






## Enhancing Risk Assessment in Toll Road Operations: A Hybrid Rough Delphi-Rough DEMATEL Approach

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### Abstract

This study aims to identify significant risks and their relationship to the successful operation of the Trans-Sumatra toll road in Indonesia. The research utilizes the Delphi and DEMATEL methods, along with rough set analysis, to identify and evaluate 28 risks associated with toll road operations in Sumatra. The research identifies 13 dominant risks, including policy changes, government intervention, inflation, financial distress, fluctuation of interest rate, fluctuation of currency, high cost of maintenance, low volume of traffic, competitive routes, overloading vehicles, many infrastructure defects, and natural disasters. In this case, natural disasters, inflation, and vehicles with excessive loads are the most dominant cause factors because those risks have the highest cause value based on the cause-effect diagram. Furthermore, the prominence diagram reveals that income risk, policy changes, and financial distress have notable implications for operational activities. The study presents a MCDM risk assessment approach that incorporates rough set analysis, providing a comprehensive understanding of the critical risk relationship factors for toll road operations. By integrating rough set analysis, this research contributes to the field of toll road operations and risk assessment. The identified risks and their relationships serve as a foundation for developing effective strategies for toll road operational management.

*Keywords:* Toll Road Operations; Risks; Rough Set; Delphi; DEMATEL; MCDM.

## 1. Introduction

Toll roads are public roads that are part of the national road network system for which a fee is required at toll gates for passage and have a very significant role in the development of an area. In other words, toll roads are highways and national roads capable of supporting the economy. The Jakarta-Bogor-Ciawi Toll Road, or Jagorawi Toll Road, is Indonesia's first toll road, built in 1973, connecting Jakarta-Bogor-Ciawi. This toll road is managed by a state-owned enterprise and passes through East Jakarta City, Depok City, Bogor City, and Bogor Regency [1]. To support national connectivity and strengthen competitiveness, the Ministry of Public Works and Public Housing plans the construction of highways. The Trans-Sumatra Toll Road (TSTR) is one of the toll road networks in Indonesia that is projected to connect cities on Sumatra Island [2], from Lampung Province to Aceh Province, with the hope of increasing the distribution of goods and services to meet the basic needs of the people on the island.

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In addition, the Trans Sumatra Toll Road (TSTR) is a national project launched by the government of President Joko Widodo, which is intended to improve the Indonesian economy and public relations between cities, provinces, and islands in the Republic of Indonesia for the better [3], as set forth in the Strategic Plan of the Ministry of Public Works and Public Housing 2020–2024. There are 5 Sumatran toll roads that have been operating, namely Medan–Binjai for 17 km, Pekanbaru–Dumai for 131 km, Palembang–Inderalaya for 22 km, Tanjung Balai–Kayu Agung for 141 km, and Bakauheni–Tembaggi Besar for 140.94 km. As a busy, long, and new-operational road, the field's risk management must be well-coordinated to resolve or mitigate the risks quickly.

Operational risks refer to events or incidents that negatively affect the operational stage. In other words, operational risks significantly impact the effectiveness and efficiency of operational activities designed to improve the operating system if they occur. Several potential factors can affect the occurrence of operational risks in projects such as toll roads [4]. The assessment of operational risks on toll roads is important in ensuring these critical transportation infrastructures' smooth and efficient functioning. Assessing operational risks allows the stakeholder to understand the potential risks specific to toll road operations. It enables them to evaluate the importance of various risks and prioritize their management efforts accordingly. Toll road management can proactively identify and mitigate risks by conducting a thorough risk assessment before they escalate into costly issues.

A study conducted on operational toll road risks in Malaysia by Ghazali [4] identified 13 operational risks, of which only one had a high probability of occurring frequently, namely the issue of tariffs determined by the government. According to an interview with the Malaysia Highway, among the significant operational risks that could occur in highway projects in Malaysia are the initial toll tariff determined by the government, traffic congestion, alterations in road networks, and the transportation of overloaded freight. These factors have the potential to cause damage to the road surface, thereby impacting the smooth operation of a specific highway.

In Suseno's [1] study, which investigated the operational risks of toll roads in the Semarang–Solo region, the analysis focused on various aspects. The research examined the probability and impact of each risk subcategory and calculated a severity index based on input from toll road operators. By combining responses from a group of respondents, the severity level of each risk was determined. The study's findings indicated that the toll road operational phase introduced unpredictable risks. Additionally, toll road operators in the Semarang–Solo area encountered different levels of severity for various risks. Notably, the operator of Section 1 of the Semarang–Solo toll road identified high overhead costs resulting from ineffective maintenance as the only risk considered non-tolerable thus far.

Furthermore, in research conducted by Likhitrungsilp et al. [5] and Sy et al. [6] in Vietnam, six risks were identified during the operation of toll roads. Revenue risk and tariff issues are major risks that have an impact on the cash flow that occurs during the operational period. In Indonesia, Wirahadikusumah et al. [7] found that the risk of vehicle loads and competitive routes are the dominant operational risks feared by toll road companies. Furthermore, they suggested that these risks be included in the assessment assumptions in the toll road concession document. The goal is to avoid overlapping risk allocations and to filter out the possibilities where the two main risks can be included in the document.

However, from the previous study, it has been determined that the first obstacle to the operational risk management of toll roads revolves around the neglect of risk interdependence. Previous research has primarily treated toll road operation risks as independent factors. However, these studies still need to uncover the interdependencies between risks and their effects on the toll road operational stage. This becomes particularly important in the context of toll roads, which face numerous interactions between risks. Taking risk interdependence into account during risk assessment can greatly enhance the effectiveness of risk management [8] and is a crucial aspect of toll road operations.

The second challenge pertains to the subjective nature of risk assessment [9]. Decision-makers in the toll road industry often rely on personal experience, intuition, and individual risk preferences to gauge the importance of risks. While this approach may be suitable for toll road operations with similar personal intuition, individual, and experience risk preferences, identifying comparable toll road operations based solely on personal experience becomes increasingly complex, leading to inconsistencies and subjectivity in risk assessments for toll road operations.

To overcome these challenges and since studies that focus on operational and maintenance risks on toll roads are still lacking, therefore, this study focused on identifying operational risks that impact toll road development. Utilizing methods such as rough Delphi and rough DEMATEL can be valuable. Rough Delphi involves a systematic process of gathering expert opinions on toll road operations. By involving domain experts and stakeholders, it becomes possible to identify and evaluate risks more effectively. Additionally, rough DEMATEL is a technique that allows decision-makers to quantify the relationships and influence between different risk factors in toll road operations. By employing these methodologies, decision-makers can develop a more comprehensive understanding of risk interdependence and the rough set theory used to minimize subjectivity in the risk assessment process [10].

