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Original Article

WBS-Based Construction Safety Risk Management in High-Rise Building Projects Using A Design-Build Contract System

Mega Shine Payungallo[1], Rosmariani Arifuddin[2*], Rusdi Usman Latief[3], Henrianto Masiku[4]

[1]*Department of Civil Engineering, Faculty of Engineering, Universitas Hasanuddin, Gowa 91271, Indonesia.*

**Corresponding Author : rosmarianiarifuddin@unhas.ac.id*

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Abstract *- The development of high-rise building infrastructure is often associated with a country's economic progress and modernization. A design-build contract system is one of the options for implementing the construction of high-rise buildings, as it provides a unified responsibility for both design and construction. There are many construction safety risks in its implementation, both in the design and construction phases. A handling model is needed to enable design-build service providers to mitigate and minimize losses during project implementation. This research formulates a model by identifying the causes of risks through work definition using the work breakdown structure, which is then processed using quantitative descriptive and fuzzy logic methods. The research results indicate that the most risky work in the design phase is the Development of Design (DED), and the most risky work in the construction phase is foundation work, basement work, and upper structure work. It is also found that all construction safety risks at the design phase are categorized as medium risk, and at the construction phase, there are 34 high risks, 136 medium risks, and 112 low risks. Furthermore, it is found that the dominant control in both the design and construction phases is administrative control.*

Keywords *- Construction, Safety risk management, WBS, High-rise building, Design-build.*

1. Introduction

Construction is crucial in infrastructure development and significantly contributes to a country's economic progress. One of the rapidly growing infrastructure developments is the construction of high-rise buildings due to the increasing demand for housing and the limited availability of land [1]. The construction of high-rise building infrastructure is often associated with a country's economic development and modernization. In the context of accelerating development, improving efficiency and effectiveness, and avoiding work implementation stagnation, integrated work procurement contracts in the form of design-build contracts are implemented [2, 3]. According to Regulation of the Ministry of Public Works and Housing Number 25 of 2020, design-build encompasses all work related to the construction of a building where the provider has a unified responsibility for both design and construction implementation [4]. Some advantages of design-build contracts include a focus on output and outcomes, allowing measurement of work results not only based on volume and technical specifications but also on fulfilling output indicators. The executing contractor conducts the planning process, making it more effective and efficient. Bids are based on the best value, ensuring long-term funding certainty. Service providers are incentivized to improve the quality of work because the risks associated with job quality are entirely borne by the service provider. Service providers are encouraged to self-develop and adopt technology and work methods, fostering the emergence of competitive specialized contractors. Service providers have the opportunity to increase profits if they can choose the right technology for the job [5, 6]. In the implementation of projects, the level of construction accidents is a source of concern on a global scale, where high-rise building projects are the most frequent type of construction experiencing workplace accidents [7]. The construction sector is the most vulnerable phase of the industry or business to accidents due to the involvement of a large number of temporary workers, leading to a maximum number of accidents [8]. Construction accidents not only result in significant financial losses but also frequently cause severe injuries or fatalities [7]. Several previous studies have proven that high-rise building projects often generate construction safety risks during the design phase. Construction safety risks in the design phase are related to bidding, costs, specification, design, etc [6, 9]. Additionally, construction safety risks in the design phase involve inappropriate design, lack of responsibility and experience of the designer, inaccuracies or delays in third-party information, incorrect design schemes, and the risk of changes and employer reviews [10, 11]. It was found that one risk from the contractor's perspective is the failure to meet design documents according to QA/QC standards [12]. Furthermore, the risk in the design phase is conflicts among the design team. This has the potential to lead to design failures, inaccurate budget plans, etc., due to a lack of communication and conflict management among the design teams.

It has also been proven during the construction phase that high-rise building projects often generate construction safety risks. The majority of minor accidents occur due to scaffolding failures, and most severe injuries result from workers falling from heights [8, 13]. Additionally, the identified causes of fatal construction accidents are attributed to management factors, unsafe site conditions, and risky behaviors of workers [7]. Builders' demands to remove formwork more quickly and still practice traditional methods have resulted in building collapse. Considering the construction safety risks arising in both the design and construction phases, a handling model is needed to enable design-build service providers to mitigate construction safety risks, thereby minimizing losses during project execution. Compared to previous research, this research maps construction safety risks not only focusing on the construction phase but also integrating all stages of the construction project, from the design phase to the construction phase, thereby mitigating potential losses for stakeholders. Previous research has primarily focused on risks from resource or work method perspectives. Risk identification is conducted based on the WBS of high-rise building projects, which means there is a low likelihood of unidentified risks.

Data collection includes experts who will validate consultants and contractors and the data obtained to ensure that the resulting data is more comprehensive. Data analysis uses quantitative descriptive analysis and updated inferential analysis, specifically fuzzy logic, which has the ability to represent qualitative events as quantitative and conclude random number distributions, thus providing deeper and more accurate insights compared to other methods. The first step in mitigating risks is to understand the elements that influence the occurrence of a risk [7]. To identify the causes of a risk, project scope planning is necessary to define the work to be performed and break it down into work packages [14]. The WBS breaks down the project into smaller, more manageable components, commonly referred to as work packages [15]. With a well-defined WBS, risk management can be applied to all aspects of the work, thereby preventing construction accidents.

