Advanced Crane Systems: The Impact of Modern Technologies on Performance and Safety

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Introduction

Cranes have been important machines used to lift and move loads since the early periods of human history. For several centuries, power has been provided by the physical effort of people or animals. The oldest steam crane was adopted in the 18th or 19th century. Many of the old cranes continued to be used until the late 20th century (URL-1).

Today, cranes are specially designed to meet a wide variety of needs in various industries. Winches are potentially used in construction for the lifting of materials, in transportation for the loading and unloading of loads, and in the assembly of heavy equipment in manufacturing (URL-2).

Cranes generally vary according to their lifting capacities, mobility, and working environments. While some are stationary, others are mobile or portable. Modern cranes enhance efficiency and safety by utilizing advanced technologies such as hydraulic systems, electronic controls, and high-strength materials. Cranes play a critical role in industrial processes and continuously evolve with technological advancements over time (Donell, 1995). At the same time, using these machines can involve risks. Therefore, they are designed to adhere to specific standards and various tests are applied to the final product.

Innovative Aspects of Cranes

Cranes have a history dating back thousands of years to meet the needs of humanity. Crane design has evolved to meet various industrial needs. Modern cranes typically coordinate simple systems to perform complex lifting tasks, even in environments that may be dangerous for workers (Chondros, 2010).

Throughout history, cranes have played a significant role in constructing large-scale structures more quickly and safely; mechanical innovations and material developments have increased their strength and durability, allowing for the lifting of larger loads (URL-3; URL-4).

Figure 1
Modern Cranes (Zhang & Wang, 2020)

Today, modern cranes are extensively used in industrial applications such as construction, port operations, mining, and manufacturing, as well as many others. These cranes are typically provided with complex hydraulic electronic control systems and are designed to ensure human safety and efficiently manage large-scale lifting operations. Modern cranes can operate with high precision and efficiency thanks to automation and remote control technologies (Helling, 2020). In addition, by continuously monitoring the weight, balance, and movement of loads with the help of sensors and software, potential accidents are prevented. Thanks to advanced material science and engineering techniques, these cranes have become lighter, stronger, and more durable. Today's crane technologies use technologies such as machine learning, simulations, artificial intelligence, the Internet of Things, optimization algorithms, and digital twin technologies to control and alert the user (Hasan et al, 2024).

These technologies provide innovative contributions in many areas, such as (Liu et al, 2024):

- Predicting accidents that may occur during crane operation,
- Optimizing, improving, and planning crane operations,
- Detecting and preventing the risk of cranes colliding with other objects,
- Monitoring and controlling the operational status of cranes,
- Ensuring the balance and safety of cranes,
- Optimizing crane performance,
- Real-time monitoring of crane operations

These technological advancements have increased the performance and safety of cranes while reducing their operational costs. Electrically powered cranes that provide energy efficiency and eco-friendly designs have been an important step towards sustainability. The flexibility and versatility of modern cranes have made them an indispensable tool in many industrial processes (URL-5). Thus, it has become possible to overcome more complex and challenging projects.

Crane Safety

Cranes maintain balance through counterweights during the lifting and moving of loads. For any type of crane to operate efficiently and maintain its crucial balance, it must adhere to the laws of physics. In this context, the two most important considerations are that the crane should not lift weights exceeding its nominal capacity and that stressful movements beyond the designated operational plane of each machine should be minimized. Violating these established rules can lead to crane tipping, structural damage, and serious accidents. Therefore, crane operators and technicians must thoroughly understand the limits and capacities of the cranes and always operate within these boundaries (Ramli et al, 2017).

In addition, regular maintenance and periodic inspections are critical for the safe and effective operation of cranes. Ropes, hooks, hydraulic systems, and other components should be continuously inspected and replaced as needed. Moreover, comprehensive training for operators and strict adherence to safety protocols will help prevent potential accidents. The working environment of the cranes should also be considered, with careful evaluation of ground stability and environmental conditions. These measures ensure that cranes serve reliably and safely for extended periods, preventing workplace accidents (Nazlıoğlu, 2014).