## 2. Material and Method

### 2.1. Rough Set Theory

In rough number theory, assumptions in calculations cannot be inferred with certainty but are limited by upper limits and lower limits [11].

$$\overline{APR}(r_{ij}^k) = U(X \in U/R(X) \geq r_{ij}^k) \quad (1)$$

$$\underline{APR}(r_{ij}^k) = U(X \in U/R(X) \leq r_{ij}^k) \quad (2)$$

U represents a set comprising all evaluation elements, while X denotes any element belonging to U, then the assumption from the respondents  $r_{ij}^k$  can be calculated as lower limit  $\underline{Limit}(r_{ij}^k)$  and upper limits  $\overline{Limit}(r_{ij}^k)$  with the formula:

$$\underline{Limit}(r_{ij}^k) = \frac{1}{N_l} \sum_{m=1}^{N_l} R(X) | X \in \underline{Apr} r_{ij}^k | \quad (3)$$

$$\overline{Limit}(r_{ij}^k) = \frac{1}{N_u} \sum_{m=1}^{N_u} R(X) | X \in \overline{Apr} r_{ij}^k | \quad (4)$$

In addition, it can be illustrated by the equation below [12]:

$$RN(r_{ij}^k) = [\overline{Limit}(r_{ij}^k), \underline{Limit}(r_{ij}^k)] = [r_{ij}^u, r_{ij}^l] \quad (5)$$

Then

$$RN(r_{ij}^k) = ([r_{ij}^{1l}, r_{ij}^{1u}], [r_{ij}^{2l}, r_{ij}^{2u}], \dots, [r_{ij}^{ml}, r_{ij}^{mu}]) \quad (6)$$

### 2.2. Rough DELPHI Method

The Delphi method is a widely used forecasting technique that aims to provide informed projections about complex or uncertain future situations. It involves gathering the opinions and knowledge of a panel of experts, typically consisting of 5 to 10 experts, who are well-versed in the relevant topic [13, 14]. In this case, the experts are asked to complete qualitative or quantitative questionnaires to obtain relatively accurate information and opinions about the future. This method is particularly useful in cases where objective statistical data or formal methods are insufficient for measuring or analyzing the phenomenon [15, 16]. In addition, the Delphi method is also essentially a refined version of traditional expert opinion-gathering techniques, such as brainwriting and surveying. It was developed in the 1950s as a means of obtaining expert opinions in a systematic and structured way through multiple rounds of communication and questionnaires [17, 18]. Stevic et al. [11] developed the rough set-based Delphi method. This method aims to leverage the advantages of both concepts and enable the determination of weight values of the criteria in an efficient manner. The proposed approach is specifically applied in the field of transport to evaluate key performance indicators and minimize the effects of subjectivity and ambiguity.

The Rough Delphi method was designed to provide a more objective and accurate evaluation of the performance indicators by incorporating the expertise of a panel of experts and utilizing a rough set theory to analyze the data. This approach is expected to offer an effective and reliable means of evaluating the performance indicators, and thus help to improve decision-making in every problem.

### 2.3. Rough DEMATEL Method

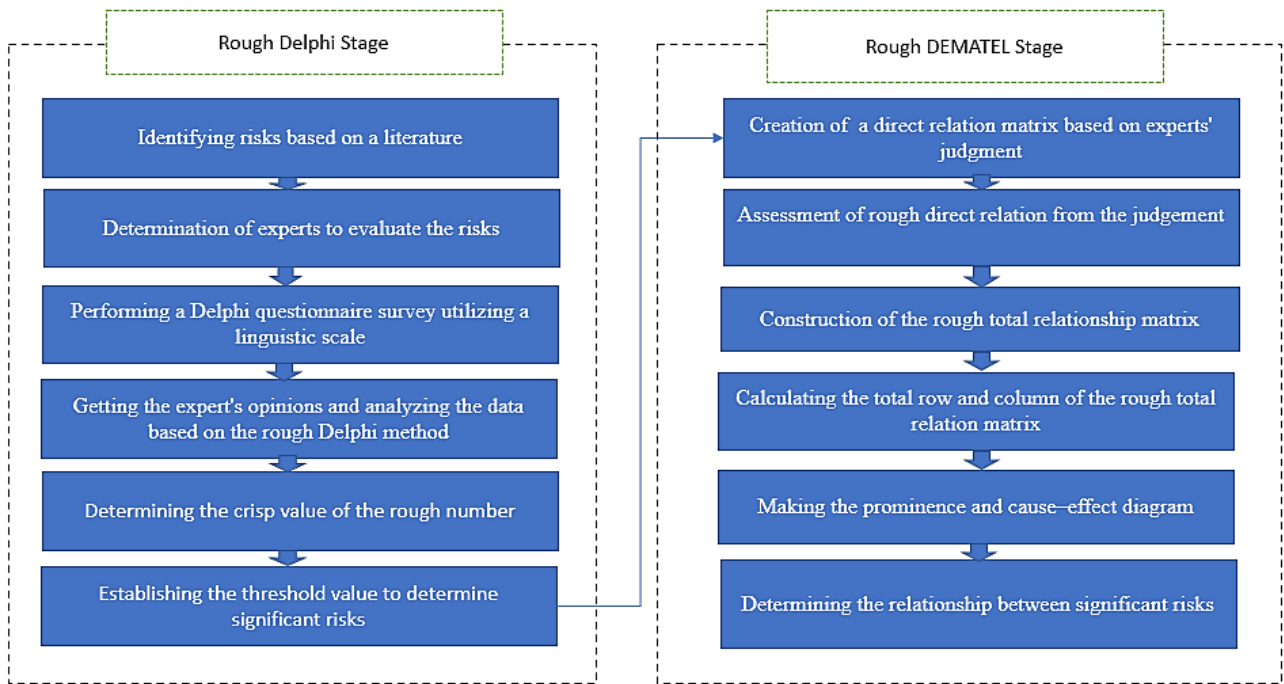
DEMATEL is an abbreviation of Decision-Making Trial and Evaluation Laboratory, which is one of the analysis methods employed to solve problems and make decisions. This method was developed in 1970 by Fontela and Gabus, and is primarily used in management, industrial engineering, and other fields related to decision-making. DEMATEL is a powerful tool for analyzing complex systems by considering both the direct and indirect relationships among factors [19, 20]. This method not only converts interdependent relationships between groups into cause and effect through matrices, but also finds critical factors in a complex system of structures with the help of an impact relationship diagram [19]. Due to its advantages and capabilities, the DEMATEL approach has received a lot of attention and many researchers have applied it to solve complex system problems in various fields [21, 22]. Additionally, it has been expanded for better decision-making under different environments because many real-world systems include imprecise and uncertain information [23].

However, the conventional DEMATEL method assumes equal importance for all evaluation criteria when analyzing their relationships. This approach needs to reflect real-world situations due to language uncertainty and subjectivity, such as in other conventional MCDM techniques [24-26].

To address this issue, Song & Cao [12] developed a new approach that integrates rough set theory with the DEMATEL method for evaluating the interaction between requirements of a product-services system. This new method takes into account the relationships between different evaluation criteria, the rough set theory is used to minimize the information's subjectivity and uncertainty, thereby providing a more accurate evaluation.

**2.4. Rough Set based Delphi-DEMATEL Method**

In order to elucidate the intricacies of the rough Delphi and rough DEMATEL methods, a flowchart has been prepared. This graphical representation serves as a comprehensive guide, outlining each sequential step involved in implementing these methodologies and depicting the intricate relationships and interdependencies between different stages. The flowchart of the research methodology that was used to achieve the study's aims is shown in Figure 1.



**Figure 1. The Rough Delphi and Rough DEMATEL Flow Charts**

In this section, rough Delphi was proposed to achieve the objectives of this study. The steps of the rough Delphi method are presented below:

Step 1. Gathering potential risks. Finding the potential risks involves a comprehensive review of relevant literature to collect and classify all identified risks.

