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Construction and Application of Safety Management Scenarios at Construction Sites

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Abstract: With the rapid development of the construction industry, there have been an uncountable number of damages caused by safety accidents at construction sites. Traditional safety management methods are no longer able to meet the needs of production. This paper presents the concept of constructing safety management scenarios for construction engineering sites. Using a production base project as a research case, it analyzes the natural and human factors involved in constructing spatial–temporal scenarios at construction sites. By employing a spatial–temporal overlay method to analyze multiple safety assessment indicators, a spatial–temporal safety management scenario for the production base project is established. Subsequently, BIM and GIS technologies are applied to perform a spatial–temporal simulation of the construction site safety management scenario. This process delineates safety and hazard areas across different construction phases based on time and spatial dimensions, enabling a comprehensive safety assessment of the construction site of the production base project. The study offers a reference and guidance for improving the level of safety management at construction project sites.

Keywords: construction site safety management; scenario construction; space–time simulation; safety assessment

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Citation: Yang, Q.; Yan, X.; Chen, W.; Fan, J. Construction and Application of Safety Management Scenarios at Construction Sites. *Appl. Sci.* **2024**, *14*, 404. https://doi.org/10.3390/app14010404

Academic Editors: Luis Laim, Aldina Santiago and Nicola Tondini

Received: 20 November 2023
Revised: 29 December 2023
Accepted: 30 December 2023
Published: 1 January 2024

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1. Introduction

With the continuing rapid expansion of the construction industry, where since 2013–2022, the value added of China's construction industry as a share of GDP has been greater than or equal to 6.89% and the share has been stable at more than 7% in 2018–2021 (data obtained from http://www.zgjzy.org.cn/) (accessed on 25 March 2023), the position of the construction industry as a pillar of the national economy is becoming stronger and stronger [1]. In 2022, a total of 20,963 people died in various types of production safety accidents across the country, a decrease of a total of 22,099, or 51.32%, compared with 43,062 in 2016 (data obtained from https://www.mem.gov.cn/xw/) (accessed on 26 March 2023). Although the number of deaths in all types of production safety accidents nationwide has been decreasing year by year and the growth rate has been gradually slowing down from 2016 to 2022, the safety problems at the construction sites of building projects, if not controlled effectively [2], can even affect social stability [3]. In the field of civil engineering and construction management research, an urgent need arises for methods that can enhance coordination during the construction process, visualize construction sites, and simulate construction operations. This situation has led to the emergence of construction safety management centered on Building Information Modeling (BIM) technology [4].

Traditional hazard identification relies heavily on operator subjectivity, which is often influenced by subjective factors. Scholars have recently improved this process by combining spatial information, Internet of Things (IoT) technology, and personnel judgement, resulting in improved efficiency in hazard identification. Pandit Bhavana et al. (2020) discovered that ensuring a secure working environment and establishing a social network for secure communication among staff aids in identifying potential sources of danger [5]. Xu Xingwu and colleagues (2022) identified limitations to the LEC approach in assessing construction site hazards. The study revealed the impact of human factors on the results obtained [6]. In the field of safety assessment for building construction sites, researchers are enhancing the precision and efficiency of identifying hazardous sources owing to the intricate combination of natural geography, human activities, and hazardous sources present at these sites. (1) One way in which this goal is achieved is through the construction of building construction scenarios. These scenarios involve the application of drone aerial photography technology and a deep learning method to identify the construction site scenes and pinpoint the hazardous sources present. Accordingly, managers can adequately carry out safety control measures. Wang Chen and colleagues (2022) developed a deep learning approach utilizing artificial intelligence's visual relationship capabilities to efficiently detect critical construction scenes on highway bridges [7]. Zheng Shuai and colleagues (2023) constructed an image database for construction site scene recognition and introduced deep learning methods to achieve efficient identification of construction site safety hazards [8]. (2) Another strategy is to create a simulated fire scene at the construction site, utilizing software to accurately reproduce the construction environment. The current fire status can be analyzed in real time using fluid and path analysis software to aid in the rescue efforts during an actual fire emergency at the site. Zulmajdi Iffah Umairah and colleagues (2022) assessed the modelling performance in relation to specific fire phenomena by utilizing B-RISK and simplified models, enabling fire engineers to develop scenarios objectively [9]. Jin Yiyang and colleagues (2023) employed the B-RISK model to simulate fire occurrence and evaluate the related risks in a ship scenario [10]. Scholars have used the method of fire scenario construction to effectively improve the efficiency of construction site safety management and reduce the incidence of onsite fire accidents. In 2022, 825,000 fires were reported nationwide, with 2053 deaths, 2122 injuries, and CNY 7.16 billion in direct property damage. Compared to 2021, the number of incidents and deaths increased by 7.8% and 1.2%, respectively, and the number of injuries and property damage decreased by 8.8% and 0.9%, respectively. Additionally, the number of fire accidents at construction sites and in high-rise buildings has risen significantly (data from https://www.119.gov.cn/ (accessed on 26 December 2023)). In the construction site fire visualization study, BIM and GIS technologies are used to simulate the fire scene onsite and locate the fire-prone areas to help managers carry out control. Qiu Wenting et al. (2013) designed and implemented an electrical fire early warning system based on the CORTEX-M3 platform, which is designed to prevent electrical fires by determining the residual current and the ambient temperature, as well as having a friendly human–computer interaction interface [11]. Li et al. (2014) constructed an environmentally aware RF beacon deployment (EASBL) algorithm based on sequential localization, which is able to locate first responders and people trapped in buildings during firefighting emergency operations [12].

A safety evaluation of a construction site necessitates identifying the levels of safety impact associated with hazardous sources. This target can be achieved by developing a construction site safety evaluation index system that considers key parameters relating to personnel, environment, goods, technology, management, and other relevant factors. By using this system to evaluate safety, accurately determining the safety status of the construction site becomes possible. Zhang Wenjing and colleagues (2022) developed a safety evaluation system for subterranean construction, focusing on people, events, and objects. The C-OWA algorithm was employed to assess the significance of safety evaluation criteria [13]. Chern Wei-Chih and colleagues (2023) determined that assessing worker safety within their work environment achieves precision when the Personal Protective Equipment (PPE) system is used [14].

The use of BIM technology in a construction site safety management initiative is equivalent to the second revolution in the construction industry; it is widely used in bridge engineering, municipal engineering, mechanical and electrical engineering, tunneling, room engineering, railroad engineering and other construction projects [15]. Traditional construction safety management mostly adopts 2D and 3D management tools, mostly using 3D models to reproduce the site situation and identify the sources of danger by comparing the model with the construction nodes on site in order to achieve safety control. However, as China's urbanization process continues to accelerate, urban land resources are greatly reduced; in order to effectively use the land space, high-rise buildings as well as ultra-high-rise buildings came into being [16]. The traditional 2D and3D construction management tools can no longer meet the needs of production, and the application of BIM will soon go beyond 3D into nD [17]. "D" comes from "dimension". Four-dimensional BIM adds a time dimension to the 3D building information model, associating the project schedule with the model, which enables the simulation and visualization of the project's progress [18]. Five-dimensional BIM involves the addition of cost dimensions to the building information model, linking the project's material and resource information to the model, allowing for real-time monitoring of changes in project costs and cost analysis and optimization [19]. Scholars have conducted much research on construction site safety management using BIM technology involving six aspects: personnel safety training [20], construction visualization management [21], safety monitoring [22], virtual construction [23], spatial conflict management [24], and site planning and layout [25]. The introduction of 4D and 5D technologies can effectively improve the efficiency of construction site management [26].

In summary, despite certain research results on construction safety management, various areas still have room for expansion, as follows: (1) Regarding the construction of safety management scenarios at construction sites, despite existing breakthroughs in scenario studies of indoor fires, research on systematically constructing safety management scenarios for construction sites remains limited. A comprehensive consideration of the interaction of multiple factors, their mutual impact, and their collective safety effects from both temporal and spatial dimensions proves challenging. (2) As for studies on individual elements such as construction site machinery, personnel management, and fire escape routes, the methodologies and technologies are relatively mature. However, construction conditions are complex and continuously changing with the progress of work, involving a substantial amount of spatial–temporal information. Therefore, the application of BIM technology can effectively improve the management efficiency of information at the construction site, providing data support for safety management. (3) Despite the productive results in safety management research for pit monitoring, thorough research on safety management is lacking during the main structural construction and decoration phases, leading to an incomplete study of safety management throughout the entire construction process. Thus, improvement in construction site safety management can occur in terms of methods, technology, and research approaches. This study aims to construct safety management scenarios for construction engineering sites. Additionally, combined with the actual implementation of engineering projects, comprehensive safety control of construction sites can be achieved. The main contents include (1) proposing and comprehensively analyzing the concept of constructing safety management scenarios at construction engineering sites, (2) building safety management scenarios for production base project construction sites, and (3) conducting spatial–temporal safety evaluations for production base project construction sites.

2. Materials and Methods

2.1. Ideas for Building Construction Site Safety Management Scenarios

The management of safety on construction sites for engineering projects depends on several factors, such as the natural geography, construction conditions, and the construction process. Therefore, conducting an in-depth exploration and understanding of Geographic Information System (GIS), geographic elements, and spatial models, among other things, is essential to ensure safety during construction.

The construction of geographic scenes based on the concept of three-dimensional reality is becoming increasingly prevalent with the ongoing development of GIS technology. A geographic scene consists of a highly complex integrated region comprising various elements, including human society, natural phenomena, and geographic data. These elements interweave and interact with one another within a specific time and space scope, enabling the scene to fulfill its unique functions. By integrating the surrounding topography with building-related data, a virtual geographical environment is created [27]. Geo-scenarios can visualize differences between locations and patterns of human activity and can meet a variety of planning needs [28]. Accordingly, several academics have begun researching the optimal utilization of this technology to enhance the advantages of urban planning and design.

In the field of construction engineering site safety management, this paper proposes the concept of geographic scene construction as a means to integrate various information elements, such as personnel, materials, machinery, management, and the environment throughout the construction project. By analyzing the interactions between these elements, incorporating computer information technology and other analytical tools, the project can ultimately achieve the goal of producing a safe work environment.

This study carries out research on the construction and application of safety management scenarios at construction sites of building projects. Figure 1 illustrates the technical route.

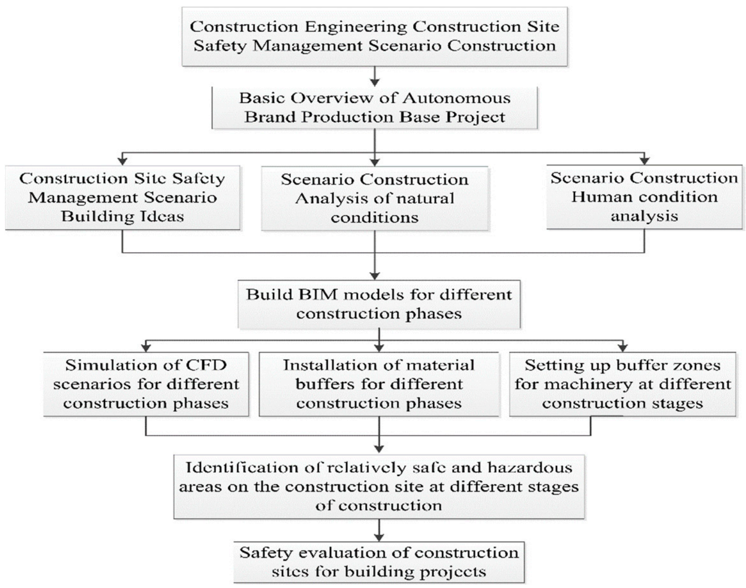

Figure 1. Technology Roadmap.