Figure 2
Crane Safety (URL-6)

The effective operation and safety of cranes are closely tied to the laws of physics, and there are several key considerations to take into account in crane design:

- **Lifting Capacity**: A crane must have the capacity to lift the weight of the load it is designed to handle. This capacity depends on the durability and strength of the lifting mechanisms, ropes, hooks, and other components on the crane. The crane should be designed and configured to safely bear the weight of a given load while lifting.
- **Balance and Stability**: A crane must be designed to maintain its balance during lifting operations. The tipping or falling of a crane can result in serious damage and safety risks. Therefore, the configuration and placement of the crane should be carefully planned according to the stability of the working area and the solidity of the ground. Additionally, the crane should be designed with safety factors in mind to remain stable during lifting operations.
- **Force and Motion Control**: The force and motion control of cranes ensure the precise and safe movement of loads. Hydraulic and electronic control systems allow for the precise control of crane movements and lifting operations. These systems ensure the correct positioning of loads and the prevention of potential accidents.

- **Safety and Maintenance**: Regular maintenance and safety inspections are necessary for the safe operation of cranes. Ropes, hooks, hydraulic systems, and other components should be periodically checked and replaced when necessary. It is also critical that operators receive proper training to ensure safe usage.
- **Environmental Conditions**: The conditions of the environment in which cranes operate are important for both design and operation. Environmental conditions such as high winds, rain and temperature changes can impact the performance of cranes. Therefore, cranes should be designed to withstand these conditions, and protective measures should be taken if necessary.

Designing and utilizing cranes with these considerations in mind are crucial for both efficiency and safety. Taking these factors into account ensures that cranes serve reliably and safely over their lifespan (URL-7).

Cranes have been customized to meet the varying needs of different sectors as indispensable tools in industrial processes. With high lifting capacities and flexibility of movement, they are used in many fields, including aviation, shipyards, manufacturing plants, and construction. These machines efficiently perform the tasks of transporting, assembling, and positioning finished and semi-finished products. The flexibility and lifting power provided by cranes support the acceleration of production processes, increase efficiency, reduce labor, and enhance operational safety(Doğan, 2023).

Crane Types

Each type of crane is designed for a specific industry or application. Choosing the right crane is crucial for performing work efficiently and safely (Samset, 2013). There are many different types of cranes designed for specific uses.

Gantry Crane

Gantry cranes are a type of overhead crane that travels on a rail system with independent legs or moves on wheels. They typically have a single or double girder structure and operate on a straight line over a rail or rail system embedded in the ground within a specific area. Smaller portable gantry systems work on wheels or tracks, allowing for easy mobility for maintenance or light manufacturing tasks. The design of gantry cranes involves two legs that move on rails embedded flush with the ground surface, enabling equipment like scissor lifts and forklifts to pass underneath (Gerdemeli & Serpil, 2013).

Figure 3
Gantry Crane (URL-8)

Gantry cranes are ideal for load-handling applications both indoors and outdoors. The systems where bridge girders are mounted on gantry legs, which move on the ground over a rail system, offer high portability and flexibility. Double-girder and single-girder gantry cranes are advantageous for load stacking and usage purposes with the flexibility of right/left cantilever use. The design of gantry cranes eliminates the need for support columns and vertical runway beams, as they do not need to be attached to a building's support structure.

These cranes are widely used in various sectors including industrial manufacturing plants, workshops, hydroelectric power stations, dams, marble-cutting facilities, storage warehouses, ports, and similar environments. The flexibility and lifting capacity provided by gantry cranes enhance efficiency and make operational processes more effective in these areas (Burul et al, 2010).

Jib Crane

Jib cranes are primarily used in construction and heavy load-handling applications. They are effective for placing and moving large concrete blocks, beams, or other heavy structural elements. In the industry, they are also used for transporting parts between different machine stations and work areas. Jib cranes are versatile and typically used for repetitive lifting tasks within a smaller work area (Solazzi & Danzi, 2024).

Equipped with one or more rotating arms, jib cranes allow for the movement of loads across a wide area. Usually mounted on a fixed base, these cranes enable precise positioning of loads thanks to their rotating arms. The crane arm contains a robust mechanism and is typically operated by hydraulic or electric systems.

Figure 4

Jib Crane (URL-9)

During the use of jib cranes, the operator can rotate the crane arm in the desired direction and move the load in various directions. The mobility of jib cranes provides advantages, especially in areas where large and heavy loads need to be placed. Installation and operation are typically carried out by professional teams. These cranes, consisting of components such as the column and boom, have capabilities ranging from 250 lbs to 15 tons. Integrated ergonomic design enhances worker productivity in manufacturing environments, reduces workplace injuries, and improves overall safety. Key components include the horizontal boom, mast or support column, bearing system, crane, and controls (Dhanoosha & Reddy, 2016).