Step 2. Determination of expert selection by identifying a group of experts who have at least 10 years of experience and at least a bachelor's degree to evaluate the risks.

Step 3. Performing a Delphi questionnaire survey utilizing a linguistic scale. In this step, the n expert team evaluates the criteria by the Likert scale with number values specified. The scale is a 0-1 interval, where 0 means Very Not Important, 0.25 means Not Important, 0.5 means Moderately Important, 0.75 means Important and 1 means Very Important.

Step 4. The rough number formulation of  $RN (d_i^k)$  can be expressed with the following equation [25].

$$RN (d_i^k) = [Limit (d_i^k), \overline{Limit} (d_i^k)] = [d_i^{Kl}, d_i^{Ku}] \tag{7}$$

Then, the rough number  $RN (d_i^k)$  can be illustrated in the following equation:

$$Limit (d_i^k) = \frac{1}{N_{il}} \sum_{m=1}^{N_{il}} a_i \tag{8}$$

$$\overline{Limit} (d_i^k) = \frac{1}{N_{iu}} \sum_{m=1}^{N_{iu}} b_i \tag{9}$$

$a_i$  and  $b_i$  describe the lower and upper approximations of  $d_i^k$ , therefore the rough group can be obtained by the average of the rough interval using the following equation with  $m$  experts:

$$RN (\bar{d}_i) = [\bar{d}_i^l, \bar{d}_i^u] \tag{10}$$

Then,

$$\bar{d}_i^l = \frac{1}{m} \sum_{k=1}^m d_i^{kl} \tag{11}$$

$$\bar{d}_i^u = \frac{1}{m} \sum_{k=1}^m d_i^{ku} \tag{12}$$

The value of  $\bar{d}_i^u$  is the average of the upper limit and the value of  $\bar{d}_i^l$  is the average of the lower limit.

Step 5. Determining the crisp value. For the rough Delphi method, the crisp value will be defined based on the following equation:

$$d_i^{der} = \frac{\bar{d}_i^l + \bar{d}_i^u}{2} \tag{13}$$

Step 6. Determining important risks. The important risks will be identified based on  $d_i^{der} > 0.7$ . If it is below 0.7, then it is not significant. According to previous studies that value is a value that is often used to determine the number of thresholds for the fuzzy Delphi method [27-29].

Step 7. Measuring the relationship between interrelated risks. In this stage, an assessment of the intensity of the relationship between factors was carried out to determine the impact and effectiveness of the relationship. The size of the rating scale varies depending on the intent and purpose of the researcher. The larger the rating scale, the greater the probability that the expert will assess the DEMATEL questionnaire. The scale shown is 0-1, where 0 means no relation and effect, 0.25 means low effect, 0.5 means medium effect, 0.75 means high effect, and 1 means very high effect.

Step 8. Assessing the relationship and impact. Based on the expert's assessment of the relationship and impact, the list was made into the direct relationship matrix. At this stage, if there is more than one expert who makes an assessment, then the average rough value between the experts is sought. In the matrix,  $Z_{ij}$  is the impact of the effects i on j, while the main diagonal line of the matrix is set as 0 as done by Kiani Mavi & Standing [30] and previous studies.

$$Z^{(k)} = \begin{bmatrix} 0 & Z_{12}^{(k)} & \dots & Z_{1n}^{(k)} \\ Z_{21}^{(k)} & 0 & \dots & Z_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1}^{(k)} & Z_{n2}^{(k)} & \dots & 0 \end{bmatrix} \tag{14}$$

where  $Z_{ij}^{(k)}$  is the assessment of crisp numbers from respondents k<sup>th</sup>, then,  $Z^{(k)}$  direct relationship matrix can be described as below:

$$Z^{(k)} = \begin{bmatrix} \{0,0 \dots, 0\} & \{z_{12}^{(1)}, z_{12}^{(2)} \dots, z_{12}^{(m)}\} & \dots & \{z_{1n}^{(1)}, z_{1n}^{(2)} \dots, z_{1n}^{(m)}\} \\ \{z_{21}^{(1)}, z_{21}^{(2)} \dots, z_{21}^{(m)}\} & \{0,0 \dots, 0\} & \dots & \{z_{2n}^{(1)}, z_{2n}^{(2)} \dots, z_{2n}^{(m)}\} \\ \vdots & \vdots & \ddots & \vdots \\ \{z_{n1}^{(1)}, z_{n1}^{(2)} \dots, z_{n1}^{(m)}\} & \{z_{n2}^{(1)}, z_{n2}^{(2)} \dots, z_{n2}^{(m)}\} & \dots & \{0,0 \dots, 0\} \end{bmatrix} \tag{15}$$

Step 9. Assuming that there is a set of m classes of human judgments  $Z_{ij}^{(k)} = \{z_{ij}^1, z_{ij}^2, \dots, z_{ij}^m\}$ , ordered in the manner of  $z_{ij}^1 < z_{ij}^2 < \dots < z_{ij}^m$ , U represents a set comprising all evaluation elements, while X denotes any element belonging to U, Then the lower and the upper approximation can be described with the following formulation:

$$\overline{APR}(Z_{ij}^k) = U(X \in U / R(X) \geq Z_{ij}^k) \tag{16}$$

$$\underline{APR}(Z_{ij}^k) = U(X \in U / R(X) \leq Z_{ij}^k) \tag{17}$$

Step 10. Constructing the rough direct relation matrix. Assumptions in calculations cannot be inferred with certainty but are limited by upper limits and limits.  $x_{ij}$  and  $y_{ij}$  describe the lower and upper approximations of  $z_{ij}^k$  and it can be illustrated with the following formulation:

$$\underline{Limit}(z_{ij}^k) = \frac{1}{N_{ijl}} \sum_{m=1}^{N_{ijl}} x_{ij} \tag{18}$$

$$\overline{Limit}(z_{ij}^k) = \frac{1}{N_{iju}} \sum_{m=1}^{N_{iju}} y_{ij} \tag{19}$$

$\overline{Limit}(z_{ij}^k)$  and  $\underline{Limit}(z_{ij}^k)$  describe the rough number value of each respondent judgment and it can be illustrated with the following formulation:

$$RN(Z_{ij}^k) = [\underline{Limit}(z_{ij}^k), \overline{Limit}(z_{ij}^k)] = [z_{ij}^{kl}, z_{ij}^{ku}] \tag{20}$$