Referring to Regulation of the Minister of Public Works and Housing No. 10 of 2021, construction safety risk management is carried out to ensure the technical safety of construction, occupational health and safety, environmental safety, and public safety [16]. Planning, identifying, analyzing, and responding to construction safety risks on a project is expected to enhance the opportunities and positive impacts of events while reducing the likelihood and negative impacts of adverse events on the project. Based on the aforementioned problem phenomenon, this research is developed to answer the following research questions:

- Research Question 1 (RQ1): To identify the construction safety risks that occur in high-rise building projects with an integrated design-build contract system;
- Research Question 2 (RQ2): To analyze the level of construction safety risks in high-rise building projects with an integrated design-build contract system;
- Research Question 3 (RQ3): To develop the handling and control of construction safety risks in high-rise building projects with an integrated design-build contract system.

2. Literature Review

2.1. Building Construction Projects

Based on the Republic of Indonesia Law No. 28 of 2002, a building is a physical form resulting from construction work that is integrated with its location, partly or entirely above and/or below the ground and/or water, serving as a place for human activities, whether for residence, religious activities, business activities, social, cultural, or special activities. A high-rise building is a building with more than eight floors [17].

2.2. Risk Management

According to the PMBOK 6th edition, risk management strategies consist of risk management planning, identification, qualitative risk analysis, quantitative risk analysis, risk response planning, implementation, and risk monitoring and control [14].

2.3. Construction Safety

According to Regulation of the Ministry of Public Works and Housing Number 10 of 2021, construction safety is all technical activities to support construction work in achieving compliance with standards of security, safety, health, and sustainability that ensure technical construction safety, worker safety and health, public safety, and environmental safety [16].

2.4. Work Breakdown Structure (WBS)

According to PMBOK 6^{th} edition, WBS is a hierarchy of project scope that must be considered by project team members to achieve project goals and meet final deliverable requirements [14]. WBS provides several advantages, including providing a list of tasks to be completed, serving as a basis for estimating resources, developing schedules, calculating costs, considering potential work risks, and encouraging more careful consideration before initiating a project.

2.5. The Design-Build Contract System

The integrated design-build contract is established by the Indonesian government in Articles 12 and 15 of Law No. 2 of

2017 concerning construction services. This contract is one type of construction service business, which includes integrated construction work covering construction consulting services and construction work (design-build) [18]. The differences between the design-bid-build contract and the design-build contract can be seen in Table 1.

Table 1. The differences between the design-bid-build contract and the design-build contract

Design-Bid-Build	Design-Build
The service users prepare Detailed Engineering Design (DED)	The service users prepare the basic design
"The service users conduct quality control through supervision consultants	The service users are oriented towards quality assurance audits through construction management consultant
The creative intellectual innovation of service providers is limited due to the implementation of work based on the specified Detailed Engineering Design (DED) by the service users.	Opening opportunities for the intellectual creativity of service providers
The procurement period takes longer and occurs in phases	The procurement period is shorter and parallel

2.6. Fuzzy Logic

Fuzzy logic can be used to model information that contains ambiguity through the concept of fuzzy numbers and can process these fuzzy numbers using ordinary arithmetic operations [19]. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox, namely Mamdani and Sugeno type [20].

However, in this research, the Mamdani type is used. The Mamdani method is also often known as the Min-Max method. This method was introduced by Ebrahim Mamdani in 1975. To obtain the output, four phases are required: the formation of fuzzy sets, determination of membership functions, determination of fuzzy function rules, and defuzzification.

3. Materials and Methods

To achieve RQ1, the research commenced with developing a Work Breakdown Structure (WBS) for high-rise building projects. The WBS was developed through a document analysis of literature reviews, including project reports and relevant journals. Subsequently, based on the high-rise building project WBS, risk identification was conducted for each activity, referencing previous related journals. Subsequently, the WBS and identified risks were validated through a perception survey involving expert validation and a questionnaire survey. Four experts were involved in validating the WBS and risk through in-depth interviews. The expert selection was based on stakeholders' criteria, including at least 10 years of experience in construction projects, a minimum of a bachelor's degree in engineering, and a safety certificate and/or a building-related certificate with at least an intermediate level qualification. Data from the expert validation was processed using descriptive analysis to obtain valid WBS-based risks for high-rise building projects.

To achieve RQ2: The level or degree of risk based on the valid WBS for high-rise building projects was determined through a questionnaire survey containing frequency and severity items with a Likert scale, which was then processed using fuzzy logic and descriptive analysis. A total of 40 respondents were involved in the questionnaire survey.

The criteria for respondents in the questionnaire survey were those who had been involved in building projects for at least 3 years, had a minimum of a bachelor's degree in engineering, and held a safety certificate with at least a junior-level qualification. The determination of the risk level refers to the following formulation:

Risk Level = Probability × Impact

Criteria for probability level can be seen in Table 2.

Table 2. Criteria for probability level

Probability Level	Description	Definition
5	Extremely probable	There is a high probability of accidents occurring during work. The probability of experiencing more than two accidents in a year is likely.
4	Highly probable	There is a high probability of accidents occurring during work under almost all conditions; There was a probability of one accident occurring in the past year.
3	Moderately probable	There is a probability of accidents occurring during work under specific conditions; There was a probability of two accidents occurring in the past three years.
2	Moderately improbable	There is a low probability of accidents occurring during work under specific conditions; There was a probability of one accident occurring in the past three years.
1	Extremely improbable	Accidents can occur during work under specific conditions; There was a likelihood of more than one accident occurring over the past three years.