2.2. Influencing Factors of Construction Site Safety Management Scenario Construction

Occupational health and safety management system refers to the organization taking a coordinated and systematic approach, through the effective operation of the system, to achieve sustainable improvement and dynamic, systematic, and institutionalized prevention-oriented management to provide products and services to meet the national laws and regulations on occupational health requirements. China's construction industry employs a large number of people, the OHS problem is serious, and how to protect the OHS of personnel is an important goal of construction site safety management [29]. An effective OHS system takes into account multiple elements, such as people, money, equipment, materials, technology and software. Factors affecting the construction site safety management scenario are as follows.

(1) Spatial and temporal effects of construction projects. For a construction project from the foundation and basement construction stages to the main structure construction stage in the early, middle and late stages to the renovation construction stage, with the changes in the height and length of the building, along with the changes in the climatic conditions of different seasons, the focus of safety control at the construction site will also change. All these factors will directly or indirectly affect the working conditions of the

construction personnel. Failure to accurately control the sources of danger at each stage will lead to safety accidents, which will have an impact on the construction progress and quality of the entire project and will cause economic losses. Therefore, according to the spatial and temporal effects of the construction project, considering the actual situation of different seasons at the construction site, safety management scenarios are constructed for different construction stages of the construction project to simulate the actual hazardous conditions most in line with the actual construction site and to provide the most valuable guidance for the safety management of the construction site.

(2) Natural environment of the construction site. In the construction site outdoor wind environment simulation of climate conditions, selection needs to consider the most unfavorable site safety management climate conditions when choosing construction safety management reference value. Therefore, in the construction site safety management scenarios created in the natural conditions analysis, this paper selected the average highest state of the air-, temperature- and wind-related data to simulate the actual situation on the construction site to ensure that the construction site safety management guidance is representative.

(3) Stacking of materials and arrangement of machinery on the construction site. When analyzing geographical scenarios, buffer zones in the scene system are typically established and further processed to obtain the required scene area data. A buffer zone is an area established at a fixed distance from the points, lines, or surfaces of the objects to be analyzed, identifying the influence range of these objects on the surrounding environment. Overlay analysis refers to the process of generating a new data area by combining, erasing, clipping, and intersecting the data from multiple buffer zones. The resulting area in the overlay analysis combines the characteristics of multiple buffer zone data. Therefore, in the analysis of artificial conditions in constructing safety management scenarios, this study overlays the wind field at the construction site, buffer zones for machinery layout, and buffer zones for material storage to analyze the relatively safe areas and areas with higher risks, providing guidance for the safety management of construction site personnel.

(4) Personnel safety education and training. Construction engineering construction site accidents occur mainly due to unsafe behavior, construction site operations are required to operate the personnel to complete, the different operating state of the personnel determines the safety state of the construction site objects; therefore, the construction site is particularly important (for the safety management of the operating personnel [30]). Before the personnel on the job, the project department of the personnel safety briefing, explain how to wear the correct safety protection equipment, participate in the safety education test and so on.

(5) Project Safety Management System. The general contracting construction unit should establish a perfect safety management system and conduct a safety briefing for the construction unit, auditing unit, supervisory unit, and design unit involved in the whole process of the project construction so that the project safety management system will work in the whole cycle of the project [31]. The project safety management system not only involves the development of some safety management systems on site but also includes the matrix of project personnel responsibilities, site layout, emergency plans, etc.

(6) Project safety production costs. Currently, many construction units for the management of production safety fees are not standardized, which is reflected in the amount of production safety costs input without a plan or a plan that is not perfect; as the category of production safety fees is not clear, there is no professional guidance, the production safety fees of each project should be different, there are no clear boundaries stipulated in the input ratio, construction project production safety fee investment is insufficient to lead to the site safety pro-establishment, the project management personnel can not judge in a timely manner to increase the input, etc. [32].

2.3. Methods of Spatial and Temporal Analysis of Construction Site Elements

(1) Air conditions at the construction site

This study focuses on simulating the outdoor wind environment on a construction site using natural ventilation. The scope of this paper excludes the use of mechanical or artificial means to regulate air conditions. The air pollution index in the simulated outdoor wind environment is assumed to be zero.

When modelling the outdoor wind environment at a construction site, two important parameters in terms of air conditions are air density and air viscosity. Density of Air is the mass per unit volume of air at a given temperature and pressure and is calculated by the following formula

$$AD = 1.293 \times (AP/SAP) \times (273.15/AAT) \tag{1}$$

$$AT = CT + 273.15 \tag{2}$$

According to the above equation, the actual absolute temperature (AAT) range of the average maximum outdoor air temperature in Nanjing for all seasons is between 9 °C and 31 °C. The air density (AD) in this temperature range is calculated at an absolute pressure (AP) of 0.1 Mpa and 1 standard atmospheric pressure (SAP). Additionally, the result is 1.2 kg/m^3 with one decimal place, according to which, the air density in the wind environment simulation in this study is set to 1.2 kg/m^3.

Air viscosity is the value when the friction force per unit area in the air movement of the velocity gradient of 1, its size, and the temperature are closely connected with the formula for its calculation:

$$\mu = \tau/\frac{dv}{dn} \tag{3}$$

Where τ is the friction force per unit area, and $\frac{dv}{dn}$ is the velocity gradient.

According to the above equation, the air viscosity enlarges with the increase in temperature, and the calculated air viscosity value is approximately equal to 1.8×10^{-5} PaS in the range of the average annual maximum air temperature of 9 °C–31 °C in Nanjing area, according to which, the air viscosity is set to 1.8×10^{-5} PaS in the wind environment simulation process in this study.

(2) Spatial and temporal modelling approach to the wind environment on construction sites

Computational Fluid Dynamics (CFD) is a comprehensive discipline formed from the development of computer technology and fluid dynamics. CFD is the fundamental theory used in constructing scenarios. It emerged in the 1960s, and the continuous development of computer technology ensured rapid improvement in the CFD software series during the 1990s. Currently, CFD has replaced the conventional method of manpower in acquiring flow simulation data and serves as a significant tool for computer-based simulations of indoor and outdoor environmental building conditions [33].

In the simulation of the outdoor wind environment of a building, this paper defines the gas flowing around the building as turbulence in the ideal state, which is viscous and incompressible. The standard *k*-*ε* model is used to solve the state of the surrounding environment. The gas motion in the flow field primarily involves the continuity equation, momentum equation, and energy equation; additionally, the numerical values are obtained by solving the differential equations, controlling the fluid motion, and deriving the distribution of the flow field in a specific area [34]. The general equation formulation for modelling the outdoor wind environment of a building is as follows [35]:

$$\frac{\partial(\rho\varnothing)}{\partial t} + div\left(\rho\vec{v}\varnothing\right) = div(\Gamma_{\varnothing} grad\varnothing) + S_{\varphi} \tag{4}$$

where $\varnothing$ is velocity, turbulent kinetic energy, but also turbulent dissipation rate, and temperature; ρ is the density (kg/m^{-3}); $\vec{v}$ is the velocity vector (m/s); $\Gamma_{\varnothing}$ is the generalized diffusion coefficient; and S_{φ} is the original item.

Table 1 presents the computational equations analyzed for the simulation of different scenarios:

Table 1. Simulation of computational equations in different scenarios.

Equations	Variant	$\Gamma_{\emptyset}$	S_{φ}
Continuity equation	1	0	0
X-momentum equations	u	$\mu_{eff} = \mu + \mu_t$	$-\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial x}\right)$
Y-momentum equations		$\mu_{eff} = \mu + \mu_t$	$-\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial y}\right)$
Z-momentum equations	w	$\mu_{eff} = \mu + \mu_t$	$-\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial z}\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial z}\right) + \frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial z}\right) - \rho g$
Turbulent kinetic energy equation	k	$\alpha_k \mu_{eff}$	$G_K + G_B - \rho\varepsilon$
Turbulent dissipation rate equation	ε	$\alpha_\varepsilon \mu_{eff}$	$C_{1\varepsilon}\frac{\varepsilon}{K}(G_K + C_{3\varepsilon}G_B) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{K} - R_\varepsilon$
Temperatures	T	$\frac{\mu}{P_\gamma} + \frac{\mu_t}{\sigma_T}$	S_T

The formulas for calculating the common parameters involved in the table are shown below:

$G_K = \mu_t S^2$, $S = \sqrt{2S_{ij}S_{ij}}$, $S_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)$, $G_B = \beta_T g \frac{\mu_t}{\sigma_T}\frac{\partial_T}{\partial_y}$, $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$, $C_\mu = 0.0845$,
$C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$, $C_{3\varepsilon} = \tanh\left|\frac{v}{\sqrt{u^2+w^2}}\right|$, $\sigma_T = 0.85$, $\sigma_C = 0.7$,
$\alpha_k = \alpha_\varepsilon$ funded by $\left|\frac{\alpha-1.3929}{\alpha_o-1.3929}\right|^{0.6321}\left|\frac{\alpha+2.3929}{\alpha_o+2.3929}\right|^{0.3678} = \frac{\mu}{\mu_{eff}}$, in this equation $\alpha_o = 1.0$.
If $\mu \ll \mu_{eff}$, then $\alpha_K = \alpha_\varepsilon \approx 1.393$, $R_\varepsilon = \frac{C_\mu \rho \eta^3 (1-\eta/\eta_o)}{1+\beta\eta^3} \times \frac{\varepsilon^2}{K}$,
In this equation, $\eta = SK/\varepsilon$, $\eta_o = 4.38$, and β = 0.012.

3. Results

3.1. Basic Overview of the Production Base Project

This research focuses on the production base of server machines and key components belonging to an independent brand in the Nanjing Intelligent Manufacturing Venture Park. The project is situated in the Jiangbei New District of Nanjing, adjacent to the Sisters-in-Law River to the east, Kechuang Avenue (Zhongxin Road) to the south, Kefeng Road to the west, and the Diversion River Road to the north. The project site area spans 94,878.00 m^2, while the total construction area is 202,140.50 m^2.

The production base project of our independent brand comprises two service buildings, three factory buildings, and one basement. The language used is neutral and avoids fillers, ornamental language and emotional evaluations. Among them, Service Building No. 1 (for testing) occupies a construction area of 28,892.82 m^2, has a total of 13 floors, and a building height of 57.10 m; meanwhile, the secondary building has a height of 19.20 m. Service Building No. 2 (for integrated services) has a floor area of 24,672.69 m^2, 9 floors, a building height of 41.90 m, and a secondary building height of 16 m. All technical term abbreviations have been defined, and a logical flow of information is ensured. The three buildings numbered 3 to 5 each have a height of 90 m. Building No. 3 has a floor area of 43,400.62 m^2, spans over 5 floors, and has a building height of 36.10 m. Building No. 4 has a floor area of 43,400.62 m^2, covers 5 floors, and has a building height of 36.10 m. Building No. 5 features a floor area of 46,444.75 m^2, spans over 5 floors, and has a building height of 36.10 m. The basement has a floor area of 14,094.66 m^2, 1 floor, and a height of 4.85 m (Figure 2).

3.2. Analysis of the Elements of Safety Management Scenarios during the Foundation and Basement Construction Phases

3.2.1. Construction Schedule for the Foundation and Basement Construction Phases of the Manufacturing Base Project

Construction on the production base project began in 2021. Initially, only Plant No. 4 was on schedule for construction due to heritage surveys, whereas the other four buildings remained suspended until the start of 2022 when the surveys were completed. Since then, construction work on site has resumed systematically. The production base project underwent foundation and basement construction, main structure construction, and renovation construction phases in 2022. Each phase occurred primarily between spring and winter of that year.

Figure 2. Project rendering diagram.

