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IQLM: Application for Rail Systems

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SUMMARY & CONCLUSIONS

Cost-effectiveness is an evaluation involving both performance and cost. The best performing rail system may not be the most cost effective one. Therefore, when analyzing the acquisition of a rail system, both performance and cost must be considered. The Integrated Quality & Logistics Management (IQLM) methodology presented in this paper demonstrates how to evaluate cost-effectiveness for a system that involves both measurable and assessed characteristics for better decision making. In addition, the method demonstrates that decision making under uncertainty requires thorough sensitivity analysis to generate robust results.

1. INTRODUCTION: QUALITY VERSUS LOGISTICS

The decision maker seeks to optimize the balance between performance and functionality on one side and cost on the other. The basic problem is to determine an interaction between Pre-Acquisition, Acquisition, Verification, Operations & Maintenance, and ILS costs as a function of logistics and quality parameters (e.g., MTBF, Stoppages per million km, Documentation completeness). An innovative solution for this problem has been developed by the authors. It is based on the Qualimetry approach, which provides methodology and tools for optimization and trade-offs between the above characteristics, thus supporting cost effective management [1].

2. INTEGRATED QUALITY AND LOGISTICS MANAGEMENT BREAKDOWN STRUCTURE

Quality is related to a combination of many properties and features, and may be considered as a measure of a hierarchical multilevel complex of attributes that reflect an entity's ability to satisfy stated or implied needs. Needs may include usability, safety, tonnage, reliability, availability or any other attribute. An attribute can either be assessed (qualitative) or measured (quantitative) to determine its conformity or nonconformity to requirements.

Based on experts' knowledge, customers surveys, and regular common sense, one can build an IQLM Breakdown Structure, which reflects the hierarchical multilevel complex of a system's attributes, and contains a complete set of its quality, performance, and functional characteristics [2].

It is not feasible to invent an absolute and unconditional metric for such a hierarchical complex; instead, we will establish a relative and comparative metric. Almost all quality estimation and decision making problems can be treated as relative comparisons of several alternatives.

In its most general form, the model for quality assessment uses the Integrated Quality & Logistics Management Index as the quality estimate, and incorporates the Integrated Quality & Logistics Management Breakdown Structure (IQLMBS), Importance Rankings, Quality Ratings, etc.

An IQLMBS consists of items and branches. Each item represents one Quality Characteristic. Items on the bottom level represent Primary Characteristics (PC), and items on higher levels represent Complex Characteristics. Quality Characteristics having the same parent comprise a Quality Characteristic Group (QCG).

The most widely used method of creating tree-like structures like the IQLMBS is the "top-down" approach. Using this method, the top of the tree (the Quality Characteristic named, as a rule, "Integrated Quality & Logistics Management Index") is broken down into Quality Characteristics such as Logistics, Customer Satisfaction, and Product Competitiveness (see Figure 1 below). These complex characteristics are then further broken down in an iterative manner until each branch is decomposed into the lowest level—groups of the Primary Characteristics.

Note that a PC can appear at the lowest level of more than one branch, if more than one Complex Characteristic depends upon it.

3. EXAMPLE

A national railway authority has been assigned to plan and purchase a train system. The authority must select between two possible suppliers. One supplier offers a "low cost - medium quality" system with an attractive price yet expensive maintenance. The other supplier offers a "high cost - high quality" system that is more expensive, yet requires cheaper maintenance. To evaluate the performance of each alternative, we construct an IQLM Breakdown Structure, illustrated in Figure 1.

IQLMBS items such as Maximal Speed, PHST (Packaging, Handling, Storage & Transportation), and Safety are *primary characteristics*. Supplier Logistics, Reliability and Customer Satisfaction are *complex* characteristics. PHST, Spares & STE (Support Test Equipment), Manpower Management, Documentation and Customer Training comprise one *group* under the Customer Site Logistics.

