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Analysis of the Complex Causes of Death Accidents Due to Mobile Cranes Using a Modified MEPS Method: Focusing on South Korea

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Abstract: The convenience and efficiency of mobile cranes are expanding their applicability in industrial sites, but fatal accidents continue to occur as their use increases. There were 56 cases in South Korea from 2015 to 2019, killing 59 workers. To accurately investigate the cause of a fatal accident, accident investigation reports were used. Since they are used not only as the cause of the accident but also as a result of judicial treatment, only direct causes are mentioned. Thus, indirect causes in this study were separately analyzed to induce a complex cause analysis. The man-made, management, economic, physical, political, and social (MEPS) analysis method, developed by the National Institute of Disaster in South Korea, is a type of root cause analysis (RCA), used to derive the fundamental causes of various types of disasters, mainly social ones. The complex causes of fatal accidents were analyzed by applying a modified MEPS method to mobile cranes. The MEPS method investigated three categories, namely man-made, management, and physical factors, among six categories and a newly established level four, to find the root cause of fatal accidents. The analysis results showed that violations of procedures and regulations were the most frequent causes in the man-made factors. A lack of general and special safety education was the most common cause in the management factor, and the overturning, falling, and jamming of the mobile crane were the most frequent causes in the physical factor.

Keywords: mobile crane; complex cause; MEPS analysis; RCA analysis; accident investigation report

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1. Introduction

Mobile cranes are widely used for transporting, loading, and unloading heavy goods in various industrial sites, including the manufacturing and construction industries [1]. As the scale of construction increases and structures become high-rises in the construction industry, mobile cranes have become indispensable facilities in the construction process. This is because cranes can easily move by their own power and are specialized in transporting heavy loads [2,3]. Therefore, cranes are regarded as essential facilities for construction work [4].

As of today, major disasters caused by mobile cranes continue to occur worldwide. Owing to their on-site mobility, mobile cranes are more dangerous than other types of cranes, such as tower cranes, overhead cranes, and gantry cranes, and legal sanctions in terms of safety management are being strengthened [5,6]. According to the U.S. Bureau of Labor Statistics, an average of 28 workers per year in the past five years are known to have died during mobile crane operations [7]. According to Safe Work Australia (2016), an average of approximately 240 serious injury claims are reported each year due to crane safety accidents [8]. In South Korea serious disasters frequently occur, not only in construction sites but also in various industrial sites, due to the use of mobile cranes. Various types of serious disasters occur every year, such as a worker being crushed by falling heavy objects or a broken boom of a crane carrying heavy objects, causing nearby

workers to die from being hit by the boom. There have also been several accidents involving a large number of fatalities while working with a mobile crane [9].

Various studies have been conducted in order to improve the safety of mobile cranes and to effectively prevent fatal accidents caused by them. Raviv et al. (2017) evaluated the potential risk of a near-miss accident that can develop into a serious disaster when working with a mobile crane at a construction site using the analytic hierarchy process (AHP) technique. This study examined the correlation between technical and human factors [10]. Pana et al. (2017) carried out a simulation of mobile crane operations in consideration of the complexity and dynamics of the construction site in order to improve the safety and work efficiency of mobile cranes [11]. Based on the results of these studies an approach for determining the working location of a mobile crane was proposed. Fang et al. (2016) attached a sensor to the moving part of a mobile crane to implement a function that provides real-time danger information to the driver when driving a mobile crane [12]. Based on this information, they analyzed the risk that the crane machine itself or a heavy object being lifted might collide with nearby structures and proposed a plan to prevent accidents by transmitting information in real time to the crane driver through 3D visualization. Al-Humaidi and Tan (2009) proposed a technique to determine the safe distance between the transmission line, considering the rotation angle of the mobile crane boom, and investigated it to prevent death accidents caused by contact between the mobile crane and the transmission line [5].

The analysis of the exact cause of an accident is a prerequisite for preventing deaths caused by mobile cranes [13]. Swuste (2008) argues that it is important to understand the causes of safety incidents in the working environment in order to differentiate between factors that require safety measures and factors that are negligible [14]. Cranes are complex machines that require considerable knowledge to operate safely, which can only be obtained through proper training and practical experience. In particular, the ability to understand and use a mobile crane's loading charts correctly is critical to its safe operation [15]. Due to these factors, the complexity of the causes of the accident should be considered in terms of not only structural failure but also human factors. Therefore, continuous safety activities, such as site managers and workers actively identifying risk factors at a site through risk assessment, are required to improve workplace safety. Cranes' risk assessment is carried out in four steps: identifying hazards, assessing risks, controlling risks by preparing safety measures, and reviewing control measures [16]. However, studies on risk assessment are very limited due to the lack of detailed crane accident classifications and types of occurrence [17].

Based on data on the causes of deaths due to mobile cranes in South Korea for five years, from 2015 to 2019, we performed an in-depth analysis of the type of occurrence, the type of business, the time of occurrence, and the complex causes of fatal accidents and derived implications from them. For an accurate analysis, the analysis was performed using the official accident investigation report. Through a more sophisticated MEPS (man-made, management, economic, physical, political, and social) analysis, based on an RCA (root cause analysis) in South Korea, the root cause of fatality was identified, and a comprehensive analysis of complex accidents was performed in which human error and structural failure were combined. Through this study, it is intended to be used as basic data to effectively mitigate major disasters caused by mobile cranes.

2. Literature Review

2.1. Accident Data Analysis of Cranes

Milazzo et al. (2017) analyzed 937 crane accidents between 2011 and 2015, accounting for 72% of all mobile crane accidents. Accidents caused by crane overturning account for 45% of mobile crane accidents [18]. In addition, there are differences in the types of accidents between tower cranes and mobile cranes. Accidents caused by structural collapse account for approximately 38% of tower crane accidents, along with crane overturning, boom bucket/jib collapse, and electrocution. They claimed that the prevalence of crane

safety accidents could be significantly underestimated in the analysis due to the limitations of information and available data sources, in addition to the fact that the actual in-depth analysis data were limited. In addition to structural failure in mobile cranes, there is a high possibility of accidents due to human errors, because mobile crane operations are much less automated than tower crane operations [4,19]. The environment in which mobile cranes operate is constantly changing, which causes it to be more difficult to rely on automation and safety measures that cannot determine safety-related changes in the operating environment [20].

In the United States the increasing use of cranes in the construction industry has led to a growing interest in fatal accidents. Shepherd et al. (2000) reported about 30 to 50 crane deaths per year, and Peraza and Travis (2010) reported that accidents between 1992 and 2006 resulted in the death of 42 construction workers per year on average [21,22]. However, it is difficult to accurately understand the extent of fatal accidents if accident data are classified incorrectly [21]. Beavers et al. (2006) analyzed 125 crane safety accidents that resulted in 127 deaths in the United States between 1997 and 2003, and found that most of them were related to mobile cranes (88%). Of these, 56% were claimed to be related to lattice-boom-type mobile cranes [23]. According to the OSHA website, 505 out of 937 deaths in 2015 were associated with mobile cranes. This means that tragic accidents due to mobile cranes continue to occur despite the continuous efforts made by various countries to increase crane safety practices [24,25].

