JURNAL ILMIAH TEKNIK INDUSTRI
ISSN: 1412-6869 (Print), ISSN: 2460-4038 (Online)
Journal homepage: http://journals.ums.ac.id/index.php/jiti/index
doi: 10.23917/jiti.v21i1.17429

Modeling Underlying Pattern Making Construction Safety Risk Mitigation Decisions Using Dynamic Systems

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Abstract. *The Occupational Health and Safety Management System (SMK3) is one of the factors that must be always monitored during the implementation of construction in achieving the success of project objectives. The implementation of SMK3 and decision-making still comes from project actors with different levels of experience gaps, causing the decisions taken to be less systematic and affecting the productivity of project performance. The purpose of the research is to conduct risk management simulations to increase insight into risk management and mitigation as a support for appropriate decision making in supporting project productivity, quality, and cost. Risk identification process through brainstorming, interviews, and observations with competent resource persons and project actors who have more than 5 years of experience in railway projects. Risk identification generates parameters and measures project risk by processing data using SPSS V23 software and dynamic simulation using Vensim PLE software. Simulation shows that there is a decrease in risk parameters in design and technology by -6.29%, construction management -5,12%, work safety and environment -5,90%, materials and equipment 3,37% and logistics -6,23%. Management of SMK3 by combining methods can increase accuracy in making risk mitigation decisions and can improve and understand the complexity of overall risk management performance from time to time.*

Keywords: *dynamic simulation, risk identification, risk mitigation*

I. INTRODUCTION

Data from the International Labor Organization (ILO) shows that 250 million work accidents occur every year and 160 million get sick due to workplace hazards and 1.2 million die due to accidents and illness at work (Haworth & Hughes, 2012) and the death rate in the construction industry reaching 30-40% in many countries, making it the deadliest of all industrial fields (Shohet et al., 2019). The construction industry is one of the most accident-prone sectors in the world (Jin et al., 2019) with very dynamic project characteristics and complexity (Guo et al., 2015) so that the implementation of effective safety risk management is a concern among the construction industry (Hinze, 2008). Developments in conducting work accident analysis with accident-causing models, statistical analysis, and economic costs can support the implementation of occupational safety and health (Sanchez, Fabián Alberto Suarez Pelaez & ALÍS3, 2017). The high number of accidents is due to poor job planning, poor safety training, lack of budget for safety, and investigations or evaluations of accidents that do not meet standards. A comprehensive risk management system that handles different projects with long-term project performance data can help validate the initial identification stage, calculation, implementation allocation, and response to identified risks (Saad & Asce, 2010). The guidelines for the Occupational Health and Safety Management System (SMK3), in the form of Law No. 1 of 1970, and updated by Law. 23 of 2009, strengthened by Government Regulation no. 50 of 2012 concerning SMK3 (Government Regulation Number 50, 2012). According to data from the Ministry of Transportation, users of rail transport experienced a significant increase in 2030 by 929.5 million people/year, so that the development of railway infrastructure is needed, improvement of railway safety and management support activities and technical support is required (Perhubungan, 2018). Currently, the

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Submited: 03-02-2022 Revised: 14-05-2022
Accepted: 10-06-2022

government is intensively accelerating development, projects for toll roads, airports, ports, railroads, and other infrastructure. According to Law no. 13/1992 the railway is one of the modes of transportation that has special characteristics and advantages, especially in the ability to transport people and goods (Undang-Undang Republik Indonesia Nomor 13 Tahun 1992 Tentang Perkeretaapian, 2009).

The increasing need for travel requires infrastructure to provide services and convenience for service users. Acceleration of development needs to be balanced with quality according to standards. The implementation process produced follows occupational health and safety standards (Undang Undang Republik Indonesia Nomor 2 Tahun 2017 Tentang Jasa Konstruksi, 2017). The development of a risk management plan in the initial phase of the project's tender and estimation phase is an important process for management in controlling critical issues and risks that arise (Hlaing et al., 2008). So that the role of SMK3 is needed in creating occupational safety and health by involving elements of management, labor, conditions, and an integrated work environment to prevent and reduce accidents and occupational diseases and create a safe, comfortable, efficient, and productive workplace.

The application of SMK3 can reduce or minimize the problem of work accident rates. SMK3 has not been managed properly due to a lack of knowledge and benefits in project implementation. Health and safety training is an important part of a prevention program. The process of implementing supply chain system risk management based on risk stratification with the aim of the risk management process being an implementation model at the chain or network level to provide benefits in risk management (Prakash et al., 2017). SMK3 plays a role in identifying jobs that have the highest accident potential and measuring the risk value. An integrated approach of interpretive rating process (IRP) and dynamic system (SD) for modeling the main risk factors of construction projects can facilitate in designing risk mitigation strategies (Mhatre et al., 2017). The risk of the double-track railway project is quite high with 19 unexpected risks and 12 acceptable risks (Munang et al., 2016). The work with the highest accident risk value is monitored and repaired to reduce the accident rate. Variables of the implementation of K3, socialization, and promotion of K3, work protective equipment, personal protective equipment, K3 personnel, health facilities, signs, have an overall effect on the cost of construction projects.

