Supplier Selection of Equipment Components for the Construction of Nuclear Facilities: AHP-Based Approach Integrated with Risk Assessment

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Abstract

Supplier selection is one of the most influential decision an organization can make towards their operational efficiency. However, this activity can become highly resource-intensive in the absence of a structured framework, especially in supply chains involving large numbers of components. This research aims to utilize risk assessment as a tool to screen for construction equipment components that should be considered for re-sourcing to new suppliers. The severities of risks are evaluated by cost of poor quality and occurrence by the frequency of nonconformities. High-risk components were selected for a change of suppliers. Multi-criteria decision-making – analytic hierarchy process (MCDM-AHP) is then used to determine the suitable weights of 12 supplier evaluation criteria between four different managers. Suppliers with the highest results are selected. Once new suppliers are selected, a second risk assessment is conducted to review the impact of the change in suppliers to the cost of poor quality and frequency of nonconformities.

Keywords
Supplier selection, supply chain management, analytic hierarchy process (AHP), risk assessment, cost of poor quality

1. Introduction
According to the International Energy Agency (IEA), nuclear power generation is an integral part for the world to reach the global objective of decarbonization. One of the most challenging entry barriers for new nuclear energy for many nations are the high initial construction costs and negative public opinions on nuclear power (OECD and Nuclear Energy Agency 2020). It does not help that many recent nuclear projects have been plagued with astronomical cost overruns. For example, the construction of Flamanville-3 nuclear power plant in France started in 2007 and was originally planned to be in operation by June 2012. 11 years later, the construction cost now is projected to reach 12.7 billion euros, which is over 4 times the initial estimate or an equivalent of 10,000 euros added to every hour of delay (Overstraeten and Mallet 2022). Naturally, these figures would scare off most countries from investing into any new nuclear power plants.

Although there are a multitude of reasons that would drive up the construction costs of a nuclear project, this research is focused on a specific area of cost overruns originating from delays caused by faulty construction equipment components from the equipment manufacturers' supply chain. While construction equipment used by the nuclear industry may not be specialized inventions, but equipment which is also used in the construction of conventional buildings, their reliability level which might have been acceptable elsewhere may have a profoundly different level of impact to the nuclear energy industry.

Given this context of massive costs for every hour of delays, it is of paramount importance for the construction equipment of nuclear facilities to operate as smoothly as possible without interruption. Otherwise, the overrun costs arising from the delays could quickly turn into hefty fines and penalties, beyond the price of the equipment themselves, to the organizations supplying them to the nuclear industry. Thus, for the construction equipment manufacturers, choosing the right supplier selection strategy is key to being able to secure an efficient component supply chain and meet the needs of the lucrative nuclear market.

In the pursuit of an excellent supply chain, equipment manufacturers are often faced with the problem of sourcing and managing hundreds or thousands of components. Without prioritization, manufacturers would become bogged down in performing ineffective actions without observing any meaningful impact to the quality level of their supply chain. In this, risk assessment offers a utility in separating the wheat from the shaft to identify where actions would have the most impact.

Even with priorities defined, different roles and function within the same organization are seldom in agreement on how to tackle their common problem. Without a clear framework, biases from non-rational and irrational decisions may lead all the efforts made and good intentions down a dead-end path (Guitouni and Martel 1998). To climb out of this trap, multi-criteria decision-making tools, like the Analytic Hierarchy Process, offers an avenue to provide a semblance of structure to a previously unstructured problem. Together with the risk assessment, this research aims to point out how an equipment manufacturer could add new weapons to their arsenal of improvement tools in an industry where any mistakes would spell disaster for all.

1.1 Objectives

The objectives of this research are to establish a robust machinery component supplier selection process using an AHP-based approach integrated with risk assessment to reduce the level of risk associated with poor quality and standardize the supplier selection method for equipment manufacturers.

2. Literature Review

Established works in the field of risk assessment, supplier selection, group decision making, and cost of quality are examined for this research to build upon.

2.1 Risk Assessment

While a variety of risk assessment guidelines are available, as shown in the annexes of the ISO/IEC 31010 (2019) standard, this research opted to use the risk assessment criteria defined by the Department of Industrial Works, Ministry of Industry of Thailand, Regulations on Criteria for Hazard Evaluations, Risk Assessment, and Establishment of Risk Management Plans B.E. 2543 (2000), for its simplicity, clear-cut definitions, and adaptability towards the analysis of this research on supplier selection models.

2.2 Supplier Selection

Supplier selection is key to minimizing supply chain risks before they risks develop into undesirable incidents and claims. At the broadest level, supplier selection strategies can be classified into four categories: mathematical, statistical, artificial intelligence, and an integrated model using more than one method. Amongst the different models available, the Analytic Hierarchy Process (AHP), the Analytic Network Process (ANP), or an integrated method using one of the two methods are some of the most popular models for their reliability and simplicity in solving complex problems (Mukherjee 2017).

