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# Application of Tools of Quality Function Deployment and Modified Balanced Scorecard for Optimal Allocation of Pavement Management Resources

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**ABSTRACT** Pavement management is a set of tools used to evaluate and maintain pavements so that the pavements can be used safely and effectively over a certain period. Many traditional methods were and are still being used by entities related to pavement management to increase the efficiency of management in decision-making and in coordinating the different activities that have a direct impact on pavement systems. Most of the pavement management entities are driven by optimization models that allow the optimization of a single objective. There is no specific method that focuses on analyzing and prioritizing multiple pavement perspectives in view of financial goals. This paper aims to provide the pavement management sector with a new methodology that prioritizes various pavement perspectives in view of financial perspectives. This prioritization would lead to a better assessment of multiple pavement management goals. The quality function deployment (QFD) and balanced scorecard (BSC) were adopted and modified to achieve the study objectives. Consequently, the outcome of QFD-BSC analysis is studied in the Fishbone Diagram and Cause-Effect Analysis to graphically present how significant factors in four perspectives will lead to better financial goals in the pavement management industry. Prioritization of pavement goals would help better to allocate optimal resources by pavement management professionals.

**INDEX TERMS** Pavement management, pavement perspectives, pavement condition, pavement management model, balanced score card, quality function deployment.

## I. INTRODUCTION

In the pavement sector, organizations should remain profitable while satisfying the needs of clients; this is possible when the organization addresses the critical financial perspectives relevant to the project. The allocation of pavement funds to the right objectives is an essential goal for highway agencies because highway agencies periodically spend considerable amounts on managing pavement infrastructure effectively. There is no specific method that focuses on analyzing and prioritizing multiple pavement perspectives in view of financial goals. There is a strong need to define perspectives that affect pavement management performance and link them to the financial goals of this industry. This paper targets to develop a framework for pavement management professionals to optimize multiple objectives in view of financial goals. With this framework, the industry is expected to reduce costs on pavement management in the short and long-run. The scope of this paper is to use the tools of Quality Function Deployment (QFD) and Modified Balanced Scorecard (BSC) for better pavement management in short and long-terms. QFD is a method that is mostly used by the engineers so that the consumer's demands and quality features could be incorporated into the design of the product. On the other hand, the BSC tool is a process that helps to translate the objectives of the company into the various measures for the performance and also helps to develop a framework that could further provide direction to the strategic mission of the organization. The BSC tool is used for measuring the financial perspectives of the project. The original BSC

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was modified for this research to include the four different aspects of pavement management, defined after an excessive literature and industry review. The newly established four BSC perspectives are financial, public authorities, scheduling and innovation, and operational. These four perspectives were determined based on the nature of the work and discussion with the experts in the field. They will capture the short-term and long-term needs of the pavement management industry and provide a map for reshaping the industry's priority areas for research and development. These new perspectives and their relevant references can be seen in Table 1.

The modified BSC perspectives have then formed the primary structure of the QFD, which was used to prioritize objectives in view of financial goals. With the application of the QFD and modified BSC, the industry professionals in the pavement management would be able to combine short-term and long-term strategies on financial, scheduling, public authorities, innovation, and operational perspectives. QFD and modified BSC are two powerful tools to capture these needs [71]. The reason for combining QFD and BSC is to capture and quantify the relationship between four perspectives in the modified BSC with the financial views in the QFD. This way (QFD and BSC together), a powerful tool is developed to quantify the financial, scheduling, public authorities, innovation, and operational perspectives in correlation with the financial goals. Then the outcome of QFD-BSC analysis is studied in the Fishbone Diagram and Cause-Effect Analysis to graphically present how significant factors in four perspectives will lead to better financial goals in the pavement management industry. There are several studies available on pavement management and pavement condition assessment in the literature. However, there is a gap in the literature and in the pavement management industry on how to define, analyze, and prioritize multiple pavement perspectives in view of financial goals. To the authors' knowledge, this paper is the first study in the literature using QFD and BSC tools together to achieve short and long-term strategies on pavement management.