The analysis of the causes of mobile crane accidents is important for preparing safety policies in the future. According to the U.S. Bureau of Labor Statistics, 632 deaths due to cranes between 1992 and 2006 were reported, of which at least 71% were attributed to mobile cranes [26]. Some of these mobile crane accidents took place due to overhead power incidents (number of deaths: 157), getting struck by the crane load (number of deaths: 132), crane collapses (number of deaths: 89), and boom/jib incidents (number of deaths: 64). According to OSHA Data Services (ODS), over 90% of accidents caused by various types of cranes used in construction projects from 1997 to 1999 were related to mobile cranes [27]. Moreover, the contact between energized power lines appears to be the main cause of crane accidents: approximately 40% of all deaths were due to electrocution. In addition, there were accidents that occurred due to crane assembly and disassembly (approximately 12%), boom buckling (8%), rigging failures (7%), and crane overturning (7%). Hamid et al. (2019) analyzed 44 cases of crane accidents at construction sites in Malaysia from 2009 to 2016 [28]. Of these, 24 cases occurred due to mobile cranes, and the fatality rate was higher than that of other cranes. In addition, toppling and overturning accounted for 39% of all accidents caused by cranes. Although structural failure was investigated as the main cause of accidents, it was also found that these accidents occur frequently due to human factors. Kan et al. (2018) argued that the overloading of mobile cranes was a result of poor safety management and/or improper planning due to operator error (related to overload) [29]. Sertyesilisik et al. (2010) argued that accidents involving mobile cranes in the UK construction industry happened due to a lack of industrial inspectors with in-depth knowledge of crane safety issues as well as unreasonable work by unqualified workers. For lifting managers and slingers/signalers, they analyzed the causes/contributing factors of defects at the educational level and also suggested reasons for the need for more stringent requirements and processes for lifting work planning [30]. However, it is difficult to systematically analyze crane safety accidents in countries or studies because there is no common taxonomy that can be used to classify the causal/contributing factors [9].

2.2. Crane Safety Practices

OSHA in the United States regulates safety measures related to construction equipment, including cranes, and employers are required to fulfill the obligations set out in law (OSHA 29 CFR 1926.1441) [31]. Mobile cranes, boom truck cranes, and service trucks are all included, according to the OSHA construction safety and health regulations. To prevent the structural failure of a crane it is subject to inspection by the American National Standards

Institute (ANSI), and violations are subject to very strict penalties. To operate a mobile crane, it maintains a system to prevent accidents caused by human error by allowing it to be manipulated if it has been trained and certified by an accredited institution.

The UK's Health and Safety at Work Act 1974 presents general principles and possible goals; detailed safety and health standards are included in the Approved Code of Practice and the Safety and Health Administration (HSE) under the Safety and Health Commission (HSC). The lifting operations and equipment regulations were enacted in 1998 as laws that impose certain obligations on people or companies who own or operate lift trucks [32]. The range of equipment included in the lift is quite wide, including all equipment used to lift or lower objects, and this includes all the accessories necessary for the lift. The regulations for the use of work equipment (1998) contain information on inspection and maintenance. According to this law all cranes must be inspected regularly by government-designated inspection agencies. In a report published by the Health and Safety Executive (HSE), the owners, users, and other qualified persons of lift trucks, including lorry-lifted cranes, are given the subject of inspection, and specific methods are used for each piece of equipment. Although the license system for construction equipment drivers is not established as a legal system, the Construction Industry Training Board (CITB), a private organization, trains construction equipment drivers and provides them with registration cards (private qualifications).

In accordance with the Labor Safety and Health Act in Japan, mobile cranes are included in specific machinery subject to inspection, and regular inspections are performed by the Japan Crane Association [33]. According to the Occupational Safety and Health Act, the qualifications and training contents of cranes, the line hangers of mobile cranes, and signal services are classified according to the lifting load, and necessary training is conducted differently.

In South Korea mobile cranes are classified as hazardous and dangerous. Obligations are imposed which are to be observed by the provider and borrower [34]. A mobile crane must be designated as a machine subject to safety certification and manufactured with safety certification, and users are required to use safety-certified products. A safety inspection is required to prevent structural failure due to an increase in the use period. In addition, various safety rules for the use of mobile cranes are prepared to prevent accidents, and license regulations for mobile cranes have been introduced to prohibit maneuvering by unqualified persons.

3. Materials and Methods

The Occupational Safety and Health Act was enacted in South Korea in 1981, establishing a legal foundation with which to protect workers from industrial accidents and promote various activities to prevent these accidents. The enactment of these laws clearly defines the requirements and procedures for various industrial sites. Severe accidents under the Occupational Safety and Health Act are defined as accidents in which one or more workers die, two or more injured persons require medical treatment for three months or more at the same time, or ten or more persons are injured or suffer from occupational diseases simultaneously [35]. In the event of a serious accident at an industrial site the employer in the relevant workplace must report the occurrence of a serious accident to the Ministry of Employment and Labor, which oversees and manages the prevention of industrial accidents. The cause of the disaster is investigated to determine whether it violates the Occupational Safety and Health Act, and it is the duty of the employer to protect the company. When the investigation of a major disaster is completed, accident-related information identified in the workplace is recorded through a computerized system and a database is established. Reports on major industrial accidents investigated by the Ministry of Employment and Labor, a government agency, are analyzed. Based on these statistics, 59 deaths caused by mobile cranes from 2015 to 2019 were classified from the original data, and the detailed cause of the accident was analyzed in 56 cases. In contrast to the OSHA classification, service trucks are not included in mobile cranes, so they are not included

in this study. Original data were analyzed, focusing on deaths caused by mobile cranes; accidents due to injuries were excluded. When workers claim insurance benefits a database related to occupational accidents is established, but it is difficult to find the exact cause of the accident, as it contains only the accident summary written by the workers. Therefore, mobile crane accidents for which detailed information, such as injuries, was usually not provided were excluded from the study.