Following the seasonal development sequence, this report categorizes the different stages of the production base construction site starting with foundation and basement construction during spring, followed by main structure construction in summer and autumn, and ending with renovation stage construction in winter. The report constructs a safety management model for the construction site across various time periods. The construction site's outdoor wind environment is simulated in various construction phases. Results from these simulations are then used to determine the relative safe and hazardous zones of the site during different construction stages in conjunction with an analysis of buffer zones for the machinery and construction materials. These determinations aid in the spatial–temporal safety management of the personnel, materials, and machinery on the construction site.

Based on a drone aerial photograph of the production base project's foundation and basement construction stages (Figure 3) during the spring construction period, Plant No. 4's main structure was mostly finished, while only 30% of Plant No. 5's main structure was completed. Additionally, Plant No. 3 was in the foundation layer construction stage, while the comprehensive Service Building Nos. 1 and 2 were in the basement construction phase. In general, the majority of the construction site is currently in the foundation and basement construction stages. Consequently, when developing the construction site scenario model, it was based on the aforementioned completed construction conditions on site. In addition, the scenario simulation parameters were established on the bases of the spring weather conditions outlined in Table 2.

Table 2. Wind environment simulation of climatic conditions.

	Spring	**Summer**	**Autumn**	**Winter**
Average maximum indoor temperature (°C)	21.5	27.9	21.8	12.3
Average maximum outdoor temperature (°C)	18.5	30.9	24.8	9.3
Average maximum wind speed (m/s)	4	6.5	4.8	5.5
The direction of the wind	Southeast	Southeast	Northwest	Northwest

Figure 3. Aerial view of the site during the foundation and basement construction phases.

3.2.2. Analysis of Natural Conditions for the Construction of Scenarios during the Foundation and Basement Construction Phases of the Production Base Project

(1) Analysis of temperature conditions at the construction site

The production base project is located in Nanjing, a subtropical monsoon climate area. As a result of the westerly belt circulation effects, Nanjing experiences four clearly marked seasons. During the summer season, precipitation tends to be plentiful due to the impact of the low-pressure system from the Asian-European continent. Conversely, during the winter months, the weather becomes noticeably cold and dry due to the influence of the cold air from the Asian–European continent. In spring and autumn, a prevalence of cool and dry climatic conditions typically occur.

This paper utilizes meteorological data from Nanjing in 2022 as the reference basis and employs Ecotect Analysis software to model the spatial and temporal outdoor wind environments of Nanjing across all four seasons. After inputting meteorological data into the Weather Tool, the measured weather data of Nanjing can be retrieved for several years. Such information includes data on latitude, longitude, solar radiation, relative humidity, wind speed, wind direction, wind frequency, rainfall, and other relevant information regarding the Nanjing region.

Based on the Nanjing four-season wind average temperature map (Figure 4), the four-season temperature situation in the Nanjing area can be summarized as follows: the temperature can be observed to vary across the year. During spring, temperatures are low due to cold air from the near-surface system and westerly circulation. However, the intensity of the circulation is weaker than during winter, and temperatures gradually increase with an average maximum of 18.5 °C. In June and July, precipitation is prevalent in the middle and lower areas of the Yangtze River, where Nanjing is located. This phenomenon leads to an elevation in both rainfall and air humidity, along with a decrease in barometric pressure that can induce discomfort in the chest. The rainy season ends in July–August with the onset of the dry season, during which temperatures are high. The extreme highs can reach up to 43 °C, while the average highs are 30.9 °C. The temperature typically remains at an average high of 30.9 °C throughout the season. In autumn, temperatures remain high in September and October due to the influence of the subtropical high pressure. However, within the following 15–20 days, temperatures plummet as cold air moves from the north to the south, with average maximum temperatures reaching 24.8 °C. During winter, cold air moves south from the north every 10 days, which affects the Nanjing region. Consequently, temperatures drop with some exceptionally low periods reaching as low as −14 °C. In Nanjing, the temperature is also extremely low, with a maximum of −14 °C. Additionally, the average high temperature during this season is 9.3 °C.

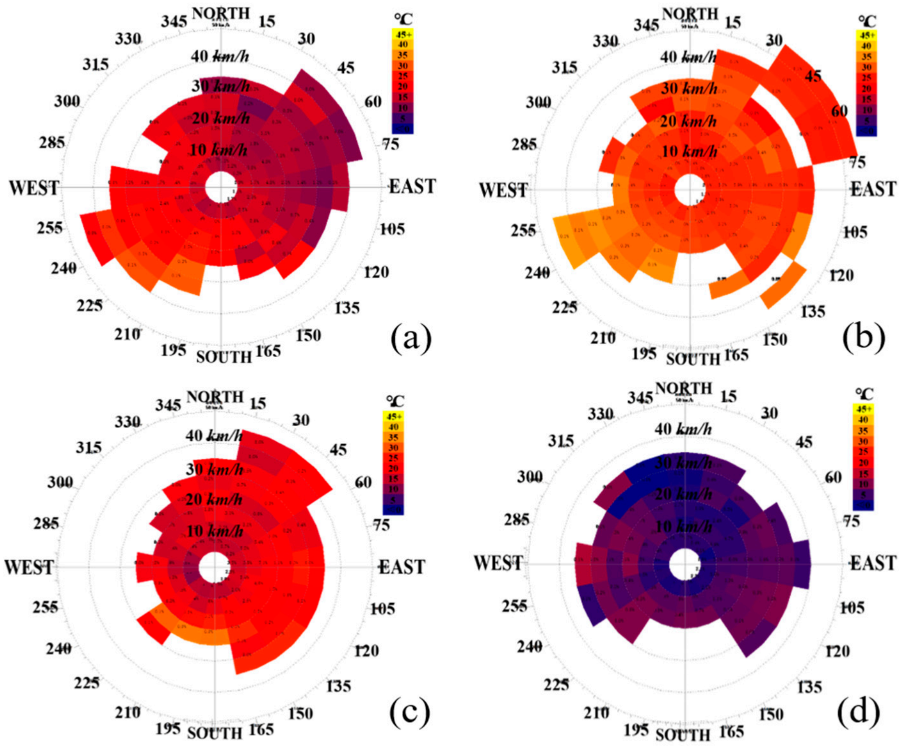

Figure 4. Graph of average temperatures for the four seasons: (**a**) spring (**b**) summer (**c**) autumn (**d**) winter.

In the simulation of the thermal environment of an open building, the difference between indoor and outdoor temperatures in the unheated state of the building is 1.29 °C to 2.99 °C on the south-facing side of the building, and the difference between indoor and outdoor temperatures on the north-facing side of the building is −0.5 °C to −0 °C. In the case of a heated building, the difference between indoor and outdoor temperatures can be 10 °C or more [36]. As no heating or cooling indoors will be available during the construction of the building project, the average maximum indoor temperature at the construction site is selected by adding or subtracting 3 °C from the average maximum outdoor temperature derived from the above analysis, i.e., the maximum average indoor temperatures for the seasons of spring, summer, autumn, and winter are 21.5 °C, 27.9 °C, 21.8 °C, and 12.3 °C, respectively.

(2) Analysis of the wind environment at the construction site

Based on data from the official National Meteorological Information Centre website (http://data.cma.cn/ (accessed on 26 December 2023)) and the four-season wind frequency diagram (Figure 5), a summary of Nanjing's wind speed and direction during all seasons is presented: Spring starts in late March and finishes in early June with predominantly south-easterly winds and an average maximum wind speed of approximately 4 m/s. Summer commences in early June and concludes in mid-September with primarily southeasterly winds and an average maximum wind speed of approximately 6 m/s. Autumn in Nanjing typically spans from mid-September to mid-November. During this period, the winds are generally northwesterly with occasional northeasterly winds. The city experiences an average maximum wind speed of approximately 4.8 m/s. Winter commences in mid-November and lasts until late March of the following year, characterized by mostly north-westerly winds. The average maximum wind speed in winter is approximately 5.5 m/s. Nanjing's main wind directions are north-west and south-east and are affected by 1–2 typhoons annually. Typhoons occur most frequent from early summer to early autumn, with the highest likelihood of occurrence in August and the second highest in July. The wind direction during typhoon days is not fixed. This period coincides with a high incidence of hazardous sources. Therefore, based on various considerations, the months of March, June, September, and December were chosen to model the outdoor wind environment for the production base project. They represent spring, summer, autumn, and winter, respectively. These four-month periods will be used to simulate wind conditions at the construction site. Wind direction and maximum wind speed will be the variables analyzed.

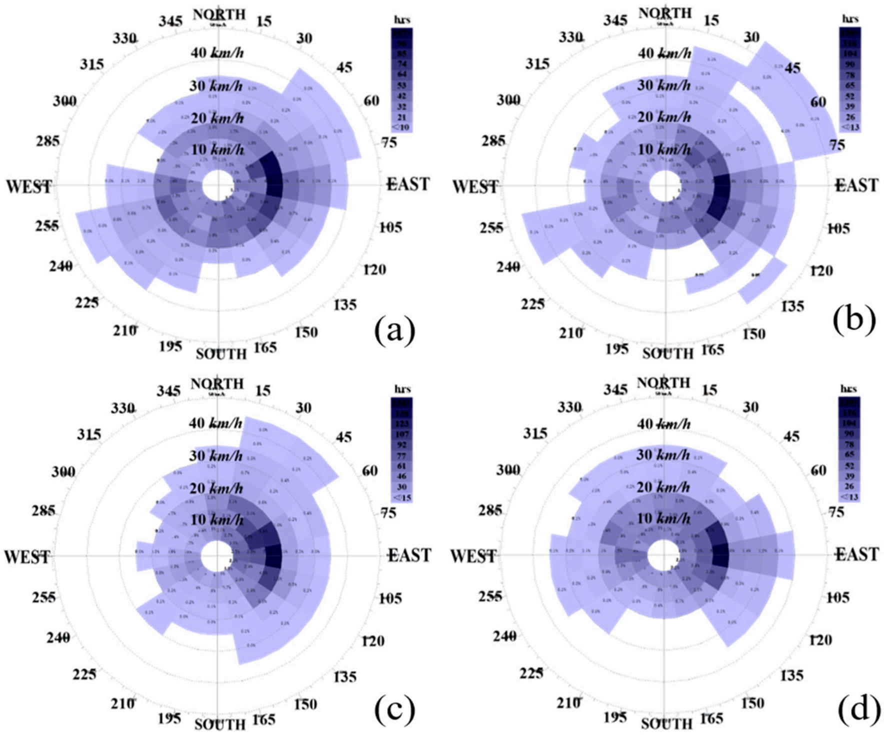

Figure 5. Wind Frequency Chart for the Four Seasons: (**a**) Spring (**b**) Summer (**c**) Autumn (**d**) Winter.

(3) Comprehensive analysis of wind and climate conditions on construction sites

Based on data analysis of the maximum indoor and outdoor temperatures, wind speed, wind direction, and other natural conditions, safety management scenarios for the production base project have been constructed using the climatic data parameters displayed in Table 2 to simulate the wind environment. The subsequent chapters incorporate spatial and temporal scenarios of the construction site and values derived from the data in Table 2. No further repetition of this data will occur.

(4) Analysis of natural conditions during the foundation and basement construction phases

By modelling the wind conditions present onsite during the construction of the foundation and basement phases, a 1.5 m air flow map was generated for the construction site (Figure 6). As Supporting Service Building Nos. 1 and 2 and Plant No. 3 have not yet reached the positive and negative 0 interface during the foundation and basement construction stages, only Plant Nos. 4 and 5 are affected by the XY direction wind field at 1.5 m from the construction site. During spring, the construction site experiences a prevailing southeast wind. As the wind advances, it encounters an obstruction to the east of Plant No. 5, causing the airflow to be redirected and create a phenomenon known as bypass in which part of the airflow passes through the middle of Plant Nos. 4 and 5 and both sides of the road, while the rest rises and forms a northeasterly wind towards the southwest. In the springtime on the construction site, the simulation scenario indicates the highest average wind speed. Supporting Services Building No. 1 experiences this situation, along with Plant No. 3, which are in the area of the highest wind speed, exceeding 4 m/s. Supporting Services Building No. 2 is situated in the second-highest wind speed area, although not as high as the aforementioned locations. The height of the second building is approximately 0 with reduced wind speeds in the wind shadow area north of Plant Nos. 4 and 5 due to the influence of the northeast–southeast wind direction convergence.