Simulation of dynamic systems can provide a short- and long-term picture of productivity and safety, can evaluate risk mitigation initiatives and allow experimentation in new information structures to improve security (Kontogiannis, 2012). System dynamics is a methodology used to analyze dynamic problems that arise in complex systems and explore the interrelationships of change over time.

In a dynamic risk management system, there is a risk tracking process which is an important part containing risk exploration, risk re-identification, risk treatment and risk tracking report generation (Castelli et al., 2012). Accurate and reliable prediction of project performance is critical to the success of construction projects and companies. The combination of project implementation data can be used as a modeling reference so that it helps in achieving a project goal. Improved understanding of the modeling relationship between project performance indices and developing reliable models so that they can be used to predict the impact of external interventions as an illustration of future project performance (Leon et al., 2018).

The important role of project managers in managing team communication, motivating all teams to proactively identify risks in work assignments and increasing understanding of risks that all team members are part of the integration in meeting project goals (Buganová & Šimíčková, 2019). The risk management decision-making approach by integrating the similarity algorithm and the correlation algorithm of this method can reduce the loss of important correlated information and draw conclusions from various sources (Jiang et al., 2020). Effective safety management by compiling safety risk knowledge, then identifying and reusing it and establishing a construction safety risk management decision system.

PT XYZ is one of the contractors for the Kutoarjo-Keroya double railway line construction project. In practice, the risk management decision-making process is still based on the experience of the project actors so that all decisions are still sourced from the project manager, and the resources that deal with risk management are still limited. With these problems, research is needed in modeling SMK3 using a dynamic system. The accuracy of decision-making in the prevention of construction risk is very important in maintaining the safety, quality, and cost of the project. The model generated by the dynamic system can help make decisions quickly in project implementation.

II. Research Method

The method is explained in detail. Contains an explanation of the research design, location and time, population, sample, sampling methods, research variables, data collection and data analysis. This research is an observation of the implementation of the Occupational Health and Safety Management System (SMK3) in the double-track railway construction project. The research location in the Kutoarjo district at PT. XYZ. Collecting research data by conducting a survey of 40 contractor workers. The survey was conducted on internal contractors, subcontractors, consultants, and project workers with more than 5 years of experience. Collecting data by conducting observations, interviews, and study of research supporting documents.

Data collection by brainstorming, observation, and interviews were used to identify project risks. Phase 1 questionnaire is the result of risk identification given to project workers. Furthermore, the results of the questionnaire were tested for validation and reliability to eliminate the identified risks. The results of the validity and reliability tests will produce a list of project risks.

The list of valid risks is the basis for the phase 2 questionnaire. Questionnaires are still given to project workers to determine the level of risk occurrence and the impact caused by the risk. The assessment is carried out to determine the level of risk that occurs. The results of the risk assessment become the initial data in rating the level of risk based on project performance.

The results of the risk rating are used to perform simulations and analyze the sensitivity of the risk factor model. The simulation model is made using Vensim PLE software. The use of simulation in this study is intended to determine project risk behavior over time so that project management can determine the best decision to mitigate project risk (reduce project risk).

In general, according to (Series & Sterman, 2003) System Dynamics modeling has 5 stages: 1. Making Causal Loop Diagram (CLD), 2. Making Stock Flow Diagrams (SFD), 3. Model verification and validation, 4. Base-run simulation, and 5. Scenario analysis (sensitivity analysis)

The making of the Risk Factor model in this study uses the following assumptions:

1. The model is built using the variables obtained from the risk rating results.
2. The level of risk is obtained from the comparison of the mean ratings of performance measurement in one risk parameter. For example, in the Design and Technology risk parameter there are 5 performance measurements, then the performance measurement that has the highest mean will get a weight of 5/15 and the other performance measures adjust accordingly.
3. Risk Factor Value is obtained from the average value of all risk factor values for risk parameters.
4. The level of risk reduction is inversely proportional to the weight of the risk level. For example, the performance measurement variable from the Design and Technology risk parameter has a risk level weight of 5/15, so the risk reduction level is 1/15.

III. Result and Discussion

Occupational Health and Safety Management System

Occupational health and safety management system are important and a priority. Prevention of work accidents and occupational diseases is caused by various dangerous factors, derived from the use of work tools, the work environment, and the actions of the workers themselves. The implementation of SMK3 is carried out by providing direction, training, and providing facilities to support the work of employees in achieving goals. Standard Operating Procedures (SOPs) are important to avoid work accidents because the indicators KPI (Key Performance Indicator) is a performance target, in which there is the achievement of zero accidents.

