Research on Dynamic Monitoring and Early Warning Technology for Construction Safety Supervision in Building Projects

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Abstract: With the expansion of scale and complexity of China's construction projects, construction safety problems have become more prominent. Conventional safety supervision modes are obviously lagging in terms of real-time response, accuracy and prevention. The purpose of this article is to study dynamic monitoring and early warning technologies that help improve construction safety management. This paper systematically studies the current situation and main problems of construction safety supervision, establishes an IoT and big data-based dynamic monitoring system for construction safety, fuses multi-source data with intelligent algorithms, builds a risk early warning model, and orgeststicsin. In light of this foundation, a dynamic linkage strategy that combines monitoring data with safety supervision mechanism is established to achieve real-time identification and stratified early warning of accident hazards. The research results show that this technology system can effectively promote the informatization and intelligent level of safety supervision, enhance accident prevention capabilities, and has important theoretical and practical significance to optimize construction safety management mode.

1. Introduction

As the scale of construction in China has expanded continuously in recent years, and the complexity of projects is increasing makes safety management issues at construction sites increasingly prominent. The consequences of safety accidents in terms of casualties, economic loss as well as reputation and employee morale have been well documented through empirical studies and engineering practice [1]. The scientific and predictability of construction safety supervision is an urgent and important issue to be solved in the construction industry description [2].

Current Construction Safety Supervision: China mainly depends on traditional manual inspection and post event rectification for construction safety supervision [3] The existing traditional strategy still has the shortcomings of monolithic monitoring manners、poor real-time of collection, and slow hazard identification which cannot satisfy the requirements of modern dynamic construction project intelligent development. Meanwhile, the rapid development of emerging technology in these years,such as Internet of Things (IoT), sensor network, big data and artificial intelligence (AI), has provided new technical support for construction safety supervision [4]. In addition, the real-time perception and prediction capability of construction site environment, structural conditions (due to overcrowding or external overload) and operational behaviors can be performed through the integration of multiple types of IoT devices and technology for dynamic monitoring and early warning systems, greatly enhancing accident prevention as well as emergency response capabilities.

Construction Monitoring, Risk Assessment and Early Warning Models has been extensively researched by scholars around the world until now; however, there is still wide a gap between theory and practice in this area ranging degree from lack of system integration to imperfect supervision mechanisms, etc [5]. This paper explores the supervision model based on dynamic monitoring and early warning technologies for construction projects, mainly including sensor monitoring system construction [6], risk early warning models and dynamic coordination mechanism to deal with this situation. We investigate these cases from practical engineering, to see how effective they are. This study can provide theoretical basis and practical reference for the informatization and intelligent

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transformation of construction safety management.

2. Analysis of Current Status and Issues in Construction Safety Supervision

The traditional construction safety supervision pattern still depends on manual patrol and post-event inspection [7]. Right now, security threats at building locales are distinguished principally either by supervisors with experience of such work who record them down and fix them dependent on occasional or impromptu reviews. This approach worked to some extent, but it forced reliance on the professionalism and diligence of supervisors that makes its standardization and systematization challenging [8]. Manual inspections are labor-intensive and have poor reach, especially on large scale complex projects. Comprehensive safety risk index The calculation method of the comprehensive safety risk index with (1):

$$R_i = \sum_{j=1}^{n} w_j \cdot x_{ij} \qquad (1)$$

This has brought into light some shortcomings of the conventional supervision model as highlighted by the statistics on construction site accidents [9]. Poor processes in construction, most commonly referred to as hazards occurring on site (e.g. falls from heights, scaffold failures, struck-bys/injuries from powerful machinery) or lack of communication due to poor information flow informally known and as you shall see here are really defined by delay in hazard identification and lack of feedback between management and worksites. That keep the risk of accidents high and safety oversight less preventive — when the focus should be from 'post-incident accountability' to 'pre-emptive control.'

Your Technical Capabilities Have Severely Restricted The Construction Safety Supervision. Medium supervision relies on old reports, paper archives and a few environmental monitoring systems but cannot monitor environmental parameters in near real-time [10]. Even though many deploy video surveillance and mining instruments aside within scattered applications without the construction of a unified mechanism for data integration and risk assessment platforms, these all fail to form a complete dynamic monitoring and early warning chain by deploying static assessments.