2.3 Multi-Criteria Decision Making (MCDM)

Human decision making can be classified into three types: rational, irrational, and non-rational. Rational decisions are made by evaluation all possible alternatives, while non-rational decisions are made with biases based on one's past experiences and knowledge, and irrational decisions are made with biases based on personal preferences (Guitouni and Martel 1998). As pairwise comparisons are typical behavior inherent to human decision making, the pairwise comparison mimicked by multi-criteria decision-making (MCDM) tools are consequently useful in reaching a group decision in complex problems (Mukherjee 2017). Furthermore, Havranek et al. (2023) described how not every decision requires an MCDM process, and only a small portion would benefit from a stochastic MCDM.

2.4 Analytic Hierarchy Process (AHP)

One of the most widely used multi-criteria decision-making methods is the Analytic Hierarchy Process (AHP), first developed by Thomas L. Saaty in the 1970s to help structure group decision making. AHP quantifies the weight of decision criteria using pairwise comparisons and the relationship between each criterion. The popularity of AHP has only grown since it has been made available as a software (Mu and Pereyra-Rojas 2016). One of the available software tools is the AHP Online System (AHP-OS)(Goepel 2018).

2.5 Cost of Quality

According to the American Society for Quality, cost of quality can be a useful tool for an organization to determine the effectiveness of the resources used for the prevention of poor quality. Cost of quality is comprised of two parts, cost of good quality and cost of poor quality. Cost of good quality includes the prevention and appraisal costs, such as quality assurance, training, audits, and supplier selection. Cost of poor quality comes in the form of wastes, scrap, rework, failure analysis, repairs, claims, complaints, or returns (Duffy 2013).

3. Methods

This research is conducted on actual data from a medium-sized construction equipment manufacturer supplying to the nuclear industry worldwide. The manufacturer performs the design, assembly, testing, and delivery of completed equipment while subcontracting the fabrication of components for the equipment to its supply chain. The methodology employed by this research is shown in Table 1.

Table 1. Research procedure

Research Procedure	How
Collect data ↓	Collect data from the nonconformity logs, transactions in the ERP, and accounting ledgers to identify and analyze the cost of poor quality and number of nonconformity reports.
Assess risk ↓	Perform an assessment of the risk level by using the cost of poor quality as the magnitude for severity and number of nonconformity reports as the occurrence frequency.
Identify high risk components ↓	Consider switching to new suppliers for high-risk components identified.
Set criteria for supplier evaluation ↓	Define the supplier evaluation criteria and sub-criteria to reduce the overall cost of poor quality.
Weigh the scoring ↓	Conduct an AHP questionnaire with 4 managers from 4 departments and normalize the weights of the criteria.
Evaluate suppliers ↓	Perform supplier evaluation by applying the average weighted score from the AHP results.
Select suppliers ↓	Select the new supplier based on the results of the evaluation.
Assess risk with selected suppliers ↓	Perform an analysis of the total costs associated with the switch to new suppliers by reconducting the risk analysis.
Conclude	Review the results of the research to determine the applicability of AHP as a supplier selection model for equipment components.

3.1 Supplier Selection

The weighted criteria from the AHP framework provides a basis of a fair and balanced supplier selection model. This approach takes into account the diverse criteria in terms of quality, cost, delivery and services, resulting in a comprehensive evaluation that extends beyond intuitive selection with irrational or non-rational decisions (Mukherjee 2017).

The identification of top-scoring suppliers within this framework reflects an informed decision made from a structured methodology that offers a strategy to improve the supply chain performance of equipment components.

4. Data Collection

4.1 Cost of Poor Quality

Data for this research was gathered in Figure 1 from 211 nonconformity reports (NCR), and the associated transactions in the ERP and accounting ledgers involving 62 components references over a period of 12 months. The cost of poor quality identified can be broken down into the following categories in Figure 1.

