

## Article

# Risk Analysis Using Failure Modes, Effects, and Criticality Analysis for Transmission Network Assets

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**Abstract:** In this paper, we apply the Failure Modes, Effects, and Criticality Analysis (FMECA) approach to the criticality and risk analysis of the efficiency, safety/reliability, environment, and financial criteria of the high voltage transmission line. In the efficiency analysis, the weighting-scoring method and analytical hierarchy process are applied to obtain the line renovation index, which is interpreted as efficiency severity. The safety/reliability severity relates to the system impacts caused by failure of the equipment and the system. The environmental severity takes social impacts and pollution into consideration. The financial severity involves the cost of spare parts and maintenance costs, which are interpreted as the financial severity of the lines. Twenty practical transmission lines in Thailand with actual data for 115, 230, and 500 kV were studied. The transmission line components are divided into eight components including the conductor, conductor accessories, insulator, steel structure, foundation, lightning protection system, tower accessories, and right-of-way. The severity and criticality of the components and transmission lines are analyzed and plotted in criticality matrices based on four criteria. This criticality matrix is presented at four different levels including very low, low, medium, and high risk, as represented by four color bands: green, yellow, orange, and red, respectively. The results show that three 115 kV lines are the first priority for short-term reconstruction planning because of their unacceptable condition and high risk in terms of safety/reliability and financing. Recommendations for maintenance strategy and risk mitigation are proposed for the utility according to the utility's actual criticality. Ultimately, maintenance planning of the transmission system can be effectively managed with higher reliability, a lower risk of failure, and a lower cost of maintenance.

**Keywords:** criticality analysis; severity analysis; risk analysis; FMECA; maintenance strategy; renovation index; weighting and scoring method; transmission system



**Citation:** Suwanasri, C.; Saribut, S.; Suwanasri, T.; Phadungthin, R. Risk Analysis Using Failure Modes, Effects, and Criticality Analysis for Transmission Network Assets. *Energies* **2021**, *14*, 977. <https://doi.org/10.3390/en14040977>

Academic Editor: Enrico Zio

Received: 10 January 2021

Accepted: 8 February 2021

Published: 12 February 2021

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## 1. Introduction to FMECA

Economic problems have forced electric utility providers to provide better quality electricity under lower operating and maintenance costs. Therefore, the effective and efficient use of transmission assets is of prime concern to gain maximum benefits, whereas maintenance costs should be reduced [1–8]. Currently, some high voltage (HV) transmission lines in Thailand are very old and deteriorated. From a database of technical information on overhead transmission lines in Thailand, approximately 35% of all transmission lines are over 30 years of age, which leads to a continual increase in the deterioration and failure of the line components. Consequently, new investments into the replacement and refurbishment of such aged and deteriorated transmission lines must be properly allocated according to the risk of transmission line usage. Therefore, a concrete transmission line

condition assessment procedure should be developed to determine the actual risk of the transmission lines.

In general, the uprating, upgrading, or renovation/replacement of transmission lines have been performed to fulfill new system requirements, such as increasing the load current and short circuit current, as well as due to climate change [9–11]. However, the criteria for deciding to engage in the uprating, upgrading, or renovation/replacement of transmission lines have not been clearly defined. Therefore, condition and importance assessments of the transmission lines and their components have been proposed based on the health index, importance index, reliability index, etc. [12–16] to support this type of analysis. For this reason, transmission system risk assessments have challenged the utility and power industry to determine the actual risk in order to manage the relevant assets with optimal costs and maintain system reliability [17–20]. To fulfill the risk assessment, various aspects affecting the transmission system, such as condition, social and environmental concerns, safety and reliability, and financial costs have been considered [21–24].

The Failure Modes, Effects, and Criticality Analysis (FMECA) method, which has different applications in power systems [25–30], is a crucial technique for technical maintenance management. The key objectives of FMECA are to identify and analyze feasible severities and criticalities causing unwanted effects on system performance, to recognize system risks resulting in equipment damage and financial losses, to identify effective techniques for improving system reliability, and to provide proper maintenance planning to reduce system risk. Generally, the FMECA procedure involves breaking the system into components and exploring the failure modes and the associated effects for all components. Then, the severity and criticality of the components and the system are analyzed and plotted in a criticality matrix. The failure modes along and potential risk management of all the components and systems are prioritized. The FMECA is an effective tool to evaluate and improve system reliability, thereby reducing costs associated with maintenance, and is used in a wide range of industries.

In this paper, an FMECA analysis for overhead transmission network assets is proposed. For this study, 20 transmission lines in Thailand with actual data at 115, 230, and 500 kV are presented. The transmission lines and their components are shown in Figure 1. The major components are classified into eight groups including conductor, conductor accessories, insulator, steel structure, foundation, lightning protection system, tower accessories, and right-of-way, as given in Table 1. The sub-components are also given. The eight major components and their sub-components are classified according to their function, test, and inspection methods, as well as their order of inspection and installation location in the tower to facilitate convenient routine inspection.

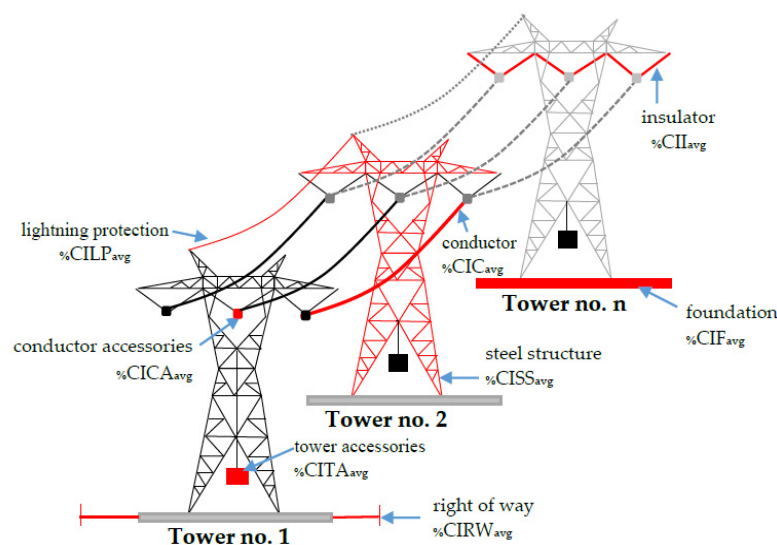


Figure 1. Overhead transmission line components for condition assessment.