Thus, the direct relationship measured from each respondent can be described as follows:

$$RN(\tilde{Z}_{ij}) = [\bar{Z}_{ij}^l, \bar{Z}_{ij}^u] \tag{21}$$

Therefore, the rough group can be obtained by the average of the rough interval using the following equation with m experts

$$\bar{Z}_{ij}^l = \frac{1}{m} \sum_{k=1}^m z_{ij}^{kl} \tag{22}$$

$$\bar{Z}_{ij}^u = \frac{1}{m} \sum_{k=1}^m z_{ij}^{ku} \tag{23}$$

The value of  $\bar{Z}_{ij}^u$  is the average of the upper limit and the value of  $\bar{Z}_{ij}^l$  is the average of the lower limit. Then, the direct relation matrix with the rough set can be obtained below

$$\bar{Z}^l = \begin{bmatrix} 0 & \bar{Z}_{12}^l & \dots & \bar{Z}_{1n}^l \\ \bar{Z}_{21}^l & 0 & \dots & \bar{Z}_{2n}^l \\ \vdots & \vdots & \ddots & \vdots \\ \bar{Z}_{n1}^l & \bar{Z}_{n2}^l & \dots & 0 \end{bmatrix} \tag{24}$$

$$\bar{Z}^u = \begin{bmatrix} 0 & \bar{Z}_{12}^u & \dots & \bar{Z}_{1n}^u \\ \bar{Z}_{21}^u & 0 & \dots & \bar{Z}_{2n}^u \\ \vdots & \vdots & \ddots & \vdots \\ \bar{Z}_{n1}^u & \bar{Z}_{n2}^u & \dots & 0 \end{bmatrix} \tag{25}$$

Step 11. Making the normalized matrix after finding the direct relationship of the rough numbers, the matrix is normalized with the equation below:

$$\check{Z} = \begin{bmatrix} \overline{RN(\tilde{Z}_{11})} & \overline{RN(\tilde{Z}_{12})} & \dots & \overline{RN(\tilde{Z}_{1n})} \\ \overline{RN(\tilde{Z}_{21})} & \overline{RN(\tilde{Z}_{22})} & \dots & \overline{RN(\tilde{Z}_{2n})} \\ \vdots & \vdots & \ddots & \vdots \\ \overline{RN(\tilde{Z}_{n1})} & \overline{RN(\tilde{Z}_{n2})} & \dots & \overline{RN(\tilde{Z}_{nn})} \end{bmatrix} \tag{26}$$

The value of  $\overline{RN(\tilde{Z}_{ij})}$  is obtained from the equation below:

$$\overline{RN(\tilde{Z}_{ij})} = \frac{RN(\tilde{z}_{ij})}{\gamma} = \left\{ \frac{\bar{z}_{ij}^l}{\gamma}, \frac{\bar{z}_{ij}^u}{\gamma} \right\} \tag{27}$$

where:

$$\gamma = \max_{1 \leq i \leq n} (\sum_{j=1}^n RN(\tilde{Z}_{ij})) \tag{28}$$

The  $\check{Z}$  matrix that has been created was then built in direct and indirect matrix relations.

Step 12. Constructing the group total relation matrix. The total relation matrix is obtained by using the equation:

$$RN(\tilde{T}_{ij}) = [T_{ij}^l, T_{ij}^u] \tag{29}$$

$$\tilde{T} = \check{Z} \cdot (I - \check{Z})^{-1} \tag{30}$$

From the equation above, the results are obtained as follows:

$$\tilde{T} = \begin{bmatrix} RN(\tilde{T}_{11}) & RN(\tilde{T}_{12}) & \dots & RN(\tilde{T}_{1n}) \\ RN(\tilde{T}_{21}) & RN(\tilde{T}_{22}) & \dots & RN(\tilde{T}_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ RN(\tilde{T}_{n1}) & RN(\tilde{T}_{n2}) & \dots & RN(\tilde{T}_{nn}) \end{bmatrix} \tag{31}$$

Next, the calculation of the prominence and the cause-effect diagram was carried out.

Step 13. Calculating the total row and column of the rough total relation matrix. After creating the  $\tilde{T}$  matrix, then the total row  $RN(R_i)$  and total column  $RN(C_j)$  were calculated using the following equation:

$$RN(R_i) = (R_i^l, R_i^u) = ([\sum_{j=1}^n RN\{\tilde{T}_{ij}\}]) = ([\sum_{j=1}^n (T_{ij}^l)], [\sum_{j=1}^n (T_{ij}^u)]) \tag{32}$$

$$RN(C_j) = (C_j^l, C_j^u) = ([\sum_{i=1}^n RN\{\tilde{T}_{ij}\}]) = ([\sum_{i=1}^n (T_{ij}^l)], [\sum_{i=1}^n (T_{ij}^u)]) \tag{33}$$

Step 14. Calculating the crisp value based on the total value of the row and column in rough numbers. The crisp value of the rough set number is carried out with the Equation 34 o 38. Therefore, the determination of the crisp value for the rough DEMATEL method uses the following equation:

$$\tilde{R}_i^l = (R_i^l - \min_i R_i^l) / \Delta_{Min}^{Max} \tag{34}$$

$$\tilde{R}_i^u = (R_i^u - \min_i R_i^l) / \Delta_{Min}^{Max} \tag{35}$$

$$\Delta_{Min}^{Max} = \max_i R_i^u - \min_i R_i^l \tag{36}$$

$\min_i R_i^l$  is the smallest value of  $R_i^l$  and  $\max_i R_i^u$  is the *max* value of  $R_i^u$ . Furthermore, the beta value of the following equation was determined:

$$\beta_i = \frac{\tilde{R}_i^l \times (1 - \tilde{R}_i^l) + \tilde{R}_i^u \times \tilde{R}_i^u}{1 - \tilde{R}_i^l + \tilde{R}_i^u} \tag{37}$$

Then the final crisp value was also determined using the following equation:

$$\tilde{R}_i^{der} = \min_i R_i^l + \beta_i \cdot \Delta_{Min}^{Max} \tag{38}$$

In this case, the value of  $\tilde{C}_j^{der}$  can be determined with a similar formula.

Step 15. Making the prominence and cause–effect diagram. The prominence and cause–effect diagram was drawn after obtaining the horizontal axis  $\tilde{R}_i^{der}$  and the vertical axis  $\tilde{C}_j^{der}$ . Meanwhile,  $(\tilde{R}_i^{der} + \tilde{C}_j^{der})$  refers to the prominence among criteria and  $(\tilde{R}_i^{der} - \tilde{C}_j^{der})$  refers to the influence relation among criteria.

$$Prominence = \tilde{R}_i^{der} + \tilde{C}_j^{der} \tag{39}$$

$$Cause\ and\ Effect = \tilde{R}_i^{der} - \tilde{C}_j^{der} \tag{40}$$

Step 16. Determining the relationship between significant risks. After identifying the causal and effect variables, the next step is determining the direction of the relationships between these variables. According to Zhang et al. [21], the first step to finding the relationships is to create crisp values from Equations 34 to 38. The direction of the relationships between variables is determined based on the significance of the total values generated in the previous step, which have values greater than the threshold value. According to Roy et al. [31], the threshold value can be determined as follows:

$$Threshold\ Value = \frac{\sum_{i=1}^n \sum_{j=1}^n RN(\tilde{T}_{ij})}{w} \tag{41}$$

where, *w* denotes the number of rough matrix elements, after that, identifies the relationships between variables with a total value greater than the threshold value. The relationships between variables with a total value above the threshold value indicate variables that significantly influence other variables.

By determining the relationships between variables in the total relationship map, a clearer understanding of the structure and interactions between variables can be obtained, thus aiding in more accurate decision-making in a system.

### 3. Case Study

The research framework for evaluating operating risks on rough-based Delphi and DEMATEL for toll road operations is divided into 2 stages, namely identifying risks that occur at The Trans-Sumatera Toll Road in the operational stage based on relevant literature reviews. Then, the rough Delphi was used to identify significant risks. The Delphi panel consisted of academia, government, and toll road owner companies. The second stage is identifying the relationship as well as indicators, which is the impact or cause, and finding the relationship between indicators with the rough DEMATEL method.