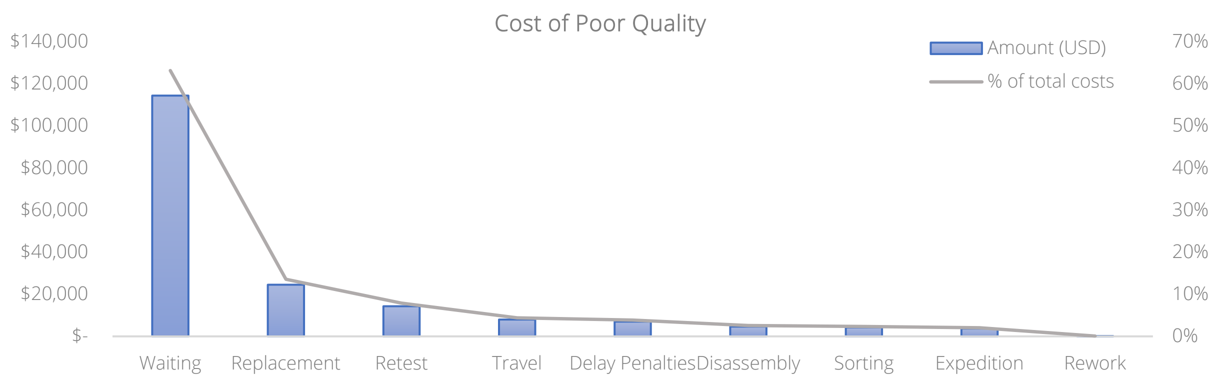

Figure 1. Cost of poor quality disseminated into 9 categories

From the data gathered, it can be observed that the largest proportion of costs are currently from the waiting time. These costs originate from the complexity of the manufacturing process of these nonconforming components. Some components may require special processing, such as heat treatment, hard chrome plating, painting, etc., which are subcontracted to a second tier of service providers. Similarly, some components may be subassembly units requiring specialized parts to be imported to complete the component, for example, valves, pumps, or oil coolers from specific brands with 3-4 months of waiting time. These delays would translate into wasted labor cost, at approximately 60 USD per person per day.

Next in the order of magnitude are the replacement costs. Other than components used for the manufacturing of new equipment, existing equipment at construction sites may also requires replacements. Should the equipment break down during their warranty periods, manufacturers are often contractually obliged to supply replacements components to their customers, free of charges. Additionally, some components cannot be replaced individually and must be replaced as a set, increasing the replacement costs even further. Replacement costs are almost always accompanied by expedition costs, such as airfreight, to prevent the interruption at the nuclear construction sites and the associated fines.

Retesting costs are time and testing resources used to re-verify the conformity of parts for a second time after the reproduction or rework of components not meeting the specified requirements. However, some types of issues cannot be detected with conventional measuring tools prior to the assembly of the equipment and require the entire equipment to be completed before the nonconformity can be observed. Examples of these types of nonconformities include leaks in the hydraulic cylinders or pumps that are not able to build their pressure up to specific levels. These nonconformities would result in the disassembly of the entire equipment for diagnosis, repairs or replacement, reassembling, and retesting of the equipment for a second time after its completion. Costs of the labor in this type of operation would generally last 3-5 days and involve the cost of 60 USD per technician per day, with the addition of engineers required to perform the diagnosis and retesting at 120 USD per person per day.

Travel costs are incurred from the traveling and accommodation of after sales service technicians dispatched to resolve nonconformities at the construction sites. As this research is focused on the equipment components supply chain, only travel costs directly linked to nonconformities originating from the quality of components are considered. Travel costs associated with other reasons, such as design or commercial purposes are not considered. Particular to the organization studied in this research, as personnel already employed by the manufacturer are routinely relocated to the nuclear construction sites, the figure that appears in this research may be lower than the case for other manufacturers.

Delays penalties are contractual requirements for the on-time delivery of completed equipment. Penalty costs in this research are identified as 0.01% of the selling price of the equipment per day, up to a maximum of 5 to 10% of the equipment price. It should be noted here that the penalties costs in the actual data collected in this research did not make up the largest proportion of the total cost of poor quality. This is not a misrepresentation, as the data is collected from an organization already supplying to the nuclear industry, with organizational procedures in place to mitigate the delay penalties, such as having spare equipment in stock to prevent penalties from nuclear worksites. The civil works contractors themselves may have also provisioned for the possibility of equipment delays by having a surplus of equipment stationed at the worksites. It is not the objective of this research to examine these organizational procedures.

Sorting and rework costs are labor costs and lost time associated with the disposition actions after the detection of a nonconformity, such as reexamination of components already in stock or repairs by equipment technicians that would result in a faster resolution than returning all suspected components to the supplier.

4.2 Risk Assessment of Nonconformities

Once the cost of poor quality has been identified, this research adapted risk assessment criteria from the Department of Industrial Works (2000) to the historical data on nonconformance reports (NCRs) associated with the different component references to form the occurrence level. Together, these data form the basis of the inherent level of nonconformity risks in each component shown in Table 2, 3, and 4:

Table 2. Severity level based on the cost of poor quality

Severity	Cost of poor quality	Score
Low	Less than $ 2,000.00	1
Medium	$ 2,000.00 – $ 4,999.99	2
High	$ 5,000.00 – $ 10,000.00	3
Very high	More than $ 10,000.00	4

Table 3. Likelihood of a nonconformity to occur

Likelihood	Number of NCRs	Score
Rare	1 - 3	1
Unlikely	4 - 6	2
Moderate	7 - 10	3
Likely	More than 10	4

Table 4. Risk levels for each type of component

4 x 4 Risk matrix	Low (1)	Medium (2)	High (3)	Very high (4)
Rare (1)	1	2	3	4
Unlikely (2)	2	4	6	8
Moderate (3)	3	6	9	12
Likely (4)	4	8	12	16

Once the level of risk has been determined, it would form the basis to select high-impact components whose supply chain should be examined further by this research. The significance of each risk level is shown in Table 5:

Table 5. Interpretation of the risk levels

Risk level	Score	Significance
1	1 - 2	Low level of risk
2	3 - 6	Acceptable level of risk, which should be reviewed
3	8 - 9	High level of risk, which should be reduced
4	12 - 16	Unacceptable level of risk, which requires immediate actions to address the risk

4.3 Identified High-Risk Components

As this research is focused on nonconformities originating for the supply chain, the cost of poor-quality disparity between the sources of each high-risk components are compared to their new suppliers. The new suppliers are considered in this context due to the recurrence frequencies identified by the risk assessment performed. Their high-risk statuses indicate that the previous suppliers of these components have not been able to resolve the recurrence of nonconformities.