**Table 1.** Transmission line components.

Group	Component	%CI <sub>avg</sub>	Sub-Components
1	conductor	%CIC <sub>avg</sub>	conductor
2	conductor accessories	%CICA <sub>avg</sub>	spacer, damper, joint, dead end, PG clamp
3	insulator	%CII <sub>avg</sub>	insulator, fittings, arrester
4	steel structure	%CISS <sub>avg</sub>	structure, anchor and guy
5	foundation	%CIF <sub>avg</sub>	concrete foundation, grillage foundation, stub
6	lightning protection	%CILP <sub>avg</sub>	overhead/optical ground wire, fittings, marker, grounding system
7	tower accessories	%CITA <sub>avg</sub>	danger sign, tower number sign, phase plate
8	right of way	%CIRW <sub>avg</sub>	right of way

To calculate the overall transmission line renovation index, we use the average percentage condition index (%CI<sub>avg</sub>) of each component of a transmission tower along a transmission line, including the %CIC<sub>avg</sub> for conductors, %CICA<sub>avg</sub> for conductor accessories, %CII<sub>avg</sub> for insulators, %CISS<sub>avg</sub> for steel structures, %CIF<sub>avg</sub> for foundations, %CILP<sub>avg</sub> for lightning protection, %CITA<sub>avg</sub> for tower accessories, and %CIRW<sub>avg</sub> for right of way, as illustrated in Figure 1. Then, a criticality analysis of the components and transmission lines is performed.

## 2. Criticality Analysis

The criticality analysis was performed by considering the occurrence and severity together. The severity is classified into four aspects, such as efficiency to identify the relationship between the failure frequency of the line and the actual conditions of the transmission tower. This sub-system is evaluated based on the inspection and test results. The safety/reliability is the second aspect that reflects the importance of the transmission line in the electrical system in terms of power transmission, redundancy, etc. The environment is the third aspect and reflects the impact from human activity, the operating environment, and pollution on transmission line failure. Finally, the financial aspect considers maintenance costs together with the actual conditions from the first aspect to support spare part management. The criticality of the transmission line is plotted in a criticality matrix, which is divided into four levels: low, medium, high, and very high risk. Maintenance strategies according to the obtained risk are also recommended.

For the criticality analysis of each criterion, both failure occurrence and severity are needed to calculate the criticality, as shown in Equation (1):

$$CR = SE \times OC \quad (1)$$

where CR is criticality, SE is severity, and OC is the occurrence of an individual severity criterion.

The occurrence implies a statistical record (events/year) of the malfunction or failure of the transmission lines. In Table 2, the occurrence score is differentiated and classified into five levels from 1 to 5 (from low to high failure frequency).

**Table 2.** Failure record and score for occurrence analysis.

Occurrence Score (OC)	1	2	3	4	5
Failure Record (events/year)	0	1	2–5	6–10	>10
Failure Frequency	very low	low	moderate	high	very high

Figure 2 shows the coordination of occurrence and severity plotted in a criticality matrix with 5 × 5 dimensions. The risk is classified into only 4 levels as low (L), moderate (M), high (H), and very high (VH) and differentiated into four color bands as green, yellow, orange, and red. The criticality is obtained by multiplying the severity with the occurrence of four severity criteria. The numbers 1–3, 4–9, 10–15, and 16–25 represent the risk as the L, M, H, and VH risk level, respectively. The aims of applying the L, M, H, and VH levels are to visually recognize issues for maintenance engineers and technicians, to realize the actual risk in the matrix of all components and transmission lines, and to reduce complexity

while increasing simplicity in risk management and maintenance strategies, as mentioned in Table 3.

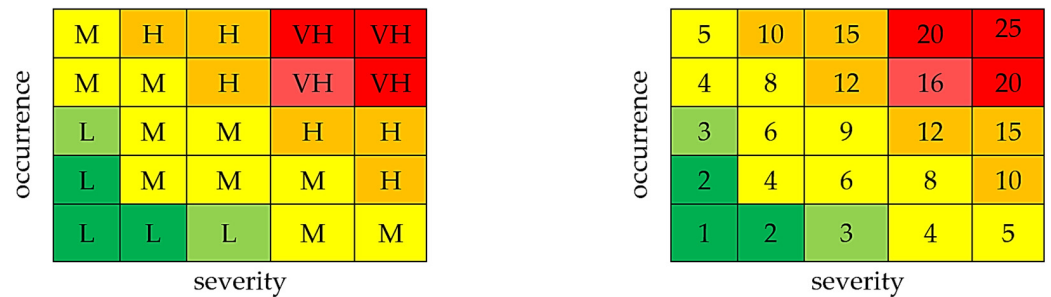


Figure 2. Criticality matrix.

Table 3. Criticality analysis and its maintenance management.