The IQLMBS illustrated in Figure 1 represents the general case of product manufacturer who must support both internal

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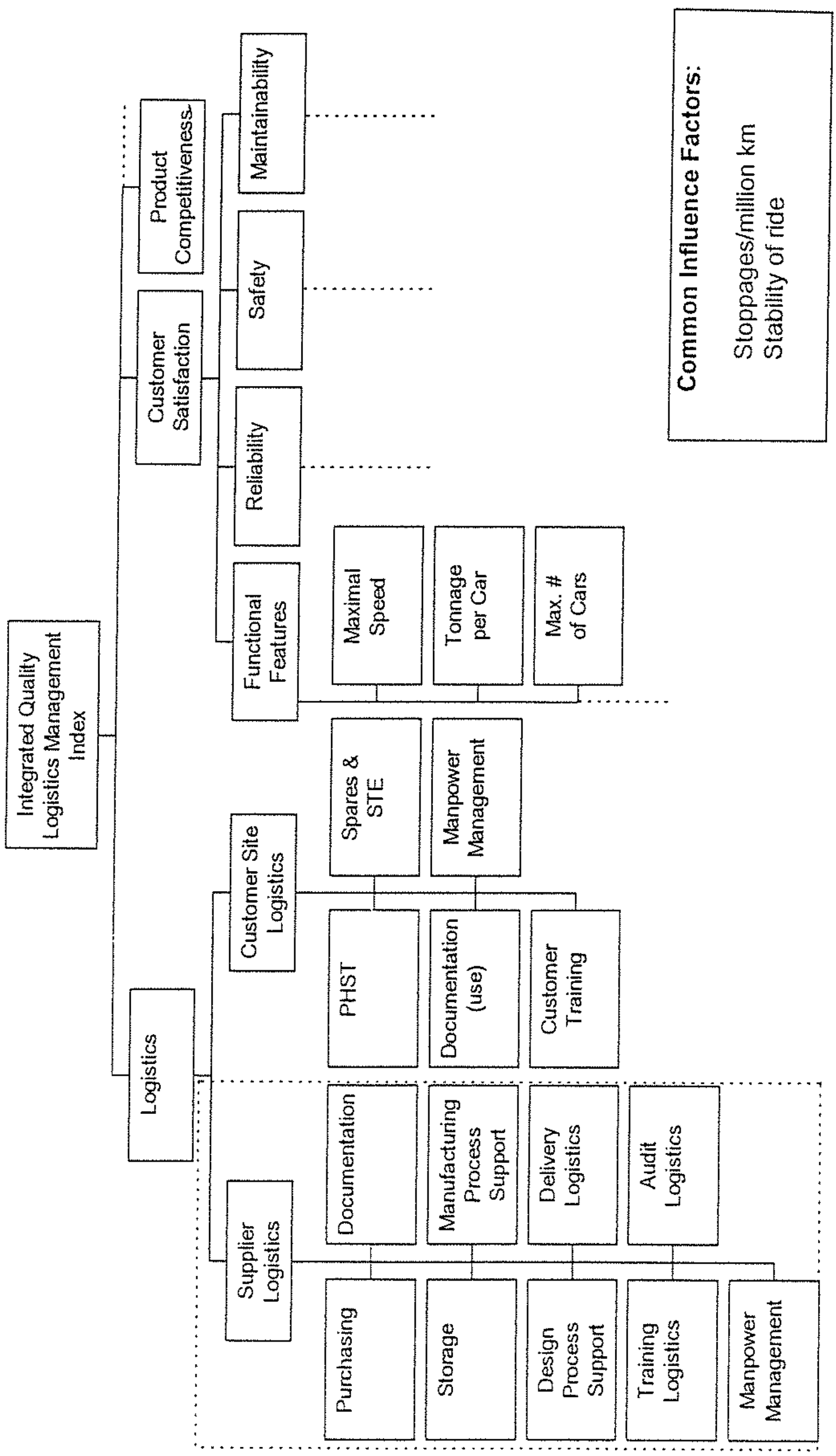


Figure 1. Example Fragment of IQLM Breakdown Structure

supplier logistics (those existing within the factory) and external *customer site logistics* (those existing outside the factory). The product providing the maximal support for both these logistics functions is, in fact, the one that provides the best Integrated Quality and Logistics Index. In our example, however, we are concerned solely with a purchasing problem. The buyer does not need to bifurcate logistics into internal and external environments; as a result, the segment surrounded by the dotted line in Figure 1 drops off the tree, and the remaining levels under Customer Site Logistics are restructured under the "Logistics" element.

4. *QUANTITATIVE TRANSFORMATIONS FOR IQLMBS ELEMENTS*

Each element of the IQLMBS is determined by two quantitative transformations: a Quality Rating (QR) and an Importance Rating (IR).