Despite their various types, jib cranes vary depending on their area of use. They come in several varieties, including wall-mounted, pillar-type, and freestanding cranes. Selecting the appropriate type of jib crane based on the application and working environment enhances job efficiency and safety (Karpe et al, 2014).

Monorail Crane

Monorail crane systems are ideal for lifting and transporting various products along a fixed track. They operate using wheels that move along the flange beneath an I-beam (Feit et al, 2008). These systems are used to enhance efficiency in manufacturing environments, assembly lines, and other workplaces.

Figure 5
Monorail Crane (URL-9)

Monorail systems are preferred for transporting goods in narrow spaces and production areas requiring continuous operations. They offer a simple and economical solution for transferring materials such as motors, pumps, and valves to specific locations within industrial buildings. These systems can be used without the operational flexibility and cost associated with overhead bridge cranes. Some monorails include both curved and straight sections, providing additional flexibility. The use of monorail cranes increases efficiency in production processes and reduces operational costs (Woolcock et all, 2011).

Overhead Bridge Crane

The fundamental components of bridge cranes include the walkway and the bridge that moves on it. The bridge comprises a traveling trolley and a lifting system connected to the transport trolley. The lifting system is driven by a manual remote control (Öğün, 2014).

The operational mechanism of a bridge crane consists of the operating mechanism and the hoisting mechanism:

Hoisting Mechanism: This mechanism is responsible for hoisting objects vertically. It is therefore the foremost significant and fundamental mechanism of the crane.

Operating Mechanism: This mechanism is used for moving objects horizontally, typically through a crane or hoisting trolley. It could be categorized into two types: rail-based, and rail-free operation.

Figure 6
Double Girder Cranes (URL-9)

Most gantry cranes start a vertical or horizontal movement after lifting the load. When it reaches its destination point, it unloads the load and then returns to the starting point, completing one working cycle. This is followed by a second lifting operation (Erdil, 2007). Overhead cranes are widely used in factories, warehouses, shipyards, and various production facilities. The efficient working cycles of these cranes speed up operational processes and increase labor productivity. They also ensure safe and fast transportation of loads of different capacities. This minimizes occupational accidents and material damage. Gantry cranes, single-girder cranes, double-girder cranes, and semi-gantry cranes are available in various types (Mojallizadeh & Brogliato, 2023).

Mobile Crane

Mobile cranes are cranes with high mobility, capable of lifting and transporting various loads.

The mobile crane is essential and one of the most widely used construction equipment for handling materials, ingredients, temporary works, etc. on building sites. It can move and maneuver within a site (Gou et al, 2021).

Figure 7
Mobile Crane (URL-10)

Mobile cranes generally have two main characteristics: Firstly, unlike the horizontal lateral support of tower cranes, the inclined boom of mobile cranes generally spans a significantly larger operational area in three dimensions. Secondly, mobile cranes possess the capability to traverse the entire worksite to carry out particular lifting tasks, rather than remaining stationary (Shapira & Jay, 1996).

Selecting the appropriate type and model of mobile crane ensures its efficient utilization, leading to cost savings and a higher likelihood of completing the construction project. The right choice of crane maximizes operational efficiency, increases occupational safety, and minimizes occupational accidents (Dalalah et all, 2010). Truck-mounted Cranes can be categorized as *Telescopic Cranes* and *Crawler Cranes*.

Due to their mobility, they can quickly reach different work sites. They can be used in various works and in different ground conditions. They increase work efficiency due to their short installation and dismantling time. They can lift and carry heavy loads (Balkan, 1996).

Tower Crane

Tower cranes are high crane types that are used when constructing high-rise buildings and can lift large loads. They are widely preferred especially in skyscrapers, bridges, and large-scale construction projects. Tower cranes are mounted on a vertical tower and equipped with a lifting boom for transporting loads (Elliott, 2015). The boom can cover extensive distances at the crane's height and typically rotates 360 degrees. Constructed primarily from steel or aluminum, tower cranes are highly durable and resistant to wind and other environmental factors that may impact them due to their significant height (Kaveh & Vazirinia, 2018).

Figure 8
Tower Crane (Burkhardt et al, 2023).