Score	Criticality	Maintenance Strategy
1–3	low	There is minimal risk of use with good condition of the component, and an acceptable level without risk control, and no additional management is needed. General corrective maintenance (CM) with routine inspection and time-based maintenance (TBM) can be applied. The component and system have a low probability of malfunctions with low impact to the customer. These components can be used in the system with normal maintenance based on safety/reliability and environmental aspects. In the financial criterion, the components are of low value with a large number of items in stock and a low failure frequency. There is no great interference on the network and the components need little care. Here, a two-bin inventory policy could be applied.
4–9	medium	There is medium risk of use with moderate condition at an acceptable level, but these components must be controlled to prevent risk, which could increase to an unacceptable level. TBM can be applied together with condition-based maintenance (CBM) by increasing the inspection and maintenance cycle to monitor the condition and replace broken parts. For safety/reliability and environment issues, tracking of the malfunction rate is required. Medium-term planning to improve the overall condition and reduce impacts from pollution is needed. In terms of spare part management, the spare parts are ordinary with a low failure frequency. Here, standard care is needed. The economic order quantity (EOQ), safety stock, and reorder level based on the demand rate policy can thus be applied.
10–15	high	There is a high risk of use with unsatisfied/unacceptable conditions. TBM and CBM must be intensively applied. Short-term maintenance planning for repairing/refurbishment/replacement/reconstruction must be economically used. For safety/reliability and environmental criteria, a plan to reduce the importance of the parts to the system are requested, i.e., reducing power transmission, adding parallel transmission lines, etc. These parts are vital spare parts that have a high impact on the system with a medium failure frequency. The network may not work without the spare parts. Refurbishment or replacement may be required, while maintenance may take several days. Therefore, an intensive EOQ, safety stock, and reorder level based on the demand rate policy should be applied.
16–25	very high	There is very high use of a component with bad condition, whose maintenance needs to be expedited to manage the risk to an acceptable level. Due to having the highest risk, refurbishment/replacement of such components must be performed immediately. For safety/reliability criterion, downgrading the line's importance in the system should be prioritized, i.e., reducing power transmission and adding parallel transmission lines. Upgrading and refurbishment of transmission lines due to aging could be conducted if the old design is not compatible with today's applications. For environment issues, correcting the condition and controlling/removing the impact from pollution to reduce the transmission line's malfunction rate are needed. Here, spare parts are critical and the most expensive, also have the highest failure frequency. These parts need special care because they can have the highest impact on the network. Engaging in maintenance or reordering the new part may take several weeks. Here, minimum stock policy-based failure rate data can be applied.

The criticality of the transmission line components and sub-components can be plotted in the criticality matrix shown in Figure 2. The risks of transmission line components are located under different colors depending on the conditions and risks. After the criticality levels of the transmission line components and sub-components are analyzed, the maintenance strategy, failure mitigation method, and spare part management [31–36] are addressed, as outlined in Table 3.

### 3. Severity Analysis

The four criteria of efficiency, safety/reliability, environment, and finance are taken into consideration for the risk analysis.

#### 3.1. Severity for the Efficiency Criterion

In [31–37], different testing methods and visual inspection techniques for assessing the condition of transmission line components were needed, and the weighting and scoring method (WSM) was applied. The WSM method considers a score representing the condition and a weight representing the importance of the considered criteria. The Analytical Hierarchy Process (AHP) technique [38,39] can then be applied to identify the importance weight of each testing method. The structure for the condition assessment of the transmission line in the transmission system is shown in Figure 3.