Project Risk Identification

Risk identification survey by conducting brainstorming and interviews with parties who have the competence to risk. The survey results are in the form of a risk list in the form of a questionnaire which is then given to the project team and workers to test the validity and reliability using SPSS v23 software. The results of the validity and reliability test allow that there are several risk items that fall out so that the risk list of the questionnaire has been valid (valid and reliable) into a questionnaire and can be used as an SMK3 research instrument. Respondents who fill out the questionnaire can be seen in Table 1.

Table 1. Questionnaire to Respondents

No	Skill Qualification	# of Workers	Work Experience/ year
1	Project Manager	1	10-15 year
2	Site Manager	2	6-10 year
3	Supervisor	7	6-15 year
4	Administrasi	2	1-5 year
5	Logistics	2	6-10 year
6	Train watcher	3	1-3 year
7	Surveyor	3	6-8 year
8	Operator	3	3-8 year
9	Subcontrcator	2	3-7 year
10	Day Worker	15	1-5 year

Table 2. Measurement of Possible Risk

No	Risk Parameters	Mean	SD
1	Design and Technology	2.6500	1.03579
2	Construction Management	2.7925	1.12811
3	Work Safety & Environment	2.9571	1.41141
4	Materials and Equipment	3.2375	0.97102
5	Logistics	3.0000	0.98948

Table 3. Risk Impact Measurement

No	Risk parameters	Mean	SD
1	Design and Technology	2.7500	1.02113
2	Constrcution Management	2.8175	1.05924
3	Work Safety & Environment	2.8143	1.07487
4	Materials and Equipment	3.0375	0.94726
5	Logistics	3.0375	0.99088

Table 4. Project Risk Rating

No	Risk Factor	Rank Risk	Acceptability of Risk
1	Change of working drawing	4	*Unacceptable*
2	Lack of work safety resources	4	*Unacceptable*
3	Inhibited socialization of work	4	*Undesirable*
4	High rental rates/ compensation	4	*Undesirable*
5	Public facilities damaged	4	*Undesirable*
6	Material exceeds volume	4	*Undesirable*
7	Work safety support facilities	4	*Undesirable*
8	Missing project materials	4	*Undesirable*
9	Project material delay	4	*Undesirable*
10	Damage to project equipment	4	*Undesirable*

The results of risk identification obtained 5 risk parameters and 30 project performance measurements. The list of risk events includes identified risks, risk factors, risk ratings, and controls. The second stage of the questionnaire was conducted to determine the level of risk and impact. The results of the questionnaire can be seen in Tables 2 and 3.

Each risk event that occurs is classified into a risk rating to obtain general and qualitative technical recognition to provide guidance on risk decisions. The level of risk is determined by the likelihood and impact factors at the time of risk measurement. From the results of the measurement of the level of possible risk and the impact that will be caused, a risk assessment process can be carried out which can be seen in Table 4.

Dynamic System Modeling

Monitoring of each identified risk and risk source using a dynamic system will be used to reduce the risk value to a lower level. The first stage in making the Risk Factor model is to create a CLD which can be seen in Figure 1 and the naming of the variables used in the CLD can be seen in Table 5.

The purpose of making CLD is to determine the causal relationship between parameters that affect the high and low-risk values of the project. In this Risk Factor model, the Risk Factor value is determined by the value of the risk parameters, namely Design and Technology, Construction Management, Work Safety, and Environment, Materials, and Equipment, and Logistics. Each risk parameter is influenced by the value of its risk performance. The value of the Design and Technology parameter is affected by the change value of the working drawing. Construction Management parameter value influenced by the value of delays in socializing project work, high rent/compensation prices, and damaged public facilities. The value of the Occupational Safety and Environment parameter is influenced by the value of the lack of work safety resources, the absence of work safety supporting facilities, and damage to work safety supporting facilities. The value of the Material and Equipment parameter is affected by the value of lost project materials and damage to project equipment. The value of the Logistics parameter is affected by the value of the material exceeding the volume and delay of the project material. The value of each risk performance is influenced by the value of the risk rate and its reduction rate.

Table 5. Naming of Variables

Symbol	Variables
Design & Tech	Design and Technology
Manaj Konstruk	Constrcution Management
Logistik	Logistics
Mat dan Alat	Materials and Equipmen
Kesht Keslm Lingk	Work Safety dan Environmen
V1	Change of working drawing
V6	The delay in project work socialization
V11	High rental rates/compensation
V13	Public facilities damaged
V16	Lack of work safety resources
V17	The absence of work safety support facilities
V18	Damage to work safety support facilities
V23	Missing project materials
V24	Damage to project equipment
V26	Material exceeds volume
V30	Project material delay
W1, Rate1	Weight and risk rate V1
W6, Rate6	Weight and risk rate V6
W11, Rate11	Weight and risk rate V11
W13, Rate13	Weight and risk rate V13
W16, Rate16	Weight and risk rate V16
W17, Rate17	Weight and risk rate V17
W18, Rate18	Weight and risk rate V18
W23, Rate23	Weight and risk rate V23
W24, Rate24	Weight and risk rate V24
W26, Rate26	Weight and risk rate V26
W30, Rate30	Weight and risk rate V30
X1, mitigation1	Weight and reduce rate V1
X6, mitigation 6	Weight and reduce rate V6
X11, mitigation11	Weight and reduction rate V11
X13, mitigation13	Weight and reduction rate V13
X16, mitigation16	Weight and reduction rate V16
X17, mitigation17	Weight and reduction rate V17
X18, mitigation18	Weight and reduction rate V18
X23, mitigation23	Weight and reduction rate V23
X24, mitigation24	Weight and reduction rate V24
X26, mitigation26	Weight and reduction rate V26
X30, mitigation30	Weight and reduction rate V30