To determine the dominant risk in the Trans-Sumatera Toll Road operation process, this study used two methods, namely qualitative and quantitative methods. The qualitative input is based on interviews with experts from the government, toll road companies, and academia. Qualitative results were carried out to obtain and select appropriate risk indicators obtained from literature studies, then these results were entered as input for quantitative methods involving the experts (Table 1). The experts on the panel comprised three institutions, two from the government, six from toll road owner companies, and two from academia. All experts have 24.6 years of average experience. In identifying the significant risks, this study used a threshold value of 0.7 in accordance with the normal threshold. The questionnaire was designed to determine significant risks at the operational stage based on experts.

**Table 1. The results of aggregated experts' values**

Code	Risk	Ref. Number	$\bar{d}_i^l$	$\bar{d}_i^u$	Crisp	Criteria
<i>Policy Risk</i>						
X.1.1	Change in Policy or Regulation	Likhitruangsilp et al. (2017) [5], Sy et al. (2016) [6] and Wirahadikusumah et al. (2018) [7]	0.719	0.880	0.799	<b>Accept</b>
X.1.2	Intervention by Government	Likhitruangsilp et al. (2017) [5], Sy et al. (2016) [6], and Wirahadikusumah et al. (2018) [7]	0.708	0.841	0.775	<b>Accept</b>
X.1.3	Corruption	Wirahadikusumah et al. (2018) [7] & Febrianto et al. (2023) [32]	0.385	0.846	0.616	<b>Reject</b>
X.1.4	Politic Situation in the Country	Wirahadikusumah et al. (2018) [7]	0.522	0.864	0.693	<b>Reject</b>
<i>Economic Risk</i>						
X.2.1	Inflation	Ghazali (2009) [4], Wirahadikusumah et al. (2018) [7] and Febrianto et al. (2023) [32]	0.719	0.880	0.799	<b>Accept</b>
X.2.2	Financial Distress	Likhitruangsilp et al. (2017) [5] and Sy et al. (2016) [6]	0.734	0.913	0.824	<b>Accept</b>
X.2.3	Fluctuation of Interest Rate	Suseno et al. (2015) [1]	0.672	0.877	0.774	<b>Accept</b>
X.2.4	Fluctuation of Currency	Suseno et al. (2015) [1]	0.663	0.838	0.750	<b>Accept</b>
X.2.5	Increase in Tax Fee	Suseno et al. (2015) [1]	0.501	0.749	0.625	<b>Reject</b>
<i>Revenue Risk</i>						
X.3.1	Operator Default	Likhitruangsilp et al. [5]	0.433	0.721	0.577	<b>Reject</b>
X.3.2	Excess Operational Cost	Wirahadikusumah et al. (2018) [7]	0.538	0.858	0.698	<b>Reject</b>
X.3.3	High Cost of Maintenance	Wirahadikusumah et al. (2018) [7]	0.670	0.959	0.814	<b>Accept</b>
X.3.4	Tariff Issue	Likhitruangsilp et al. (2017) [5], Sy et al. (2016) [6], Wirahadikusumah et al. (2018) [7] & Febrianto et al. (2023) [32]	0.486	0.864	0.675	<b>Reject</b>
X.3.5	Income Risk	Likhitruangsilp et al. (2017) [5] and Sy et al. (2016) [6]	0.754	0.976	0.865	<b>Accept</b>
X.3.6	Demand Risk	Likhitruangsilp et al. (2017) [5] and Sy et al. (2016) [6]	0.504	0.798	0.651	<b>Reject</b>
X.3.7	Low Volume of Traffic	Ghazali et al. (2009) [4], Wirahadikusumah et al. (2018) [7] and Febrianto et al. (2023) [32]	0.813	0.979	0.896	<b>Accept</b>
X.3.8	Competitive Route	Likhitruangsilp et al. (2017) [5], Sy et al. (2016) [6], and Wirahadikusumah et al. (2018) [7]	0.603	0.927	0.765	<b>Accept</b>
<i>Operational Services Risk</i>						
X.4.1	Lack of Operator Ability	Sy et al. (2016) [6]	0.414	0.735	0.574	<b>Reject</b>
X.4.2	Lack of Service Quality	Likhitruangsilp et al. [5]	0.479	0.765	0.622	<b>Reject</b>
X.4.3	Ineffectiveness and Efficiency of Operation and Maintenance	Wirahadikusumah et al. (2018) [7] and Febrianto et al. (2023) [32]	0.444	0.751	0.597	<b>Reject</b>
X.4.4	Many Traffic Accidents	Suseno et al. (2015) [1], Ghazali et al. (2009) [4], Wirahadikusumah et al. (2018) [7] & Febrianto et al. (2023) [32]	0.386	0.728	0.557	<b>Reject</b>
X.4.5	Overloading Vehicles	Suseno et al. (2015) [1], Ghazali et al. (2009) [4], Wirahadikusumah et al. (2018) [7] & Febrianto et al. (2023) [32]	0.623	0.911	0.767	<b>Accept</b>
X.4.6	Many Infrastructure Defects	Ghazali et al. (2009) [4] and Wirahadikusumah et al. (2018) [7]	0.569	0.871	0.720	<b>Accept</b>
<i>Force Majeure</i>						
X.5.1	Natural Disasters	Suseno et al. (2015) [1] and Ghazali et al. (2009) [4]	0.708	0.841	0.775	<b>Accept</b>
X.5.2	Bad Weather	Suseno et al. (2015) [1] and Ghazali et al. (2009) [4]	0.451	0.694	0.573	<b>Reject</b>
X.5.3	Toll Road Operation Disruptions Due to Demonstrations	Wirahadikusumah et al. (2018) [7] and Febrianto et al. (2023) [32]	0.467	0.691	0.579	<b>Reject</b>
X.5.4	Vandalism	Suseno et al. (2015) [1] and Febrianto et al. (2023) [32]	0.433	0.721	0.577	<b>Reject</b>

Based on stage 1, which included a literature study on the risk of operational activities in several ASEAN countries, including Indonesia, and interviews with experts based on the literature, 28 risks were identified in the operational activities of the Trans-Sumatra toll road. Among the 28 risks, only 13 risks were identified as important barriers in the operational management of toll roads. The significant risks to the operational management of the Trans-Sumatra toll road are in the table below (Table 2):



**Table 2. The Significant Risk**

Code	Significant Risk
SR1	Change in Policy or Regulation
SR2	Intervention by Government
SR3	Inflation
SR4	Financial Distress
SR5	Fluctuation of Interest Rate
SR6	Fluctuation of Currency
SR7	High Cost of Maintenance
SR8	Income Risk
SR9	Low Volume of Traffic
SR10	Competitive Route
SR11	Overloading Vehicles
SR12	Many Infrastructure Defects
SR13	Natural Disasters

Based on the results above, to evaluate the effect between risks, the questionnaire was filled out through a direct relation matrix. Five experts from previous stages of the institution provided responses that evaluated the direct relationship between risks by assessing: 0 - No influence (NI); 0.25 – Low influence (LI); 0.5 – Medium influence (MI); 0.75 – High influence (HI); 1 – Very high influence (VHI).