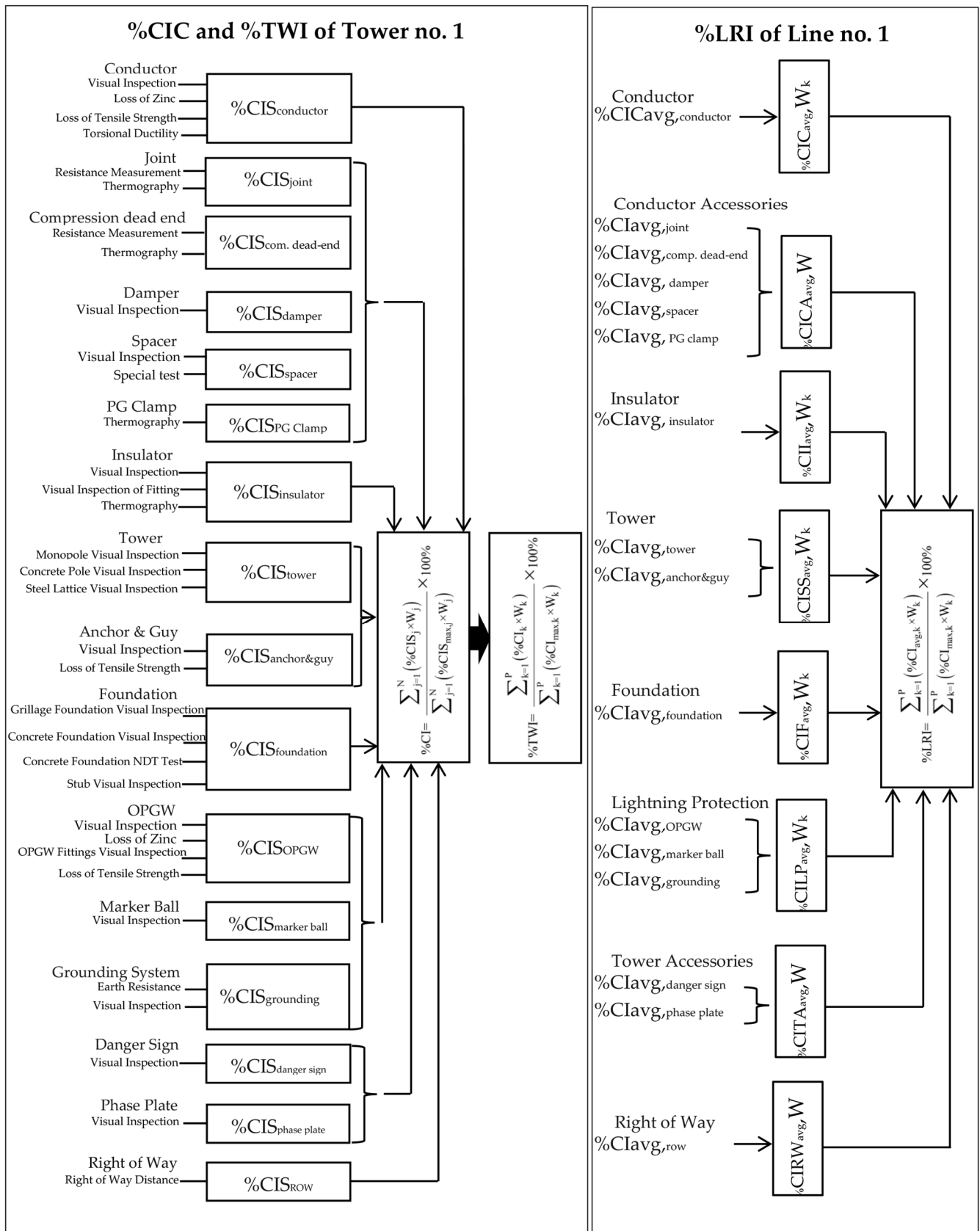


Figure 3. Structure for the condition assessment of transmission lines in a transmission system.

Firstly, the WSM method is used to calculate the percentage condition index of the sub-component (%CIS), as written in Equation (2):

$$\%CIS = \frac{\sum_{i=1}^M (S_i \times W_i)}{S_{\max}} \times 100\% \quad (2)$$

where  $S_i$  and  $S_{\max}$  are the assigned score and maximum scores of testing method  $i$ ,  $W_i$  is the weight of testing method  $i$ , and  $M$  is the number of testing methods of the considered sub-component. There are four testing methods: visual inspection, loss of zinc, loss of tensile strength, and torsional ductility, as recommended in [31–35] for practical transmission condition assessments.

Next, the percentage condition index of each component (%CI) of the tower is determined using Equation (3). The components are the conductor, conductor accessories, insulator, steel structure, foundation, lighting protection, tower accessories, and right-of-way.

$$\%CI = \frac{\sum_{j=1}^N (\%CIS_j \times W_j)}{\sum_{j=1}^N (\%CIS_{\max,j} \times W_j)} \times 100\% \quad (3)$$

where  $\%CIS_{\max,j}$  is the maximum %CIS of sub-component  $j$ ,  $W_j$  is the weight of sub-component  $j$ , and  $N$  is the number of sub-components of each component. There are five sub-components of conductor accessories, including the joint, compression dead end, damper, spacer, and PG clamp, as shown in Figure 3.

Then, the tower renovation index (%TWI) is obtained using Equation (4):

$$\%TWI = \frac{\sum_{k=1}^P (\%CI_k \times W_k)}{\sum_{k=1}^P (\%CI_{\max,k} \times W_k)} \times 100\% \quad (4)$$

where  $\%CI_{\max,k}$  is the maximum %CI of component  $k$ ,  $W_k$  is the weight of component  $k$ , and  $P$  is the number of components of each tower.

Lastly, the overall transmission line renovation index (%LRI) is determined using Equation (5). The average %CI ( $\%CI_{\text{average},k}$ ) of component  $k$  along a transmission line is further used to calculate the overall transmission line renovation index:

$$\%LRI = \frac{\sum_{k=1}^P (\%CI_{\text{avg},k} \times W_k)}{\sum_{k=1}^P (\%CI_{\max,k} \times W_k)} \times 100\% \quad (5)$$

where %LRI is the percentage renovation index of an OTL,  $\%CI_{\text{average},k}$  is the average %CI<sub>k</sub> of component  $k$  along a transmission line,  $W_k$  is the weight of component  $k$ , and  $P$  is the number of components of each tower.

Then, the %LRI is used to identify the severity score based on the efficiency criterion ( $SE_{\text{efficiency}}$ ), as given in Table 4.

**Table 4.** %LRI interpretation as the severity score based on the efficiency criterion.

Severity Score ( $SE_{\text{efficiency}}$ )	%LRI	Severity in Condition
1	0–30	very good
2	31–40	good
3	41–60	moderate
4	61–80	bad
5	81–100	worst

### 3.2. Severity for the Financial Criterion

The financial severity score ( $S_m$ ) of eight components applies directly to the condition index of the component (%CI), as outlined in Table 5, because the maintenance budget should be set according to the condition of the component. However, the financial severity score ( $SE_{\text{finance}}$ ) of the transmission line is calculated as expressed using Equation (6). In this equation, the percentage cost (%Cost) of the eight components includes spare parts and the maintenance cost from the total cost of the tower span. Then, this %Cost is set as the importance weight ( $W_m$ ) used to calculate the financial severity score of the transmission line. In Table 5, the overall and percentage costs of the 230 kV line, double circuit, and

1 × 1272 MCM ACSR/GA based on the utility's actual maintenance costs are given as an example to determine the financial severity score mentioned above. The %Cost is classified into five levels of cost: "1" as very low, "2" as low, "3" as medium, "4" as high, and "5" very high. As shown in Table 6, spare part policies are usually assigned as the minimum stock for expensive items, the economic order quantity for moderately priced items, and the two bin policy for cheap items. These policies are an important part of the maintenance strategy in Table 3 to handle financial criticality and severity.