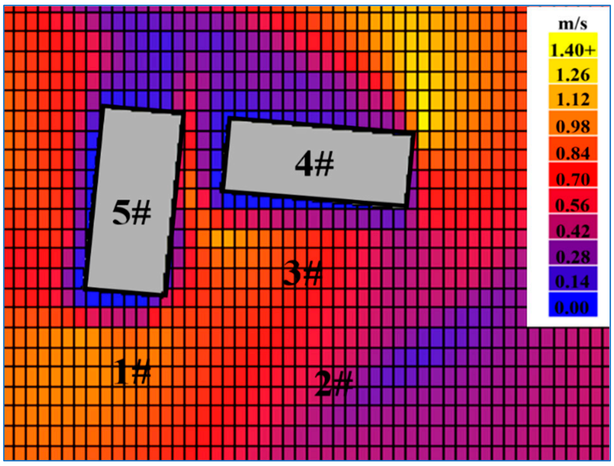

Figure 6. Air flow diagrams for foundation and basement construction phases.

3.2.3. Analysis of Artificial Conditions for the Construction of Scenarios in the Foundation and Basement Construction Phases of the Production Base Project

(1) Analysis of mechanical arrangements during the foundation and basement construction phases

Tower cranes are frequently utilized at the construction site of the production base project. Five tower cranes were arranged on the site, situated to the north of Building No. 1, between the main building and the podium of Building No. 2, east of Plant No. 5, and to the north of Plant No. 3. The boom length of Tower Crane No. 1 was 50 m, and that of Tower Crane No. 2 was 65 m. Tower Crane Nos. 3, 4, and 5 each had a 70 m boom length (Table 3).

Table 3. Basic information on tower cranes at construction sites.

Buildings	Tower Crane Model	Tower Crane Number	Tower Crane Arm Length	Tower Crane Foundation Forms
Building 1	QTZ100 (C6013)	1#	50 m	Rectangular latticework
Building 2	QTZ200 (C7015)	2#	65 m	Rectangular latticework
Plant 3	QTZ250 (XGT7022-12S)	3#	70 m	Rectangular Plate
Plant 5	QTZ250 (XGT7022-12S)	4#	70 m	Rectangular Plate
	QTZ250 (XGT7022-12S)	5#	70 m	Rectangular Plate

In the process of tower crane operation, for each tower crane, in any position within the swinging range of its big arm is dangerous. If the tower crane operator incorrectly directs the crane, the suspended goods may fall and injure the personnel. If the arm lifting height is not suitable, the arm may collide with the building. If the crane is not operated properly, the big arm could drop the goods, which is a serious situation that could even cause the tower crane to topple over. Therefore, with the tower crane base as the center of the circle and the tower crane arm length as the radius, the first level of the buffer zone is established; then, a secondary buffer zone was created with the intersection area of the five tower crane booms.

Mobile truck cranes were employed to assist with the lifting operation at the production base construction site, where the tower crane's jib did not cover the necessary area. The Plant No. 4 is a steel structure, while the floor slabs of Plant Nos. 3 and 5 are made of steel trusses. The steel structure project uses the prefabricated component splicing technique. This method involves the production of specific structural compo-nents, such as steel columns, steel beams, and steel truss floor slabs, in specialized fac-tories. These parts are then transported to the construction site using automobiles. The tower crane and mobile truck crane work collaboratively to carry out the lifting opera-tions.

Table 4 illustrates the model of the truck cranes used in the production base pro-ject, in the foundation and basement construction stages. Given that Plant No. 3 is in the cultural relic survey stage, Tower Crane No. 3 cannot be installed. Therefore, in this construction stage, Truck Crane No. 1 is used for Plant No. 4's structural steel engi-neering assembly and has a rated lifting capacity of 80 tons. Car Crane Nos. 2 and 3 each have a rated lifting capacity of 25 t, and are mainly used for the west side of Plant No. 5, the south side of Plant No. 3, and the east side of Plant No. 4 to cooperate with the tower crane in transporting the steel truss floor slabs and decoration materials.

Table 4. Basic situation of construction site truck cranes.

Truck Crane Numbers	Truck Crane Models	Factory Owners	Rated Lifting Capacity	Truck Crane Boom Length
1#	XZJ5507JQZ80	Xuzhou Construction Machinery Group Limited	80 t	47.5 m
2#	STC250T4	Sany Automobile Company Limited	25 t	35 m
3#	XZJ5331JQZ25K	Xuzhou Construction Machinery Group Limited	25 t	39 m

Truck cranes used in construction must strictly adhere to the "Safety Regulations for Hoisting Machinery" (GB6067-2010). A safety cordon should be established within the truck crane's lifting range of 5 m. A jib operating angle of elevation that is too large may cause the crane to topple, whereas an angle that is too small may impede the con-struction process. Safe operation must be ensured by following these guidelines. Therefore, the boom of the truck-mounted crane is operated at an elevation angle of 30°–78°. Following the aforementioned analysis, a safety zone is designated at the con-struction site of the production base project. The second level buffer zone is established by taking the slewing center of the truck crane as the center of the circle and the working radius of the boom elevation angle of 30° as its radius. The first level buffer zone should be established by taking the concentric circle with a radius of 5 m outside the working radius of the boom elevation angle of 30° as its center. The specific loca-tion and number of truck cranes to be used should be determined on the basis of the progress of the construction site.

In the stages of foundation and basement construction, given that the main construction scope of the construction site includes Plant Nos. 4 and 5 and the basement area, the construction site has enabled three tower cranes, i.e., Nos. 1, 4 and 5. Owing to the previous cultural relic survey operation, Plant No. 3 has only recently begun its foundation construction; thus, Tower Crane No. 3 has not been installed and used. Ac-cordingly, Car Crane No. 1 is allotted to Plant No. 4's steel structure project for lifting operations. In this construction phase, machinery sets up the buffer zone as shown in Figure 7a. Tower Crane Nos. 1 and 4, Tower Crane Nos. 4 and 5's boom operation cross area, and Car Crane No. 1's boom elevation angle of 30° in the range of the area for the second level of buffer zone pose greater risks; the rest of the first level of the buffer zone of this area within the scope of the safety management personnel needs continuous monitoring to strengthen the safety control.

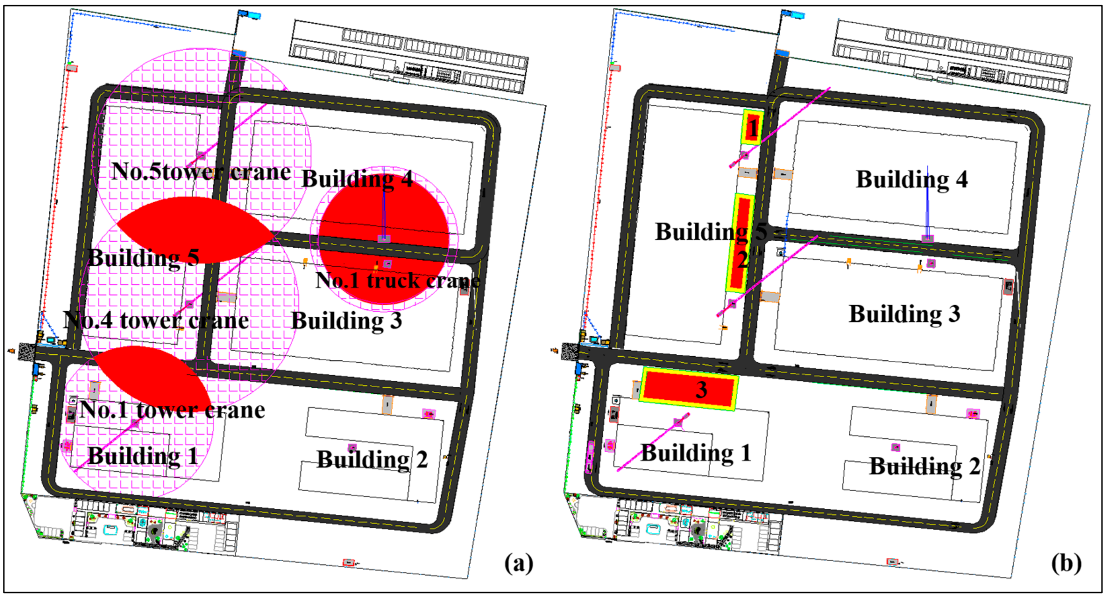

Figure 7. Mechanical buffers (**a**) and Material buffers (**b**) for foundation and basement construction phases.

(2) Analysis of material staging during the foundation and basement construction phases

The majority of the designated material storage areas on the production base construction site are located along the eastern road of Plant No. 5, the northern road of Plant No. 3, and the northern road of Building No. 1. As required by construction demands, the site's material storage areas primarily consist of a reinforcement bar raw material zone, a reinforcement bar semi-finished product processing zone, a reinforcement bar finished product storage zone, a floor slab processing area, a carpentry processing area, and a curtain wall stacking area. According to the regulations set out in GB50348-2012 for Safety at Construction Sites, the following safety management requirements are necessary for different kinds of materials at construction sites: (1) the rebar must be stacked neatly with a maximum height of 1 m, cushioned with wooden squares, and kept away from rainwater; (2) bricks and blocks must be stacked on pallets with a maximum height of 1 m. Square piles must be stacked at least 5 m away from the trench edge to prevent collapse. Gravel materials must be stacked in piles, with a maximum height of 1.5 m, depending on gravel diameter. Templates must be stacked according to their specifications. To prevent collapse, piles of gravel materials should not exceed a height of 0.5 m. Furthermore, the gravel materials must be sorted according to their diameter. Templates must also be sorted according to their specifications and stacked with an anti-tipping mechanism, ensuring that their height does not exceed 1.5 m.

The vicinity where material stacking occurs is designated as a secondary buffer zone. In this area, non-compliant stacking may transpire, leading to unstable and excessively high stacking, which can cause pile collapses and pose a high safety accident risk. The first-level buffer zone is established within a 3 m radius outside of the material stacking area. This area presents a danger to individuals due to the lack of windproof measures for the materials. The material buffer zones for various construction stages must adhere to the maximum height requirement for material stacking, as specified above. Material stacking areas that fall considerably below these specifications are not considered in this study.

During the foundation and basement construction stages, the material stacking areas were mainly concentrated on the east side of Plant No. 5, the north side of Plant No. 3, and the north side of Building No. 1. However, given that the foundation construction work only started in Plant No. 3 at this stage, the height of rebar stacked on the north side of Plant No. 3 was much lower than 1 m. Therefore, when setting up the buffer area for material stacking at this stage of construction (Figure 7b), three material stacking areas were set up for Nos. 1, 2 and 3, and the material stacking area on the north side of Building No. 3 was not studied.

3.3. Analysis of Safety Management Scenario Elements in the First Phase of Main Structure Construction

3.3.1. Construction Progress of the First Phase of the Main Structure Construction of the Production Base Project

During the summer construction, the first stage of the main structure construction of the production base project was evaluated using an aerial photo (Figure 8). Evidently, the primary structure of Building No. 4 is finished, while Building No. 5's primary structure is 90% complete. Building No. 3 is presently in the foundation layer construction stage. Additionally, the main structure of the apron in the comprehensive Service Building No. 1 is complete, and the primary structure of the main building is 50% complete. Similarly, the primary structure of the apron in the comprehensive Service Building No. 2 is complete, and the main building's primary structure is 40% complete. The primary framework of the main building is fully constructed. In general, the majority of the site is currently in the main structure construction stage. Hence, when creating the scene model of the construction site, it is based on the aforementioned completed construction status. Additionally, the simulation parameters of the scene are set according to the summertime climate conditions mentioned in Table 2.