4.1 Quality Ratings

The Quality Rating (QR) for a Primary Characteristic is assessed as a function with values in the range from 0 to 1, that is: $0 \le Q_i = f(P_i) \le 1$, where P_i is a discrete or continuous PC. A Quality Rating function transforms some physical continuous characteristic (e.g., length, maximum speed) or discrete grade (e.g., documentation completeness, maintenance policy, stability of ride) into a qualimetric scale measured over the interval 0 to 1. A QR function reflects the relative measure of satisfaction with the PC's possible value as a fraction of full satisfaction when achieving the PC's best value. Such functions can be defined by analytical or statistical calculation, expert's assessment, or customer reviews.

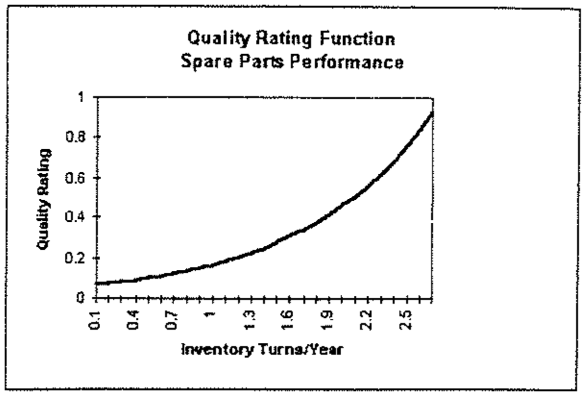
There are two main methods for defining QR functions: graphical and tabular. In the graphical method, the expert chooses a function or curve that best represents the relationship between any possible characteristic value and the corresponding Quality Rating. In the tabular method, the expert assigns a quality rank for each possible performance grade. Figure 2 gives examples of both the tabular and graph methods for relating Primary Characteristics to the QR.

All QR functions can be divided into three primary classes. The first class includes regular mathematical functions of a measurable characteristics. An example in railways application is No-Shortage Probability as a function of quantity of spares (Figure 3a). In this case, the No-Shortage Probability can be interpreted as the Quality Rating of "quantity of spares".

Another class maps a measurable characteristic onto an assessed (or subjective) rating. An example of this mapping is maximal train speed vs. safety. While maximal speed is a characteristic that can be measured, "safety" is a term that requires assessment, evaluation, and consensus.

The last class maps an assessed characteristic onto an assessed quality rating. This type of mapping typically

Graphical Method



Tabular Method

Documentation Completeness	QR
None	0.00
Some	0.20
Fair	0.50
Good	0.80
Excellent	1.00

Figure 2. Graph Function and Table relating PQC to QR

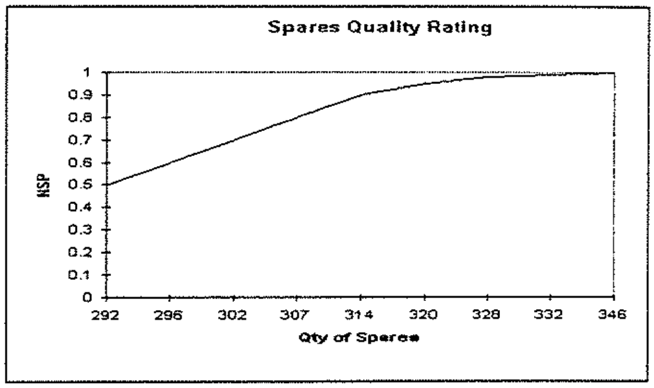


Figure 3a. Quality Rating Function - Measurable Characteristic to Measurable Rating Scale

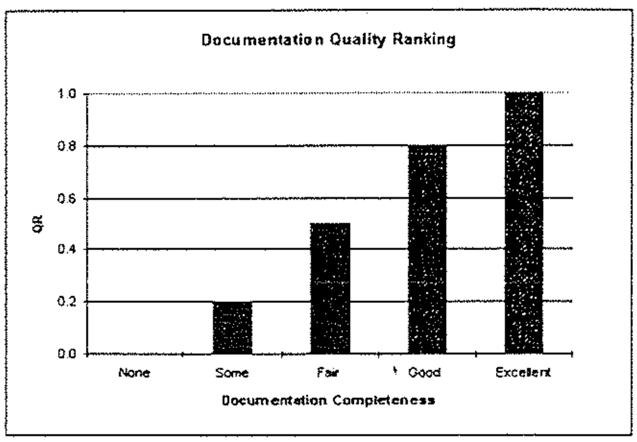


Figure 3b. Quality Rating Function - Assessed Characteristic to Assessed Rating Scale

occurs when neither the characteristic being evaluated nor the target Quality Rating can be objectively measured. Railway equipment documentation is a good example (Figure 3b). "Level of documentation" is a term that cannot be specifically measured. This is because many components are involved, not all of which are quantitative (completeness, accessibility, diction, syntax, style, etc.). The quality rating of documentation is subjective as well; one reader may find a particular style well written, while another reader may find the same material difficult to use.