In this study the causes of death are classified into man-made, management, environmental, economic, physical, political, and social factors (level one), according to the Korean disaster cause classification system. The detailed classification is presented in Table 1. According to the National Institute of Disaster and Safety, MEPS consists of levels one and two, subordinate factors, and level three [36]. The Disaster Cause Classification (MEPS) system is an RCA-based technology, which is composed of a large classification that encompasses disaster types, and is then subdivided to reflect the characteristics of each disaster type. The MEPS method was initially used to systematically analyze accident types such as complex social disasters that occurred in South Korea. This is an optimized accident analysis tool created by the government to create a detailed classification system and identify the root cause through this method. By extending this classification method this study intends to analyze the underlying factors of industrial accidents, especially complex casualties caused by mobile cranes. The mobile crane accident investigation report was used to secure the reliability of the study, and although the accident process and legal violations are sufficiently explained the application of RCA is insufficient. To compensate for these shortcomings, the existing three levels of MEPS, as shown in Table 1, was further subdivided to create level four in this study. Detailed accident factors were presented in level four through the analysis of the accident investigation report, and the analysis results are presented in Section 4.2.6. They are largely inexperienced in operation, violation of the Occupational Safety and Health Act, negligence at work, insufficient safety devices, insufficient on-site management supervision, lack of safety education and training, equipment defects, and equipment deterioration, inappropriate use of equipment, etc.

Table 1. MEPS classification system for the causes of mobile crane accidents.

Causes		
Level 1	**Level 2**	**Level 3**
Man-made	Fault/error	Inexperienced operation, noncompliance with procedures and laws, and carelessness
	Human activity	Production activities (agricultural, industrial), development activities (private, public)
Management	Management system	Nonestablished safety rules, no safety measures, and lack of regular inspections
	Organizational activities	Lack of management and supervision, on-site command and control
	Safety education	Safety education and training
Economic	Business economy	Unreasonable management for ignoring safety
Physical	Technical	Poor construction, poor design, and risk factors for facilities
	Unstable conditions	Aging, corrosion/damage, and failure
Political	Related regulations/laws	Lack of laws and systems, lack of cooperation and management systems
	Manual	Lack of manual establishment
Social	Disaster prevention system	Insufficient local safety measures
	Safety awareness	Lack of safety awareness, heightened anxiety
	Conflict	Conflict in response to on-site coverage and follow-up measures

4. Results and Discussion

4.1. Registration of Mobile Cranes

Table 2 shows the annual registration of mobile cranes. These data indicate that about 74% of mobile cranes used at construction sites in South Korea are old cranes that are more than 10 years old; there is a high possibility of fatal accidents due to structural failures. Although safety inspections are legalized and set differently depending on the production year, fatal accidents continue to occur in the form of boom breakage or the nonoperation of safety measures. It also does not mention these data; it appears that there are similar numbers of mobile cranes by regions. This means that the use of mobile cranes has become common. However, the number of mobile cranes is decreasing over the years, which is interpreted as the strengthening of the relevant laws and regulations according to the occurrence of disasters.

Table 2. Number of mobile cranes registered in South Korea.

Year	Number of Mobile Cranes
~1994	7707
1995–2000	7681
2001–2005	6436
2006–2010	4343
2011–2015	5180
2016–2019	3944
Total	35,291

4.2. Analysis of the Causes of Mobile Crane Safety Accidents

4.2.1. Overall Mobile Crane Accidents

In South Korea a total of 56 accidents occurred due to mobile cranes in the last five years, from 2015 to 2019, resulting in the death of 59 workers. The detailed information is shown in Table 3. The number of deaths gradually increased from 11 in 2015 to 16 in 2017, and then decreased to six in 2018. With 12 deaths in 2019, the temporary decline disappeared. Most mobile crane fatalities were characterized by one case to one death, but one accident resulted in a number of deaths in 2015 and 2016. The reason for the decline in deaths in 2018 is not clear, but it is believed that this was due to strong regulatory policies following the increase in the number of deaths in the construction industry in 2016. Although the number of fatal accidents caused by mobile cranes temporarily decreased, it increased again in 2019, and the number of deaths compared to the number of accidents was small compared to other occupational accidents. However, if regulations to ensure safety are not strictly enforced, the possibility of fatal accidents caused by mobile cranes in the field is expected to increase.

Table 3. Mobile crane fatalities in South Korea in the past five years.

	2015	2016	2017	2018	2019	Total
No. of accidents	10	12	16	6	12	56
No. of deaths	11	14	16	6	12	59

Table 4 shows the number of deaths due to mobile crane work divided into workers and drivers. Through this analysis the impact of fatal accidents on workers in the workplace was evaluated. Of the 59 deaths, 46 were workers and 13 were mobile crane drivers. The result of the analysis of accidents in which mobile crane drivers died demonstrates that many accidents occurred as result of crane overturning due to defects, such as the installation of outriggers supporting the mobile crane. It was found that many accidents occurred when communication between the driver and worker was not smooth during these operations. In addition, as a result of analyzing the actual accident investigation report, it was found that the safety management of the site is the most important, because

most accidents that occurred during the work process using the mobile crane occurred at the work site.

Table 4. Classification of mobile crane fatalities.

Classification	Number of Fatalities
Workers participating in mobile cranes	46
Drivers of mobile cranes	13

4.2.2. Types of Mobile Crane Accidents

Figure 1 shows the classification of the types of mobile crane accidents. Fatal accidents caused by falling were the most frequent, followed by deaths caused by hitting objects. The analysis of the accident investigation report reveals that occupational safety and health laws prohibit the attachment and use of boarding equipment for workers to board mobile cranes in South Korea. However, as a result of considering only the convenience of work by attaching illegal boarding equipment and not complying with laws and regulations, many deaths occurred due to falling accidents. The investigation of mobile crane accidents reveals that safety inspections were performed normally, but that it was installed arbitrarily for the convenience of work after the safety inspection. The fact that 46% of the fatal accidents occurred due to falling shows many differences in the types of accidents due to electrocution in the United States. It can be said that it is a type of human error caused by attaching illegal boarding equipment to mobile cranes for convenience by workers to perform other tasks. Although certification inspections are being strengthened to prevent such industrial accidents, recent accident investigation reports show that these illegal acts still occur after certification inspections. Accidents of hitting objects were caused by the improper implementation of measures that prohibit workers from approaching the working radius, but the safety measures prescribed in the Occupational Safety and Health Act were not followed. It was also demonstrated that accidents that happened due to crushing and overturning were mainly caused by the overturning of the outrigger.

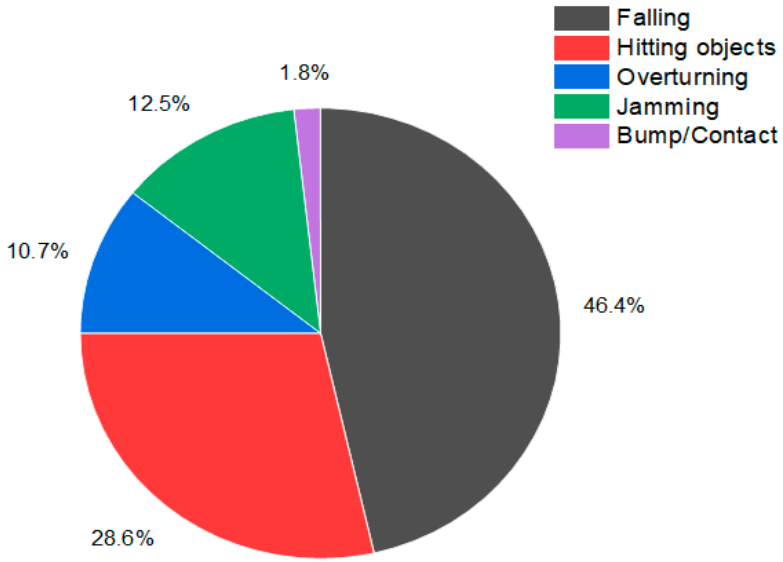

Figure 1. Analysis of the causes of mobile crane accidents in South Korea.