Based on the rating above, by filling in the non-integrative integer from 0 to 1, the matrix relationship  $k(k=1, 2, \dots, 5)$  can be done based on the Equations 16 and 17, then the individual filling by the expert was made into a group direct-relation matrix as shown in the table below (Table 3):

**Table 3. The verbal scores of direct relations between factors**

CODE	SR1	SR2	...	SR12	SR13
SR1	{0,0,0,0}	{0.75,0.75,0.75,1,0.75}	...	{0,0,0,0}	{0,0.75,0.75,0.25,0}
SR2	{0.75,0.75,0.75,0.75,0.75}	{0,0,0,0}	...	{0,0,0,0}	{0,0,0,0.25,0,0}
SR3	{0.25,0,0,0.5,0}	{0.5,0,0,0.75,0}	...	{0,0,0,0}	{0,0,0,0.5,0,0}
SR4	{0,0,0,1,0}	{0.25,0,0,0.75,0}	...	{0,0,0,0}	{0,0,0,1,0}
SR5	{0,0,0,0.5,0}	{0.5,0,0,0.25,0}	...	{0,0,0,0}	{0,0,0,0.25,0}
SR6	{0,0,0,0.5,0}	{0.5,0,0,0.25,0}	...	{0,0,0,0}	{0,0,0,0.25,0}
SR7	{0,0,0,0.25,0}	{0,0,0,0.5,0}	...	{0,0,0,0}	{0,0,0,0}
SR8	{0.5,0,0,0.5,0}	{0,0,0,0.5,0}	...	{0,0,0,0}	{0,0,0,0}
SR9	{1,0,0,0.5,0}	{0.5,0,0,0.25,0}	...	{0,0,0,0}	{0,0,0,0}
SR10	{1,0.75,0.75,0.75,0.25}	{0.75,0,0,0.5,0}	...	{0,0,0,0}	{0,0,0,0}
SR11	{0.5,0.5,0.5,0.25,0.25}	{0.25,0,0,0.25,0}	...	{1,1,1,1,1}	{0,0,0,0}
SR12	{0,0,0,0}	{0,0,0,0}	...	{0,0,0,0}	{0,0,0,0}
SR13	{1,0.75,0.75,1,0}	{1,0.75,0.75,0.25,0}	...	{0.75,1,1,0.25,0.5}	{0,0,0,0,0}

A Rough number was used to reduce subjectivity and imprecision from the data obtained from the experts [31]. Based on Equations 18 to 23, the value of the direct-relation matrix can be seen in the table below (Table 4), from each expert's perspective.

**Table 4. The group direct-relation matrix in the rough interval form**

Code	SR1	SR2	...	SR12	SR13
SR1	{0}	{0.76,0.84}	...	{0}	{0.16,0.56}
SR2	{0.75,0.75}	{0}	...	{0}	{0.01,0.09}
SR3	{0.04,0.265}	{0.08,0.43}	...	{0}	{0.02,0.18}
SR4	{0.04,0.36}	{0.05,0.37}	...	{0}	{0.04,0.36}
SR5	{0.02,0.18}	{0.04,0.265}	...	{0}	{0.01,0.09}

Code	SR1	SR2	...	SR12	SR13
SR6	{0.02,0.18}	{0.04,0.265}	...	{0,0}	{0.01,0.09}
SR7	{0.01,0.09}	{0.02,0.18}	...	{0,0}	{0,0}
SR8	{0.08,0.32}	{0.02,0.18}	...	{0,0}	{0,0}
SR9	{0.09,0.53}	{0.04,0.27}	...	{0,0}	{0,0}
SR10	{0.57,0.83}	{0.08,0.43}	...	{0,0}	{0,0}
SR11	{0.34,0.46}	{0.04,0.16}	...	{1.00,1.00}	{0,0}
SR12	{0,0}	{0,0}	...	{0,0}	{0,0}
SR13	{0.48,0.89}	{0.31,0.78}	...	{0.51,0.89}	{0,0}

After calculating the direct relation matrix using Equations 18 to 23 (results in the table above), then determined the total value of the rough number total relationship matrix using Equations 24 to 31 (Table 5).

**Table 5. The total value of the rough number total relationship map**

Code	SR1	SR2	...	SR12	SR13
SR1	{0.019,0.086}	{0.120,0.189}	...	{0.008,0.032}	{0.025,0.107}
SR2	{0.117,0.145}	{0.014,0.038}	...	{0.001,0.01}	{0.004,0.032}
SR3	{0.013,0.132}	{0.014,0.137}	...	{0.006,0.026}	{0.004,0.055}
SR4	{0.009,0.118}	{0.010,0.111}	...	{0.001,0.022}	{0.006,0.075}
SR5	{0.005,0.076}	{0.008,0.08}	...	{0.001,0.012}	{0.002,0.034}
SR6	{0.005,0.08}	{0.008,0.085}	...	{0.001,0.012}	{0.002,0.033}
SR7	{0.006,0.064}	{0.005,0.06}	...	{0.008,0.018}	{0.001,0.019}
SR8	{0.019,0.118}	{0.007,0.085}	...	{0.001,0.015}	{0.001,0.025}
SR9	{0.017,0.136}	{0.010,0.093}	...	{0.001,0.014}	{0.001,0,026}
SR10	{0.092,0.188}	{0.023,0.124}	...	{0.002,0.019}	{0.002,0.028}
SR11	{0.055,0.118}	{0.013,0.072}	...	{0.154,0.162}	{0.001,0.021}
SR12	{0.004,0.035}	{0.002,0.025}	...	{0.000,0.004}	{0.000,0.007}
SR13	{0.082,0.239}	{0.058,0.211}	...	{0.079,0.16}	{0.002,0.041}

After determining the  $\tilde{T}$  matrix, we performed the calculation of the total row crisp value ( $\tilde{R}_i^{der}$ ) and the total column crisp value ( $\tilde{C}_j^{der}$ ) with Equations 34 to 40. Calculating the total row ( $\tilde{R}_i^{der}$ ) and the total column ( $\tilde{C}_j^{der}$ ) was carried out to obtain the importance and relationship of each risk event. Table 6 is a calculation of  $\tilde{R}_i^{der}$  minus  $\tilde{C}_j^{der}$  ( $\tilde{R}_i^{der} - \tilde{C}_j^{der}$ ), and  $\tilde{R}_i^{der}$  added to  $\tilde{C}_j^{der}$  ( $\tilde{R}_i^{der} + \tilde{C}_j^{der}$ ).