Source: Regulation of the Minister of Public Works & Public Housing Republic of Indonesia No. 10 of 2021

Criteria for impact level can be seen in Table 3.

Table 3. Criteria for impact level

Impact Level	Construction Safety Consequence Scale			
	Human	**Equipment**	**Materials**	**Environment/Public Facilities**
5	An incident resulting in more than one fatality and/or more than one permanent disability	Multiple major equipment failures have occurred, resulting in a work stoppage exceeding one week.	The damage to materials necessitates sourcing replacement materials, a process that is expected to take longer than a week and will inevitably lead to a work interruption.	Causing air, water, soil, or noise pollution that results in complaints from the public; or Causing environmental damage within the National Park, affecting flora and fauna, or Causing significant damage to the assets of the surrounding community or Causing severe damage to road access and impacting the community or Causing traffic congestion lasting more than two hours
4	Resulting in one fatality (death) or one permanent disability	Involved the complete failure of one major piece of equipment, resulting in a work stoppage of one week	Requiring the replacement of damaged materials, a process that takes one week and results in a work stoppage	Causing air, water, soil, or noise pollution without eliciting public complaints; or Causing environmental damage affecting flora and fauna; or Causing partial damage to the assets of the surrounding community or Causing partial damage to public road access; or Causing traffic congestion lasting for 1-2 hours
3	An incident occurred, resulting in more than one worker requiring inpatient medical treatment and time off work.	Multiple pieces of equipment were damaged and required repair, causing a work stoppage of less than seven days.	Materials were damaged and required replacement, which took more than one week to procure but did not result in a work stoppage.	Causing air, water, soil, or noise pollution affecting the workplace environment; or Causing environmental damage to vegetation within the workplace or Causing damage to access roads within the workplace or Causing traffic congestion lasting between 30 minutes - 1 hour
2	An incident occurred, resulting in one worker requiring inpatient medical treatment and time off work.	One piece of equipment was damaged, requiring repair, and caused a work stoppage of more than one day.	Materials were damaged and required replacement, which took less than one week to procure but did not result in a work stoppage.	Causing air, water, soil, or noise pollution affecting a portion of the workplace; or Causing partial damage to access roads within the workplace.
1	An incident occurred requiring only first aid treatment, resulting in no lost work time.	One piece of equipment was damaged, requiring repair, and caused a work stoppage of less than one day.	No material damage occurred	No environmental impact was observed

Source: Regulation of the Minister of Public Works & Public Housing Republic of Indonesia No. 10 of 2021

The risk level for each identified risk was categorized using the risk matrix as outlined in Table 4.

Table 4. Risk level

	Impact				
Probability	1	2	3	4	5
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

Source: Regulation of the Minister of Public Works & Public Housing Republic of Indonesia No. 10 of 2021

Notes:
1-4 : Low Risk
5-12 : Medium Risk
15-25 : High Risk

Probability and Impact data were analyzed using descriptive statistics with mean analysis, which was subsequently verified using fuzzy logic. Based on the risk matrix, a risk level category was assigned to each risk in the high-rise building project.

To achieve RQ3, the author conducted a literature study to formulate risk controls for the top 20% of the highest-ranked risks based on the Pareto Theory. Subsequently, a survey was carried out for expert validation and model validation through a questionnaire to be presented during brainstorming sessions. The third-stage survey results in the control of safety risks in high-rise building projects using an integrated design-build contract system.

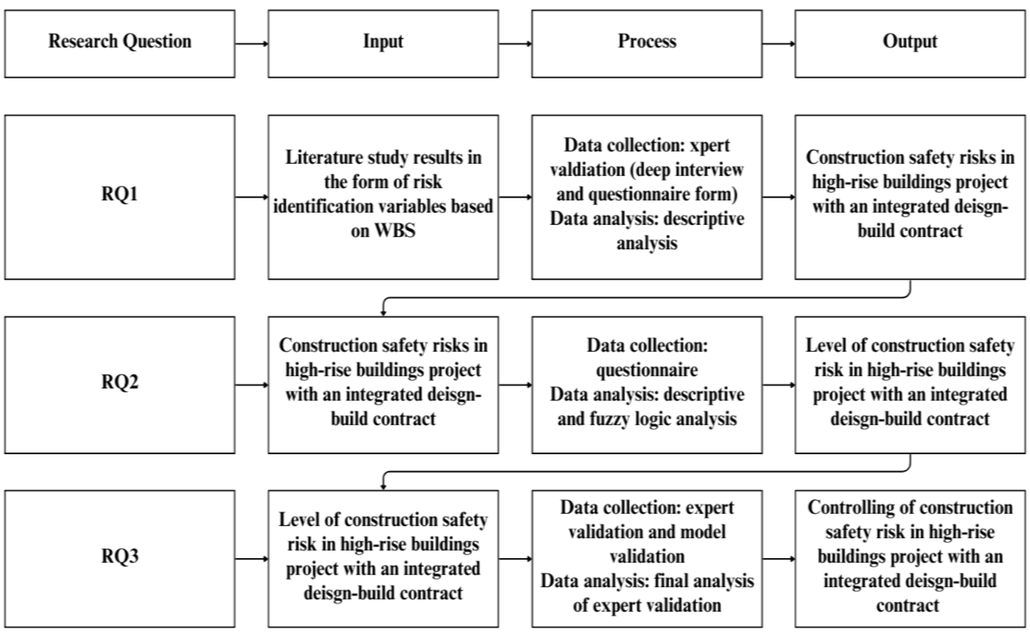

Fig. 1 Research process diagram

4. Results and Discussion

4.1. Result of Research Question 1 (Risk Identification)

Risk identification is organized based on four types of construction safety: technical safety, occupational health and safety, public safety, and environmental safety.