4.2.3. Place and Type of Work

There were many fatal accidents during the working process caused by mobile cranes, and as the use of mobile cranes increases the types of industries in which accidents occur are classified, as shown in Figure 2. The results of this analysis show that the most common fatal accidents caused by mobile cranes occurred at construction sites, accounting for approximately 75% of the total deaths. However, it was found that more than 80% of accidents

occurred when actual mobile cranes were used at public institution construction sites. This can predict the possibility of increasing usability due to the mobility and convenience of operating mobile cranes at construction sites. Nevertheless, this problem occurred because the workplaces employing accident-prone workers were not classified as construction businesses. To prevent such accidents, the special supervision and reinforcement of work using mobile cranes should be made not only at construction sites but also at similar types of work sites.

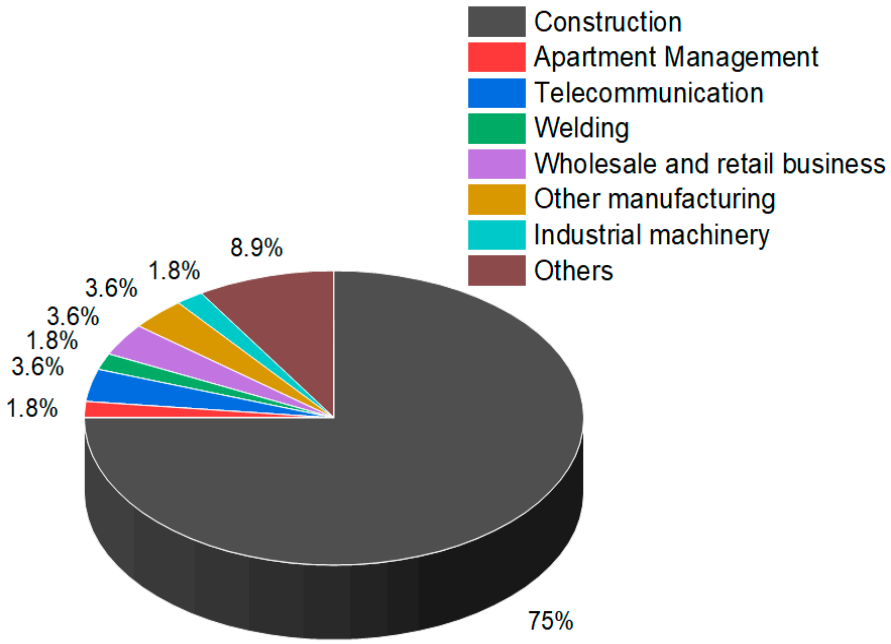

Figure 2. Analysis of industries belonging to workers.

4.2.4. Time Analysis of Mobile Crane Accidents

Figure 3 shows the time when a fatal accident occurred due to a mobile crane. The analysis is classified into one-hour increments from 7 o'clock, when work started. The analysis reveals that fatal accidents frequently occurred between 7:00 and 9:00, not long after work started, and between 13:00 and 16:00, when lunch was over and work was resumed. In the case of morning accidents, many accidents occurred when safety education was over and the routine began, but it seems that these accidents occurred due to a lack of safety education at the site. The figure also shows that many fatal accidents that occurred after lunch mainly took place due to a lack of awareness of safety accidents. To reduce the safety accidents caused by mobile cranes, thorough and field-oriented safety training before starting work should be provided.

In Table 5, the work that caused fatal accidents was analyzed using a mobile crane. Approximately 70% (39 cases) of accidents occurred while working with a mobile crane, and approximately 30% (17 cases) were accidents during the lifting operation. This analysis result means that thorough safety management, such as preparing a safety plan when working with a mobile crane, is required.

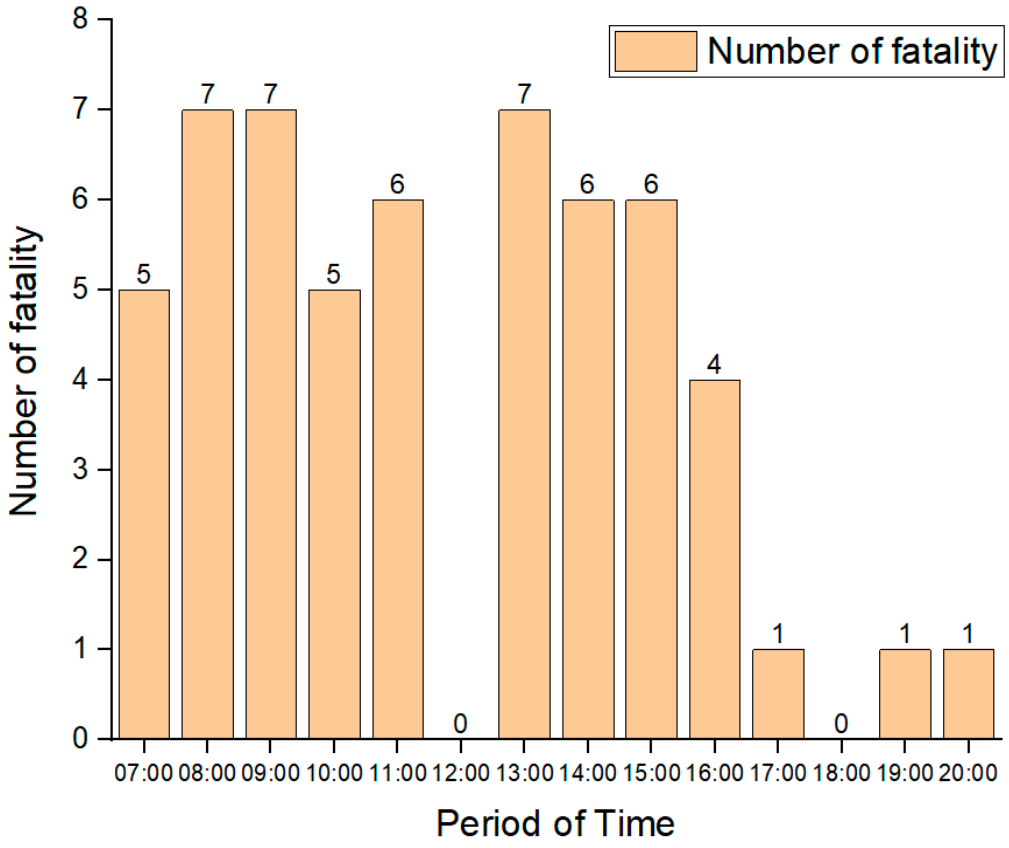

Figure 3. Analysis of the occurrence time of mobile crane accidents.