4.2 Importance Ratings

The Importance Rating (IR) reflects the relative importance of the Quality Characteristics in the same Group (QCG), and should be defined by expert(s). To assess an IR one should consider all quality characteristics of each group, i.e., all "children" of each complex characteristic in the IQLMBS.

The Importance Rating interacts with the corresponding characteristics of the next higher level of the IQLMBS. Figure 4 below shows an example of how two characteristics in the same group have weights (IR) that sum to one.

4.3 Integrated Quality & Logistics Management Index

The Integrated Quality & Logistics Management Index (IQLMI) is defined as the weighted average estimate of the quality of a system under consideration. Technically, the IQLMI is calculated as a weighted average of the children's quality indices.

In general, any correct averaging method can be used to calculate the IQLMI and quality indices for Complex Characteristics. The most widely used method is arithmetic averaging:

$$Q_\Sigma = \sum_{i=1}^{n}(W_i \cdot Q_i) / \sum_{i=1}^{n} W_i$$

where:

Q_i is the Quality Rating estimate of the ith characteristic

W_i is the Importance Rating (Weight Factor) estimate of the ith characteristic

n is the number of characteristics in the Group

For example, Figure 4 shows how the quality index for Logistics is calculated as a weighted average of the quality indices for the two lower level characteristics, Supplier Logistics and Customer Site Logistics.

5. COST BREAKDOWN STRUCTURE

To enable study of how effective the train's performance is, cost must be considered. The IQLM approach requires that performance quality be measured per unit cost. In the example project, "cost" means the life cycle cost (LCC) for the entire train system.

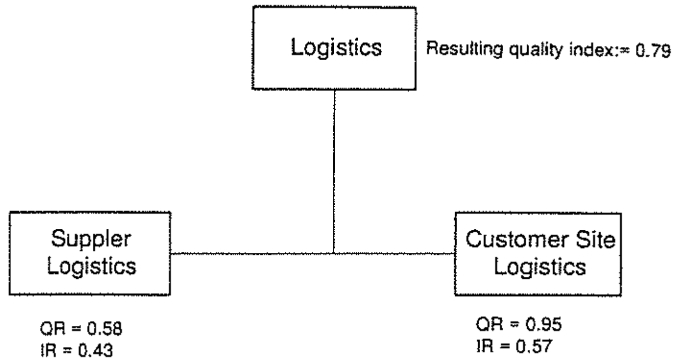


Figure 4. IQLMBS segment showing Quality Index computation

Using well known LCC techniques, the project's cost breakdown structure (CBS) is constructed (Figure 5). Next, total life cycle cost is computed. Further in this paper, the result is used in the sensitivity analysis to evaluate system cost-effectiveness.

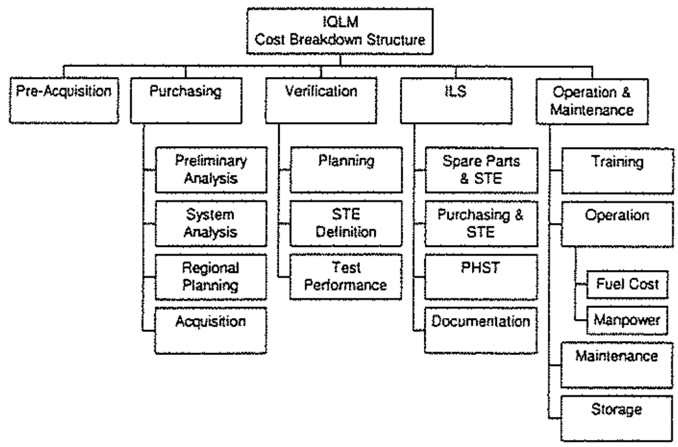


Figure 5. Example IQLM Cost Breakdown Structure

6. COMMON INFLUENCE FACTORS

As a rule, Primary Characteristics are affected by various external parameters called Common Influence Factors (CIF). CIFs can affect more than one IQLMBS or CBS element, even if they are not actually part of the tree.