After identifying the parameters used in the CLD model and determining the relationship between the parameters, the CLD model will be defined quantitatively into SFD using Vensim Software. Figure 2 shows the SFD Risk Factor model.

Validation of the simulation model is used to see the similarities of the simulation model with the model in the real world. According to (Qudrat-Ullah & Seong, 2010), tests that can be used to validate dynamic system models include:

1. Boundary test. A boundary test is done by checking the suitability of the variables used in the model with the research objectives. All variables used in the Risk Factor model are variables obtained from literature studies and surveys with project workers and have been processed to obtain the most influential risk variables.
2. Structure verification. Structure verification is used to ensure that the structure of the model is logical and that there is a reference for each relationship between its variables. In this study, the model was developed based on references from the literature study and the results of a

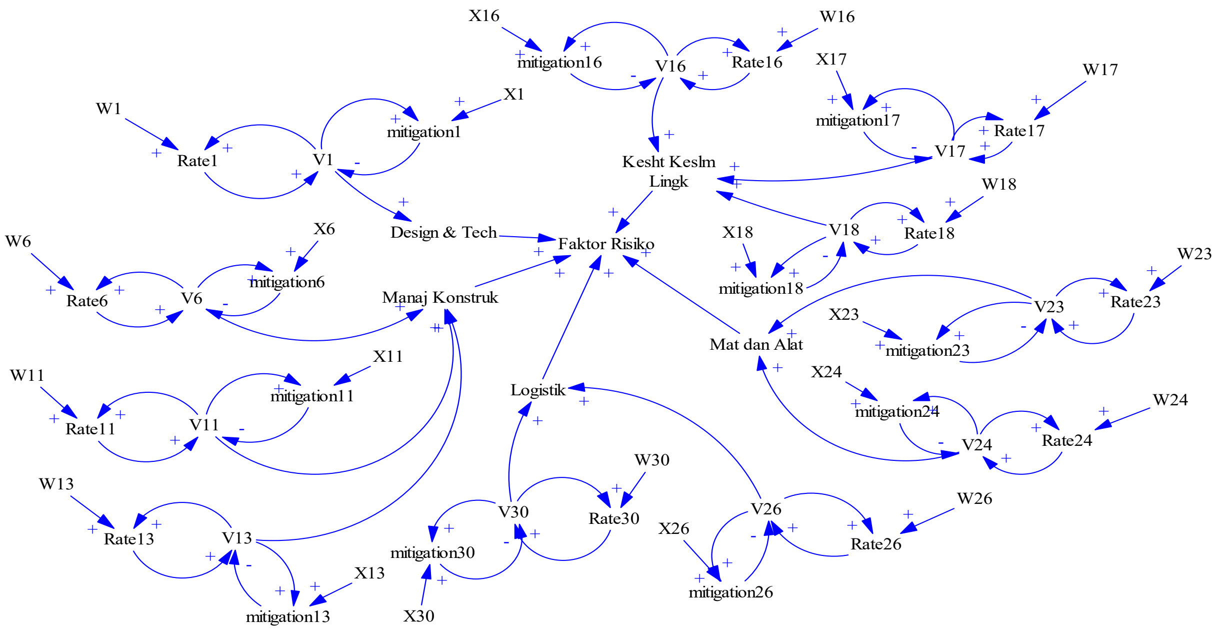

Figure 1. Causal Loop Diagram Risk Factor Model

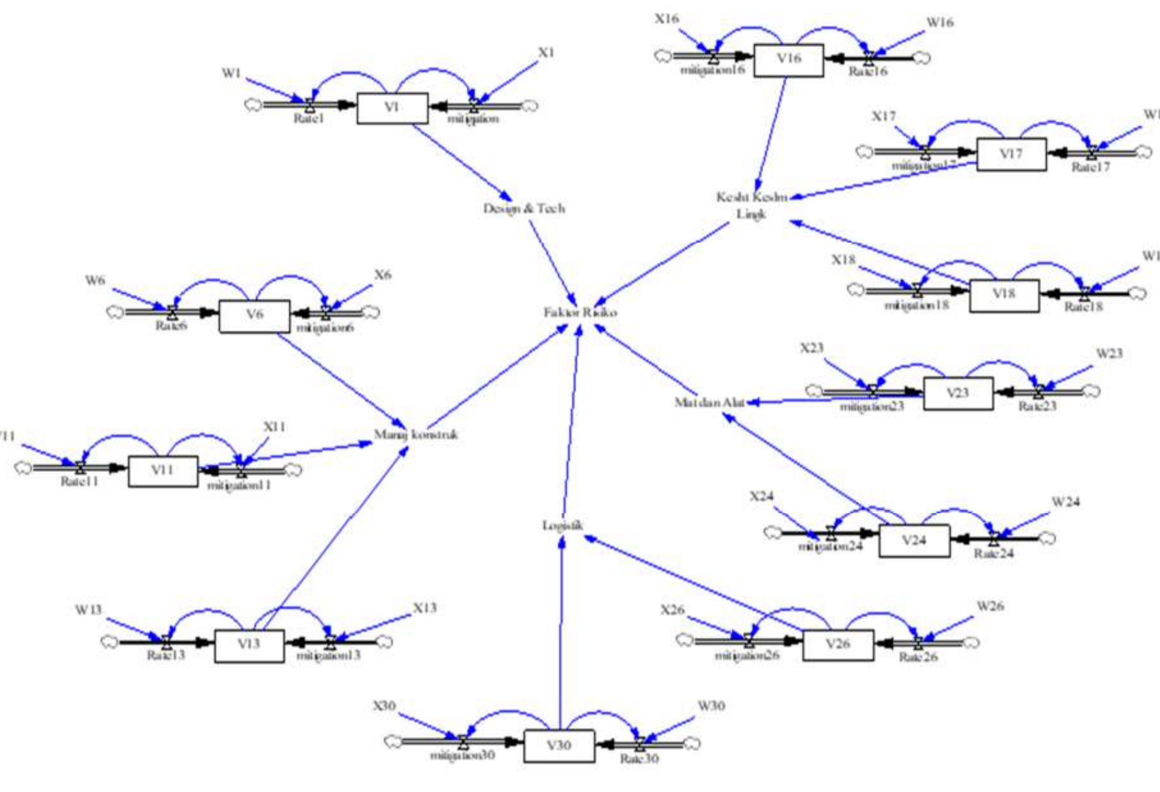

Figure 2. Stock Flow Diagram of Risk Factor Model

survey with project workers. To test the structure of the model based on the behavior of the model, it can be done by comparing the causal relationship between the variables in the