Figure 8. Aerial photo of the site during the main structure construction Stage I.

3.3.2. Analysis of Natural Conditions for the Construction of Scenarios in the First Stage of the Main Structure Construction of the Production Base Project

By conducting simulations of wind patterns at the main structures' initial construction site, we have generated an air flow diagram of the construction area (Figure 9). As the third plant currently remains in the foundation layer construction stage with the main body not yet reaching the interface of plus and minus zero, the wind field in the XY direction at the 1.5 m construction site still does not affect the third plant. Additionally, the wind field in the XY direction at the 19.4 m construction site does not involve the podium of Supporting Services Building Nos. 1 and 2.

During the summer construction season, south-easterly winds are predominant at the worksite. As the wind advances, it encounters obstacles in the form of buildings, specifically Service Building Nos. 1 and 2. This scenario results in the airflow being redirected, generating a phenomenon known as a bypass. A portion of the airflow goes through the western side of Building 1, while another portion goes through the eastern side of Building 2. These two distinct airflows merge in the southern part of the worksite, resulting in the formation of a northeasterly wind that blows toward the southwest. Owing to the Supporting Services Building Nos. 1 and 2's main body being only half of the total height, as the winds encounter each other south of Plant No. 4 and east of Plant No. 5, a roundabout flow is produced. Some of the airflow passes through the middle of the road between Plant Nos. 4 and 5 and on both sides, while the remaining airflow rises and returns toward the southwest direction. During summer, the construction site was subjected to simulations of high wind speeds. Within the region, Plant Nos. 4 and 5 were situated in the middle of the road, where wind speeds were considerably higher due to their location in the corner wind area. The highest wind speed recorded was over 6 m/s. In the same region, Plant No. 5 and Supporting Services Building No. 1 were positioned between the road and the south side of Building No. 1, where the wind speed was second highest. Owing to the main structure's height, the 3rd plant is not situated in the area with higher wind speeds. However, the wind speed is lower in the wind shadow area, which includes the north side of Plant No. 4, the west side of Plant No. 5, the northern side of Building No. 2, and the podium in the middle of the main building area.

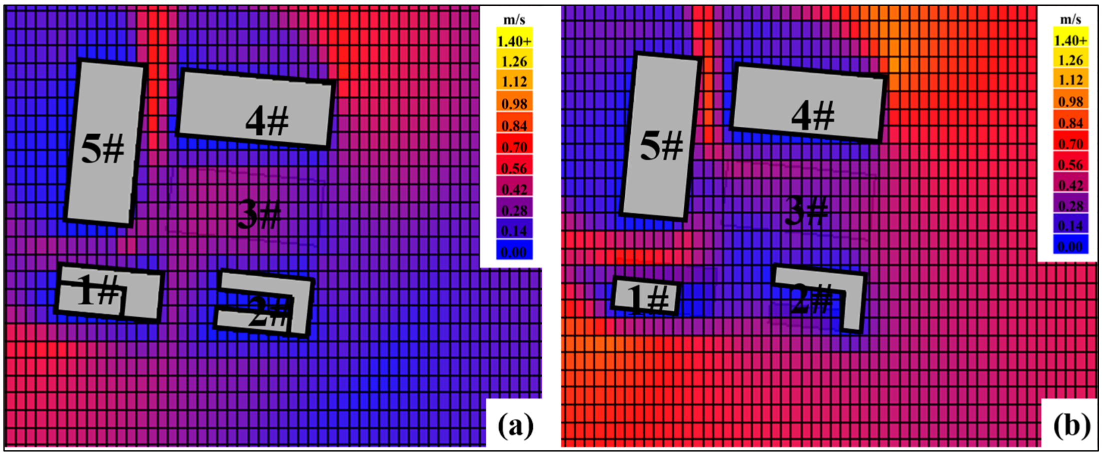

Figure 9. Air flow diagram for the first stage of the main structure construction (**a**) at 1.5 m (**b**) at 19.4 m.

3.3.3. Analysis of the Artificial Conditions for the Construction of Scenarios in the First Stage of the Main Structure Construction of the Production Base Project

(1) Analysis of machinery arrangement in the first stage of main structure construction

In the first stage of main structure construction on the construction site, except for Plant No. 3, the rest of the buildings are in the main construction stage; additionally, all tower cranes on the construction site are operational. Given that Plant No. 5 in this stage of the construction of the construction of the rhythm of close, the project department placed Tower Crane No. 3 on the west side of Plant No. 5 for the lifting of steel truss floor joists and construction of auxiliary materials. Figure 10a illustrates the main structure construction of the first phase of the mechanical arrangement of the buffer zone set up. In this stage of construction, Car Crane No. 3's construction range and Tower Crane Nos. 4 and 5's boom construction range of the cross-over area (the area that is more dangerous) need strengthened safety control. The five tower crane boom operation cross-over area also needs strengthened monitoring of the rest of the level of the buffer area. Safety management personnel must function in accordance with the regulations of routine checking.

(2) Analysis of material staging for the first phase of main structure construction

During the initial stage of constructing the primary structure, Plant No. 3 is lagging behind due to construction progress. Consequently, the material stacking height on the northern side of the material stacking area in Plant No. 3 is less than 1 m. This study does not consider such a problem. However, the flooring slabs, wooden squares, reinforcing bars, and other materials have met the highest specification requirements in the material stacking areas for Nos. 1 to 5. Based on the latter, a buffer zone for the material will be set up (Figure 10b).

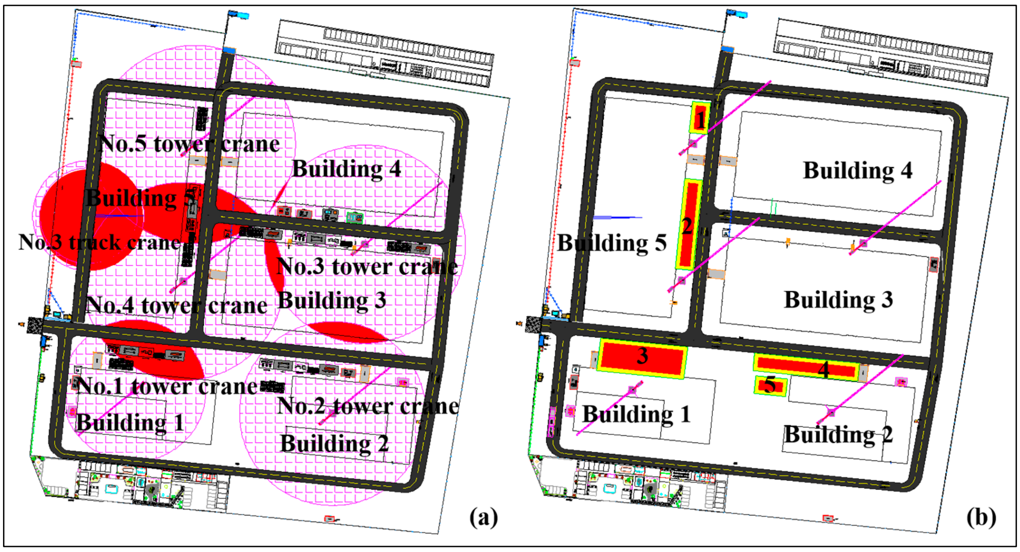

Figure 10. Mechanical buffer (**a**) and Material buffer (**b**) for the first phase of the main structure construction.

3.4. Analysis of Safety Management Scenario Elements in the Second Phase of Main Structure Construction

3.4.1. Construction Progress of the Second Phase of the Main Structure Construction of the Production Base Project

During the autumn construction period, an aerial photo of the second stage of the production base project's main structural construction (Figure 11) revealed the completion of the main structures for Building Nos. 4 and 5, a 40% completion of Building No. 3's main structure, a 90% completion of Building No. 1's comprehensive service structure, and a completed main structure for Building No. 2's comprehensive service structure. In general, the bulk of the construction site is in the principal structure construction phase. Therefore, while building the site model, it must be constructed on the basis of the completed construction situation mentioned earlier. The parameters of the simulation are set according to the autumn climatic conditions specified in Table 2.

Figure 11. Aerial photo of the site during the main structure construction Stage II.

3.4.2. Analysis of Natural Conditions for the Construction of the Second Stage Scenario of the Main Structure Construction of the Production Base Project

Owing to delayed progress in the primary construction site of Plant 3, the wind flow in the XY direction at the site's 19.4 m range did not involve the aforementioned Plant 3 structure (Figure 12). During the autumn season, northwest winds dominate the construction site. As the wind advances toward the north of Plant Nos. 4 and 5, it encounters obstructions. This phenomenon generates an air flow bypass, with some of the air flow passing to the west of Building No. 5 and to the east of Building No. 4, while the other part passes through the middle of the road, en route to Plant Nos. 4 and 5. Clear causal connections between statements help ensure a logical flow of information in the text. At present, the construction site is undergoing a simulation of the highest average wind speed during the autumn. The road located between Plant Nos. 4 and 5, as well as the road in the middle of Building Nos. 1 and 2, are also affected by this simulation. The fifth plant is situated in a region with higher wind speed; it is positioned at a corner and experiences a maximum wind speed of over 5 m/s. Ancillary services of Building Nos. 1 and 2 are adjacent to the road with wind speed, which is next to Plant No. 3. Owing to the main structure's relatively low height, the wind speed between Plant Nos. 2 and 4 is faster. The wind speed in the immediate vicinity is greater. However, the southern portion of Plant No. 4, the southern and eastern sections of Building No. 2, and the area between the main building and the podium building experience reduced wind speeds due to being located in the wind shadow.

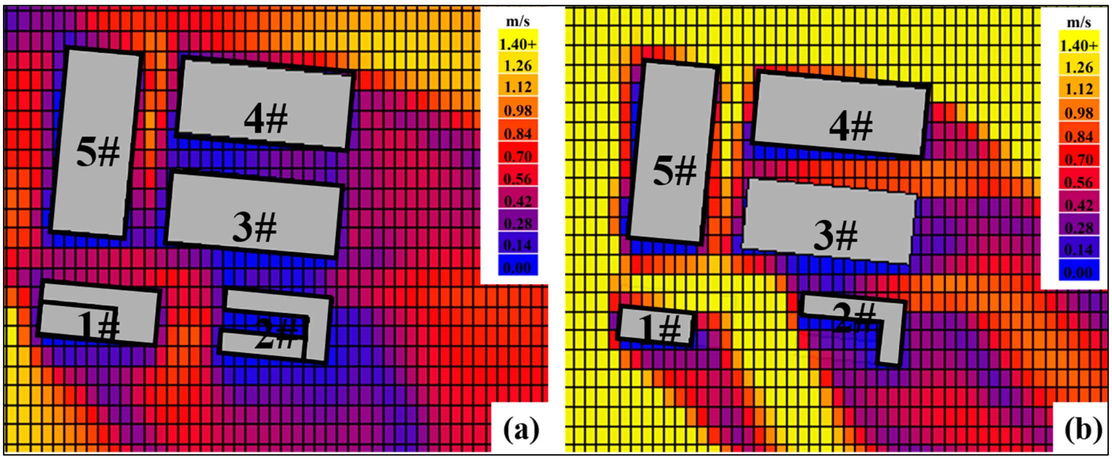

Figure 12. Air flow diagram for the second stage of the main structure construction (**a**) at 1.5 m (**b**) at 19.4 m.