**Table 5.** Maintenance cost of 230 kV #1, double circuit, and 1 × 1272 MCM ACSR/GA.

Component	Score (S <sub>m</sub> )	Cost of Spare Part; RPC (THB/km)	Maintenance Cost; MC (THB/km)	%Cost (W <sub>m</sub> )
conductor	%CIC	900,000.00	50,000.00	22.20
conductor accessories	%CICA	67,500.00	40,000.00	2.51
insulator	%CII	72,000.00	150,000.00	5.19
steel structure	%CISS	1,800,000.00	114,000.00	44.72
foundation	%CIF	750,000.00	100,000.00	19.86
lightning protection	%CILP	150,000.00	40,000.00	4.44
tower accessories	%CITA	5000.00	5000.00	0.23
right of way	%CIRW	18,000.00	18,000.00	0.84
total cost		3,762,500.00	517,000.00	100.00
		total maintenance cost (RPC + MC) = 4,279,500.00		

**Table 6.** Proposed spare part policy in an inventory management system for individual transmission components.

%Cost	Score (S <sub>m</sub> ) of Component	Severity in Cost	Spare Part Policy
0–5%	1	very low	two-bin policy
5.1–20%	2	low	EOQ, safety stock, and reorder level policy
20.1–60%	3	medium	EOQ, safety stock, and reorder level policy
60.1–80%	4	high	minimum stock-policy-based failure rate
80.1–100%	5	very high	minimum stock-policy-based failure rate

### 3.3. Severity for the Safety/Reliability Criterion

In the safety/reliability criterion, the five sub-criteria of current loading, system usage, voltage level, contingency analysis, and age of transmission line are taken into consideration. Line loading (%) considers the maximum percentage of the highest power flow compared to the MVA rating of the line. Higher loading can cause a greater impact among customers if any outage occurs. System usage is important and is based on the types of line usage, such as connection to the power plant, tie transmission lines, rapid load shedding, radial lines, or loop lines, which can have different impacts on the electrical system. The voltage level is considered based on the capability of power transmission through the line; i.e., a 500 kV line would have more power transferred and greater impacts than a 115 kV line when a fault occurs. Contingency analysis relates to the redundancy (N-1) of the line affecting the ability and reliability to supply electricity. The age of the transmission line could reflect invisible deterioration, resulting in a high probability of power outages. Age may also relate to an old design whose specifications are lower than the actual usage conditions. The sub-criteria and their scores and weights in the safety/reliability criterion are given in Table 7. These factors will be interpreted to obtain a single severity score for the safety/reliability criterion in Section 3.4.

**Table 7.** Score and weight for safety/reliability criteria.

Sub-Criterion	Score (S <sub>n</sub> )					W <sub>n</sub>
	0	1	2	3	4	
line loading (%)	0–20	21–30	31–40	41–50	>50	20
voltage level (kV)	–	≤115	–	230	500/300 kV DC	7
system usage	–	no tie line	–	radial line	tie-line/rapid load shedding/generator connected	15
contingency analysis	non	–	n – 2	–	n – 1	14
age (year)	0–10	11–20	21–25	26–30	>30	44

### 3.4. Severity for the Environment Criterion

The three sub-criteria of impact on customers, pollution level, and impact on community are considered in the environment criterion. Impact on customers considers the important load or area of the line supplying power. The transmission line with a higher impact will affect many priority customers. Pollution refers to a polluted area near the installed transmission line and relates to the dust levels, sea spray, chemicals, accumulation of moisture, and smoke from burning plants, possibly causing transmission line outages. Public image represents the impact on the utility image from a customer point of view, environmental-friendliness issues are also taken into account, such as design structure, sound and noise, technical impacts like electric/magnetic field interference, and power outages causing usage interruptions. The sub-criteria and their scores and weights for the environment criterion are given in Table 8. These factors will be interpreted to obtain a single severity score for the environment criterion in Section 3.4.

**Table 8.** Score and weight for the environmental criteria.

Sub-Criterion	Score ( $S_o$ )					$W_o$
	0	1	2	3	4	
human impact	normal province	–	–	–	industrial estate/big province/tourist and business area	33
pollution	–	rice field/agricultural area	plant burning fire	bird droppings	coastal area/industrial estate	24
public image	–	normal line	–	–	compact line	43

### 3.5. Single Severity Score Calculation for Severity in the Finance, Safety/Reliability, and Environmental Criteria

For the critically analysis, a single severity score for the financial, safety/reliability, and environmental criteria must be determined. However, there are different percentages of component costs and many sub-criteria involved in safety/reliability, as well as environmental criteria, as mentioned in Sections 3.2–3.4. Therefore, a single severity score needs to be calculated. The WSM method is applied to calculate the percentage of the severity score ( $\%SE_{\text{finance}}$ ,  $\%SE_{\text{safety/reliability}}$ , and  $\%SE_{\text{environment}}$ ), as written in Equations (6)–(8).

$$\%SE_{\text{finance}} = \frac{\sum_{m=1}^Q (S_m \times W_m)}{S_{\text{max},m}} \times 100\% \quad (6)$$

$$\%SE_{\text{safety/reliability}} = \frac{\sum_{n=1}^R (S_n \times W_n)}{S_{\text{max},n}} \times 100\% \quad (7)$$

$$\%SE_{\text{environment}} = \frac{\sum_{o=1}^T (S_o \times W_o)}{S_{\text{max},o}} \times 100\% \quad (8)$$

where  $S$  is the score of each sub-criterion,  $S_{\text{max}}$  is the maximum score of the sub-criteria, and  $W$  is the weight of each sub-criterion.  $Q$ ,  $R$ , and  $T$  represent the number of components for finance, safety/reliability, and environmental criteria, respectively.

Finally, the obtained  $\%SE$  is converted to a single severity score ( $SE_{\text{finance}}$ ,  $SE_{\text{safety/reliability}}$ , and  $SE_{\text{environment}}$ ), as written in Table 9.