4.4 Set Criteria for Supplier Evaluation

Supplier evaluation criteria are selected from both organizational requirements and established works in procurement marketing (Koppelman 1998) and supplier selection models (Ávila et al. 2012)(Saputro 2023)(Boonsong 2020)(Chu and Varman 2011). The evaluation criteria are classified into 4 categories, as shown in Table 6.:

Table 6. Evaluation criteria for supplier selection.

Criteria		Sub-criteria	Criteria		Sub-criteria
Quality	Q1	Supplier performance	Cost	C1	Price level
	Q2	Number of complaints		C2	Payment term
	Q3	Audit score		C3	Request-for-quotation turnaround
Delivery	D1	On-time delivery	Service	S1	Reliability
	D2	Standard lead time		S2	Documentation accuracy
	D3	Supplier distance		S3	After-sales service

4.5 Weighing of the Selection Criteria by AHP

To obtain quantitative data, AHP questionnaires were distributed to 4 selected assessors. The 4 assessors are: procurement manager, quality assurance manager, supplier quality manager, and planning manager. The questionnaire sought their opinions on the relative importance of each criterion and sub-criterion for supplier evaluation. Participants were asked to perform pairwise comparisons to establish the weighing of the evaluation factors, as shown in Figure 2. For practicality, the AHP Online System (AHP-OS) by Goepel (2018) was utilized in this research to calculate the results.

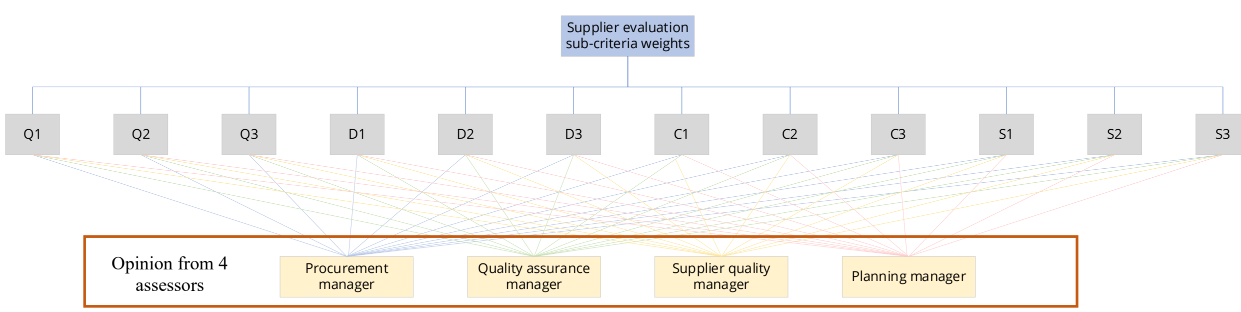

Figure 2. A Hierarchy model of supplier evaluation

The order of importance from the results of AHP is shown in Table 7. Managers were asked to repeat their questionnaire until their Consistency Ratio (CR) is less than or equal to 10%.

Table 7. The ratio scale and definition of AHP (Saaty 1990)

Intensity of importance	Definition
1	Equal importance
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2, 4, 6, 8	Intermediate values

4.6 Weights of the Evaluation Criteria for Supplier Selection from AHP by Individual Assessors

The outcomes of the weighing evaluation conducted through the Analytic Hierarchy Process (AHP) are presented in Tables 8, 9, 10, and 11 for the procurement manager, quality assurance manager, supplier quality manager, and planning manager respectively.

The procurement manager rated quality the highest at 47.9%, followed by service at 20.4%, cost at 17.6%, and delivery at 14.1%, as shown in Table 8.