3.4.3. Analysis of Artificial Conditions for the Construction of Second-Stage Scenarios for the Main Structure of a Production Base Project

(1) Analysis of machinery arrangement for the second stage of main structure construction

In the second stage of the main structure construction, the construction sites of the five buildings are in the main construction stage, and the construction sites of the five tower cranes are put into use. Owing to delays in the construction period caused by the survey of Plant No. 3's cultural relics, the project department used Truck Crane No. 2 to work with the tower crane at this stage to speed up the process of construction while ensuring safety. Figure 13a illustrates the buffer zone set up for the mechanical arrangement of the second phase of main structure construction. In this construction phase, a secondary buffer zone is set up in the cross-operation area of Automobile Crane No. 2 and Tower Crane Nos. 2 and 3, where multiple cross-operations occur. The danger is also high, thereby requiring a focus on control. The site's several tower cranes' cross-operation areas also pose greater risk, which needs to be strengthened by control. For the rest of the site-level buffer zone, project safety management personnel need to follow the safety checklist method for regular safety inspection and monitoring. In the second stage of main structure construction, the construction sites of the five buildings are in the main construction stage. Thus, the construction sites of the five tower cranes are put into use. Owing to delays caused by the cultural relic survey in the previous period, Plant No. 3 was affected. At this stage, the project department used Truck Crane No. 2 to work with the tower crane to speed up construction while ensuring safety.

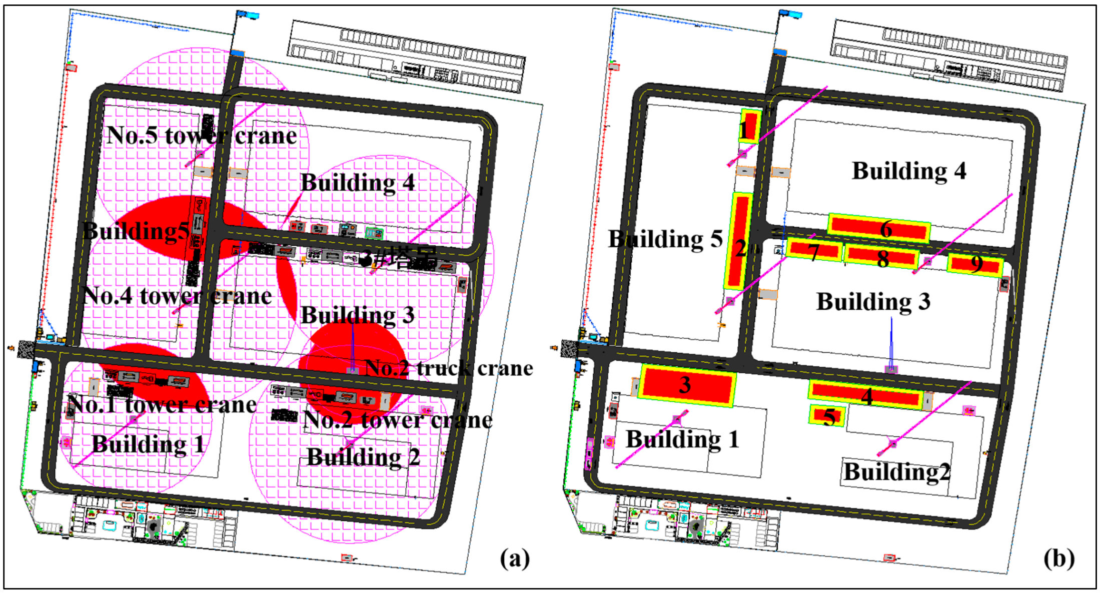

Figure 13. Mechanical buffer (**a**) and Material buffer (**b**) for the second phase of the main structure construction.

(2) Material staging analysis for the second phase of main structure construction

In the second stage of main structure construction, all five buildings on the construction site are in the main construction stage. Accordingly, the material stacking areas next to the five buildings are also put into use. Figure 13b displays the material stacking buffer zone set up in the second stage of main structure construction. In this stage of construction, the materials stacked in areas 1, 2, 3, 5, 7, and 9 are mainly steel truss floor slabs, while the materials stacked in areas 4, 6, and 8 are mainly steel reinforcement. Some materials such as wood cubes and gravel materials are also stacked at the site. However, they are excluded from this study because their stacking heights do not reach the hazardous height specified.

3.5. Analysis of the Elements of Safety Management Scenarios in the Renovation Construction Phase

3.5.1. Construction Schedule for the Fit-Out Construction Phase of the Manufacturing Base Project

During winter construction, based on a drone aerial photo of the production base project during the renovation construction stage (Figure 14), the main structure of the construction site has been roughly completed except for the roof of Plant No. 3, where two-thirds of the area of concrete has not been poured. The exterior decoration of Plant No. 4 has been completed, and the remaining buildings are undergoing exterior decoration works. Generally, most of the construction site is in the stage of decoration construction. Therefore, when constructing the scene model of the construction site, it is constructed according to the above completed construction situation of the site, and the scene simulation parameters are set according to the winter climate conditions in Table 2.

3.5.2. Analysis of Natural Conditions for Scenario Construction in the Renovation and Construction Phase of a Production Base Project

By simulating the wind environment at the site during the renovation construction stage, the airflow diagram of the construction site was obtained (Figure 15). In winter, northwest wind prevails at the construction site, and the wind encounters obstructions on the north sides of Plant Nos. 4 and 5 during its advance, causing airflow to bypass them. Some airflow passes through from the west side of Plant 5 and the east side of Plant 4, while the other part passes through from the road between Plant Nos. 4 and 5. At this time, the construction site in winter undergoes simulation under the highest average wind speed. The roads between Plant Nos. 4 and 5 and between the first building and Plant 5 are in regions with higher wind speeds, belonging to corner winds. The highest wind speed is over 6 m/s, and corner winds encounter blockages from buildings during their movement, generating roundabout phenomena once again. The roads between the first and second auxiliary service buildings, as well as those between Plant Nos. 3 and 4, have wind speeds next to that to the east of Plant 4. Moreover, the south and east of the second building and the middle area between its main building and podium building are in wind shadow areas with low wind speeds.

Figure 14. Aerial view of the site during the renovation and construction phase.

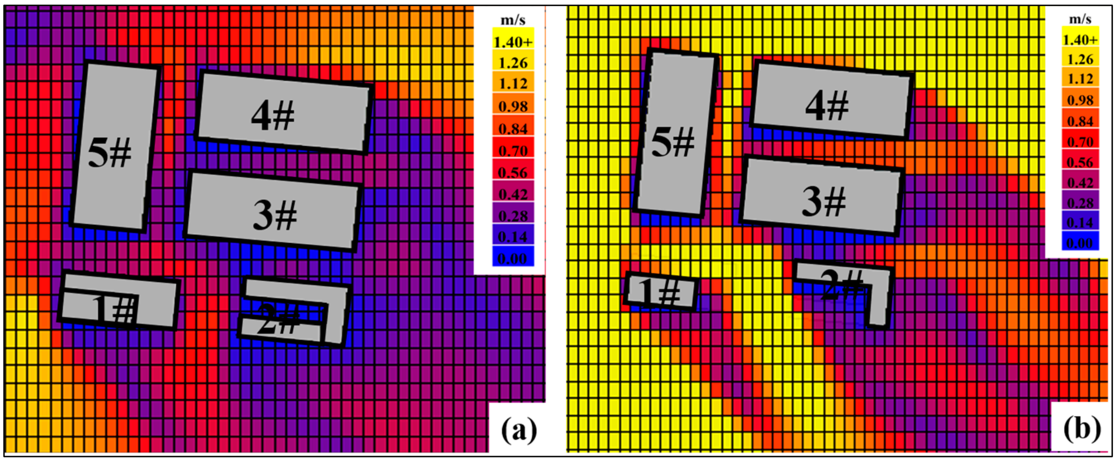

Figure 15. Air flow diagram for renovation construction phase (**a**) at 1.5 m (**b**) at 19.4 m.

3.5.3. Analysis of Artificial Conditions for Scenario Construction in the Renovation and Construction Phase of a Production Base Project

(1) Mechanical layout analysis for the renovation construction phase

During the renovation construction stage, the main structure of the remaining buildings on the construction site has been roughly completed except for Plant No. 3. In addition, Tower Crane No. 5 on the construction site has stopped operation in preparation for dismantling. Meanwhile, Automobile Crane No. 3 is put into use to cooperate with the remaining four tower cranes to carry out lifting operations. Figure 16a displays the setup of a mechanical buffer zone during the decoration construction stage. Thus, during this construction stage, the area of the secondary buffer zone for construction site machinery has decreased substantially more than the foundation and basement construction stage and the main structure construction stage. Hazardous factors at the construction site in terms of mechanical arrangement have been reduced. However, safety monitoring and control of the secondary buffer zone still needs to be strengthened, and potential hazardous sources in the primary buffer zone have to be continually monitored. Safety control must be implemented to ensure construction safety.

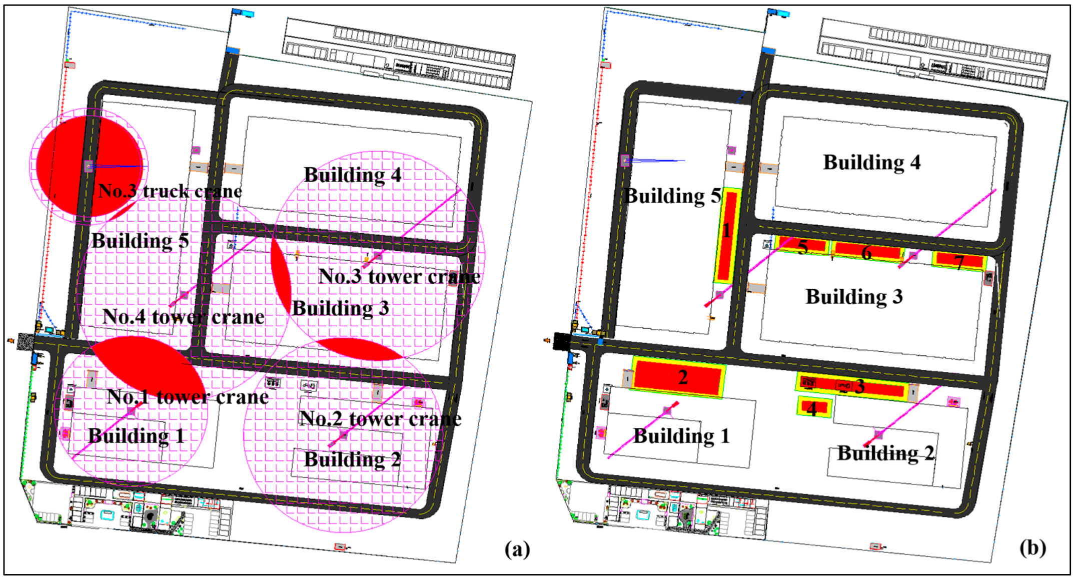

Figure 16. Mechanical buffer (**a**) and Material buffers (**b**) during the construction phase of the renovation.

(2) Analysis of material stacking during the construction phase of renovation

During the renovation construction phase, the main structures of the remaining buildings on the construction site, except for Plant No. 3, were largely completed. As a result, some of the material stockpiling areas on the construction site were cleared. The Autoclaved Aerated Concrete Blocks were primarily stockpiled in the material stockpiling areas from Nos. 1 to 4 to be used for external renovation works. Materials such as steel truss floor joists, reinforcement bars, and timber squares remained in the material stockpiling areas from Nos. 5 to 7 to be used in the final toughening up of the construction of Plant No. 3's main structure (Figure 16b).

4. Discussion

4.1. Scenario Construction and Safety Evaluation of Foundation and Basement Construction Phases

Through the analysis of natural and man-made conditions in Section 3.2 for the construction of the foundation and basement of the production base project, and considering the time limit of the spring construction, the simulation of the outdoor wind environment in the spring of the construction phase (Figure 6), the mechanical buffer zone (Figure 7a), and the material buffer zone (Figure 7b) are superimposed to construct a safety management scenario for the construction of the foundation and basement of the production base project (Figure 17).