4.1.1. Result of Research Question 1 at the Design Phase

Based on the data processing results from expert validation, the initially identified research variables were reduced from 257 to 205. These risks consist of 8 risks in the team mobilization design work, 6 risks in site survey work, 20 risks in soil bearing capacity testing work, 12 risks in initial design work, 135 risks in Design Development (DED) work, and 24 risks in the conceptual design document work for SMKK. Therefore, the most risky work during the design phase is the development of Detailed Engineering Design (DED). These processed results are identified as construction safety risks based on the Work Breakdown Structure (WBS) in a building project using an integrated design-build contract system at the design phase.

4.1.2. Result of Research Question 1

Based on the data processing results from expert validation, the initially identified research variables were reduced from 412 to 282. These risks consist of 18 risks in preparation work, 23 risks in land preparation work, 70 risks in foundation work, 64 risks in basement work, 53 risks in upper structure work, 9 risks in roof structure work, 8 risks in architectural work, 20 risks in Mechanical, Electrical, Plumbing (MEP) work, 9 risks in finishing work, and 8 risks in final completion work. Therefore, the most risky works during the construction phase are foundation work, basement work, and upper structure work. These processed results are identified as construction safety risks based on the Work Breakdown Structure (WBS) in a building project using an integrated design-build contract system during the construction phase.

4.2. Result of Research Question 2 (Risk Analysis)

4.2.1. Result of Research Question 2 at the Design Phase

The data processing results in descriptive analysis (mean), which were further processed in a fuzzy inference risk map in the form of the level of construction safety risk during the design phase, can be seen in Table 5.

The results are presented as a sample of 41 risks with the top ranking (20% of the total risks) using fuzzy logic analysis.

Table 5. The level of construction safety risk in high-rise building projects using an integrated design-build contract system at the design phase

Variable Number	Construction Safety Risk	Risk Level	Ranking
X.3.1.5	Workers slipped, stumbled, and fell	Medium	1
X.4.1.6	Workers experience stress and fatigue in formulating the initial design criteria	Medium	2
X.5.2.1.2.2	Lack of adequate drainage planning to protect the basement structure	Medium	3
X.6.1.2	The capabilities and experience of the service provider are inadequate in preparing the construction safety plan documents	Medium	4
X.4.1.4	Workers experience low back pain due to prolonged sitting while formulating the initial design criteria	Medium	5
X.5.2.1.2.1	Errors in load calculations led to an inadequate basement structure and caused the building to collapse	Medium	6
X.4.1.5	Workers experience stiffness in the muscles of the hands, arms, and neck due to continuous work in front of the computer while formulating the initial design criteria	Medium	7
X.5.1.6	Workers experience stress and fatigue during the development of room program analysis	Medium	8
X.3.2.1.5	Workers slipped, stumbled, and fell	Medium	9
X.5.1.4	Workers experience low back pain due to prolonged sitting during room program analysis	Medium	10
X.6.1.1	The supporting data for the construction safety plan is incomplete	Medium	11
X.4.1.2	The data required to formulate the initial design criteria is incomplete or inaccurate	Medium	12
X.5.2.1.1.10	Workers experience low back pain due to prolonged sitting during the analysis of foundation structure calculations	Medium	13
X.5.2.1.1.6	Not considering soil conditions, topography, or other environmental factors that could pose a potential risk of collapse	Medium	14
X.5.2.1.2.7	Not considering soil conditions, topography, or other environmental factors that could pose a potential risk of collapse	Medium	15
X.5.4.8.1	Errors in the calculation of the work budget plan	Medium	16
X.5.2.1.2.9	Calculation of the basement structure by an incompetent service provider	Medium	17
X.5.2.1.1.12	Workers experience stress and fatigue during the development of foundation structure calculation analysis	Medium	18
X.4.2.6	Workers experience stress and fatigue during the development of the initial design	Medium	19
X.5.1.5	Workers experience stiffness in the muscles of the hands, arms, and neck due to continuous work in front of the computer during room program analysis	Medium	20
X.5.3.2.1.2	Calculation of electrical power needs by an incompetent service provider	Medium	21
X.5.4.6.1	Error in the calculation of worktime	Medium	22
X.6.2.1	The supporting data for the construction work quality plan is incomplete	Medium	23
X.6.4.1	The supporting data for the job traffic management plan is incomplete	Medium	24
X.5.2.1.2.3	Errors in the calculation of moment forces and shear forces	Medium	25
X.5.3.1.1.2	The selection of materials that do not match the procurement needs for the elevator	Medium	26
X.5.3.1.1.3	The selection of the elevator work implementation method that is not in accordance with the requirements	Medium	27
X.4.1.1	Errors in determining the criteria for the initial design	Medium	28
X.5.1.3	Workers experience eye irritation and headaches due to continuous exposure to computer light during room program analysis	Medium	29