Table 8. Criteria weights by the procurement manager

	Q1	Q2	Q3	D1	D2	D3	C1	C2	C3	S1	S2	S3	Weight	Total	CR
Q1	1	2	4	4	9	9	5	7	7	3	3	8	25.0%	47.9%	9.9%
Q2	1/2	1	5	3	8	7	2	6	7	4	3	7	18.9%		
Q3	1/4	1/5	1	1/3	3	4	1/5	1	7	1	1/3	1/4	4.0%		
D1	1/4	1/3	3	1	7	7	2	4	5	4	2	3	11.8%	14.1%	
D2	1/9	1/8	1/3	1/7	1	1/2	1/9	1/7	1/4	1/9	1/8	1/9	1.1%		
D3	1/9	1/7	1/4	1/7	2	1	1/9	1/7	1/3	1/8	1/7	1/9	1.2%		
C1	1/5	1/2	5	1/2	9	9	1	6	8	2	3	3	12.1%	17.6%	
C2	1/7	1/6	1	1/4	7	7	1/6	1	5	1/3	1/3	1/4	3.7%		
C3	1/7	1/7	1/7	1/5	4	3	1/8	1/5	1	1/5	1/6	1/6	1.8%		
S1	1/3	1/4	1	1/4	9	8	1/2	3	5	1	1	1	6.3%	20.4%	
S2	1/3	1/3	3	1/2	8	7	1/3	3	6	1	1	1	7.0%		
S3	1/8	1/7	4	1/3	9	9	1/3	4	6	1	1	1	7.1%		

The quality assurance manager's AHP results in Table 9 weighted quality the highest at 48.5%, followed by service 30.6%, cost at 10.8%, and delivery at 10.2%.

Table 9. Criteria weights by the quality assurance manager

	Q1	Q2	Q3	D1	D2	D3	C1	C2	C3	S1	S2	S3	Weight	Total	CR
Q1	1	2	1	3	5	7	3	5	9	3	1	3	16.4%	48.5%	9.3%
Q2	1/2	1	5	5	7	9	4	7	9	3	5	7	24.2%		
Q3	1	1/5	1	3	5	5	1	5	7	1/3	1/3	1	7.9%		
D1	1/3	1/5	1/3	1	7	7	2	5	7	1/3	1/3	1	6.8%	10.2%	
D2	1/5	1/7	1/5	1/7	1	3	1/7	1/3	3	1/5	1/5	1/3	2.0%		
D3	1/7	1/9	1/5	1/7	1/3	1	1/9	1/3	3	1/7	1/7	1/5	1.4%		
C1	1/3	1/4	1	1/2	7	9	1	7	9	1/3	1/3	1	7.2%	10.8%	
C2	1/5	1/7	1/5	1/5	3	3	1/7	1	5	1/7	1/7	1/5	2.5%		
C3	1/9	1/9	1/7	1/7	1/3	1/3	1/9	1/5	1	1/7	1/9	1/5	1.1%		
S1	1/3	1/3	3	3	5	7	3	7	7	1	1	3	12.2%	30.6%	
S2	1	1/5	3	3	5	7	3	7	9	1	1	3	12.8%		
S3	1/3	1/7	1	1	3	5	1	5	5	1/3	1/3	1	5.6%		

The supplier quality manager's results in Table 10 yielded quality as the highest-ranking criteria at 48.4%, followed by service at 27.9%, cost at 13.6%, and delivery at 10.4%.

Table 10. Criteria weights by the supplier quality manager

	Q1	Q2	Q3	D1	D2	D3	C1	C2	C3	S1	S2	S3	Weight	Total	CR
Q1	1	1/2	4	5	8	6	3	5	6	3	1	3	17.1%		
Q2	2	1	3	5	8	7	5	7	9	3	1	3	20.6%	48.4%	
Q3	1/4	1/3	1	4	5	3	3	5	6	2	1	1	10.7%		
D1	1/5	1/5	1/4	1	7	5	1/5	4	6	1	1/3	1	5.9%		
D2	1/8	1/8	1/5	1/7	1	1/4	1/5	1	3	1/4	1/5	1/5	1.8%	10.4%	
D3	1/6	1/7	1/3	1/5	4	1	1/7	1/3	5	1/3	1/5	1/3	2.7%		9.2%
C1	1/3	1/5	1/3	5	5	7	1	5	8	3	1/3	1/2	9.4%		
C2	1/5	1/7	1/5	1/4	1	3	1/5	1	4	1/3	1/5	1/3	2.7%	13.6%	
C3	1/6	1/9	1/6	1/6	1/3	1/5	1/8	1/4	1	1/5	1/7	1/5	1.2%		
S1	1/3	1/3	1/2	1	4	3	1/3	3	5	1	1/3	1/2	5.2%		
S2	1	1	1	3	5	5	3	5	7	3	1	5	15.3%	27.9%	
S3	1/3	1/3	1	1	5	3	2	3	5	2	1/5	1	7.4%		

The planning manager's results in Table 11 revealed a quality rating at 46.6%, delivery at 22.6%, service at 22.0% and cost at 8.6%. Notable, the planning manager value delivery in 2nd place, while all other managers rated service as their second-most important criteria.