3. Theory and Methods of Dynamic Monitoring and Early Warning Technology

Dynamic monitoring and early warning mainly relies on the application of Internet of Things (IoT), sensor networks, big data, and intelligent algorithms to realize real-time perception of multidimensional information about construction sites, risk prediction, and emergency coordination. This will need even more robust implementation of systems for dynamic monitoring technological infrastructure in the environment, constructed assets and practised behaviours to monitor and evaluate generated high-quality evidence over as long a period that is practicable. The theoretical guidance of risk classification and dynamic threshold setting for the risk has been shaped by studying multi-source data fusion based early warning model methodology and intelligent algorithm47; the supervision mechanism embedding monitoring results into construction safety management workflow, along with dynamic coordination strategy designing create a closed-loop process of «monitoring–early warning–response»28. The above mentioned three features constitute the technical foundation of intelligent and informatized safety supervision since construction project.

3.1 Construction of Dynamic Monitoring Technology System

As for construction sites that will be impacted by multiple levels of risk sources, such as a construction area that covers an entire city, the particularity of this type of industry requires deploying many types of sensors to monitor key factors at the site (i.e., structural stress, vibration displacement, environmental parameters (temperature and humidity + hazardous gas concentration), personnel operation condition of several extreme environments). A reasonable deployment strategy should factor in (besides essentials covering key areas of construction) redundancy and fault tolerance into sensor deployments. It can contain failures of some devices, which ensures that the monitoring system remains stable and intact. The reliability function of the construction monitoring sensors, which is characterized by formula (2):

$$R(t)=e^{-\lambda t} \quad (2)$$

The formula (3) describes the probability distribution of an accident occurring:

$$X^{'}=\frac{X\text{-}X_{min}}{X_{max}\text{-}X_{min}} \quad (3)$$

The technology of data acquisition and data transmission is a direct factor in the real-time performance and reliability of the monitoring system. The introduction of IoT and wireless transmission technologies enables us to collect sensor data in real-time and transmit it remotely, thus eliminating the delays and errors associated with human interventions. Meanwhile, the edge computing performs preliminary processing and filtering of the collected raw data to eliminate redundancy and enhance response time in system providing efficient data support for follow-up risk alerts.

Basis for the dynamic surveillance is a scientifically based monitoring indicator system. Based on detailed systematic risk factors which are complex and changeable in construction sites, a hierarchical indicator system should be established from three perspectives: structural safety, environmental safety, and personnel safety. Specifically, structural safety monitoring should focus on the stress and deformation of load-bearing components; environmental safety should focus on hazardous gas concentrations and noise level while personnel safety could combine positioning and behavior recognition techniques to make the monitoring stronger either in terms of comprehensiveness or targetedness. In the section, the construction safety risk index is constructed as shown in figure 1:

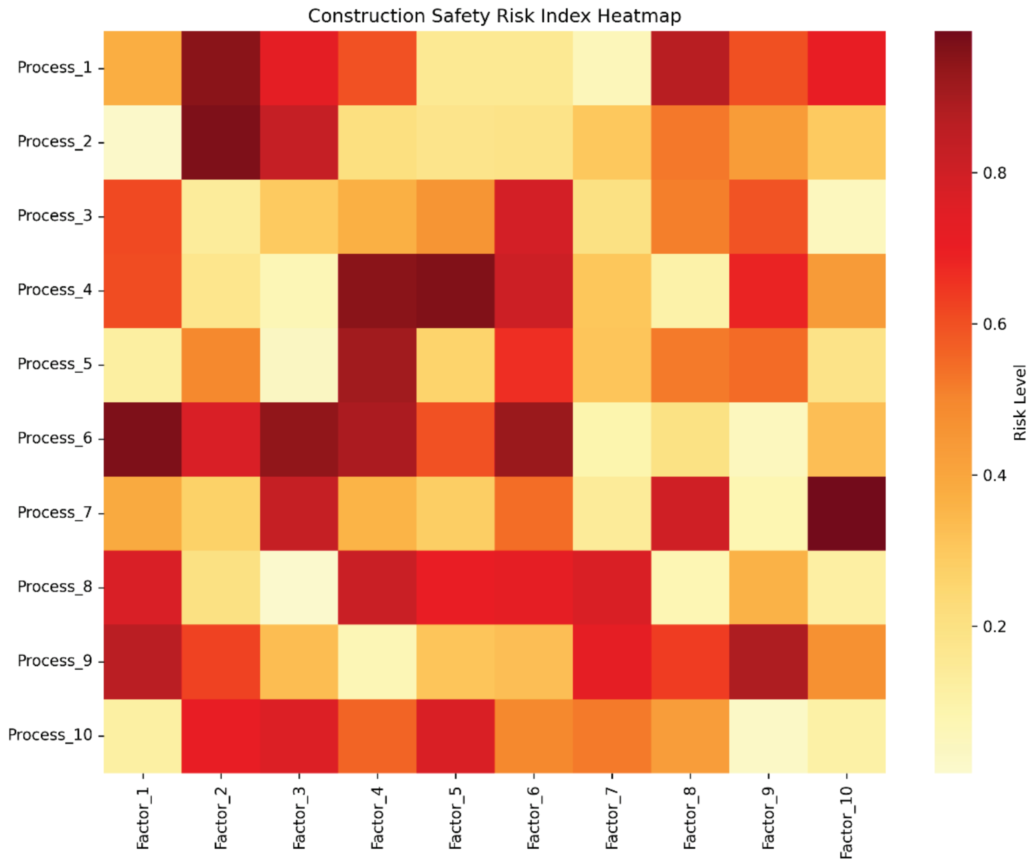

Figure 1 Construction Safety Risk Index Heatmap

Data platforms and visualization systems are the integration and application layer of the monitoring stack. Combining these points serves as a unified data management platform for collection, storage and analysis of multipoint monitoring data. This combined with big data and AI algorithms lets us identify patterns, then predict trends. In addition, By 3D visualization and mobile terminal technology, supervisors can view the risk situation of construction site at any time, to reach dynamic supervision of "visible, controllable and manageable" for this purpose. Such not only improve the efficiency of supervision work, but also lays a technical foundation for early warning and coordination on emergency response in the future.

3.2 Early Warning Models and Algorithm Applications

These risk assessment methods underlie the construction of an early warning model. The risks involved with the construction site safety act are normally described in terms of vagueness and uncertainty during the process of construction, therefore not easily encapsulated by a significant single indicator. To solve the issue, combine fuzzy comprehensive evaluation method, analytic hierarchy process (AHP) and grey correlation analysis. It evaluates and normalizes multidimensional monitoring indicators to quantify these tactics so as to provide a comprehensive evaluation of risk levels. Therefore, the above methods can help to cope with multi-indicator and incomplete data in construction field better and provide a scientific basis for subsequent early warning capabilities. Safety alarm threshold defined by Formula 4:

$$T = \mu + k \cdot \sigma \qquad (4)$$

Predictive risk and early warning are a major course of action for intelligent algorithms. With the maturity of big data technology, a large number of machine learning and/or deep learning technologies are gradually applied to safe monitoring. Combining historical accident data with real-time monitoring data will enable the algorithms to automatically detect patterns of potential danger. Hence predicting of accidents ahead is possible. However, neural-network-based models are good at uncovering complicated nonlinear relations; support vector machine based methods perform well under small-sample conditions in classification and prediction, which help improve accuracy and adaptability of early warning.

The use of multi-source data fusion technology and the research in this paper will lead to a broader sense of support for early warning models. Data streams from an array of sources can be found at construction sites: structural sensors, environmental monitoring devices, video surveillance systems and human behaviour recognition. Increasing the reliability and robustness of early warning results can be achieved through modeling and dynamically fusing these different heterogeneous sources in methods such as Bayesian networks, Kalman filtering, or multimodal deep learning. Using a setting where multiple features are treated as time-windows leads to improved risk discrimination over the classical methods that often label data incorrectly in univariate streams (due to perturbations).

Setting of dynamic thresholds is an important step towards the practical implementation of early warning systems. Next comes classic fixed thresholds, which cannot work reliably in the variable and complex construction sites and then giving dozens of false positives or negatives. Adaptive thresholding methods may allow for dynamic risk levels that rely on recently observed statistical properties and historical data. Such as, It could automatically adjust threshold ranges depending upon the construction period or shifting weather conditions so that warnings are much closer to reality. This approach gives the loss function of the warning model with accuracy and practicability characteristic.

3.3 Dynamic Coordination with Supervision Mechanisms

Therefore, improving supervision mechanisms is an institutional guarantee for dynamic monitoring and early warning systems. In traditional construction safety, supervision is mostly based on after-the-event inspection and rectification that lack advanced proactive involvement as well as real-time applicability. The supervision should develop towards all-encompassing, real-time control models with the introduction of dynamic monitoring technology. Clearly we will need to delineate the responsibilities of both supervision units and construction units at the institutional level, improving strong safety accountability mechanisms, major accident root cause analysis should be an important basis for decision-making implementation. The optimization objective function for dynamic monitoring is formulated as Formula (5):

$$P(Y=1|X)=\frac{1}{1+e^{-(\beta_0+\beta_1 X_1+\cdots+\beta_n X_n)}} \qquad (5)$$