Tower cranes are designed to lift and transport loads from heights. The crane operator lifts the load with the help of a hook and moves the crane trolley along the boom to move the load to the desired location. The upper part of the crane can rotate 360 degrees horizontally thanks to the rotation mechanism. This feature provides a wide working area (Brain, 2023).

Indispensable for modern construction projects, tower cranes are critical tools for tall buildings and large-scale construction projects. These powerful machines speed up construction processes, increase work efficiency, and ensure the safe transportation of heavy loads.

The advantages of tower cranes include:

- Capacity to lift heavy loads to high points,
- A wide working area thanks to the boom length and rotation mechanism,
- High stability thanks to their robust construction and counterweights,
- Allowing precise positioning of loads

These features make tower cranes indispensable tools for the modern construction industry (Alămoreanu & Vasilescu, 2009).

Port Crane

As centers of global trade, ports are critical points where logistics and technology converge. Port cranes are used for loading and unloading cargo onto ships and for construction work. Playing a major role in maritime transportation and logistics, these cranes speed up loading and unloading processes and are often used to transport containers, bulk cargo, and heavy materials (Matheus, 1996).

Figure 9
Port Crane (URL-11)

These cranes, which operate with mechanical systems, increased the volume of trade by accelerating the transportation of goods and reducing the need for labor. The development of harbor cranes made a significant contribution to the growth and enrichment of cities as well as maritime trade (Wei et al, 2023). These technological advances laid the foundations of modern ports and pioneered the advanced crane systems used today.

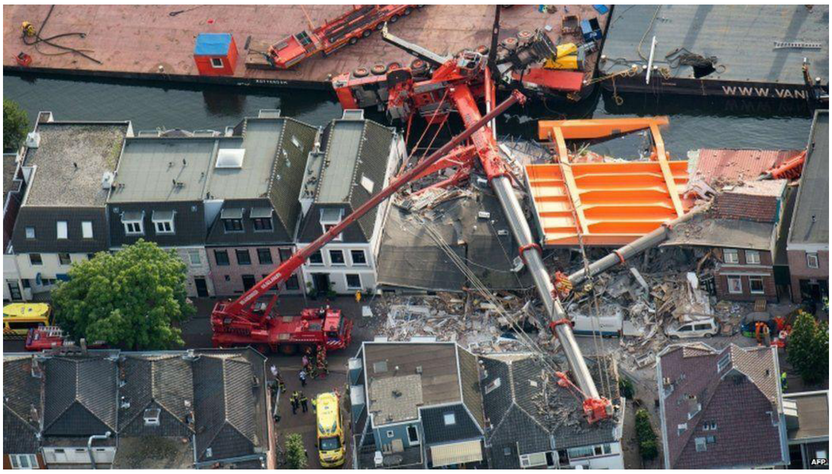
The structure of harbor cranes includes components such as a boom, tower, hook or spreader, trolley, base, and hydraulic and electrical systems. Different types of harbor cranes include gantry cranes, ship-to-shore cranes, telescopic cranes, mobile harbor cranes, and floating cranes. These cranes are used in various areas such as container ports, bulk cargo ports, Ro-Ro ports and because of their high carrying capacity and wide range of operations (Gaspar et al, 2019).

However, as demands for efficiency and sustainability increase, the industry is responding with a range of innovations in the design and operation of harbor cranes. As the port industry adapts and evolves to the challenges of the 21st century, innovations in harbor cranes will continue to play an instrumental role in increasing operational efficiency and environmental sustainability (Meisel & Bierwirth, 2021).

Risks That May Occur in The Use of Cranes

Cranes play a crucial role in various sectors, including industrial and mining enterprises, ports, rail transportation, and real estate (Zhu et al, 2014). While they are indispensable for many industries, cranes must be recognized as high-risk devices. Despite their utility, crane operations present substantial safety concerns, posing significant threats to both individuals and property (Li & Zhao, 2017).

Figure 10
Mobile Crane Accident (URL-12)



One of the primary causes of fatalities in construction is the use of cranes or towers during lifting operations. Studies indicate that over 84% of crane and tower-related fatalities involve the use of mobile cranes with lattice and telescopic booms, as well as truck or crawler cranes. The authors believe that to reduce the crane fatality rate, crane operators and operators need to be qualified and requalified each time (Beavers, 2006).