Table 11. Criteria weights by the planning manager

	Q1	Q2	Q3	D1	D2	D3	C1	C2	C3	S1	S2	S3	Weight	Total	CR
Q1	1	3	3	2	5	3	5	7	7	3	2	5	20.4%		
Q2	1/3	1	3	2	3	3	4	7	9	3	2	3	15.5%	46.6%	
Q3	1/3	1/3	1	1	5	5	3	5	6	2	1	2	10.7%		
D1	1/2	1/2	1	1	5	5	5	8	9	2	3	2	14.3%		
D2	1/5	1/3	1/5	1/5	1	1/2	2	3	3	2	1/3	1/3	4.2%	22.6%	
D3	1/3	1/3	1/5	1/5	2	1	1/3	5	7	1/3	1/5	1/3	4.1%		9.0%
C1	1/5	1/4	1/3	1/5	1/2	3	1	7	9	1	1/3	1	5.4%		
C2	1/7	1/7	1/5	1/8	1/3	1/5	1/7	1	3	1/3	1/5	1/3	1.8%	8.6%	
C3	1/7	1/9	1/6	1/9	1/3	1/7	1/9	1/3	1	1/3	1/5	1/3	1.4%		
S1	1/3	1/3	1/2	1/2	1/2	3	1	3	3	1	1/3	2	5.4%		
S2	1/2	1/2	1	1/3	3	5	3	5	5	3	1	5	11.3%	22.0%	
S3	1/5	1/3	1/2	1/2	3	3	1	3	3	1/2	1/5	1	5.3%		

5. Results and Discussion

5.1 Risk Assessment

The overall risk assessment of 62 components was conducted through the examination of their cost of poor quality, expressed in severity levels, coupled with the consideration of the number of nonconformity reports (NCRs), expressed as occurrence levels. The results of the initial risk assessment are shown in Figure 3.

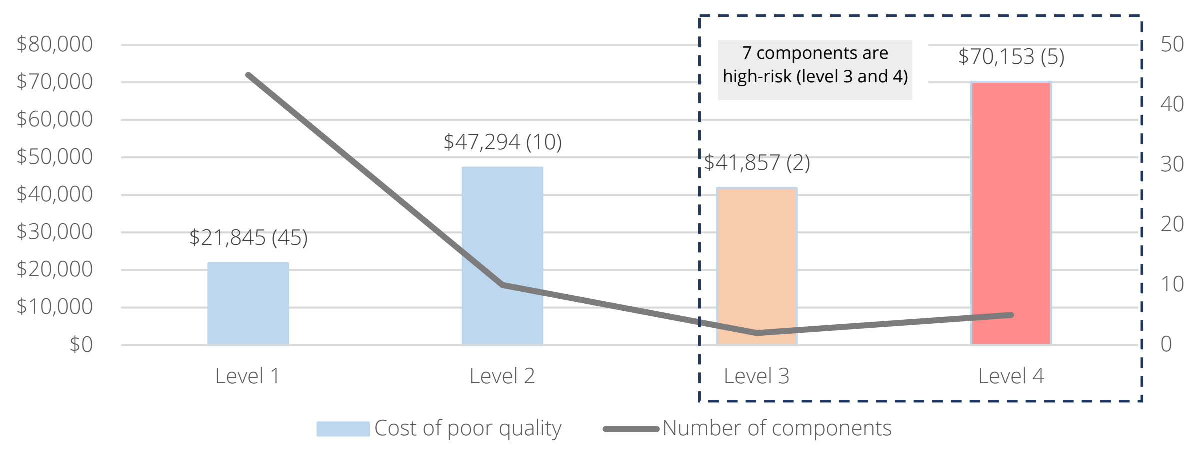

Figure 3. Relationship between the cost of poor quality and number of components in each risk level

A total of 7 components are identified as high-risk and need to be considered for new suppliers. Figure 3 illustrates that there are 5 components classified as unacceptable risks (level 4), incurring $70k USD in cost of poor quality and 2 components in the high risks (level 3) category, with a cost of poor quality at $41k USD. Upon combining the two high risk levels, the cumulative cost of poor quality is at $112k USD, or 61.83% of the total cost of poor quality incurred. This risk assessment demonstrates the importance of corrective measures to mitigate the risks associated with level 3 and level 4 components in order to reduce the overall exposure to cost of poor quality.

5.2 Sources of High-Risk Components

The sources of the 7 high-risk components previously identified can be attributed to 3 suppliers, called V4, V5, and V6, as shown in Figure 4. These 3 suppliers are identified as the top contributing suppliers to the cost of poor quality. Notably, components MC1, MC3, MC4, MC6, and MC7 fall under the unacceptable risk category (level 4), while components MC2 and MC5 falls under the high-risk category (level 3). While MC2 exhibits the highest cost of poor quality, its likelihood is considerably lower, leading to its lower classification. On the other hand, MC4 component with the second-highest costs has a higher frequency of occurrence, taking it to the level 4 classification.