For example, the Primary Characteristic "Spare Parts & STE" appears in both the IQLMBS (see Figure 1) and the CBS (see Figure 5). One CIF that impacts both these items is number of Stoppages Per Million Kilometers (SPMK). The more stoppages a train suffers, the higher the required level of spare parts stocks and associated test equipment. Figure 6 illustrates how SPMK impacts the performance and cost of Spare Parts and LCC for one of the alternatives (the "low cost - medium quality" supplier) being considered in an actual railway system procurement study. Note that the high quality train does not suffer such degradation, since its average SPMK is lower.

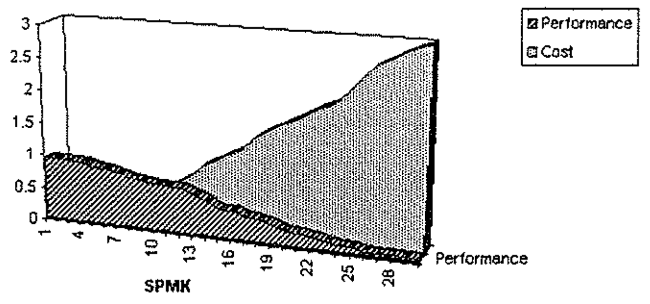


Figure 6. Impact of SPMK on Spares Performance and Cost

7. SENSITIVITY ANALYSIS

Even if we do not take into account errors in measuring physical or statistical parameters (like number of stoppages per million km), the aggregate estimate of system performance always contains some uncertainty.

- The Quality Rating function maps a characteristic to a value. Except for the class that maps a measurable characteristic to a measurable level of performance (see section 4.1 above), these mappings require expert evaluation or subjective judgment.
- Importance Ratings are the result of a subjective comparison among IQLMBS elements performed by experts.

Irrespective of the number of experts and their level of qualification, a point QR estimate will contain some uncertainty which in principle cannot be eliminated. Therefore, any IQLMI point estimate, and the corresponding cost-effectiveness computation, will provide some *indication* of comparison between alternatives, but it may not be a satisfactory basis for decision making. The best way to increase the confidence of the obtained results is to perform Sensitivity Analysis of the IQLMI and LCC versus basic Primary Characteristics and/or CIFs.

Minor deviations in a Primary Characteristic's value may change the difference between IQLMI point estimates for several alternatives. Furthermore, in some cases a small deviation in a PC value may lead to an opposite decision regarding the best alternative—depending on the PC value.

In general, the following principal rule is true: it is impossible to *a priori* know what effect the CIF variation will have on the IQLMI. The only way to get a clear understanding of a CIF's influence is to perform sensitivity analysis.

Therefore, when IQLM is used for evaluating a serious problem, it is strongly recommended to perform Sensitivity Analysis versus each PC. This will accomplish the following tasks:

1. Check the robustness of the final decision obtained by comparing IQLMI point estimates for all alternatives under analysis.
2. Determine which PC has the greatest impact on the IQLMI.

As noted in section 6, Primary Characteristics are affected by various Common Influence Factors. Therefore, modifying one CIF may lead to improved performance on several PCs—thus improving the total IQLM and LCC. Using the Qualimetry methodology, we can construct a relationship between this CIF and corresponding IQLMBS elements.

Figure 7 depicts the evaluated IQLMI for both train suppliers. We see that for the current level of SPMK (100%), supplier B results in a higher IQLMI than supplier A. When SPMK is increased to 109% of the current level (point *o*), supplier A becomes equal to supplier B; at 120%, supplier A already dominates supplier B.

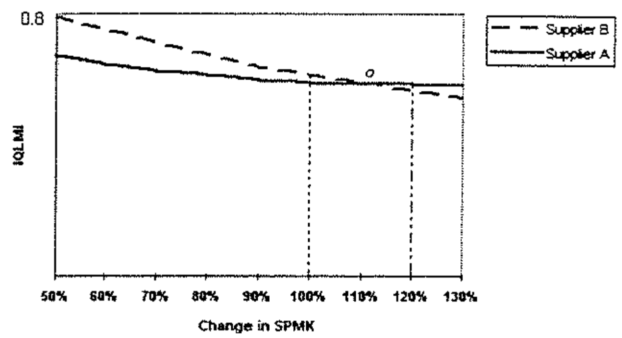


Figure 7. Sensitivity Analysis versus CIF "SPMK"

8. LCC AND COST-EFFECTIVENESS

As mentioned in section 1, a railway system buyer seeks not just a high quality system, but one that is cost effective as well. The IQLMI itself, while an excellent measure of performance, excludes cost considerations.