X.5.2.1.1.1	Errors in load calculations lead to an inadequate foundation structure and result in building collapse	Medium	30
X.5.2.1.1.11	Workers experience stiffness in the muscles of the hands, arms, and neck due to continuous work in front of the computer during foundation calculation analysis	Medium	31
X.5.2.1.2.6	The selection of the basement structure implementation method that is not in accordance with the requirements	Medium	32
X.5.3.1.1.1	Errors in load calculations led to an inadequate elevator and caused the building to collapse	Medium	33
X.5.3.1.1.4	Calculation of the elevator by an incompetent service provider	Medium	34
X.5.4.8.2	The capabilities and experience of the service provider are inadequate in preparing the project cost plan	Medium	35
X.1.2.4	Traffic accident during equipment mobilization	Medium	36
X.5.2.1.2.12	Workers experience stiffness in the muscles of the hands, arms, and neck due to continuous work in front of the computer during basement structure calculation analysis	Medium	37
X.6.4.2	The capabilities and experience of the service provider are inadequate in preparing the job traffic management plan document	Medium	38
X.4.2.4	Workers experience low back pain due to prolonged sitting during the development of the initial design	Medium	39
X.4.2.5	Workers experience stiffness in the muscles of the hands, arms, and neck due to continuous work in front of the computer during the development of the initial design	Medium	40
X.5.2.1.1.2	Errors in the calculation of moment forces and shear forces	Medium	41

Through the risk level analysis, it is known that all construction safety risks at the design phase are categorized as medium risks. The risk with the highest value is the worker slipping, tripping, and falling during location/topography measurement work, with a risk level value of 7.77. The risk with the lowest value is the implementation method of sand cone testing in sand cone testing work, with a risk level value of 4.7.

4.2.2. Result of Research Question 2 at the Construction Phase

The data processing results in descriptive analysis (mean), which were further processed in a fuzzy inference risk map in the form of the level of construction safety risk during the construction phase, can be seen in Table 6. The results are presented as a sample of 57 risks with the top ranking (20% of the total risks) using fuzzy logic analysis.

Table 6. The level of construction safety risk in high-rise building projects using an integrated design-build contract system at the construction phase

Variable Number	Construction Safety Risk	Risk Level	Ranking
X.3.2.1.14	Workers fell	High	1
X.3.2.3.16	Workers are fatigued due to overtime	High	1
X.4.1.9	Workers fell into the excavation	High	1
X.4.2.1.1	Formwork collapsed	High	1
X.4.2.1.15	Scaffolding fell, hitting the workers	High	1
X.5.1.1.1	Formwork and/or scaffolding collapsed	High	1
X.5.1.1.14	Workers fell from the scaffolding	High	1
X.6.1.8	Workers fell from height during roof structure and roof covering work	High	1
X.8.1.1.4	Workers fell from height while working	High	1
X.8.1.1.5	Workers were electrocuted during elevator and air conditioning installation work	High	1
X.8.2.1.5	Workers got an electric shock	High	1
X.8.2.1.6	Workers slipped, stumbled, and/or fell during electrical power, generator, and lighting point work	High	1
X.8.2.1.7	Workers were injured due to contact with materials or equipment during electrical power, generator, and lighting point work	High	1
X.9.1.5	Workers fell from height while working	High	1
X.9.1.6	The worker slipped, stumbled, and fell	High	1
X.3.2.1.5	Unprotected holes/shafts	High	16
X.3.2.3.3	The method of concrete work implementation is not in accordance with the standards	High	16

X.3.2.4.2	Poor quality of curing compound material (if curing uses special material)	High	16
X.4.1.11	Flood	High	16
X.4.2.1.2	Erection of formwork by incompetent workers	High	16
X.4.2.1.5	Unprotected holes/shafts	High	16
X.4.2.2.14	Workers scratched and/or cut by sharp remnants/ends of iron	High	16
X.4.2.3.5	Lack of heavy equipment maintenance	High	16
X.4.2.3.16	Workers are fatigued due to overtime	High	16
X.5.1.1.4	Poor quality of formwork and/or scaffolding material (size, quantity, or type of material does not meet the requirements)	High	16
X.5.1.1.10	Lifting equipment used breaks because it is worn out or unfit for use	High	16
X.5.1.1.15	Workers injured due to contact with materials or equipment	High	16
X.5.1.2.2	Iron fabrication is done by incompetent workers	High	16
X.5.1.2.17	Workers injured while operating and/or repairing machines	High	16
X.5.1.3.9	Workers experience eye irritation due to contact with ready-mix concrete	High	16
X.5.1.3.10	Workers injured due to contact with materials or equipment in concrete work	High	16
X.6.1.1	Procurement of roof structure and roof covering systems that do not meet the standards	High	16
X.6.1.3	The method of implementing roof structure work and roof covering work is not in accordance with the standards	High	16
X.8.3.1.5	Workers slipped, stumbled, and/or fell	High	16
X.5.1.3.2	Lack of inspection in concrete work	Medium	35
X.6.1.9	Workers injured due to contact with materials or equipment	Medium	35
X.8.2.1.2	Lack of inspection during electrical power, generator, and lighting point work	Medium	35
X.1.1.1	Materials damaged during mobilization	Medium	38
X.1.2.10	The collapse of community buildings around the work site	Medium	38
X.2.2.3	The operation of equipment by an incompetent operator	Medium	38
X.2.2.6	Lack of inspection in soil compaction work	Medium	38
X.3.2.3.1	Lack of safety devices (signs, pedestrian facilities, etc.) resulting in unsafe conditions	Medium	38
X.3.2.3.5	Lack of heavy equipment maintenance	Medium	38
X.3.2.3.18	Traffic flow is disrupted if ready-mix concrete is sourced from outside	Medium	38
X.4.1.12	Landslide during excavation	Medium	38
X.4.2.1.12	Lack of inspection in formwork work	Medium	38
X.4.2.3.1	Lack of safety devices (signs, pedestrian facilities, etc.) resulting in unsafe conditions	Medium	38
X.5.1.1.2	Erection of formwork and/or scaffolding by incompetent workers	Medium	38
X.5.1.1.6	Non-standard access equipment and formwork/platform	Medium	38
X.5.1.1.7	Lack of safety devices (signs, pedestrian facilities, etc.) resulting in unsafe conditions	Medium	38
X.5.1.1.13	Lack of inspection in formwork work	Medium	38
X.5.1.2.8	Lack of safety devices (signs, pedestrian facilities, etc.) resulting in unsafe conditions	Medium	38
X.5.1.3.1	Lack of safety devices (signs, pedestrian facilities, etc.) resulting in unsafe conditions	Medium	38
X.5.1.3.3	The method of concrete work implementation is not in accordance with the standards	Medium	38
X.5.1.3.4	Lack of heavy equipment maintenance	Medium	38
X.5.1.3.7	Overloaded ready-mix concrete, causing the concrete bucket to fall from the crane	Medium	38
X.5.1.5.2	Test results do not meet the requirements	Medium	38