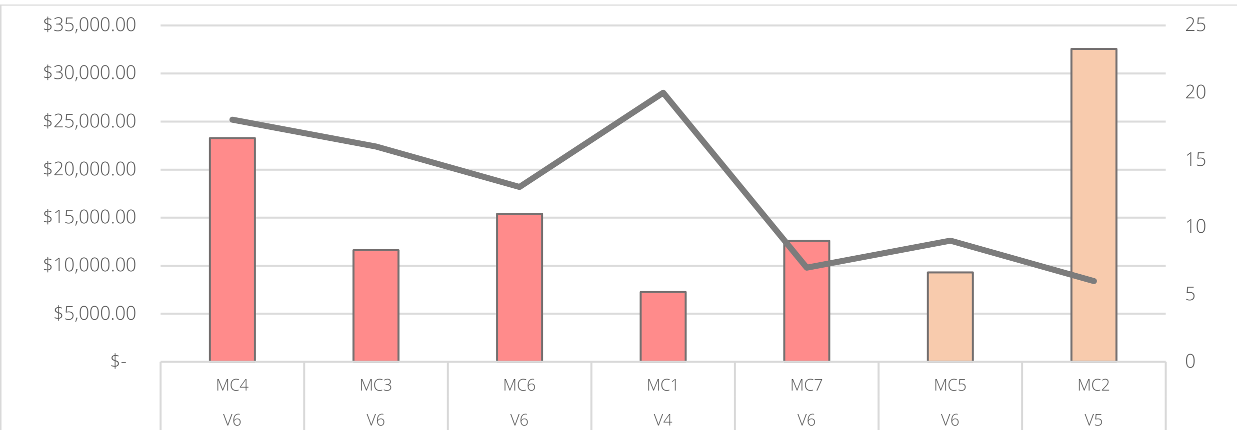

Figure 4. Correlation between the cost of poor quality and the number of nonconformity reports for each component sourced from previous suppliers

5.3 Weighted Evaluation Criteria for Supplier Selection

Based on the outcome of the AHP evaluations in Tables 8 through 11, an averaged consensus of each sub-criterion can be drawn. The collective weighted criteria are shown in Table 12, revealing the top-ranking criteria to be quality with the highest combined weight at 47.8%, followed by service at 25.3%, then delivery at 14.3%, and finally cost at 12.6%.

Table 12. Weighted evaluation criteria by AHP from 4 managers

Manager	Q1	Q2	Q3	D1	D2	D3	C1	C2	C3	S1	S2	S3
Procurement	25.0	18.9	4.0	11.8	1.1	1.2	12.1	3.7	1.8	6.3	7.0	7.1
Quality assurance	16.4	24.2	7.9	6.8	2.0	1.4	7.2	2.5	1.1	12.2	12.9	5.6
Supplier quality	17.1	20.6	10.7	5.9	1.8	2.7	9.4	2.7	1.2	5.2	15.3	7.4
Planning	20.4	15.5	10.7	14.3	4.2	4.1	5.4	1.8	1.4	5.4	11.3	5.3
Average	**19.7**	**19.8**	**8.3**	**9.7**	**2.3**	**2.3**	**8.5**	**2.7**	**1.4**	**7.3**	**11.6**	**6.4**

5.4 Supplier Evaluation Results

Following the establishment of weighted supplier evaluation criteria, components suppliers V1 through V6 can now be evaluated. The result of this evaluation is shown in Table 13. Suppliers V1, V2, and V3 are new suppliers, while V4, V5, and V6 are previous suppliers.

Table 13. Supplier evaluation results

Supplier	Total Score (%)	Quality (%)			Delivery (%)			Cost (%)			Service (%)		
		Q1	Q2	Q3	D1	D2	D3	C1	C2	C3	S1	S2	S3
V1	92.46	19.73	19.80	6.69	9.70	2.28	1.88	6.40	1.07	1.10	5.82	11.63	6.35
V2	90.10	19.73	19.80	6.66	8.62	2.28	2.12	5.69	1.61	1.24	4.37	11.63	6.35
V3	86.86	17.76	15.84	7.24	9.51	2.22	1.88	6.40	1.61	1.24	5.82	11.63	5.72
V4	48.90	0.00	5.94	3.54	8.08	1.94	1.88	8.53	1.61	1.38	4.37	11.63	0.00
V5	46.62	1.97	0.00	4.21	9.26	2.17	2.12	8.53	1.34	1.24	4.37	11.41	0.00
V6	39.01	0.00	0.00	1.23	9.18	2.28	2.12	8.53	1.61	1.24	2.91	9.91	0.00

The results show that the previous suppliers all scored below 50%, while their new suppliers all scored above 80%. This substantial difference can be attributed to the higher quality and service level offered by V1, V2, and V3 suppliers compared to the existing suppliers. In contrast, the previous suppliers all scored higher in the costs category. The delivery scores of all 6 suppliers shows no significant differences.

5.5 Supplier Selection

New suppliers can now be selected. The difference between the unit purchasing price of the previous and new suppliers is shown in Table 14. All components sourced to their new suppliers show an approximate increase in raw purchasing price by 4.14%.