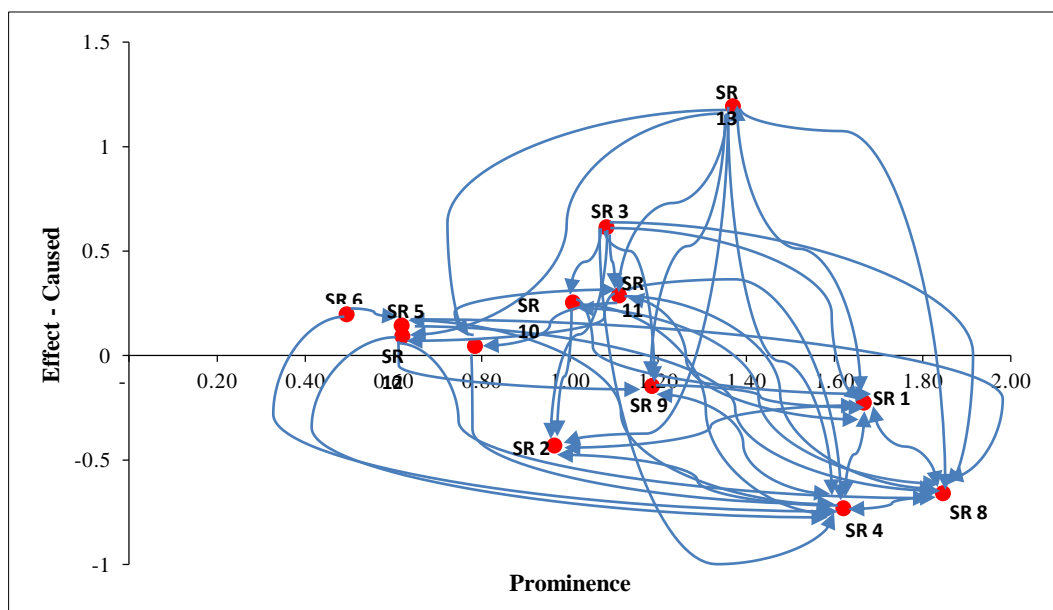
**Table 6. The sum of rows, the sum of columns, “Prominence” and “Relation”**

	RN (R <sub>i</sub> )	RN (C <sub>j</sub> )	$\tilde{R}_i^{der}$	$\tilde{C}_j^{der}$	$\tilde{R}_i^{der} + \tilde{C}_j^{der}$	$\tilde{R}_i^{der} - \tilde{C}_j^{der}$	Description
SR1	{0.28,1.28}	{0.44,1.54}	0.72	0.95	1.67	-0.23	Effect
SR2	{0.17,0.59}	{0.29, 1.32}	0.27	0.70	0.96	-0.43	Effect
SR3	{0.22,1.53}	{0.07,0.81}	0.85	0.23	1.08	0.61	Cause
SR4	{0.10,1.06}	{0.45,1.85}	0.45	1.18	1.62	-0.73	Effect
SR5	{0.16,0.85}	{0.11,0.75}	0.38	0.24	0.62	0.14	Cause
SR6	{0.10,0.88}	{0.07,0.62}	0.35	0.15	0.49	0.20	Cause
SR7	{0.19,0.87}	{0.16,0.94}	0.42	0.37	0.78	0.05	Cause
SR8	{0.24,1.12}	{0.51,1.89}	0.59	1.25	1.85	-0.66	Effect
SR9	{0.23,1.01}	{0.28,1.29}	0.52	0.67	1.19	-0.15	Effect
SR10	{0.27,1.14}	{0.13,0.99}	0.63	0.38	1.01	0.26	Cause
SR11	{0.39,1.10}	{0.18,0.98}	0.70	0.41	1.11	0.29	Cause
SR12	{0.28,0.58}	{0.26,0.51}	0.36	0.26	0.62	0.09	Cause
SR13	{0.35,1.97}	{0.05,0.5}	1.28	0.09	1.37	1.19	Cause

The cause–effect diagram was drawn after obtaining the horizontal axis  $(\tilde{R}_i^{der} + \tilde{C}_j^{der})$  and vertical axis  $(\tilde{R}_i^{der} - \tilde{C}_j^{der})$ . Meanwhile,  $(\tilde{R}_i^{der} + \tilde{C}_j^{der})$  refers to the strength of influence among criteria,  $(\tilde{R}_i^{der} - \tilde{C}_j^{der})$  refers to the influence relation among criteria. The cause–effect diagram is shown in Figure 2.

**Table 7. The crisp total relationship matrix of significant risk**

Code	SR1	SR2	...	SR12	SR13
SR1	0.041	0.171	...	0.011	0.056
SR2	0.141	0.020	...	0.002	0.009
SR3	0.061	0.066	...	0.008	0.015
SR4	0.061	0.057	...	0.004	0.031
SR5	0.029	0.035	...	0.001	0.008
SR6	0.033	0.038	...	0.001	0.008
SR7	0.021	0.022	...	0.009	0.002
SR8	0.058	0.031	...	0.002	0.004
SR9	0.070	0.038	...	0.002	0.004
SR10	0.155	0.065	...	0.003	0.005
SR11	0.089	0.032	...	0.161	0.004
SR12	0.009	0.005	...	0.000	0.000
SR13	0.177	0.140	...	0.119	0.008



**Figure 2. Relationships between the significant risks**

The total relation can be determined using Equation 41, which will help create a graphical representation of the interrelationship between the significant risks. The relationships that have a value higher than 0.043 are included in the final interactive maps depicted in Figure 2.

This study produced a network relationship diagram, as shown in the figure above. The arrows indicate the direction of influence from one risk to another; for example, “the risk of intervention by the government affects policy changes by the government, and it affects the risk of income”. It can be seen in Figure 2.

#### 4. Discussion

This study implements the Delphi and DEMATEL-based rough set theories to develop a systematic risk assessment method to identify and link the operational risks of toll road management in Sumatra. Based on the rough Delphi analysis, 13 dominant risks were obtained, namely Change in policy or regulation (SR1), Intervention by the government (SR2), Inflation (SR3), Financial Distress (SR4), Fluctuation of interest rate (SR5), Fluctuation of currency (SR6), High cost of maintenance (SR7), Low Volume of Traffic (SR9), Competitive Route (SR10), Overloading vehicles SR (11), Many Infrastructure Defects (SR12), and Natural Disasters (SR13).

Furthermore, data processing was carried out using the rough DEMATEL method after identifying the relationship between important risks. Based on the results obtained from the cause diagram, it was found that Inflation (SR3), Fluctuation of interest rate (SR5), Fluctuation of currency (SR6), High cost of maintenance (SR7), Competitive route (10), Overloading vehicles (SR11), Many infrastructure defects (SR12), and Natural disasters (SR14) were clarified as a cause criteria group. Meanwhile, the effect criteria include Policy or regulation change (SR1), Intervention by the government (SR2), Financial distress (SR 4), Income risk (SR 8) and Low volume of traffic (SR 9).

A crucial focus should be placed on the values in the cause-and-effect diagram to measure the operational risks effectively. Upon analyzing Table (6), it becomes evident that natural disasters emerge as the most dominant cause factor, boasting the highest  $\tilde{R}_i^{der} - \tilde{C}_j^{der}$  value of 1.19 compared to other factors. Previous research conducted by Wirahadikusumah et al. [7] categorizes natural disasters as a medium risk based on their analysis of probabilities and impacts on toll road operational activities under the Build-Operate-Transfer (BOT) scheme. However, this study reveals that the occurrence of natural disasters can significantly influence numerous critical risk factors within toll road operations.

The risk of inflation is in second position, with a value of 0.61. Inflation risk poses a significant threat at all stages of the toll road concessions [33]. In this study, the impact of inflation risk extends to policy changes, government intervention, and several other associated risks in the operational stages. Following that, the risk of vehicles with excessive load occupies the third position, with a value of 0.29. This risk directly contributes to the high maintenance costs of managing the Trans-Sumatera toll road and exacerbates infrastructure defects. The persistent overload of traffic leads to the deterioration of pavement and premature road surface failure, resulting in a substantial increase in expenses related to road rehabilitation [34]. Wirahadikusumah et al. [7] also highlights the risk of vehicle loads as one of the dominant operational risks feared by toll road companies.