CLD with the variable graph of the simulation results. Figure 3 shows a causal relationship in loop V1. Variables V1 and Rate1 form a reinforcing loop while V1 and mitigation1 form a balancing loop. In this model, mitigation1 has a higher value so the graph shows a downward trend. The Figure 3 shows the variables that make up the value of the Risk Factor, namely the variables of Design and Technology, Work Safety and Environment, Logistics, Construction Management, Materials and Tools. All variables have a positive effect on the Risk Factor so that the simulation results are in accordance with the causal relationship of the Risk Factor.

3. Dimension consistency. This test is conducted to find out that all units used in the model are dimensionally consistent. Vensim software provides a feature that can detect errors when there are inconsistent unit dimensions. The unit model detection results from the Vensim software show that the unit dimensions are consistent.

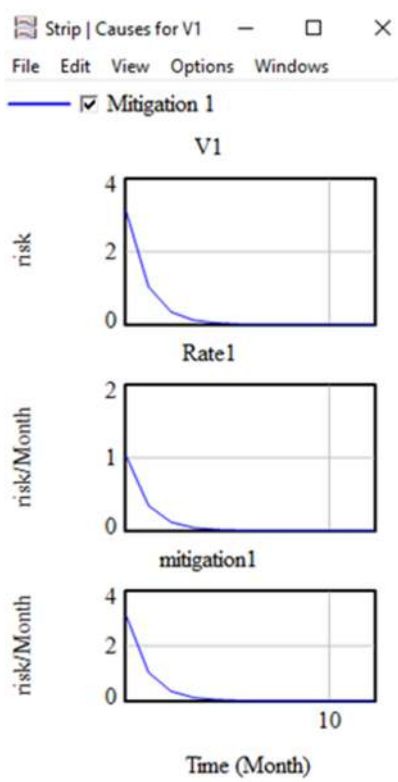

Figure 3. Graph of Cause-and-Effect Relationships in V1

4. Extreme conditions. In this test, the value of the model variable is changed in an extreme position. Figure 5 shows three simulated mitigation value conditions. The base run has a value that matches the conditions on the field. The lowest mitigation has the lowest mitigation value (0). The highest mitigation has the highest mitigation value (1). From the extreme condition simulation results, the higher the