Table 5. Analysis of mobile crane fatalities according to operation.

Classification	Number of Fatalities
Accidents due to mobile crane operations	39
Lifting operations	17

4.2.5. Structural Failure of Mobile Crane Fatalities

The direct cause analysis of mobile crane accidents was performed using the accident investigation reports; the analysis results of structural failure are shown in Table 6. The table shows the analysis results of only structural failure before determining the complex causes. Most safety accidents happen due to not only a single cause but also complex causes, such as human error and structural failure [36]. Among the 56 fatal accidents, 25 were found to happen due to equipment failure: a drop of a heavy load, such as wire rope damage (11 cases), a lack of safety measures (seven cases), and the illegal use of worktables (seven cases). Among many fatal accidents caused by structural failures, there were many accidents involving human errors; there were many cases that were specified as indirect causes in the accident investigation reports [37]. The remaining 31 accidents were caused by inappropriate factors in the work environment, such as noncompliance with safety procedures.

Table 6. Mobile crane fatalities due to structural failure based on investigation reports.

Type of Accident (No. of Accidents)	Detailed Cause of Accident	No. of Accidents
Safety measures (7)	No safety handrail	3
	Improper outrigger	1
	Defective and nonoperating emergency stop device	1
	Defective and nonoperating hook release device	0
	Defective and nonoperating overwinding protection device	2
Dropping heavy loads (11)	Damage to the raising wire rope (damage, cutting, and dropping)	5
	Crane lug, boom line bolt, and swing post bolt	3
	Material separation due to poor rowing and method of rowing	3
Improper use (7)	Illegal use of boarding equipment	7
Total		25

4.2.6. Fundamental Cause Analysis of the Complicated Causes

One fatal accident can take place due to various causes, and this was analyzed using MEPS through the following procedures. For instance, if the fatality of a mobile crane was caused by a complex effect of wire rope breakage and a negligence of supervision, it was calculated as the number of each case. Among the five classifications of MEPS, economic, political, and social causes were excluded from the analysis because they were not the reason for the accident. The MEPS analysis showed that mobile crane accidents that occurred throughout the five-year period examined in this study were due to man-made, management, and physical causes in level one. Table 7 shows the analysis results of man-made accidents. Accidents occurred most frequently due to noncompliance with procedures and laws in the case of man-made causes in level one, indicating a lack of compliance with the safety rules for mobile cranes. An average of 2.3 violations of the Occupational Safety and Health Act were found per accident. Among them, the lack of preparation/insufficiency of the work plan was the most common cause, followed by noncompliance with the work safety rules for mobile cranes. It was found that many accidents took place as result of workers' carelessness, such as workers approaching and working in areas at risk of tripping and falling. These risk factors should be reflected in the work plan to ensure safe work, but it was found that there are many cases in which such important steps are omitted or are insufficient at the actual site.

Table 8 shows the analysis results of mobile crane accidents caused by the failure of the management of the MEPS. Among the management factors that lead to accidents, inadequate safety rules prescribed by law were analyzed as the most common cause. The results of this analysis demonstrate that accidents caused by a failure to comply with the safety rules prescribed by law in South Korea continue to occur, and that countermeasures are required. In addition, accidents due to insufficient safety measures and poor inspections occur, but the number of these accidents has decreased after the implementation of the safety inspection system. There were also many accidents that occurred due to insufficient safety education and special education concerning professional installation and dismantling work due to the increasing use of mobile cranes. Since the risk of an accident is very high due to operation based on the driver's experience and vision, professional and practical training for operation is required for workers and drivers. Many safety accidents occurred during work due to a lack of safety management at the site. It was also found that a lack of safety rules and on-site safety training was common to all fatal accidents caused by mobile cranes.

Table 7. MEPS analysis of man-made causes of mobile crane accidents.

			Detailed Information	
Level 1	**Level 2**	**Level 3**	**Level 4**	**No. of Accidents**
Man-made	Fault	Inexperienced operation	Inexperienced operation by an unskilled person Operation while the operation status is not visible Tripping due to poor crane support Lack of separation of high-voltage lines Other	11
		Noncompliance with procedures and laws	Lack of preparation/insufficiency of the work plan Noncompliance with the work safety rules Noncompliance with design standards Without protective equipment Other	46
		Carelessness	Approaching and working in areas at risk of tripping and falling Use of illegal boarding equipment Not confirming moving heavy objects by the operator Other	32
	Human activity	Production activity	Construction Manufacture Local government	42
		Development activity	Schools Power plants Other	16

Table 8. MEPS analysis of the management causes of mobile crane accidents.

	Classification		Detailed Information	
Level 1	**Level 2**	**Level 3**	**Level 4**	**No. of Accidents**
Management	Management system	Insufficient safety rules	Non-rule of requirements set by law	56
		Insufficient safety measures	Safety handrail not installed Improper outrigger Other	6
		Defects of inspection	Wire rope Winding protection Fixing bolts Other	12
	Organization activity	Poor management and lack of supervision	Insufficient on-site supervision of the contractor Lack of risk assessment	24
		Site command and control	Lack of site management supervision, signal workers, and inspectors	40
	Safety education	General safety education	Special education	56
		Special education and training	Installation Operation Dismantling	37

Table 9 presents the results of the analysis of the physical factors. The table shows that accidents caused by overturning, falling, and jamming occur most frequently due to the characteristics of mobile cranes that handle heavy objects. In addition, it was found that the cause of deaths is the use of illegal boarding equipment.

Table 9. MEPS analysis of the physical causes of mobile crane accidents.

Classification			Detailed Information	
Level 1	**Level 2**	**Level 3**	**Level 4**	**No. of Accidents**
Physical	Technical	Poor construction	Poor welding of crane lugPoor boom pivot bolt Other	3
		Poor design	Installation of boarding equipment Improper wire rope overload preventive measuresWinding protection Other	14
		Facilities/equipment/risk of work	Overturning, falling, and jamming	39
	Incomplete status	Aging	Not investigated	0
		Corrosion/breakage	Corrosion/breakage	12
		Improper use and work	Use of boarding equipment	7

4.3. Case Studies of Mobile Crane Accidents

4.3.1. Falling Accident

After assembling the roof panel of the building at the construction site, the accident occurred while the victim was descending to the ground on a workbench installed at the end of the cargo crane boom. As the connecting part of the workbench and the boom fell off, it fell to the ground, about 18 m below the workbench, resulting in one person dying and one being injured. When installing a dedicated boarding facility on a mobile crane and loading a worker, safety measures should be checked in advance to prevent the boarding facility from falling. The connection between the crane boom stand and the boarding equipment is accurately fastened with bolts and pins, etc., but the accident occurred because these work rules were not observed. Figure 4a shows the accident site where a mobile crane was used, and Figure 4b shows the dropped workbench.