**Table 9.**  $\%SE$  and severity score for the financial, safety/reliability, and environmental criteria.

$\%SE$	Severity	$SE_{\text{finance}}$	$SE_{\text{safety/reliability}}$	$SE_{\text{environment}}$
0–20	very low	1	1	1
21–40	low	2	2	2
41–60	medium	3	3	3
61–80	high	4	4	4
81–100	very high	5	5	5



To avoid conflict among the various departments working with transmission lines in the utility provider and to gain a common consensus of the weights of all criteria and sub-criteria, expert persons, who have long-term experience working with transmission lines and deep knowledge of the work in several departments, such as engineering, construction, operation, and maintenance, were invited as representatives of their departments to share their opinions and take part in the weight determination. The multi-criteria decision-making technique, as an analytical hierarchy process, or the AHP technique, was applied to facilitate the comparison of various criteria. Then, an inquiry form developed in an MS Excel file was distributed to the invited experts to obtain their opinions independently for weight determination. The weighting values obtained from all experts were subsequently averaged by using the geometric mean to obtain the final weighting value so that all departments in the utility were in good agreement of this value without argument.

#### 4. Result and Discussion

In [33], a web-application asset management program for transmission network maintenance was developed and subsequently used by a utility provider not only to record all of the technical data, inspection results, and maintenance costs of transmission line in the central database, but also to evaluate the condition of overhead transmission lines. After software implementation, all technical information of every transmission line was eventually recorded in the central database, while the inspection and test results were input online via the internet by a maintenance crew. This program is now widely used by all operation and maintenance divisions in their respective areas in the utility provider to evaluate the condition and risk of all 115, 230, and 500 kV transmission lines. In this way, the actual technical and testing data of 20 pilot transmission lines recorded by technicians and engineers from all responsible regions in Thailand were able to be quickly retrieved from the database for further analysis in this paper.

The 230 kV line no. 8 was selected as an example. In this line, four severity scores of the components belonging to tower no. 1 were determined, as shown in Table 10. Finally, the criticality scores of the eight components with their symbols were calculated and are shown in Table 11. The criticalities of the eight components regarding the efficiency, safety/reliability, environmental, and financial criteria were plotted in criticality matrices, as shown in Figure 4. Almost all of the  $CR_{\text{efficiency}}$  values are located at zone 3 (the green zone) because of their very good condition with low risk. However, the  $CR_{\text{efficiency}}$  of the conductor and steel structure and insulator foundation are located at zones 6 and 9 and have medium risk. The  $CR_{\text{safety/reliability}}$  values of all the components are in zone 12 (the orange zone), indicating high risk. The  $CR_{\text{environment}}$  values are in zone 6, which is the yellow zone with medium risk because all components are located in the same tower and area. The  $CR_{\text{finance}}$  values are in zones 3, 6, and 9 with low and medium risk because of the maintenance costs of the components related to the condition of the equipment, as mentioned in Section 3.2. Almost all of the sub-criteria are in a medium risk zone, except for the safety/reliability criterion, which needs a plan to reduce the importance of the components, i.e., short-term planning to reduce power transmission or medium planning to add parallel transmission lines. The recommended maintenance strategies are outlined in Table 3.

**Table 10.** Severity scores of the four criteria and sub-criteria of 230 kV tower no. 1, line no. 8.

Severity	Sub-Criteria	Line Data	Score ( $S_m$ )	Severity Score (SE)
efficiency	conductor	%CIC	2	$SE_{\text{efficiency}} = 3$
	conductor accessories	%CICA	1	
	insulator	%CII	1	
	steel structure	%CISS	3	
	foundation	%CIF	2	
	lightning protection	%CILP	1	
	tower accessories	%CITA	1	
	right of way	%CIRW	1	

Table 10. Cont.

Severity	Sub-Criteria	Line Data	Score (S <sub>m</sub> )	Severity Score (SE)
safety/reliability	line loading (%)	48.5%	3	SE <sub>safety/reliability</sub> = 4
	system usage	low	1	
	voltage level (kV)	high	3	
	contingency analysis	very low	0	
environment	age (year)	very high	4	SE <sub>environment</sub> = 2
	human impact	very low	0	
	pollution	medium	2	
	public image	low	1	
finance	conductor	medium	2	SE <sub>finance</sub> = 3
	conductor accessories	very low	1	
	insulator	low	1	
	steel structure	medium	3	
	foundation	low	2	
	lightning protection	very low	1	
	tower accessories	very low	1	
	right-of-way	very low	1	

Table 11. Severity and criticality analysis of the 230 kV transmission line tower no. 1, line no. 8.

Component	Symbol	Severity Score (SE)				Occurrence (OC)	Criticality Score (CR)			
		Efficiency	Safety/Reliability	Environment	Finance		Efficiency	Safety/Reliability	Environment	Finance
conductor	*	2	4	2	2	3	6	12	6	6
conductor accessories	◇	1	4	2	1	3	3	12	6	3
insulator	△	1	4	2	1	3	3	12	6	3
steel structure	♣	3	4	2	3	3	9	12	6	9
foundation	◆	2	4	2	2	3	6	12	6	6
lightning protection	♥	1	4	2	1	3	3	12	6	3
tower accessories	♠	1	4	2	1	3	3	12	6	3
right-of-way	●	1	4	2	1	3	3	12	6	3