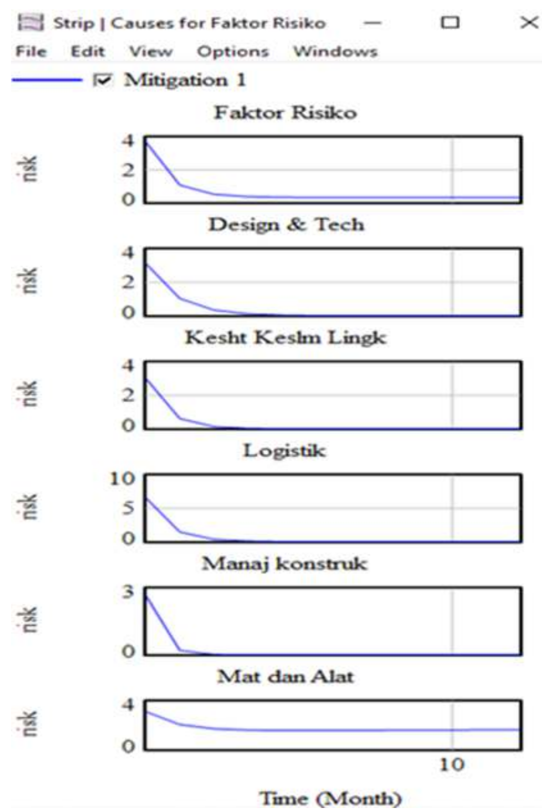

Figure 4. Graph of Cause-and-Effect Relationships on Risk Factors

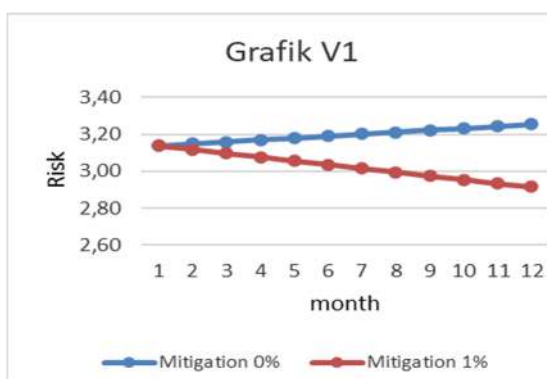

Figure 5. Graphics of extreme conditions

mitigation value, the lower the V1 parameter value. This result is in accordance with the causal relationship that the mitigation variable has a negative effect on the value of V1.

Base run simulation is based on the actual condition of the model based on data obtained from the field. The model is simulated in a period of twelve months according to the project life. The simulation results are shown in Figure 6.

From the Risk Factor graph, if no mitigation is carried out to overcome the risks during project work, then the risk will increase by approximately 3.33% at the end of project work. The overall Likert value of project risk is at a value of 3 so it is included in the medium category. Figure 7 shows a graph of the variables that affect the presence of risk factors.

From Figure 7 the variables with an increasing trend of increasing risk are the Design and Technology variable, the Work Safety and Environment variable, and the logistics variable. The variables with the highest initial risk but showing a decreasing trend are the Construction Management variable and the Materials and Tools variable. By looking at the graph, management can make decisions to prioritize variables that have a rising trend for optimal mitigation. If viewed as a percentage, the percent increase or decrease in risk for each variable is shown in Table 6.

Sensitivity analysis is used to determine how sensitive a model is to changes in model parameter values and changes in model structure (Yuan, 2012). Using sensitivity analysis will be able to know more about the effect of the model on the various responses given. In this model, the effect on the Risk Factor model will be analyzed if the value of the mitigation variable is changed to find out how much mitigation effort must be made by the project manager so that the risks in the project can be minimized. In addition, the magnitude of the influence of each variable causing the Risk Factor will be analyzed to determine the mitigation priorities that can be carried out by the project manager.

Figure 6. Graph of Base Run Risk Factors

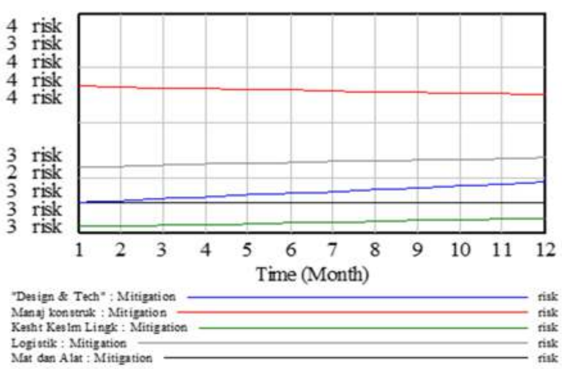

Figure 7. Graph of the variables that affect the presence of risk factors

Table 6. Percentage Increase/Decrease in Variable Risk Value

No	Risk Parameters	Percentage
1	Design and Technology	9,09 %
2	Constrcution Management	-3,77 %
3	Work Safety dan Environment	3,97 %
4	Materials and Equipment	-0,08 %
5	Logistics	4,03 %