During the foundation and basement construction stage, the production base project is in a dangerous area, specifically in the construction Area Nos. 1 and 2. In this area, the wind speed is high under the set climate conditions, and it is within the range of the secondary buffer zone for machinery and materials at the construction site. Therefore, onsite personnel should avoid staying in this area for long periods and be aware of potential dangers such as falling objects and overturning materials. Wind speeds are higher in Area Nos. 1 and 2, and if flammable materials such as formwork wood squares are present in material stacking Area Nos. 2 and 3, fire extinguishers should be placed upwind of their material stacking areas to prevent fire accidents from occurring downwind. On the other hand, the construction site 3 area is a relatively safe area in this stage of construction. It is less affected by the wind environment and is not within the first and second level buffer zones for machinery at the construction site. Additionally, no material stacking occurs here, rendering it a suitable temporary refuge for construction site personnel. The site management personnel can arrange for the orderly evacuation of personnel according to the situation onsite.

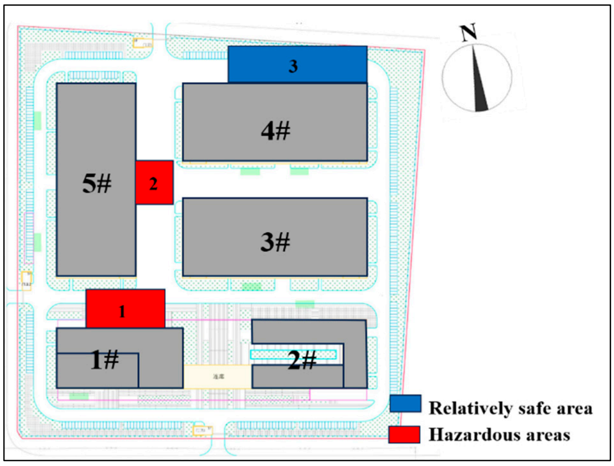

Figure 17. Scene overlay results for foundation and basement construction stage.

In the foundation and basement construction stage of the site, there are many new entrants, so to implement production base project worker entry education and training, a personnel safety education system in the safety management system is important, especially machinery operation and special operators training, so that the project department can form a perfect personnel entry process. In this construction phase, the onsite materials are mostly templates, steel pipes, reinforcing bars, etc., and there are many types of materials, so the project department should establish a job responsibility system, where the personnel in each position are jointly responsible for the safety control of project materials. The project department should supervise all kinds of mechanical equipment operators to seriously study the "safety technical regulations for the use of construction machinery" (JGJ33-2012), and mechanical equipment operators need to be licensed to work.

4.2. Scenario Construction and Safety Evaluation in the First Stage of Main Structure Construction

Through the analysis of natural and man-made conditions in Section 3.3 for the construction of the main structure of the production base project in the first phase of the safety management scenario and given the time limit of the summer construction, the following are achieved: the summer outdoor wind environment simulation (Figure 9), machinery buffer (Figure 10a), and material buffer (Figure 10b) of the construction phase are superimposed; moreover, the safety management scenario of the main structure of the production base project in the first phase of the construction is constructed (Figure 18).

During the main structure construction phase of the production base project, construction site 1 is a high-risk area. This area experiences high wind speeds under the set climatic conditions and is within the secondary buffer zone for machinery and materials. Therefore, safety management personnel must prioritize control measures for this area. The northern side of the 2nd building area is also within the machinery and materials buffer zone. However, the risk is lower than the first area due to its smaller exposure to the wind. Nonetheless, monitoring must be strengthened. The west side of the plant, where wind speeds are low, has no material buffer zone established. However, given that Car Crane No. 3 is present in this area, safety control measures must be implemented. At this stage of construction, the site is at a higher temperature in summer, and the wind speed is higher in Area 1. If there are flammable materials such as templates in material stacking Area

2, fire extinguishing equipment should be placed upwind of the stacking area to prevent fire accidents from occurring downwind. The second area is a low-risk area during this construction phase. It experiences low wind speeds and is not within the machinery and materials buffer zone. Therefore, it can be used by site personnel as a place for refuge in case of temporary risks and is a relatively safe area for construction.

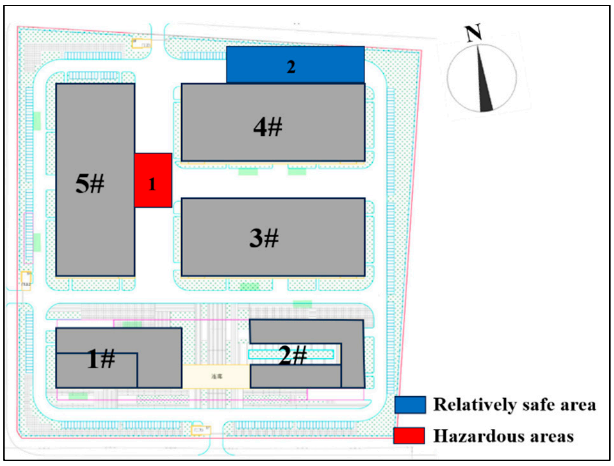

Figure 18. Main structure construction phase 1 scene overlay result map.

In the main structure construction of the first phase of the site, Plant 3 is not yet the main structure of the construction, but the rest of the buildings are in the main structure construction stage; due to the number of people working on the site, the leadership of the project needs to strictly enforce the shift inspection system. At this stage of construction, there are many types of materials on site, including raw steel, semi-finished steel, floor slabs, etc. It is necessary to carry out reasonable zoning of the site, ensuring sufficient material handling channels and fire escape routes. There are many cross operation areas for machinery on site, and warning signs should be placed outside the boundaries of the hazardous areas.

4.3. Scenario Construction and Safety Evaluation of the Second Stage of Main Structure Construction

Through the analysis of natural and man-made conditions in Section 3.4 for the construction of the main structure of the production base project in the second stage of the construction of safety management scenarios and given the time limit for construction in autumn, the following are achieved: the simulation of the outdoor wind environment in the autumn of the construction stage (Figure 12), the mechanical buffer zone (Figure 13a), and the buffer zone of the material (Figure 13b) are superimposed to construct the safety management scenarios for the second stage of the main structure construction of the production base project (Figure 19).

During the second stage of the main structure construction of the production base project, the construction site 1 area experiences high wind speeds under the set climatic conditions for wind environment simulation. It is also within the secondary buffer zone for machinery and materials, thus experiencing greater risk. Area 2, despite experiencing more moderate wind speeds, has three large-scale pieces of machinery operating within its boundaries, resulting in a larger secondary buffer zone for machinery. Additionally, the material buffer zone is superimposed on this machinery buffer zone, further increasing the risk. In this construction stage, which occurs in the fall, the site temperature is high, and the wind speed in Area Nos. 1 and 2 is large; in Material Stacking Area Nos. 2, 4 and 5, if there are templates and other flammable materials, firefighting equipment should be placed upwind of these three material storage areas in order to prevent fire accidents downwind of the mouth. Nonetheless, Area 3 is a relatively safe area during this phase of construction. It experiences low wind speeds and has no buffer zones for machinery or materials, making it a suitable temporary refuge for workers during this phase.

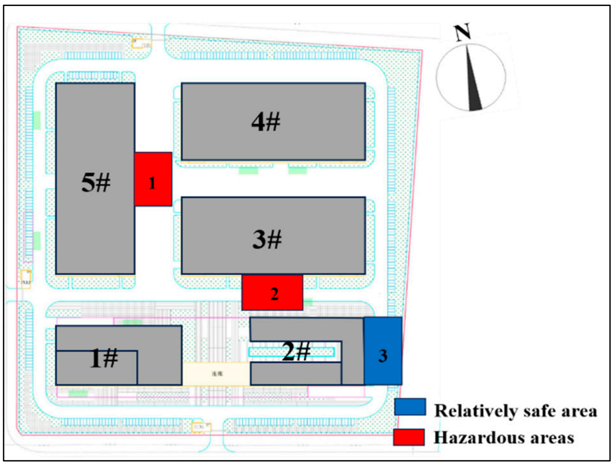

Figure 19. Main structure construction two-stage scene overlay result map.

The second phase of the main structure construction site is in the stage of full mobilization, and there are many dangerous factors; thus, great importance should be attached to the site emergency response work. In the daily construction process, the project department needs to organize personnel to carry out emergency rescue drills. For the safety management of machinery, the safety checklist method is adopted, and the site machinery is checked line by line according to the contents of the daily, weekly and monthly checklists.

4.4. Scenario Construction and Safety Evaluation in the Renovation Construction Phase

Through the analysis of natural and man-made conditions for the construction of safety management scenarios for the decoration phase of the production base project in Section 3.5 and given the time limit for winter construction, the following are achieved: the simulation of the outdoor wind environment in winter (Figure 15), the buffer zone for machinery (Figure 16a), and the buffer zone for materials (Figure 16b) during the construction phase are superimposed to construct the safety management scenarios for the production base project during the decoration phase of the construction (Figure 20).

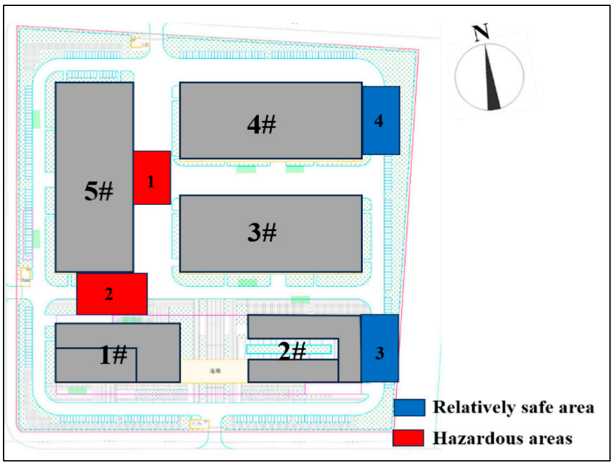

Figure 20. Renovation construction stage scene overlay results.

During the renovation stage of the production base project, Area Nos. 1 and 2 of the construction site pose greater dangers. Under the set climatic conditions, the wind environment simulation shows higher wind speeds, and these areas fall within the secondary buffer zone for machinery and materials, requiring close monitoring by safety management personnel. The area of the road on the northern side of Factory Building No. 3 experiences slightly lower wind speeds than the first two areas but has an overlapping secondary buffer zone for machinery and materials, thus resulting in a higher level of risk. This area also needs to be strengthened and monitored closely. At this stage of construction, it is winter, and cooler materials are less likely to cause fires; however, it is still important to safely monitor flammable materials such as formwork in Area Nos. 1 and 2. Area Nos. 3 and 4 are relatively safe areas of the construction site during this renovation stage. The wind speed is low in these areas, and no machinery arrangement or material stacking occurs. Therefore, they can serve as places of temporary refuge for workers during this phase of construction. In the construction phase of the renovation, the number of personnel, materials and machinery invested in the site compared with the previous stages of construction has decreased significantly, but personnel, material and machinery safety control measures at the site should not be relaxed and should continue to be implemented in accordance with the management mode of the previous stages of construction.

5. Conclusions

This study proposes a method and idea for enhancing construction engineering construction site safety management through the integration of BIM and GIS technology. By overlaying and analyzing safety management scenarios constructed during different construction phases, it determines the relatively safe areas and the more dangerous areas in different construction stages of the construction site. This approach aims to ensure the safety of personnel, materials, and machinery at the construction site. The following conclusions can be drawn from the study:

(1) This study proposes a method for comprehensively considering various factors in construction site safety management, including natural conditions such as air quality, temperature, wind speed, and wind direction, as well as man-made conditions, including machinery, materials, and software parameter settings. It also considers the spatial and temporal effects of construction projects, building height, and seasonal changes on the construction site.