Through the risk level analysis, it is found that there are 34 high risks, 136 medium risks, and 112 low risks. High risks are dominated by 26% from basement work, 26% from upper structure work, 18% from Mechanical, Electrical, Plumbing (MEP) work, 15% from foundation work, 9% from roof structure work, and 6% from finishing work. There are 15 risks at the top ranking 1 with the same value of 18.2. Meanwhile, there are 53 risks at the lowest ranking with the same value of 4.11.

4.3. Result of Research Question 3 (Risk Control)

4.3.1. Result of Research Question 3 at the Design Phase

Control is applied to the top 20% of the highest-ranking risks, resulting in 41 controlled risks out of 205 risks. Controls are organized based on control levels, namely elimination, substitution, engineering controls, administrative controls, and the use of personal protective equipment. It was found that the most dominant control in the design phase was administrative control. The risk controls can be seen in Table

7 (Appendix 1). The results are presented as a sample of the top 3 ranked risks.

4.3.2. Result of Research Question 3 at the Construction Phase

Control is applied to the top 20% of the highest-ranking risks, resulting in 57 controlled risks out of 282 risks. Controls are organized based on control levels, namely elimination, substitution, technical engineering, administrative control, and the use of personal protective equipment. It was found that administrative control was the most dominant during the construction phase. The risk controls can be seen in Table 8 (Appendix 2). The results are presented as a sample of the top 4 ranked risks.

4.4. Discussion

Based on the results of RQ1 during the design phase, Occupational Health and Safety (OHS) risks were identified as the most prevalent type of risk at this stage. This is because most of the work during the design phase is conducted indoors, where the design team is the primary workforce. Consequently, the primary target of risks is the behavior of the design team members during work. Additionally, engineering safety risks also dominated due to the outputs of the design phase, which are project design documents such as Detailed Engineering Designs (DED), Bill of Quantities (BOQ), time schedules, quality documents, construction safety documents, and various other documents. Preparing these documents inherently involves risks that must be considered to prevent construction failures.

When analyzed based on the type of work, the development of design/DED (X.5) was identified as the work activity with the highest number of construction safety risks, specifically 133 risks (61 engineering safety risks and 72 OHS risks), which constitutes 64.88% of the total identified risks during the design phase. This is due to the numerous work items involved in design development, including space program analysis, structural calculations, MEP calculations, technical drawings, project schedules, quality plans, and cost plans. These activities introduce various risks that must be identified to ensure the smooth progress of the construction project with minimal losses.

Based on the results of RQ1 during the construction phase, engineering safety risks were identified as the most prevalent type of risk at this stage. This is due to the various construction methods employed, particularly in high-rise buildings, which introduce risks that can jeopardize the safety of materials, equipment, construction assets, and the building itself. Executing high-rise building projects involves complex and sensitive construction technologies, requiring special handling to ensure the resulting building meets the specified quality standards. Occupational Health and Safety (OHS) risks also dominate because construction projects involve a diverse workforce, increasing the likelihood of accidents. Visitors, subcontractors, and suppliers also frequent the construction site, necessitating risk identification to ensure their safety.

When analyzed based on the type of work, foundation work (X.3) was identified as the work activity with the highest number of construction safety risks, specifically 70 risks (47 engineering safety risks, 17 OHS risks, 2 public safety risks, and 4 environmental safety risks), which constitutes 24.82% of the total identified risks during the construction phase. This is due to the numerous work items involved in foundation work for high-rise buildings, each of which has a high degree of complexity in terms of execution methods and technical integration, posing threats to the safety of workers, materials, equipment, the public, and the environment.

Based on the results of RQ2 during the design phase, the development of design/detailed engineering design (X5) was identified as the most risky activity. Developing design/DED involves transforming the project plan into a detailed design, examining technical issues, preparing cost and project time estimates, and obtaining final design approval from the project owner. These activities form the core of the design phase, and as such, they present risks that must be addressed and mitigated to prevent losses for the integrated design-build contractor. The development of detailed engineering design plays a crucial role in the success of high-rise building projects, leading to timely, safe, and cost-efficient construction. Based on the results of RQ2 during the construction phase, it was found that out of the 10 primary work activities, three were identified as the most risky: foundation work (X3), basement work (X4), and superstructure work (X5). Foundations, which play a crucial role in the building structure, require precise design and implementation to ensure that the initial time, cost, and quality targets are met. To minimize losses in foundation work, significant construction safety risks must be addressed due to their close relationship with engineering safety, ensuring that the final product meets the specified requirements.