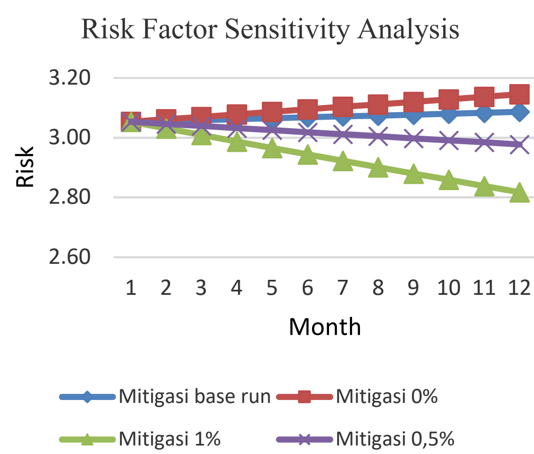

Figure 8. Risk Factor Sensitivity Analysis

In the first sensitivity analysis, the mitigation value of all variables will be converted into three values, namely the base run value or the value according to conditions in the field, a value of 0.5%, and a value of 1%. The results of the first sensitivity analysis can be seen in Figure 8.

From Figure 8 in project work in the field, with the mitigation that has been carried out, the risk value still has an upward trend and has a slight difference with the risk value of the model that is not mitigated. When the mitigation value of all variables is changed to 0.5%, the risk factor value has started to show a decline but still has not touched the zero point or there are still risk factors at the end of the project. Likewise, with the 1% mitigation value, the risk reduction trend is higher than the 0.5% mitigation value but there is still a potential risk at the end of the project with a risk value of 2.9 from the highest value of 5. This means that even though the project manager has carried out maximum mitigation on all risk parameters, the risk will still exist until the end of the project work.

The second sensitivity analysis was carried out with three scenarios to determine the most influential variables on the value of risk factors so that they can be prioritized for maximum mitigation. The scenarios carried out are as follows: (1) Increase the maximum mitigation value (1%) of variables that have a downward risk trend, (2) Increase the maximum mitigation value (1%) of variables that have an upward risk trend, and (3) Increase the maximum mitigation value (1%) for each variable

In the first scenario, there are 2 variables whose mitigation value is maximized, namely the Construction Management variable and the Materials and Tools variable, while the mitigation value of the other variables is still the same as the base run mitigation value. The simulation results in the first scenario are shown in Figure 9 and Figure 10 The first scenario can reduce the risk value by 8.48% from the base run risk value.

The second scenario uses 3 risk parameters, namely Design and Technology, Work Safety and Environment, and Logistics, while the other two risk parameters are made equal to the values in the base run. The results of the second scenario

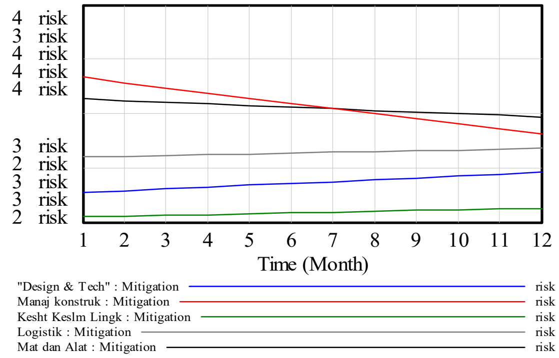

Figure 9. Graph of All First Scenario Variables

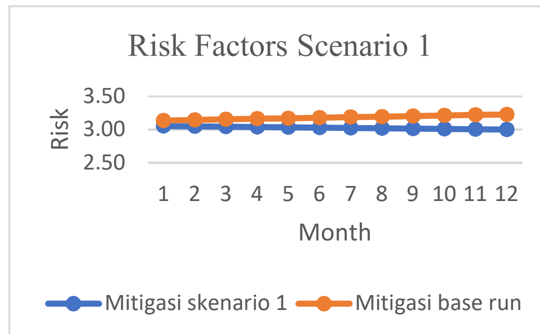

Figure 10. Comparison Graph of Scenario 1 Risk Factors with Base Run

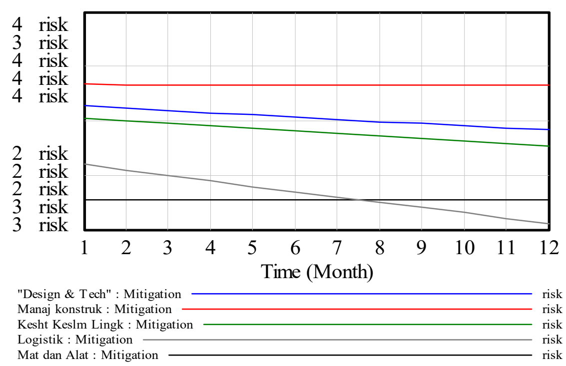

Figure 11. Graph of All Second Scenario Variables

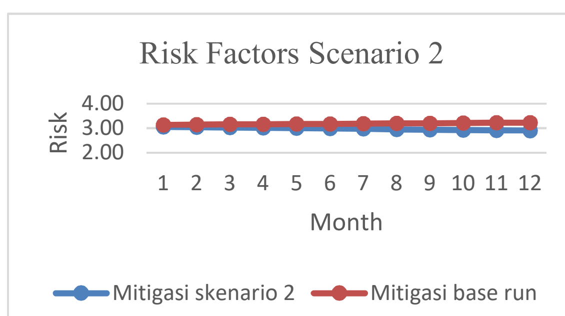

Figure 12. Comparison Graph of Scenario 2 Risk Factors with Base Run

simulation can be seen in Figure 11 and Figure 12 The second scenario can reduce the risk value by 18.43% from the base run risk value. The value of this decrease is greater than the decrease in the first scenario because there are three variables with an increase in high-risk factors for which maximum mitigation is carried out.