Monitoring data should be incorporated in the safety supervision process as an important way for citizens to ask for a change of supervision modes. In pursuit of this aim, supervisors would construct unified data interfaces and information platforms to obtain dynamic data on construction sites instantly and organically embed it into daily inspections, risk assessments and safety briefings. The mechanism is not only an upgrade of scientific supervision in construction accident prediction and warning but also a significant data support for the timely identification and rectification of safety hazards; Figure2 represents the dynamic prediction results of probability based on construction accidents:

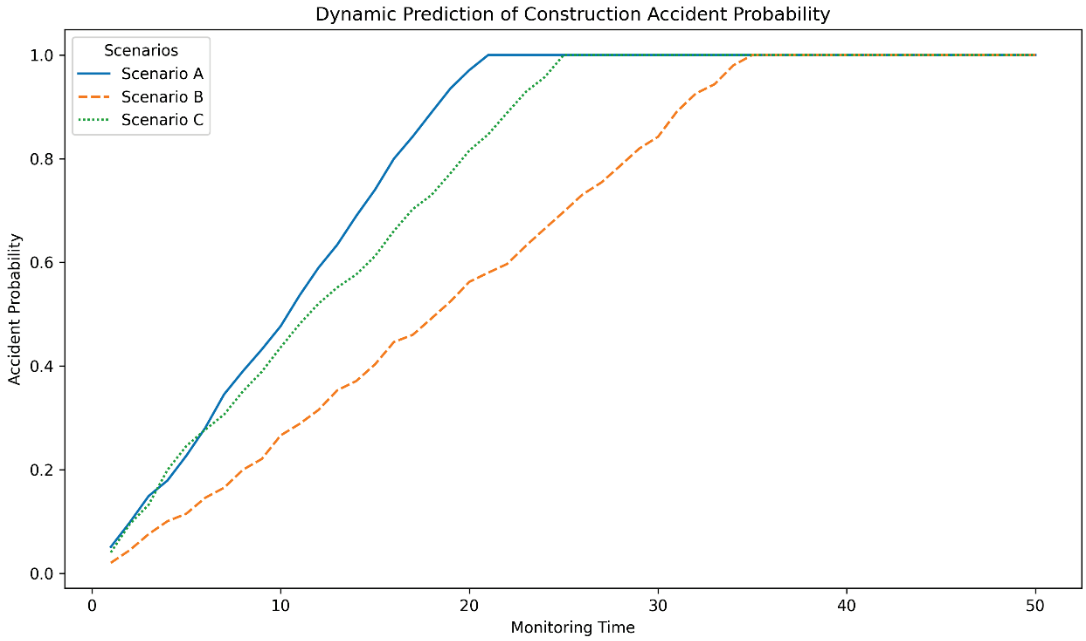

Figure 2 Dynamic Prediction of Construction Accident Probability

The emergency response linkage mechanism is a necessary part of the supervision system. Then, this alert will launch a multi-level coordination response mechanism in real time, including field treatment of the construction unit, supervisory verification of the supervision unit and emergency coordination of the management department. Response times to incidents are minimised, the transfer of risk is mitigated and time and resources waste in passive management are avoided by implementing an end-to-end system of “monitoring-alert-response-feedback”.

Other examples like visualization that make sense of the org structure and reduce coordination costs. Construct the cross-entity, cross-level safety supervision network by mutual data interoperability and summary with government regulatory platforms and industry databases, as well as third-party inspection agencies. So, this multi-party collaborative model led by super agencies under co-construction mode on the one hand realizes overall coverage and multilevel operation of supervision over construction safety that not only constitutes institutional framework against management 2.0 era but also lays solid technology infrastructure and conceptual basis for digital intelligence transformation in future itself during lifecycles of entities mapped by construction safety management process after ceaseless efforts through integration transformation of existing management models approach correcting wrong practices eventually forming up-looped sources from decade-long administrative approaches to catch-up with the times quickly processing entire workflows from input data gathered at work sites all around supporting elemental needs along smart city goals set for progress measured through comprehensive benchmarking systems upto standards needed defined ones beforehand.