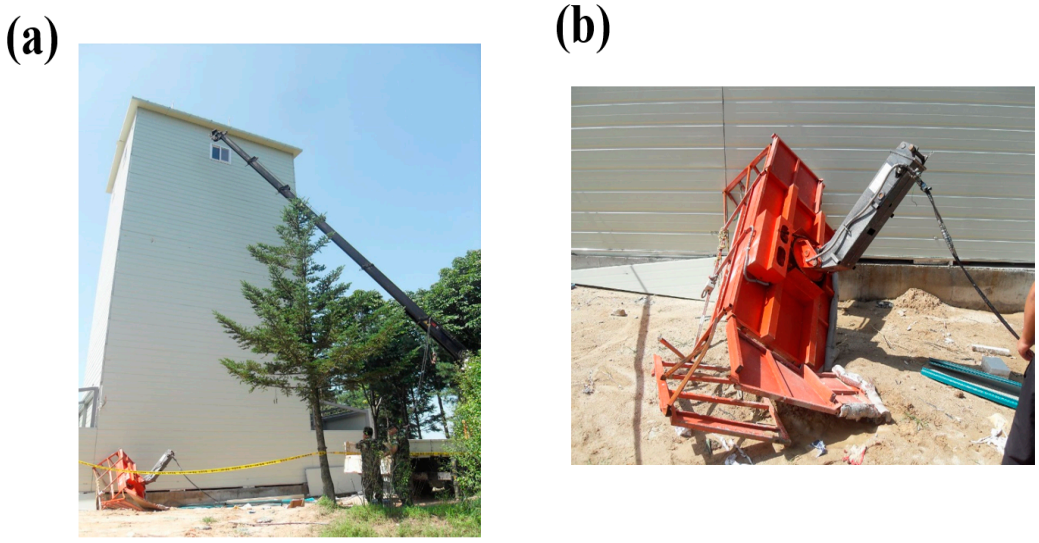

Figure 4. Falling accident from mobile crane. (**a**) Accident workplace and (**b**) falling due to breakout of the boarding equipment.

4.3.2. Overturning Accident

While lifting materials with a mobile tower crane at the Busan Opera House construction site, the equipment fell and collided with the ground due to the subsidence of the outrigger supporting the crane, causing a fatal accident. The accident occurred in

2019, resulting in fatalities and injuries. The following problems were derived through the accident investigation, as shown in Figure 5:

(i) In order to prevent danger to workers the ground condition of the workplace should be checked before starting work and a mobile crane should be installed. If there is an abnormality, measures to prevent sinking should be carried out; they were not implemented, and a work plan including safety measures to prevent the risk of overturning was not prepared.

(ii) The lender of the mobile crane did not provide the equipment user manual including the characteristics of the machine, the precautions for use, etc., to the person who used the mobile crane, even though it was necessary to take measures to prevent harm and danger due to overturning.

4.3.3. Hitting Objects Accident

In 2019 a fatal accident occurred while carrying out work to lift a bucket elevator chain part using a mobile crane. It was an accident that occurred while giving a hand signal at the end of an external roof, and was pushed by a chain part being hoisted and fell to the floor, 20 m below. It was confirmed that the deceased worker moved to the edge of the external roof on the third floor without wearing a safety belt and gave a hand signal to the mobile crane operator. The causes of the accident, as shown in Figure 6, suggested in the accident investigation report are as follows:

(i) By dismantling the safety guardrail for lifting heavy objects in a place where there was a risk of falling from a height of 20 m, no measures were taken to prevent this accident, even though the risk of falling was inherent.

(ii) Prior to the start of the work the work was carried out without a work plan for the handling of heavy objects, including measures to prevent danger, such as hanging work and signal methods, and the falling/collision of workers.

(iii) In order to prevent the risk of shaking of the heavy object during the hoisting operation an auxiliary rope should be connected to the heavy object, and then the heavy object should be hoisted. However, as these safety measures were not implemented the shaking of the heavy object could not be controlled, and the heavy object struck the injured person.

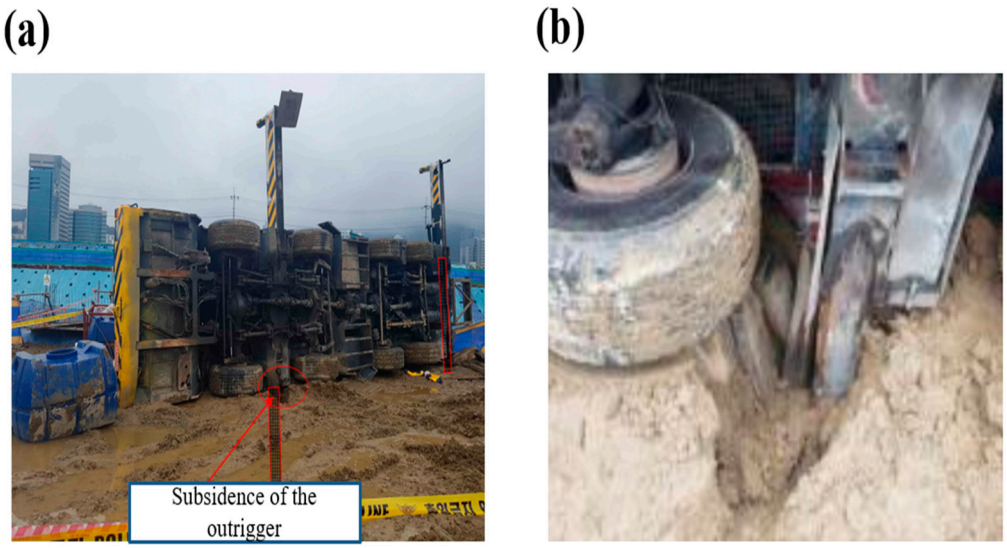

Figure 5. Overturning accident from mobile crane. (**a**) Mobile crane overturning accident and (**b**) outriggers more than 2 m into the ground.