In this study, other economic risks such as fluctuations in interest rates (SR5) and fluctuations in currency (SR6) have contributed as causal factors, the study conducted by Suseno et al. [1] shows that fluctuations in interest rates (SR5) and fluctuations in currency (SR6) pose moderate risks for the management of the Java toll road using probability and impact analysis. However, this research found that fluctuations in interest rates (SR5) and fluctuations in currency (SR6) can trigger the emergence of other risks in the management of the toll road especially in Sumatra.

Additionally, competitive routes (SR10), and numerous infrastructure defects (SR12) have contributed as causal factors. That will affect various critical risk factors within toll road operations and necessitate careful attention to risk assessment and mitigation strategies. The study conducted by Wirahadikusumah et al. [7] sheds light on an additional risk that toll road investors find concerning, which is the presence of competitive routes. The research findings revealed that the existence of competitive routes can impact the revenue generated by toll roads, thereby posing a disadvantageous situation for investors.

Furthermore, analyzing the prominence factors is crucial in managing toll road operations in Sumatra, as higher values indicate greater susceptibility to being influenced by other factors. According to the prominence diagram, income risk emerges as the most significant factor with a high  $\tilde{R}_i^{der} + \tilde{C}_j^{der}$  value of 1.88. This aligns with the well-known issue of revenue shortfalls on the Trans-Sumatera toll road, resulting in losses during the concession period [35]. Interestingly, when examining the same diagram, income risk exhibits the second lowest  $\tilde{R}_i^{der} - \tilde{C}_j^{der}$  value (-0.66), suggesting its vulnerability to influence from other factors.

Policy changes rank as the second most prominent factor affecting toll road management in Sumatra, as indicated by the prominence diagram. This classification in the effect group implies that multiple factors can influence policy changes. Currently, the public sector in Indonesia has recognized the significance of establishing a stable legal framework and regulations to ensure the successful execution of toll road operations. It is evident that insufficient legal and supervision systems and frequent changes in laws and regulations have negatively affected the management of toll roads for many years [5].

Then, financial distress acquires the third highest  $\tilde{R}_i^{der} + \tilde{C}_j^{der}$  value of 1.67, significantly impacting toll road management. Notably, financial distress possesses the lowest value on the cause-and-effect diagram (-0.73), signifying its susceptibility to be influenced by several critical risk factors, including fluctuations in interest rates (SR5), currency fluctuations (SR6), high maintenance costs (SR7), and other substantial risks depicted in Figure 2.

Analyzing the prominence factors is of paramount importance for effective toll road management in Sumatra. The prominence diagram reveals that income risk, policy changes, and financial distress have notable implications for operational activities. Income risk, with its highest  $\tilde{R}_i^{der} + \tilde{C}_j^{der}$  value, reflects the significant factor it holds over toll road operations. Conversely, income risk has the second lowest  $\tilde{R}_i^{der} - \tilde{C}_j^{der}$ . The value of the income risk underscores its susceptibility to external factors. Policy changes emerge as another prominent factor, implying the complex interplay of various influences on toll road management decisions.

Analyzing risks and understanding their causal relationships and effects is crucial for decision-makers to comprehensively analyze the impact of risks and determine how addressing one risk can influence the status of others.

By recognizing the extent to which each risk contributes to the likelihood of toll road operation, decision-makers can prioritize their focus on developing effective risk response strategies.

Integrating rough set theory in data collection processes by experts helps to manage better the subjectivity involved [10, 36]. This approach enables decision-makers to make informed and optimal choices, considering the uncertainties present in toll road operations. By incorporating rough set theory, decision-makers can attain more accurate risk assessments and, consequently, make better decisions.

Continuous identification and evaluation of risks are essential for effective risk management. Management must proactively address risks and work towards reducing the probability of significant risks occurring. This study provides decision-makers with valuable insights into the operational activities of the Trans-Sumatra toll road, allowing them to analyze the impact of risks and identify the interrelationships between different risks. By understanding how the increase in one risk may affect others, decision-makers can take appropriate measures to enhance overall risk management.

Furthermore, by employing a combination of rough set theory and MCDM techniques, this study contributes to the understanding of risk analysis and decision-making in toll road operations. The integration of rough set theory helps to address subjectivity and uncertainty in data collection, allowing decision-makers to make more informed and realistic decisions. By continually identifying and evaluating risks, decision-makers can effectively manage and mitigate risks to ensure the smooth and safe operation of the Trans-Sumatra toll road. However, the applicability and generalizability of the results obtained from these methods can be limited to the specific context and scope of the study. The findings may not directly translate to other toll road networks or regions, as the risks and dynamics can vary significantly.

## 5. Conclusions

This study combined rough set theory and MCDM techniques to conduct a comprehensive risk assessment of toll road management. By implementing the Delphi and DEMATEL-based rough set theory, a systematic approach is developed to identify and link operational risks. It identified 13 dominant risks, including policy changes, government intervention, inflation, financial distress, fluctuation of interest rate, fluctuation of currency, high cost of maintenance, low volume of traffic, competitive routes, overloading vehicles, many infrastructure defects, and natural disasters. Further analysis using the DEMATEL method specified the causal relationships among the identified risks.

Inflation, interest rate fluctuation, currency fluctuation, high maintenance cost, income, competitive routes, overloading vehicles, many infrastructure defects, and natural disasters were identified as causes. While policy changes, government intervention, and financial distress are categorized as effects. Natural disasters emerge as the most dominant cause of risk, with the highest  $\tilde{R}_i^{der} - \tilde{C}_j^{der}$  value of 1.19. Inflation and overloading vehicles rank second and third, respectively. The research also reveals that income risk, policy changes, and financial distress hold the highest prominence values in the effect criteria group.

The integration of rough set theory and MCDM techniques contributes to improved risk analysis and decision-making in toll road operations. Decision-makers can gain valuable insights into the interrelationships between risks and prioritize their focus on developing effective risk response strategies. The application of rough set theory addresses subjectivity and uncertainty in data collection, enabling more informed and realistic decision-making.

However, it is important to acknowledge the limitations of this study. The findings and conclusions may be specific to the context and scope of the research, limiting their generalizability to other toll road networks or regions. Future research should explore the applicability of the proposed risk assessment method in different contexts and consider additional factors that may impact toll road management.

In summary, this research provides a systematic risk assessment method for toll road management in Sumatra, incorporating the Delphi and DEMATEL-based rough set theory. The study identifies dominant risks and analyzes their causal relationships. The integration of rough set theory and MCDM techniques enhances risk analysis and decision-making, contributing to new knowledge in the domain of toll road operations.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, G.A.P. and Y.L.; methodology, G.A.P. and L.S.R.; validation, G.A.P., Y.L., and L.B.S.; formal analysis, G.A.P.; writing—original draft preparation, G.A.P., B.T., and L.S.R.; writing—review and editing, G.A.P., Y.L., and L.B.S.; visualization, G.A.P.; supervision, Y.L., L.S.R., B.T., and L.B.S. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

### 6.3. Funding

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### 6.5. Conflicts of Interest

The authors declare no conflict of interest.

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