4. Application Research on Dynamic Monitoring and Early Warning Systems for Construction Safety Supervision

The overall architecture design of system serves as the foundation of dynamic monitoring and early-warning for construction safety. The overall framework of the system— is a layered architecture integrating the “perception layer — transmission layer — application layer — decision layer”. Multi-type sensors have been used to collect the data of construction environment, structural status and personnel activity in real time by the perception layer. Works on the transmission layer for wireless communication and edge computing and cloud platforms for data transmission and initial processing. In the application layer, big data and AI algorithms are applied for a comprehensive analysis and prediction of risk.. The provision of decision support and emergency response plans for supervisors and managers is present in the decision layer. The purpose is to make the system more scalable and applicable across several projects with a cost-effective strategy which provides operational effectiveness and stability, by integration of multiple framework gradually in this architecture. Formula (6) is the correlation model of monitoring variables and safety outcomes:

$$\Delta S=\alpha\left(S_{target}-S_{actual}\right) \quad (6)$$

Dividing the functional modules in a rational manner is critical for implementation. The system needs to be composed of data acquisition and processing module, risk assessment and early warning module, supervision coordination emergency response module, visual management decision-making display module. 1. Data acquisition and processing module: data standardization and multi-source heterogeneous data integration for avoiding siloed information. In risk assessment and early warning module, multi-level algorithmic models are used to calculate the monitored data of each asset in real-time and classify risks. When risk signal activated, the supervision coordination and emergency response module quickly establish a collaborative response mechanism between construction units and supervision units. Based on virtual simulation, it realizes two-dimensional and three-dimensional model graphics of site safety dynamics to supervision staff.

The system has been proven feasible and effective in engineering practice. In a large-scale construction of an example such as a bridge using sensors installed in proximity to critical structural flexural members, boom arm/ tower cranes, deep excavation slopes to determine metrics e.g. stress on the structural element or stress states that arise within the internal structure (i.e. multi-directional strains), static settlement or tilt angles, etc. As readings approached or exceeded dynamic thresholds, alerts were automatically released by the system simultaneously with notifications pushed to mobile devices, the supervision platform and emergency command center. If reinforcement is applicable, construction workers can immediately do that on site or suspend work, and supervisors will verify whether the measures have been in place; this is a closed-loop operation of efficient risk control.

In pilot projects for high-rise construction, the system integrated video identification technology with personnel location systems. It not only tracked when workers encroached upon hazardous areas, but flagged breaches such as helmetless heads and overloaded transportation. This behavior fused with real time monitoring, can only detect and correct safety hazards proactively bidirectionally, which greatly lower the occurrence of accident due to human violation. Suspicion books at the construction site have helped curb and violations, while reduce accidents up to several times.

Additional Analysis Demonstrates the System Offers Substantial Economic and Societal Benefits The system creates a dynamic monitoring and early warning mechanism to prevent economic losses related to safety events and mitigate project delay risks. Supervisors can also deploy sites more efficiently by sharing information in real time and coordinating the allocation of human resources. This system application has trained construction enterprises with a community of "safety consciousness", which moves the construction industry from the traditional behavior of "reactive response" to a proactive prevention culture, and improving the overall level of safety management in the construction industry.

However, problems still exist: the high cost of equipment is one of the obstacles to deployment and maintenance, which puts pressure on the investment because some small and medium-sized construction enterprises can't afford; The large-scale processing and storage of data demand more computing power and network stability from the platform; And even some supervision personnel act not yet familiar with new technology for construction personnel system. AI needs to be further optimized for intelligence, visualization and real-time interaction, BIM and GIS integrated in construction integrated management system are gradually deepening, the cross-border complex building construction upgrading from data mining to information visualized decision-making by digital twins combined 5G index new technology. This system will also become more popular with

Policy and standardized industry, along with practical establishment of construction safety management technical support (scaffold arrest).

5. Conclusion

A study of the existing construction safety supervision approach after decades accumulation, as well as the development status of dynamic monitoring and early warning technologies indicates that they encounter some disadvantages typical to traditional methods such as heavy reliance on manual output, inability to carry out real-time monitoring of dynamic changes etc., which obviously fails to meet modern large-scale projects development tendency these days–the challenges ahead in increasingly complex projects. In construction safety management, it gives new concepts and methods to the application of Internet of Things, sensor networks, big data and artificial intelligence based dynamic monitoring and early warning technology. The three are coordinated by constructing the multi-dimensional monitoring index system, intelligent early warning model & supervision creation mechanism to enhance identification efficiency of hazard and risk prevention & control level. The practical application of this system will make fewer accidents, increase efficiency of monitoring and obtain better economic benefits and social benefits.

Simultaneously it indicates the potential impacts of current constraints in technology use such as on larger investment or maintenance expenses for equipment employed, feasible upgrades in data processing capability and improved functional skills. The next generation of dynamic monitoring and early warning technology can complement this work so that the future development of immersive system intelligence, standardization, and labor-extensive utilization of the technologies are facilitated with upcoming paradigms like BIM, GIS and digital twin. You need to build a new collaborative safety supervision based on policy regulations and industry standards. New methods will create a more powerful foundation for the virtual and intelligent transformation of construction security management.

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