Table 14. Comparison of previous suppliers and new suppliers for each component in terms of unit price ($)

Component	Order / year (pcs)	Before (Year 2022)		After (Year 2023)			
		Supplier	Unit price ($)	New Supplier	Unit price ($)	+ Differ ($)/piece	+ Differ ($)/order
MC1	22	V4	1,410	V3	1,466	56	1,232
MC2	22	V5	183	V1	206	23	506
MC3	13	V6	10,970	V3	11,294	324	4,212
MC4	22	V6	3,807	V2	4,174	367	8,074
MC5	17	V6	4,583	V2	4,653	70	1,190
MC6	16	V6	6,204	V2	6,486	282	4,512
MC7	13	V6	1,974	V2	2,059	85	1,105

From Table 14, it can be seen that the unit price of MC4 is increased by $367, or about 10%. Should the unit price be the sole selection criteria, the new supplier would not have been selected at all. Similarly, MC3 and MC6 also has a high increase in the initial until price tag.

5.6 Risk Assessment After Changing to New Suppliers

Following the transition to new suppliers for components MC1-MC7, a discernible reduction is observed in both the cost of poor quality and the number of nonconformity reports, as presented in Table 15. It can also be noted that despite the increase in unit price of MC3, MC4, MC6, their cost of poor quality has reduced considerably.

Table 15. Comparison between cost of poor quality and number of nonconformity reports before and after changing suppliers

Components	Cost of poor quality ($)			Number of nonconformity reports		
	2022	2023	% Reduction	2022	2023	% Reduction
MC1	7,262	1,292	82.21%	20	2	90.00%
MC2	32,555	506	98.45%	6	0	100.00%
MC3	11,615	4,332	62.70%	16	2	87.50%
MC4	23,275	8,254	64.54%	18	1	94.44%
MC5	9,302	1,213	86.96%	9	1	88.89%
MC6	15,405	4,587	70.22%	13	2	84.62%
MC7	12,597	1,240	90.16%	7	3	57.14%
Total	**112,010**	**21,424**	**80.87%**	**89**	**11**	**87.64%**

5.7 Reconducting the Risk Assessment

After the switch to new suppliers, the risk assessment is reconducted again to observe the effectiveness of the actions taken. The risk level comparison after the improvement actions, showing an improvement across the board in components MC1 through MC7 are shown in Table 16.

Table 16. Risk assessment reconducted after the change in suppliers

Component	Additional cost		Severity (S)		Occurrence (O)		Risk level	
	Component cost ($)	Cost of poor quality ($)	Cost impact ($)	level	Number of NCRs	Level	S x O	Level
MC1	1,232	60	1,292	1	2	1	1	1
MC2	506	0	506	1	0	0	0	No risk
MC3	4,212	120	4,332	2	2	1	2	1
MC4	8,074	180	8,254	3	1	1	3	2
MC5	1,190	23	1,213	1	1	1	1	1
MC6	4,512	75	4,587	2	2	1	2	1
MC7	1,105	135	1,240	1	3	2	2	1

6. Conclusion

The result of this research shows that when risk assessment is used to analyze the risk level from the supply chain of 62 equipment components based on the total cost of poor quality and number of nonconformity reports, only 7 components were rated as high or very high risks. However, these 7 components constituted 61% of all the total cost of poor quality generated. Therefore, new suppliers must be selected for these 7 components.

In the selection of suppliers, evaluation criteria and sub-criteria must be defined while considering the risk assessment. The criteria were classified into four categories: quality, service, delivery, and costs. The criteria were selected from both established literature and consensus between experienced personnel in the field of procurement, quality assurance, supplier quality, and planning.

Experts from each of the relevant fields determined the weight of each evaluation criteria through the use of AHP. All participants understood the context and relevance of the exercise with respect to the current quality issues faced by the organization in the supply of construction equipment to the nuclear industry. As a result, quality and service criteria received the higher weight at 47.8% and 25.3% respectively, while delivery and costs were weighed lower at 14.3% and 12.6% respectively.

From the supplier evaluation criteria, 6 suppliers were analyzed. It was observed that all previous suppliers with a risk level of 3 or higher scored below 50% in the new evaluation metric, while their new suppliers all scored above 80% with their higher level of quality and service, despite their higher initial prices.

Once the sources of components at level 3 or higher risks have been changed to new suppliers with higher evaluation scores, a revaluation of the risk level is conducted. The total cost of poor quality between the 7 parts was reduced by 80.87%, and the frequency of nonconformities have reduced by 87.64%. The second risk assessment revealed a reduction in risk level of the 7 components. 1 component is now classified in the acceptable risk category, 5 in the low-risk category, and 1 in no-risk category.

This research demonstrated the utility of risk assessment as a tool to screen and prioritize high-risk components to be re-sourced with weighted supplier evaluation criteria through AHP to reduce the cost of poor quality and frequency of nonconformities in equipment components. This type of approach is especially useful for organizations trying to improve the quality amongst a wide range of externally sourced components with limited resources. The level of severity and occurrence can be tailored to a different acceptance tolerance for a better fit with an organization's needs and available resources.

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