Therefore, an additional step is needed to compute life cycle costs using the CBS presented in Figure 5. LCC must be computed for each alternative separately. Figure 8 illustrates the life cycle costing for the "high cost - high quality" alternative. Note that the up-front acquisition costs are high, yet operation and maintenance costs remain low. A different picture would result from the "low cost - medium quality" supplier.

Clearly, the final purchasing decision must be made based on cost-effectiveness analysis. In the IQLM approach, this analysis focuses on the IQLMI per unit life cycle cost. There are two facets of cost-effectiveness analysis: point estimate and, if possible and necessary, sensitivity analysis.

8.1 Cost-Effectiveness Point Estimate

When computing cost-effectiveness, point estimates are generated for each alternative. The alternative with the highest cost-effectiveness, as measured by the IQLMI divided by LCC, is preferred.

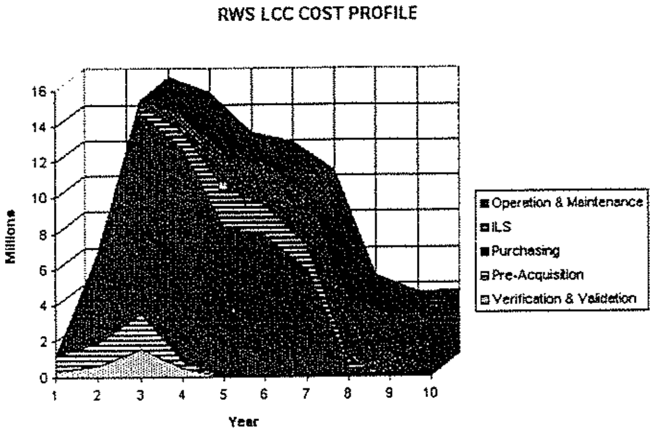


Figure 8. Railway System Life Cycle Costing

In our example, the "low price - medium quality" supplier is preferred, since a slight reduction in IQLMI is more than offset by a drastic reduction in life cycle cost.

Alternative	IQLMI	LCC (tens of millions)	Cost-effectiveness
Low Price/Quality	0.75	0.90	0.833
High Price/Quality	0.89	1.38	0.645

IQLM Railway Cost-effectiveness Computation

8.2 Cost-Effectiveness Sensitivity

The results in above table are not sufficient for sound decision making, because they are based on one single assumption regarding the SPMK rate as was promised (predicted) by the suppliers. Further analysis is required to test the robustness of the results. Will they still hold if SPMK is actually 110% of the promised value? We applied sensitivity analysis to our model, and the results are presented in Figure 9. When Stoppages Per Million Km remain at their current level (100%), supplier B is more cost effective than supplier A. But when SPMK rises to 130% of the current level, supplier A becomes preferred over supplier B. It is at this point that the purchasing team would prefer the "high cost - high quality" train.

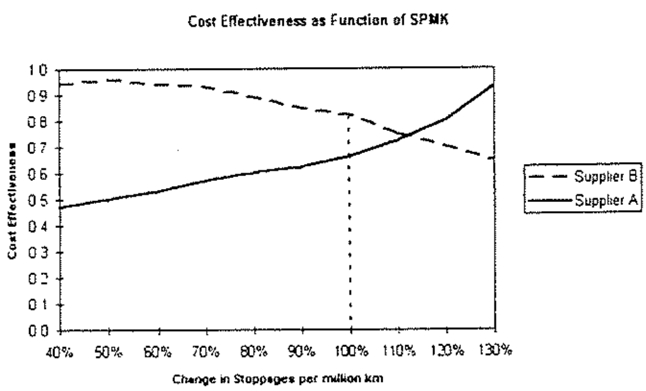


Figure 9. Cost-Effectiveness Sensitivity Analysis versus CIF SPMK

Given this uncertainty, the recommended action is that the suppliers should provide detailed field SPMK data, including confidence interval estimates with an associated confidence level. With this information, the train authority will be able to make a robust decision and proceed accordingly.

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