In some literature studies, the risks and accidents that cranes pose when they are not designed properly or when they are used in harsh weather conditions are mentioned. These transportation systems with large masses can pose great risks. In one study, it was revealed that the crane started to move under the influence of a continuous and very strong wind blowing at a speed of approximately 110 km/h and derailed after traveling approximately 60 meters. Therefore, the catastrophic derailment of a gantry crane was analyzed (Frendo, 2016). Given that gantry tower cranes typically have long, wide spans and large downwind areas on their main girders, they are particularly vulnerable to damage from destructive wind gusts. This vulnerability was highlighted in a study investigating a gantry crane overturning incident in Shenzhen, caused by an explosion. The study found that the overturning moment and shear force on the gantry crane's foundation exceeded the critical values needed to maintain stability, leading to the crane's collapse (Su et al, 2023).

Figure 11
Tower Crane Accident (Swuste, 2013).

Another study describes the collapse of a tower crane at a construction site in Rotterdam. The investigation revealed that the actual flexibility of the crane's mast and horizontal arm configuration was greater than the design engineer's calculations, leading to the crane collapsing while lifting a heavy load (Swuste, 2013).

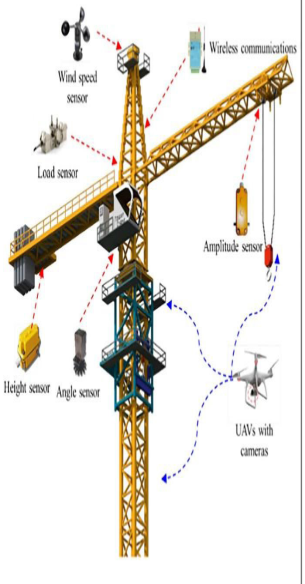
An article details the investigation into the collapse of a tower crane at an office building construction site in Bellevue. The collapse is particularly intriguing because it occurred with no load on the hook and under minimal wind conditions while the operator was shutting down the crane for the night (McDonald & Ross, 2011).

Innovative Technologies Used to Ensure Safety in the Crane Industry

To ensure a crane complies with applicable standards, it is crucial to conduct proper dynamic and structural analysis, considering the fundamental design phenomena (Choi, 2022).

Proper use of lifting machinery is vital for the safe production processes of enterprises. Therefore, it is essential to thoroughly analyze and anticipate the potential hazards and consequences associated with these machines. Assessing the safety of lifting machines involves analyzing risk factors and accident outcomes, evaluating the accident risk, and proposing safety response measures to ensure safe operations (Sadeghi et al, 2021). This comprehensive approach supports administrative departments in supervising the safety of specialized equipment effectively.

Figure 12
Technology in Cranes (Wu et al, 2023).



(a) IoT system

Contents	Inspection details
Document files	Certificates of operators, single men, and riggers
	Product certification of tower cranes
	Inspection and maintenance logbook
	Repair logbook
	Daily operation records
Hoisting parts	Braking systems
	Electrical parts for hoisting
	Hook height limit switch
	Moment cutout switch and overload cutout switch
	Gearbox oil level and refill
	Hoist winch and main axle, lubrication, and oiling
	Connections for all pulleys, hooks, and pins
	Lubrication, wear, and tear condition of wire ropes
	Swivel/ anti-twist device for wire ropes at jib
	Fixing of the base for hoisting parts, connection pins/bolts for gearbox and footings
Luffing parts	Slewing limit switch
	Electrical parts for slewing
	V-belt to the slewing motor
	Slewing gearbox oil level and refill
	Bolts of slewing bearing
	Slewing bearing with grease
	Slewing ring with grease
	Fixing of connection pins/bolts for gearbox
Steel structure and main structural parts	Tower base and mast base
	Connection of all mast sections and check for any missing split pins / bolts and nuts
	Connections and split pins at jib and other steel structural parts / bolts and nuts
	Welding parts of all structural components
	Deformation at tower mast sections, jib and counter-jib
	Connections of climbing collars
	Pins and bolts of ballast blocks
	Climbing ladders of tower crane
Hook parts	Condition of hook block

(b) Regular safety inspection content

This article describes the innovative and industrial technologies used to eliminate the risks and safety threats that may occur during the use of cranes and the intended use of these technologies (Hamka, 2017).

Accident Forecasts

Machine learning algorithms optimize previous data to predict accidents and define the factors that cause accidents. These algorithms predict the probability and severity of accidents (Tamascelli et al, 2022).