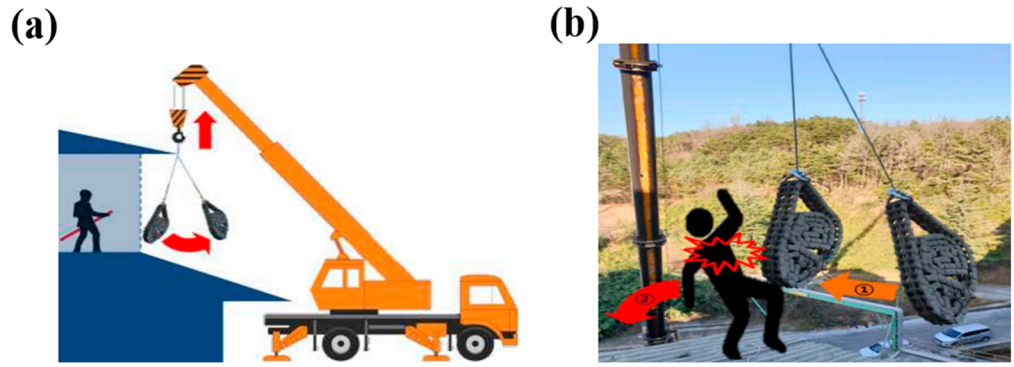

Figure 6. Hitting objects accident from mobile crane. (**a**) Schematic diagram of work at the time of the disaster and (**b**) schematic diagram of the situation at the time of the disaster.

In Table 10 the various cases presented in Section 4.3. are explained in connection with Tables 7–9. Based on these analyses, it is judged that various complex factors acted together, rather than there being a single cause of the accidents.

Table 10. MEPS analysis of the physical causes of mobile crane accidents.

Case	Level 1	Level 2	Level 3	Level 4
Section 4.3.1.	Man-made	Fault	Noncompliance with procedures and laws	Noncompliance with the work safety rules
			Carelessness	Use of illegal boarding equipment
		Human activity	Production activity	Construction manufacture
	Management	Organization activity	Site command and control	Lack of site management supervision, signal workers, and inspectors
	Physical	Technical	Poor construction	Poor boom pivot bolt
			Poor design	Installation of boarding equipment
Section 4.3.2.	Man-made	Fault	Inexperienced operation	Tripping due to poor crane support
			Noncompliance with procedures and laws	Lack of preparation/insufficiency of the work plan
		Human activity	Production activity	Construction manufacture
Section 4.3.3.	Management	Management system	Insufficient safety measures	Improper outrigger
			Poor management and lack of supervision	Insufficient on-site supervision of the contractor
		Safety education	Special education and training	Installation
	Man-made	Fault	Noncompliance with procedures and laws	Lack of preparation/insufficiency of the work plan
		Human activity	Production activity	Construction manufacture
	Management	Management system	Insufficient safety measures	Safety handrail not installed
		Organization activity	Site command and control	Lack of site management supervision, signal workers, and inspectors
	Physical	Technical	Facilities/equipment/risk of work	Overturning, falling, and jamming

5. Conclusions

In South Korea, tower crane accidents cause large-scale damage and have social impacts; thus, special measures have been taken at the government level to prevent major

disasters. Although mobile cranes lead to many deaths, many of them are small-scale fatalities, and the government's attention to them has fallen compared to tower cranes. With the increasing efficiency and convenience of their use, mobile cranes are widely used in industrial sites, resulting in an increasing number of fatal accidents. Due to the growing number of fatalities caused by mobile cranes, interest in their safe use has increased significantly in recent years.

According to accident investigation reports in South Korea, there have been 56 deaths (59 accidents) due to mobile cranes in the last five years. Most of these fatal accidents occur in the construction industry (about 75%). Therefore, it is necessary to introduce preventive measures for mobile cranes used in the construction industry. As a result of investigating the structural failures in the accident investigation reports, serious accidents occur due to boom breakage, wire rope breakage, and the illegal modification of mobile cranes. In contrast to electrocution, which is the most common type of accident in the United States, 46% of workers' deaths occur due to falls. These accidents are caused by the installation of illegal boarding equipment for convenience of work. In most cases only the direct cause is mentioned in the accident investigation report, and the fundamental cause is identified using an MEPS analysis.

In order to prevent accidents related to mobile cranes in South Korea, complex solutions from various aspects will be required. In the institutional aspect, most of the accidents caused by mobile cranes are caused by the aging of equipment and illegal modifications; therefore, system improvement is necessary to faithfully conduct safety inspections. However, many fall accidents due to illegal remodeling occurred after safety inspections, so structural changes that make illegal remodeling impossible as well as the establishment of a safety culture for workers are necessary. Currently, it is stipulated that borrowers of machinery equipment should inspect, repair, and lend the machine before lending, but since most of the owners of mobile cranes are small-scale and the risk of work is high, a policy to support this should be prepared.

The MEPS analysis method developed by the National Institute of Disaster and Safety was applied based on a major disaster report on fatal accidents for the past five years, from 2015 to 2019. The fundamental cause was identified by considering the complex factors of fatal accidents. As a result of the actual analysis, fatal accidents caused by the combination of human errors and structural failure frequently occur. The MEPS analysis investigated the man-made, management, and physical causes among the six categories to analyze the complex causes of mobile crane accidents. The analysis indicates that, among the man-made factors, noncompliance with procedures and laws was the most common cause of accidents. The number of violations of the Occupational Safety and Health Act is high, with an average of 2.3 per accident. Because it is difficult to manage and supervise the work site due to the nature of mobile cranes, it is necessary to implement a system for performing autonomous safety work. In terms of management, not only do many accidents occur during work due to the lack of general and special safety education, but serious accidents also occur due to the lack of on-site command and control by the supervisor. In addition, it was found that many fatal accidents occur due to physical factors, such as the overturning, falling, and jamming of the mobile cranes. Although the accident analysis method of MEPS was applied to mobile cranes, additional studies are planned through crossanalyses with other analysis methods in the future to obtain sustainable safety development.

