind. Ergon.* **2015**, *46*, 59–68. [CrossRef]
108. Sakhakarmi, S.; Park, J.; Singh, A. Tactile-based wearable system for improved hazard perception of worker and equipment collision. *Autom. Constr.* **2021**, *125*, 103613. [CrossRef]
109. Edwards, D.J.; Love, P.E.D. A case study of machinery maintenance protocols and procedures within the UK utilities sector Dedicated to MRS. June Edwards, a lady of great distinction who preserved the health and dignity of others for many years. A loving mother and grandmother, without whose help, this work and many achievements would not have been possible. *Accid. Anal. Prev.* **2016**, *93*, 319–329. [CrossRef] [PubMed]
110. Zhu, Q.; Xiao, C.; Hu, H.; Liu, Y.; Wu, J. Multi-sensor based online attitude estimation and stability measurement of articulated heavy vehicles. *Sensors* **2018**, *18*, 212. [CrossRef] [PubMed]
111. Edwards, D.J.; Holt, G.D. Case study analysis of risk from using excavators as 'cranes'. *Autom. Constr.* **2010**, *19*, 127–133. [CrossRef]
112. Teizer, J.; Allread, B.S.; Mantripragada, U. Automating the blind spot measurement of construction equipment. *Autom. Constr.* **2010**, *19*, 491–501. [CrossRef]
113. Ray, S.J.; Teizer, J. Computing 3D blind spots of construction equipment: Implementation and evaluation of an automated measurement and visualization method utilizing range point cloud data. *Autom. Constr.* **2013**, *36*, 95–107. [CrossRef]
114. Ferreira, C.; Kumar, S.S.; Abraham, D.M. Using Backing Cameras to Prevent Work Zone Accidents Involving Mobile Equipment. *Pract. Period. Struct. Des. Constr.* **2017**, *22*, 04017021. [CrossRef]
115. Golovina, O.; Teizer, J.; Pradhananga, N. Heat map generation for predictive safety planning: Preventing struck-by and near miss interactions between workers-on-foot and construction equipment. *Autom. Constr.* **2016**, *71*, 99–115. [CrossRef]
116. Woolley, M.J.; Goode, N.; Read, G.J.; Salmon, P.M. Have we reached the organisational ceiling? a review of applied accident causation models, methods and contributing factors in construction. *Theor. Issues Ergon. Sci.* **2019**, *20*, 533–555. [CrossRef]
117. *SL2011-36*; Work Health and Safety Regulation 2011. ACT Government: Canberra, Australia, 2024.
118. Zhang, Z.; Guo, B.H.; Chang-Richards, A.; Feng, Z.; Jin, R.; Zou, Y.; Goh, Y.M. Digital technology enhanced situation awareness for construction safety: Systematic review and future research directions. *Saf. Sci.* **2023**, *167*, 106280. [CrossRef]
119. Sherafat, B.; Ahn, C.R.; Akhavian, R.; Behzadan, A.H.; Golparvar-Fard, M.; Kim, H.; Lee, Y.-C.; Rashidi, A.; Azar, E.R. Automated methods for activity recognition of construction workers and equipment: State-of-the-art review. *J. Constr. Eng. Manag.* **2020**, *146*, 03120002. [CrossRef]
120. Salmon, P.M.; Read, G.J.M.; Walker, G.H.; Goode, N.; Grant, E.; Dallat, C.; Carden, T.; Naweed, A.; Stanton, N.A. STAMP goes EAST: Integrating systems ergonomics methods for the analysis of railway level crossing safety management. *Saf. Sci.* **2018**, *110*, 31–46. [CrossRef]
121. Woolley, M.; Goode, N.; Salmon, P.; Read, G. Who is responsible for construction safety in Australia? A STAMP analysis. *Saf. Sci.* **2020**, *132*, 104984. [CrossRef]
122. Sadeghi, S.; Soltanmohammadlou, N.; Rahnamayiezekavat, P. A systematic review of scholarly works addressing crane safety requirements. *Saf. Sci.* **2021**, *133*, 105002. [CrossRef]
123. Bayramova, A.; Edwards, D.J.; Roberts, C.; Rillie, I. Enhanced safety in complex socio-technical systems via safety-in-cohesion. *Saf. Sci.* **2023**, *164*, 106176. [CrossRef]
124. Okpala, I.; Nnaji, C.; Karakhan, A.A. Utilizing emerging technologies for construction safety risk mitigation. *Pract. Period. Struct. Des. Constr.* **2020**, *25*, 04020002. [CrossRef]