High-rise buildings typically have basements, which serve structural, functional, security, and overall project value purposes. Given the importance of basements in high-rise buildings, their construction involves critical construction safety risks related to technology, material and equipment safety, construction worker safety, public safety, and environmental safety. These risks must be carefully managed to achieve the desired outcome. The superstructure of high-rise buildings includes beams, columns, slabs, ring beams, and stairs. In terms of construction engineering, the construction of high-rise buildings involves manipulating heavy materials and large equipment. The use of heavy machinery poses inherent risks due to the potential for accidents caused by improper use, poor maintenance, or equipment failure. The instability of temporary structures or the failure of supports can lead to serious accidents.

Additionally, selecting appropriate construction methods is crucial to ensure safety and efficiency. Having a skilled and experienced workforce in construction is essential to guarantee quality and safety.

Regarding Occupational Health and Safety (OHS), safety is a top priority in construction projects, especially high-rise buildings. The involvement of workers at heights and the risk of falls must be effectively managed, as these can be caused by carelessness, adverse weather conditions, inadequate Personal Protective Equipment (PPE), and the disorganized stacking of materials. From a public perspective, the construction of high-rise buildings often takes place in densely populated urban areas, necessitating careful consideration of the safety of the surrounding community. In terms of the environment, the construction of high-rise building superstructures involves using many chemicals and noisy equipment, requiring attention to the impact on both the construction site environment and the surrounding environment. Based on the results of RQ3 during the design phase, the percentage of administrative risk control is 100%. This means that Standard Operating Procedures (SOPs) are required for all work activities to ensure safe execution, training is provided to all expert teams, and it is ensured that the expert teams are competent in their respective fields. Furthermore, the percentage of engineering risk control is 85.37%. Since the most risky activity is Design Development (DED), the expert team needs to utilize technological advancements such as Building Information Modeling (BIM) and digital collaboration tools to facilitate design development.

Additionally, since most of the work at this stage is conducted indoors, it is necessary to arrange the workspace, provide supporting work facilities, conduct medical check-ups, and regulate working hours to ensure the health and safety of workers. Then, the percentage of Personal Protective Equipment (PPE) risk control during the design phase is 41.46%. This is based on the fact that most work during the design phase is conducted indoors, so the most dominant risks are related to worker ergonomics. Therefore, the most recommended PPE is anti-radiation glasses to prevent eye irritation and headaches caused by working in front of a computer, as well as lumbar support cushions for ensuring an ergonomic posture while working. Based on the results of RQ3 during the construction phase, the percentage of administrative risk control is 100%. This means that Standard Operating Procedures (SOPs) are required for all work activities to ensure safe execution, training is provided to all teams, workers' competency is ensured, safety signage is installed at the worksite, safety inductions and toolbox meetings are conducted, and so on. Furthermore, the percentage of engineering risk control is 95.24%, which involves engineering modifications at the worksite and in the execution methods, such as installing work area protection (safety nets, guardrails, warning barriers, etc.), utilizing technological advancements, using tools that can reduce direct contact between workers and materials, conducting regular inspections of work and equipment, and arranging the positions of workers, materials, and equipment. Subsequently, the percentage of Personal Protective Equipment (PPE) risk control during construction is 85.71%. This is because the most dominant risks at this stage are workers falling from heights, being struck by heavy equipment, and being injured by materials or equipment, thus requiring the use of complete PPE when working.

5. Conclusion

1. Based on the results of the literature review and surveys, 205 construction safety risks were identified during the design phase. These risks consist of 8 risks in the team mobilization design work, 6 risks in site survey work, 20 risks in soil bearing capacity testing work, 12 risks in initial design work, 135 risks in Design Development (DED) work, and 24 risks in conceptual design document work for SMKK. Therefore, the most risky work during the design phase is the development of Detailed Engineering Design (DED). Then, 282 construction safety risks were identified during the construction phase. These risks consist of 18 risks in preparation work, 23 risks in land preparation work, 70 risks in foundation work, 64 risks in basement work, 53 risks in upper structure work, 9 risks in roof structure work, 8 risks in architectural work, 20 risks in Mechanical, Electrical, Plumbing (MEP) work, 9 risks in finishing work, and 8 risks in final completion work. Therefore, the most risky works during the construction phase are foundation work, basement work, and upper structure work.
2. Based on the data processing using the fuzzy inference method, risk maps show that all construction safety risks at the design phase are categorized as medium risks. The risk with the highest value is slipping, stumbling, and falling during location/topography measurement work, with a risk level of 7.77. The risk with the lowest value is the implementation method of sandcone testing in sandcone testing work with a risk level of 4.7. Furthermore, at the construction phase, there are 34 high risks, 136 medium risks, and 112 low risks. High risks in the construction phase are dominated by 26% from basement work, 26% from upper structure work, 18% from Mechanical, Electrical, Plumbing (MEP) work, 15% from foundation work, 9% from roof structure work, and 6% from finishing work.
3. Risk controls are organized based on control levels, namely elimination, substitution, technical engineering, administrative control, and the use of personal protective equipment. Risk controls are applied to the top 20% of the highest-ranked risks. Out of 205 risks in the design phase, 41 are controlled, while from 282 in the construction phase, 57 risks are controlled. Furthermore, it is found that the most dominant control in both the design and construction phases is administrative control.