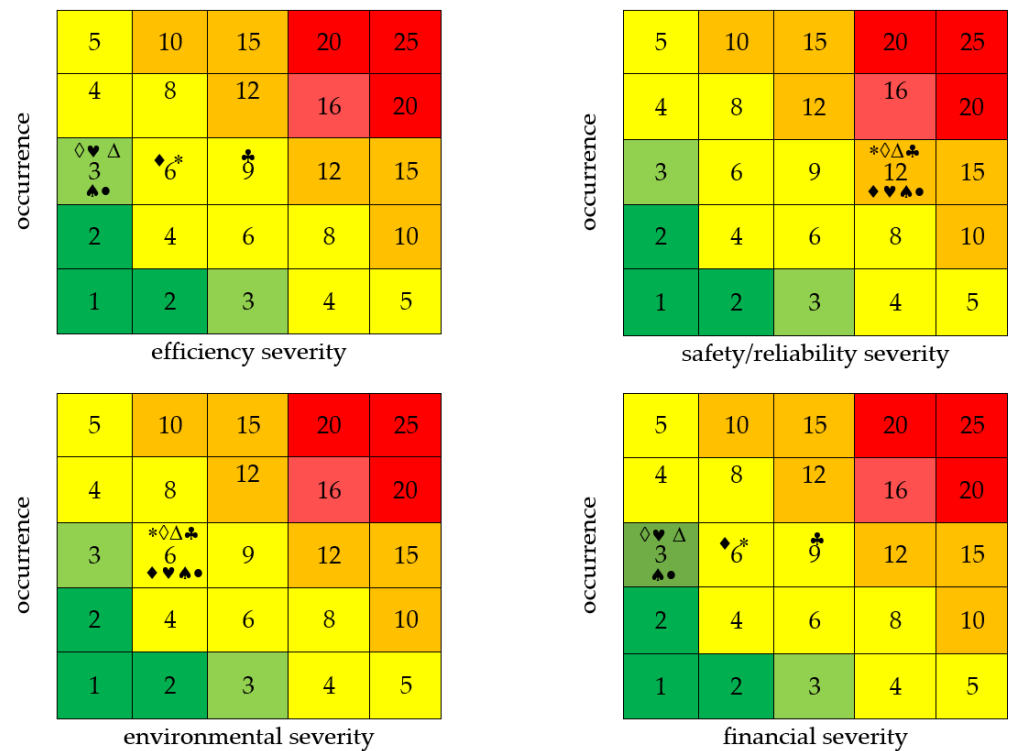


Figure 4. Criticality matrix of the sample 230 kV transmission line towers no. 1, line no. 8.

Next, the severity and criticality of 20 transmission lines were determined. The criticality scores (CR) of all transmission lines were calculated and are summarized in

Table 12. These scores were then plotted in criticality matrices of efficiency, environment, safety/reliability, and finance, as shown in Figure 5. The practical data of the 20 transmission lines are analyzed and summarized in Table 13.

Table 12. Severity and criticality analysis of the 20 transmission lines.

Line	Symbol	Severity Score (SE)				Occurrence (OC)	Criticality Score (CR)			
		Efficiency	Safety/Reliability	Environment	Finance		Efficiency	Safety/Reliability	Environment	Finance
115 kV #1	▲	3	4	2	4	3	9	12	6	12
115 kV #2	▤	3	3	2	5	1	3	3	2	5
115 kV #3	▲	4	3	2	5	2	8	6	4	10
115 kV #4	◆	4	3	2	5	3	12	9	6	15
115 kV #5	⬢	4	3	2	5	3	12	9	6	15
115 kV #6	⬢	3	3	2	4	3	9	9	6	12
115 kV #7	▴	3	4	2	5	4	12	16	8	20
230 kV #8	▲	3	4	2	3	3	9	12	6	9
230 kV #9	▤	1	3	4	1	1	1	3	4	1
230 kV #10	▲	3	4	2	4	3	9	12	6	12
230 kV #11	◆	1	3	4	3	1	1	3	4	3
230 kV #12	⬢	3	4	2	4	4	12	16	8	16
230 kV #13	⬢	1	3	4	3	3	3	9	12	9
230 kV #14	▴	1	3	4	3	3	3	9	12	9
500 kV #15	▤	1	2	2	3	4	4	8	8	12
500 kV #16	▤	2	2	2	5	1	2	2	2	5
500 kV #17	▲	3	4	1	4	3	9	12	3	12
500 kV #18	◆	3	5	1	4	3	9	15	3	12
500 kV #19	⬢	1	2	5	3	1	1	2	5	3
500 kV #20	⬢	1	3	1	2	3	3	9	3	6

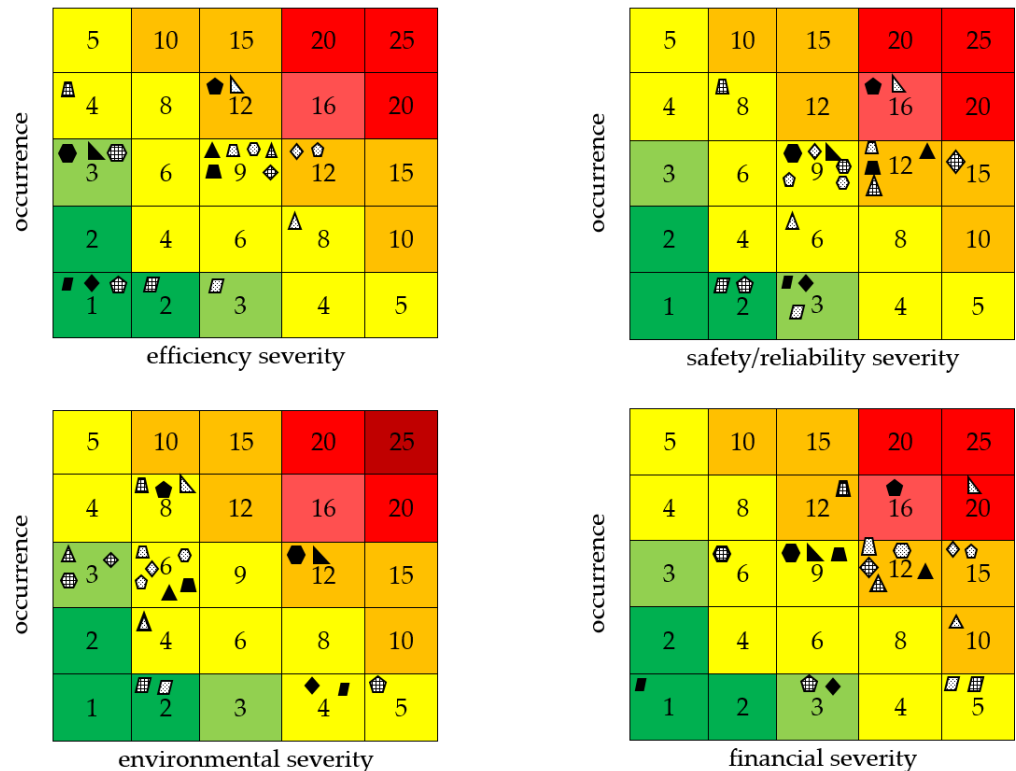


Figure 5. Criticality matrix of the sample 20 transmission lines.