Many techniques are used for accident prediction (BPNN, MIRF, etc.). An IoT-based machine learning model is used to predict the wind response of cranes during typhoons. This model measures the maximum displacement using real-time data from IoT sensors and demonstrates its effectiveness in field measurements. Analyzing past crane accidents predicts operational variables and accident probabilities.

Operation Planning

Machine learning and algorithms enable the use of data-driven techniques to plan, develop, and schedule crane operations. This is focused on making informed choices to maximize the safety, productivity, and efficient operation of crane facilities (Cho & Han, 2022).

Many algorithms are used in operation planning (CCGA, ABM, 4D-BIM, etc.). Some methods perform motion planning, some provide constraint optimization services for dynamic replanning of crane paths, while others minimize production time and study the effect of supply choices on crane productivity.

On-site Monitoring

On-site monitoring for winch operations includes observation in real time and oversight of crane operations on construction sites. This innovation ensures safety, efficiency, and regulatory compliance through sensors and data collection methods (Chae & Yoshida, 2010).

Furthermore, various sensors such as RFID, load cell sensors, localization sensors, BIM data, accelerometers and are used in integrated systems to create safety zones to warn personnel of risks. These sensors comprehensively analyze load dimensions, clearance distances, and worker movements (Luo et al, 2014). In addition, in-situ monitoring technologies are used to prevent overloading, inspect critical areas, and detect magnetic field changes.

Remote Monitoring

Remote monitoring of crane operations leverages technology and communication systems to oversee and manage crane activities at construction or industrial sites. These systems enhance safety by continuously tracking crane performance, load handling, and operator conduct, offering real-time alerts for swift issue resolution (Sitompul, 2022).

Through sensors, many functions become easy and effective, such as optimizing remote communication protocols, categorizing lifted objects, recording weights, continuously monitoring and diagnosing crane status, and exchanging data between cranes.

Collision Prevention Technologies

Crash avoidance technologies are designed to prevent physical collisions or interference between objects, vehicles, or machinery. These systems utilize sensors, algorithms, and communication networks to detect the proximity of objects and take preventive measures such as issuing warnings, altering trajectories, or halting movement to avoid collisions. When a crane contacts nearby structures, equipment, or objects during operation, the resulting collisions can cause substantial damage to both the crane and surrounding structures, posing a serious risk to the safety of crane operators and onsite personnel (Al Hattab et al, 2018).

With these technologies, it is possible to detect crane parts in the working areas, provide communication between cranes, and thus prevent collisions.

Crane and Load Stability Technologies

Stability Control Technologies encompass a range of advanced systems and features designed to maintain the stability and safety of cranes during lifting and material handling operations. These innovations are critical to prevent accidents and ensure that crane operations are efficient and precise (Shin, 2015).

This system autonomously stabilizes the crane to prevent it from tipping over, especially due to strong winds. Wind sensors continuously monitor and predict dangerous wind gusts so that preventive protective measures can be taken (Sorokin et al, 2018).

In addition, they control load stability and reduce sway by accurately estimating the displacement during crane operations, providing precise measurements of parameters such as angle, trolley position, and hook position (Zhu et al, 2022).

Conclusion

This paper provides a comprehensive overview of crane applications, their critical role in industrial processes, and safety risks. Crane technologies, which have evolved throughout history, are now equipped with machine learning, optimization algorithms, simulations, the Internet of Things (IoT), artificial intelligence (AI), and digital twin technologies. These advancements have not only improved the performance of cranes but also significantly increased their safety. For example, IoT-based machine learning models predict the wind response of cranes with real-time data, preventing accidents and ensuring the safety of operators. Sensors and software continuously monitor the weight, balance and movement of loads, helping to prevent potential accidents. Thanks to advanced materials science and engineering techniques, modern cranes have become lighter, stronger, and more durable. In addition, energy-efficient electric cranes and environmentally friendly designs have been an important step towards sustainability.

On the other hand, given the high fatality rate of crane accidents, operator training and qualification is of critical importance. Therefore, continuous training, advanced safety protocols, and technological solutions are vital requirements to improve safety in crane operations. Ensuring the safe use of cranes both raise occupational safety standards and contributes to the sustainability of industrial processes. In this context, strengthening the technological infrastructure of cranes and continuously updating safety measures are of great importance to prevent future accidents.

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