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References

1. Milazzo, M.F.; Ancione, G.; Consolo, G. Human factors modelling approach: Application to a safety device supporting crane operations in major hazard industries. *Sustainability* **2021**, *13*, 2304. [CrossRef]
2. Shapira, A.; Lucko, G.; Schexnayder, C.J. Cranes for building construction projects. *J. Constr. Eng. Manag.* **2007**, *133*, 690–700. [CrossRef]
3. Fang, Y.; Cho, Y.K.; Durso, F.; Seo, J. Assessment of operator's situation awareness for smart operation of mobile cranes. *Autom. Constr.* **2018**, *85*, 65–75. [CrossRef]
4. Raviv, G.; Fishbain, B.; Shapira, A. Analyzing risk factors in crane-related near-miss and accident reports. *Saf. Sci.* **2017**, *91*, 192–205. [CrossRef]
5. AL-Humaidi, H.M.; Hadipriono Tan, F. Mobile crane safe operation approach to prevent electrocution using fuzzy-set logic models. *Adv. Eng. Soft.* **2009**, *40*, 686–696. [CrossRef]
6. Lee, J.; Phillips, I.; Lynch, Z. Causes and prevention of mobile crane-related accidents in South Korea. *Int. J. Occup. Saf. Ergon.* **2020**, *14*, 1–10. [CrossRef]
7. U. S. Bureau of Labor Statistics 2011–2015. Available online: https://www.bls.gov/iif/oshwc/cfoi/crane_chart.htm (accessed on 1 May 2021).
8. SafeWork Australia 2016. Available online: Safeworkaustralia.gov.au (accessed on 2 May 2021).
9. 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]
10. Raviv, G.; Shapira, A.; Fishbain, B. AHP-based analysis of the risk potential of safety incidents: Case study of cranes in the construction industry. *Saf. Sci.* **2017**, *91*, 298–309. [CrossRef]
11. Pan, Z.; Guo, H.; Li, Y. Automated method for optimizing feasible locations of mobile cranes based on 3D visualization. *Procedia Eng.* **2017**, *196*, 36–44. [CrossRef]
12. Fang, Y.; Cho, Y.K.; Chen, J. A framework for real-time pro-active safety assistance for mobile crane lifting operations. *Autom. Const.* **2016**, *72*, 367–379. [CrossRef]
13. Gibb, A.; Lingard, H.; Behm, M.; Cooke, T. Construction accident causality: Learning from different countries and differing consequences. *Constr. Manag. Econ.* **2014**, *32*, 446–459. [CrossRef]
14. Swuste, P.; Frijters, A.; Guldenmund, F. Is it possible to influence safety in building sector? A literature review extending from 1980 until the present. *Saf. Sci.* **2012**, *50*, 1333–1343. [CrossRef]
15. NIOSH Alert: Preventing Work Injuries and Deaths from Mobile Crane Tip-Over, Boom Collapse, and Uncontrolled Hoisted Loads. Available online: https://www.cdc.gov/NIOSH/docs/2006-142/pdfs/2006-142.pdf (accessed on 28 April 2021).
16. Kim, J.Y.; Lee, D.S.; Kim, J.D.; Kim, G.H. Priority of accident cause based on tower crane type for the realization of sustainable management at Korean construction sites. *Sustainability* **2021**, *13*, 242. [CrossRef]
17. Kan, C.; Zhang, P.; Fnag, Y.; Anumba, C.J.; Messner, J.I. A taxonomic analysis of mobile crane-related accidents in construction industry for CPS-based simulation. In Proceedings of the 17th International Conference on Computing in Civil and Building Engineering, Tampere, Finland, 4–6 June 2018.
18. Milazzo, M.F.; Ancione, G.; Brkie, V.S.; Valis, D. Investigation of crane operation safety by analyzing main accident causes. In *Risk, Reliability and Safety: Innovating Theory and Practice*, 1st ed.; Walls, L., Revie, M., Bedford, T., Eds.; Taylor & Francis: London. UK, 2017; pp. 74–80.
19. Shapiro, H.I.; Shapiro, J.P.; Shapiro, L.K. *Cranes and Derricks*, 3rd ed.; McGraw-Hill: New York, NY, USA, 2000; pp. 114–156.
20. Yoon, B.; Lee, K.; Lee, J. Study on overturn proof monitoring system of mobile crane. *Appl. Sci.* **2021**, *11*, 6819. [CrossRef]
21. Peraza, D.B.; Travis, J.A. Crane Safety—An Industry in Flux. In Proceedings of the Forensic Engineering Congress, Washington, DC, USA, 11–14 November 2009.
22. Shepherd, G.W.; Kahler, R.J.; Cross, J. Crane fatalities-a taxonomic analysis. *Saf. Sci.* **2000**, *36*, 83–93. [CrossRef]
23. Beavers, J.E.; Moore, J.R.; Rinehart, R.; Schriver, W.R. Crane-related fatalities in the construction industry. *J. Constr. Eng. Manag.* **2006**, *132*, 901–910. [CrossRef]
24. Occupational Safety and Health Administration (OSHA). Commonly Used Statics. Available online: https://www.osha.gov/oshstats/commonstats.html (accessed on 26 April 2021).
25. Chin, L.S.; Hamid, A.R.A. The practice of time management on construction project. *Procedia Eng.* **2015**, *125*, 32–39. [CrossRef]
26. Understanding Crane Accident Failures: A Report on the Causes of Death in Crane-Related Accidents. Available online: https://www.elcosh.org/document/2053/d001029/Understanding+Crane+Accident+Failures%253A+A+report+on+the+causes+of+death+in+crane-related+accidents.html (accessed on 3 May 2021).
27. Department of Labor, Occupational Safety and Health Administration. Analysis of Construction Fatalities-the OSHA Database. Available online: www.OSHA.gov (accessed on 13 April 2021).
28. Hamid, A.R.A.; Azhari, R.; Zakaria, R.; Aminudin, E.; Jaya, R.P.; Nagarajan, L.; Yahya, K.; Haron, Z.; Yunus, R. Causes of crane accidents at construction sites in Malaysia. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *220*, 012028. [CrossRef]
29. Kan, C.; Anumba, C.J.; Fnag, Y.; Messner, J.I. In Proceedings of the Use of Analytical Tools to Mitigate Mobile Crane-Related Failure. In Proceedings of the Construction Research Congress, 2018: Construction Information Technology, New Orleans, LA, USA, 2–4 April 2018; Wang, C., Harper, C., Lee, Y., Harris, R., Berryman, C., Eds.; American Society of Civil Engineers: Reston, VA, USA, 2018.

30. Sertyesilisik, B.; Tunstall, A.; McLouglin, J. An investigation of lifting operations on UK construction sites. *Saf. Sci.* **2010**, *48*, 72–79. [CrossRef]
31. Safety and Health Regulations for Construction. Available online: https://www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.1441 (accessed on 1 May 2021).
32. Thorough Examination and Inspection of Particular Items of Lifting Equipment. Available online: https://www.hse.gov.uk/research/crr_pdf/2002/crr02429.pdf (accessed on 7 May 2021).
33. The Safety Ordinance for Cranes. Available online: https://www.jniosh.johas.go.jp/icpro/jicosh-old/english/law/crane/index.html (accessed on 10 May 2021).
34. Kim, S.; Lee, J.; Kang, C. Analysis of industrial accidents causing through jamming or crushing accidental deaths in the manufacturing industry in South Korea: Focus on non-routine work on machinery. *Saf. Sci.* **2021**, *133*, 104998. [CrossRef]
35. Rhee, K.; Choe, S.; Kim, Y.; Koo, K. The trend of occupational injuries in Korea from 2001 to 2010. *Saf. Health Work* **2013**, *4*, 63–70.
36. Kwon, H.; Kim, S.; Lee, T. Cause analysis and improvement suggestion for fire accident in traditional market based on disaster scientific investigation. *J. Korean Soc. Hazard. Mitig.* **2018**, *18*, 75–82. [CrossRef]
37. Arifuddin, R.; Latief, R.U.; Suraji, A. An investigation of fall accident in a high-rise building project. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *419*, 012144. [CrossRef]