Table 13. Necessary data and analyzed scores of all sub-criteria for the transmission lines.

Severity	Sub-Criteria	115 kV									230 kV					500 kV					
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
efficiency	%LRI	48.9	48.4	68.1	61.1	63.5	48.4	53.3	47.7	2.1	49.5	27.9	44.7	15.5	19.1	27.0	31.8	40.7	42.3	23.4	20.1

In Table 12, the results show that the  $CR_{\text{finance}}$  of the 115 kV lines #7 and #12 fall in zones 20 and 16, which are classified as very high risk (red zone) because of the very high cost of their maintenance according to their condition with high failure occurrence. The  $CR_{\text{finance}}$  values of lines #4 and #15, as well as #1, #6, #10, #17, and #18, fall in zones 15 and 12, respectively. The failure causes of these lines must be closely observed. Otherwise, the number of failures could increase, leading to line efficiency and poor reliability of the system. In addition, the utility provider should pay more attention to maintenance and spare part management.

The  $CR_{\text{efficiency}}$  values of lines #7 and #12 fall into zone 12 with high risk (orange zone) because of the poor condition of the lines with a very high number of failures. The ages of these lines are also greater than 30 years. Consequently, these lines are currently under short-term planning for line reconstruction because their actual conditions will not be able to fulfill system requirements in the near future. Similarly, lines #4 and #5 fall into zone 12 (high risk, orange zone) because of their moderate condition but also their high number of failures. Thus, the utility provider should determine the causes of failures and plan to reduce the number of failures, as well as plan to categorize those lines under the secondary priority for reconstruction planning because of their age. The other lines are in the orange zone and should be closely observed due to their problems.

The  $CR_{\text{safety/reliability}}$  values of lines #7 and #12 fall into zone 16, which indicates a very high risk (red zone) because of the low redundancy, high percentage loading, and age of the lines, while line #18 falls into zone 12, which indicates high risk (orange zone) due to a high percentage of loading and age, as well as operating at the highest (500 kV) level in the country. The importance of these lines must be reduced to maintain better reliability of the system by increasing the capability of the line loading. Then, the utility provider could plan to add a new line or parallel line for sharing the line loading. The  $CR_{\text{safety/reliability}}$  of lines #1, #8, #10, and #17 fall into zone 9, indicating high risk (orange zone) but a lower number of failures than lines #7 and #12. However, these lines are also more than 30 years old. Therefore, these lines should be given third priority for reconstruction planning, but the importance scores of these lines in terms of safety and reliability should be managed by reducing failure frequency.

The  $CR_{\text{environment}}$  values of lines #13 and #14 indicate high risk (orange zone) because of the pollution effected by animals and agriculture. These lines are located in important areas where blackouts may lead to complaints from customers. These areas must be intensively cared for with more frequent periods of maintenance. The analysis of all four critically criteria for the other transmission lines can use a similar process, and this analysis should be very detailed. The maintenance strategies outlined in Table 3 should be referred to.

Using the FMECA method, the criticality scores shown in Table 12 and the criticality matrices in Figure 5 will be very useful for the utility provider to analyze risks under the different criteria of efficiency, environment, safety/reliability, and finance. In this way, the risk of all components and transmission lines can be carefully observed, and the risk can be easily managed in depth. Then, the utility provider can prioritize the maintenance tasks of transmission lines according to the risks of the lines. Thus, the maintenance strategy for and inventory of the components can be effectively managed, and future system planning for refurbishment or replacement, including future investments, can be properly conducted.

## 5. Conclusions

In this paper, an FMECA approach for the criticality and risk analysis of HV transmission lines was introduced. The severity criteria were efficiency, safety/reliability, environment, and finance. The %LRI was interpreted as the efficiency severity score. The line loading, system usage, voltage level, contingency, and age were the key factors used to determine the safety/reliability severity score, while human, impact pollution, and public image were used to calculate the environmental severity score. The percentage costs of components and their associated maintenance costs were transformed into the financial

severity score. Then, the criticality was plotted in a criticality matrix, where the risk was differentiated and classified into four levels. Twenty practical transmission lines (115, 230, and 500 kV) in the Thailand transmission system were presented with actual data. The severity and criticality of all components and individual transmission lines were analyzed and plotted in criticality matrices based on four criteria. Consequently, the need for the maintenance, refurbishment, or replacement of the components and transmission lines was able to be ranked depending on the obtained risk. According to the results, it can be concluded that lines #7 and #12 encountered the greatest problems in the network, except for problems based on environmental criteria because the lines are located in the countryside with a medium environmental impact. These lines should be the first priority for short-term reconstruction planning because of their unacceptable condition and high risk in terms of safety, reliability, and finances. Based on these data, we formulated and presented recommendations for the utility provider to engage in maintenance strategies and risk mitigation at all levels of criticality and risk. In this way, the effective and efficient maintenance planning of the transmission system can be managed. Using these recommendations, the transmission network could maintain better condition, higher reliability, a lower risk of failure, and a lower cost of maintenance.

**Author Contributions:** Conceptualization, C.S., T.S., R.P. and S.S.; methodology, C.S. and T.S.; formal analysis, C.S., R.P. and S.S.; investigation, C.S. and T.S.; resources, C.S. and T.S.; data curation, S.S.; writing—original draft preparation, C.S., R.P. and S.S.; writing—review and editing, C.S. and T.S.; supervision, C.S. and T.S.; project administration, C.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

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

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