Author Contribution Statement

Authors M.S.P., R.A., R.U.L., and H.M., proposed the research problem. Author M.S.P., R.A., and R.U.L.: developed the theory and performed the computations. Authors M.S.P., R.A., and H.M. verified the analytical methods and investigated and supervised the findings of this work. Both authors discussed the results and contributed to the final manuscript.

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Appendix 1

Table 7. The control of safety risks in high-rise building projects using an integrated design-build contract system at the design phase

Variable Number	Construction Safety Risk	Risk Control				
		Elimination	Substitution	Technical Engineering	Administration	Personal Protective Equipment
X.3.1.5	Workers slipped, stumbled, and fell			1. Installation of police lines in locations with steep terrain.	1. Creating SOP related to the procedures for conducting location/topography measurements; 2. Installing safety signs and work safety measures at the job site; 3. Conducting safety induction and toolbox meetings before starting work; 4. Assigning competent workers who understand the procedures for job execution.	1. Using complete Personal Protective Equipment (PPE); 2. Using webbing slings in locations with steep terrain.
X.4.1.6	Workers experience stress and fatigue in formulating initial design criteria			1. Arrangement of workspaces and provision of comfortable work-supporting facilities; 2. Arranging work durations so that workers can take periodic active breaks to avoid prolonged static work; 3. Conducting relaxation to loosen muscle tension, preventing workers from fatigue due to work; 4. Sufficient rest and ensuring the body is well-hydrated (drinking enough water).	1. Creating SOP related to design work; 2. Conducting education on the importance of maintaining a healthy lifestyle and managing stress; 3. Conducting education on proper body posture when working.	1. Using safety glasses (anti-radiation glasses) to prevent eye fatigue from working in front of the computer; 2. Using earphones to relax or dampen noise so that workers do not experience stress while working. 3. Using lumbar support cushions on office chairs to prevent workers from fatigue
X.5.2.1.2.2	Lack of adequate drainage planning to protect the basement structure			1. Using technology through Building Information Modeling (BIM) and digital collaboration tools to facilitate drainage planning in basement structure work.	1. Creating SOP for design work 2. Assigning a competent expert team, proven by staff holding Building Competency Certificates, to ensure that drainage planning for the basement structure can be carried out effectively 3. Providing regular training so that every staff member can upgrade themselves and adapt to the latest technology.	

Appendix 2

Table 8. The control of safety risks in high-rise building projects using an integrated design-build contract system at the construction phase

Variable Number	Construction Safety Risk	Risk Control				
		Elimination	Substitution	Technical Engineering	Administration	Personal Protective Equipment
X.3.2.1.14	Workers fell			1. Installation of police lines and guardrails in locations with steep terrain; 2. Ensuring that the guardrail installation is carried out by competent personnel and is properly installed; 3. Conducting inspections and tests to ensure that the fall protection system is safe for use.	1. Creating SOP for job execution procedures; 2. Installing safety signs and work safety measures at the job site; 3. Conducting safety induction and toolbox meetings before starting work; 4. Assigning competent workers who understand job execution procedures.	1. Using complete Personal Protective Equipment (PPE) when working; 2. Using webbing slings in locations with steep terrain.
X.3.2.3.16	Workers are fatigued due to overtime			1. Arrangement of workspaces and provision of comfortable work-supporting facilities; 2. Conducting relaxation to relieve muscle tension, preventing workers from fatigue due to work; 3. Sufficient rest and ensuring that the body is well-hydrated (drinking enough water)	1. Creating SOP for job execution procedures; 2. Arrange work durations so workers can take periodic active breaks to avoid prolonged work durations.	1. Using complete Personal Protective Equipment (PPE) when working.

X.4.1.9	Workers fell into the excavation		1. Using heavy equipment or non-manual excavation technology reduces the risk of workers falling in.	1. Implementing stable and safe retaining structures; 2. Using automatic excavation control systems to reduce the need for workers in excavation areas; 3. Installing police lines at locations with steep terrain.	1. Creating SOP for job execution procedures; 2. Installing safety signs and work safety measures at the job site; 3. Conducting safety induction and toolbox meetings before starting work; 4. Assigning competent workers who understand job execution procedures.	1. Workers use complete Personal Protective Equipment (PPE) while working; 2. Using webbing slings in locations with steep terrain.
X.4.2.1.1	Formwork collapsed		1. Replacing formwork material with stronger and more durable materials.	1. Installing additional support or fastening systems to enhance formwork stability; 2. Using structural simulation software to ensure the strength and stability of formwork; 3. Ensuring that the formwork installation is carried out by competent personnel and is properly installed according to safety standards; 4. Conducting regular inspections on the safety of the formwork.	1. Creating SOP for formwork installation procedures; 2. Installing safety signs and work safety measures at the job site; 3. Conducting safety induction and toolbox meetings before starting work; 4. Assigning competent workers who understand job execution procedures.	1. Using complete Personal Protective Equipment (PPE) while working; 2. Using fall protection equipment at heights, such as anchors, full-body harnesses, safety belts, synthetic fiber lanyards, lifelines, or shock absorbers; 3. Ensuring workers use Personal Protective Equipment (PPE) properly and correctly.