In the third scenario, maximum mitigation is carried out on each risk parameter and leaves the other parameters having the same value as the base run value. For example, in the Design and Technology variable, the mitigation is maximized, and other variables have the same value as the base run mitigation value. Figure 13 shows the results in the third scenario. From the graph in Figure 13 the para meters that have decreased the most are the Logistics and Design and Technology parameters. So that the parameters that have the greatest influence on the value of risk factors are the Logistics and Design and Technology parameters.

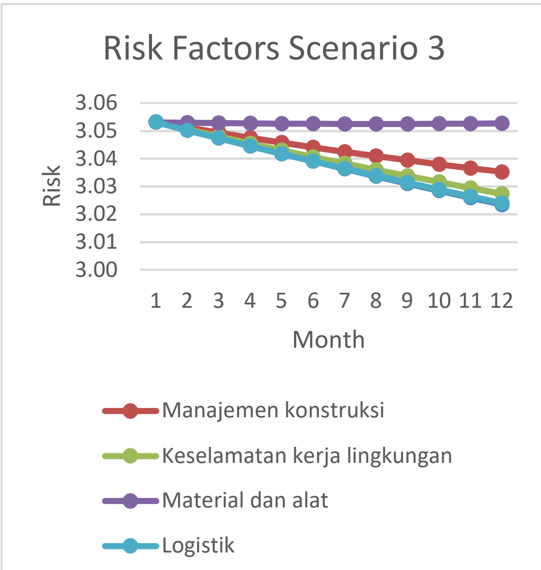

Figure 13. Shows the results in the third scenario

Table 7. Percentage Increase/Decrease in Risk Factor Value

Scenario	Percentage Increase/Decrease
First Sensitivity Analysis	
Mitigation 0%	5,93 %
Mitigation 0,5%	-10,90 %
Mitigation 1%	-26,91 %
Second Sensitivity Analysis	
Scenario 1	-8,48 %
Scenario 2	-18,43 %
Scenario 3	
• Design and Technology	-6,29 %
• Constrcution Management	-5,12 %
• Work Safety dan Environment	-5,90 %
• Materials and Equipment	-3,37 %
• Logistics	-6,23 %

The steeper the downward/increasing trend of the graph, the higher the potential to reduce the potential risk if mitigation is carried out. The project manager can prioritize the variables that have the highest increase/decrease value to reduce the risk value at the end of the project.

The results of the comparison of the value of the increase or decrease in the risk value for all scenarios can be seen in Table 7.

From the results of the Table 7, the highest decrease occurred in the model that maximally reduced all the variables causing the risk factors. However, if the project manager is not able to reduce all variables, then the variable with the highest increase/decrease value can be prioritized.

The results of simulation modelling can be used as a reference in determining strategies in preventing risks from occurring. System modeling is carried out to simulate all possible identified risks and determine strategies for dealing with risks. One of the mitigations that can be done to minimize the risk of changing the design of working drawings is to detect design errors from the start. If there are errors or omissions or design changes during project work, then what must be done is to create an effective system for checking and reviewing design documents (Anees et al., 2013).

System modeling has an important role in the risk management process in simulation and risk optimization. Research is needed by combining several methods and integrating advances in digital system technology to support the implementation of risk management in the success of project objectives.

IV. CONCLUSION

Some conclusions that can be drawn from risk management research and dynamic system simulations can evaluate the implementation of risk mitigation initiatives to increase the productivity of occupational safety and health. The use of risk management simulation in project management can estimate all project risks to the end and take the most optimal mitigation decisions to minimize project risks. Stage 3 simulation model illustrates that 2 risk parameters experienced a very significant decrease in design and technology by -6.29% and Logistics -6.23%. Simulations help project leaders and the Occupational Health and Safety division in making quick decisions as well as risk mitigation efforts. The prioritized variables to be lowered are those with the highest percentage increase/decrease. In improving the performance of occupational safety and health, a structured handling pattern is needed and considers the interaction between risk factors that influence each other. The role of the project manager is emphasized in building and encouraging communication for all project teams to be active in identifying risks and caring about risks because they are all integral parts of the success of a project.

ACKNOWLEDGEMENTS

Thank you to the Institut Teknologi Telkom Purwokerto for providing the costs and project implementing contractors providing opportunities in the research process as well as those who have assisted in completing the research.

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