(2) In spring and summer, the northern and western sides of the construction site are generally in the wind shadow area, resulting in low wind speeds. Conversely, in autumn and winter, the southern and western sides of the construction site are more often in the shadow zone, again with reduced wind speeds. The wind speed is higher along the central path of Plant Nos. 4 and 5 throughout the year. However, in autumn and winter, it is further increased by the narrowing effect of the buildings' height and length at different stages of construction, combined with the group bypassing phenomenon generated by air currents at the construction site. This scenario results in increased wind speeds and the formation of corner winds. Areas with high wind speeds and high temperatures on site are prone to fire accidents. In the event of a fire, downwind fires will be larger than upwind fires, and fire fighting measures should be installed upwind.

(3) The hazardous areas of the construction site are mostly located in areas with higher wind speeds and where an overlap of machinery and material secondary buffer zones occur. Conversely, the relatively safe areas are mostly situated in regions with lower wind speeds and where no overlap of machinery and material buffer zones occur or in areas within the inner primary buffer zone. In spring and winter, the hazardous areas of the construction site are the east side of Plant No. 5 and the north side of Building No. 1, while in summer, it is the east side of Plant No. 5. In fall, the east side of Plant No. 5 and the north side of Building No. 2 are hazardous areas. In spring and summer, the relatively safe area of the construction site is the north side of Plant No. 4. In fall, it is the east side of Building No. 2. In winter, the east side of Plant No. 4 and Building No. 2 is a safe area.

This study is a preliminary exploration of integrating BIM and GIS technology into the field of construction site safety management in construction projects, but limitations persist. First, this study utilizes CFD wind environment simulation. For the climatic conditions of the construction site, the data from the official website of the National Meteorological Information Center were used, and the highest temperature, wind speed and wind direction occurring in each of the four seasons were selected. Subsequent studies can use relevant measuring instruments on site to obtain dynamic and continuous climatic data for simulation to more adequately capture the complexity and dynamic nature of the environment at the construction site. Second, in simulating the spatial and temporal safety of personnel, materials, and machinery at the construction site, this study primarily focuses on the overlap of scenario results to determine the relatively safe and hazardous areas. Future research can be optimized following the analysis results in the layout of construction sites. Third, in this study, the use of the OHS system for construction site safety management mainly focuses on the construction phase, and less consideration is given to the cost elements in the design phase and the pre-construction project preparation phase, which can be investigated by using numerical analysis methods such as the Earned Value Approach for construction cost management in subsequent studies.

Author Contributions: Conceptualization, Q.Y. and X.Y.; methodology, Q.Y.; software, W.C.; validation, X.Y., W.C. and J.F.; formal analysis, X.Y.; investigation, J.F.; resources, X.Y.; data curation, W.C.; writing—original draft preparation, X.Y.; writing—review and editing, Q.Y.; visu-alization, W.C.; supervision, J.F.; project administration, Q.Y.; funding acquisition, Q.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA19030500).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study were obtained from the following platforms: Data on the share of value added of China's construction industry is from the official website of China Construction Industry Association (http://www.zgjzy.org.cn/ (accessed on 25 March 2023)); Data on the number of deaths in various types of work safety accidents in China are from the official website of the Ministry of Emergency Management of the People's Republic of China (https://www.mem.gov.cn/xw/ (accessed on 26 March 2023)); Data on fire losses in China are from the official website of the National Fire and Rescue Administration (https://www.119.gov.cn/ (accessed on 26 December 2023)); Climate data for wind environment simulation from the National Weather Information Center website (http://data.cma.cn/ (accessed on 15 May 2023)).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cao, L.; Li, X.; Wu, J.; Zhang, S. Safety Risk Verification of Building Construction Based on BIM-CSKB. *Sichuan Res. Build. Sci.* **2017**, *43*, 146–151.
2. Zhang, W.; Li, J. Efficiency of safety inputs for fall from height accidents in building construction based on DEA. *J. Civ. Eng. Manag.* **2017**, *34*, 72–78.
3. Xia, D. Talking about the Safety Management of Building Construction. *Sichuan Build. Mater.* **2013**, *39*, 277–278.
4. Wan, Y.; Li, X.; He, Q. Safety Risk Inspection of Cable-Stayed Bridge Construction Based on BIM & PtD. *Civ. Eng. Inf. Technol.* **2022**, *14*, 69–75.
5. Pandit, B.; Albert, A.; Patil, Y. Developing Construction Hazard Recognition Skill: Leveraging Safety Climate and Social Network Safety Communication Patterns. *Constr. Manag. Econ.* **2020**, *38*, 640–658. [CrossRef]
6. Xu, X.; Wu, H.; Liu, Y.; Zhu, B.; Gao, Y. Identification and Evaluation of Embankment Construction Hazard Sources Based on Improved LEC Method. *Hydropower Energy Sci.* **2022**, *40*, 131–134.
7. Wang, C.; Lv, J.; Geng, Y.; Liu, Y. Visual Relationship-Based Identification of Key Construction Scenes on Highway Bridges. *Buildings* **2022**, *12*, 827. [CrossRef]
8. Zheng, S.; Wang, Z.; Lv, K. Research on BIM-Based Construction Scenario and Safety Hazard Identification System. *J. Wuhan Univ. Technol. (Inf. Manag. Eng. Ed.)* **2023**, *45*, 27–33.
9. Zulmajdi, I.U.; Mohd Tohir, M.Z.; Syafiie, S. Probabilistic Fire Simulation Assessment Using Simplified Model and Zone Modelling of a Kitchen Fire Scenario. *Fire Technol.* **2022**, *58*, 3007–3037. [CrossRef]
10. Jin, Y.; Xia, J.; Huang, W.; Nan, S.; Xiao, F.; Li, K. Risk Assessment of Ship Fire Scenarios Based on Likelihood and Severity. *J. Wuhan Univ. Technol. (Inf. Manag. Eng. Ed.)* **2023**, *45*, 54–60.

11. Qiu, W.; Du, Y. Design and implementation of visualized electrical fire warning system. *J. Huaqiao Univ. (Nat. Sci. Ed.)* **2013**, *34*, 645–648.
12. Li, N.; Becerik-Gerber, B.; Krishnamachari, B.; Soibelman, L. A BIM Centered Indoor Localization Algorithm to Support Building Fire Emergency Response Operations. *Autom. Constr.* **2014**, *42*, 78–89. [CrossRef]
13. Zhang, W.; Zhou, S.; Wang, J.; Xue, K. Research on Fuzzy Comprehensive Evaluation of Metro Construction Safety Based on WSR and C-OWA. *Proj. Manag. Technol.* **2022**, *20*, 6–11.
14. Chern, W.C.; Hyeon, J.; Nguyen, T.V.; Asari, V.K.; Kim, H. Context-Aware Safety Assessment System for Far-Field Monitoring. *Autom. Constr.* **2023**, *149*, 104779. [CrossRef]
15. Wang, C. Research on the application of BIM technology and its impact on the development of construction industry. *Bulk Cem.* **2022**, *4*, 147–149.
16. Zhu, H.; Qian, K. Quality control and safety management of high-rise building construction. In Proceedings of the 2022 Shanghai Forum on Engineering Technology and New Materials (ETM 2022), Chongqing, China, 14–16 October 2022; Volume 1, pp. 75–76.
17. Koutamanis, A. Dimensionality in BIM: Why BIM Cannot Have More than Four Dimensions? *Autom. Constr.* **2020**, *114*, 103153. [CrossRef]
18. Ding, L.; Zhou, Y.; Akinci, B. Building Information Modeling (BIM) Application Framework: The Process of Expanding from 3D to Computable nD. *Autom. Constr.* **2014**, *46*, 82–93. [CrossRef]
19. Mayouf, M.; Gerges, M.; Cox, S. 5D BIM: An Investigation into the Integration of Quantity Surveyors within the BIM Process. *J. Eng. Des. Technol.* **2019**, *17*, 537–553. [CrossRef]
20. Devaiah, K.L.S.; Keshav, V. Application of BIM for Effective Construction Safety Management in High Rise Buildings. *IOP Conf. Ser. Mater. Sci. Eng.* **2022**, *1255*, 012006. [CrossRef]
21. Kim, D.; Cha, H.; Jiang, S. The Prediction of Fire Disaster Using BIM-Based Visualization for Expediting the Management Process. *Sustainability* **2023**, *15*, 3719. [CrossRef]
22. Dutta, S.; Cai, Y.; Huang, L.; Zheng, J. Automatic Re-Planning of Lifting Paths for Robotized Tower Cranes in Dynamic BIM Environments. *Autom. Constr.* **2020**, *110*, 102998. [CrossRef]
23. Terentyeva, I.; Lunev, A.; Kashina, S.; Sadrieva, L.; Korolyuk, I.; Pugacheva, N. The Virtual Construction Site: Knowledge Management in Virtual Environments. *Int. J. Emerg. Technol. Learn.* **2020**, *15*, 81–95. [CrossRef]
24. Choi, B.; Lee, H.S.; Park, M.; Cho, Y.K.; Kim, H. Framework for Work-Space Planning Using Four-Dimensional BIM in Construction Projects. *J. Constr. Eng. Manag.* **2014**, *140*, 04014041. [CrossRef]
25. Zavari, M.; Shahhosseini, V.; Ardeshir, A.; Sebt, M.H. Multi-Objective Optimization of Dynamic Construction Site Layout Using BIM and GIS. *J. Build. Eng.* **2022**, *52*, 104518. [CrossRef]
26. Doukari, O.; Seck, B.; Greenwood, D. The creation of construction schedules in 4D BIM: A comparison of conventional and automated approaches. *Buildings* **2022**, *12*, 1145. [CrossRef]
27. Yang, Q.; Yan, X.; Zhang, X.; Zhang, Z. Research on Building Fire Scenario Construction Based on BIM. *J. Wuhan Univ. Technol. (Inf. Manag. Eng. Ed.)* **2022**, *44*, 526–532.
28. Yang, Q.; Zhang, X.; Zhang, Z.; He, L.; Yan, X.; Na, J. Fire Scenario Zone Construction and Personnel Evacuation Planning Based on a Building Information Model and Geographical Information System. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 110. [CrossRef]
29. Su, Y. Comparison of Occupational Ergonomics Exposure Patterns and Health Status of Expatriate and Local Construction Eorkers in China and Sri Lanka. *Environ. Occup. Med.* **2021**, *38*, 105–112.
30. Meng, G. Safety Management of Construction Site Workers. *Constr. Saf.* **2021**, *36*, 38–40.
31. Hu, X.; Zhao, A. Discussion on Safety Management System of Overseas Railroad Projects—Taking the Bridge of Monnet Railway in Kenya as an Example. *Transp. Enterp. Manag.* **2021**, *36*, 96–98.
32. Zhao, X.; Niu, L. The Management of Safety Input Cost in Construction Enterprises. *Constr. Saf.* **2022**, *37*, 78–79.
33. Zhang, Y.; Liu, C.; Zhang, H.; Liang, C. CFD Flow Field Analysis under Natural Ventilation Condition of Cold Rice Seedling Greenhouse. *Agric. Mech. Res.* **2018**, *40*, 19–23.
34. Bian, N.; Gao, Y.; Song, T. Numerical Simulation of Air Dispersion in Fotation Tank. *Nonferr. Met. (Miner. Process. Sect.)* **2010**, *3*, 45–47.
35. Wang, F. *Analysis of Computational Fluid Dynamics*; Tsinghua University Press: Beijing, China, 2004.
36. Liu, L.; Yuan, L.; Liang, A. Research on Indoor and Outdoor Thermal Environment of Open Courtyard Space. *Build. Energy Effic.* **2018**, *46*, 92–95+143.

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