## II. LITERATURE REVIEW

### A. INTRODUCTION

A literature review was carried to collect information regarding the pavement management functions and tools used. Bardeesi and Attallah [53] have confirmed that it is crucial to analyze the performance of the pavement over some time as it shows the ability of the roadway to carry the intended traffic and also simultaneously satisfy the environment during the design life, both functionally and structurally. Tools used for pavement management should be utilized appropriately to ensure the optimal performance of the pavement. The structural and functional conditions of the pavement changes with time due to different effects like structural adequacy, volume, the composition of traffic, local environment, terms of maintenance that has been provided to the pavement. Many transportation agencies presently use pavement management systems to develop short and long-term plans for their pavement preservation and treatment strategies. This is usually achieved by collecting high-quality field data [54] and analyzing these data using pavement management software. This study combines the BSC and QFD to develop long-term plans and short-term plans as a unique tool to cover the gap on how to define, analyze and prioritize multiple pavement perspectives in the view of financial goals. Rosa *et al.* [55] studied pavement deterioration models. They developed the International Roughness Index (IRI) prediction model as a useful tool for predicting the International Roughness Index since the IRI is a primary measure of pavement performance. In a recent study by Bridgelall *et al.* [56], IRI was determined by using a connected vehicle method, which accounts for all vibration wavelengths experienced by the vehicle. An online recommendation tool for airport pavement maintenance was developed by the Texas Transportation Institute (TTI) to identify optimal cost-effective preservation treatments for flexible pavements [57]. Swei *et al.* [58] studied the importance of changes in the cost of future maintenance, rehabilitation, and reconstruction events and suggested the use of a probabilistic approach.

According to Dennis and Spulber [59], the primary factor behind the pavement failure is the traffic load. For Luhr and Rydholm [60], acquiring the data for the pavement condition is a time consuming and costly process; thus, it becomes highly essential that the pavement survey method, which is being used by agencies closely matches the available resources. From the economic perspective of pavement management, there are many methods used for the financial analysis of the pavement. In essence, one of them is the life cycle cost (LCC) analysis, which is generally used during the initial stages of pavement design. Total budget, the annual benefit, initial costs that are related to maintenance and rehabilitation, equivalent yearly uniform cost, and the alternative to the preservation and treatment are the five pavement characteristics allowing a successful process of conducting mathematical algorithms used for economic analysis. Santos *et al.* [61] found that pavement management focuses on the specific perspective of pavement to have a direct impact on pavement management functions. To establish sustainable pavement maintenance and rehabilitation strategies, a multi-objective comprehensive model covering the pavement's whole life cycle was recently developed by Santos *et al.* [62]. Another study by Nobakht *et al.* [63] used the mechanistic-empirical methodology to determine the cost-effective rehabilitation alternatives for highway agencies.

### B. THE GAP IN THE LITERATURE

Some studies are dealing with pavement condition assessment and management using multi-criteria decision and other techniques in the literature [16], [37], [72]. However, there is a gap in the literature and in the pavement management industry on how to define, analyze, and prioritize multiple pavement perspectives in view of financial goals.

**TABLE 1. Objectives for modified bsc scheme and relevant references.**

| | | |
|---|---|---|
| Financial Perspective | Reduce resources consumption | [1], [2] |
| | Reduce life cycle cost of pavement | [3], [4] |
| | Reduce or eliminate end users lawsuits due to safety issues | [5], [6] |
| | Reduce cost of data collection | [7], [8] |
| | Reduce overall costs for maintaining and rehabilitating the road network | [9], [10] |
| | Reduce vehicles operating costs | [11], [12] |
| | Work out the least cost solutions considering different alternatives | [13], [14] |
| Public Authorities Perspective | Provide clear inventory of country road network | [15] |
| | Provide proactive maintenance schedule | [16] |
| | Provide Pavement scoring system to rate condition of pavement | [17], [18], [19] |
| | Comply with environmental and safety laws and requirements and improve their procedures | [20], [21] |
| | Provide accurate decision-making techniques for pavement operations | [22] |
| | Monitor the efficiency and effectiveness of the paved roads | [23] |
| | Evaluate the consequences of delaying or postponing maintenance on future budget needs | [24] |
| | Provide a sound basis for resource allocation and optimal use of funds | [25] |
| | Increase the effectiveness of management and provide savings in expenditure | [26], [27] |
| | Reduce road congestion specially at peak periods | [28] |
| Scheduling Perspective | Provide on-time future schedule for maintenance activities based on pavement type and condition. | [29] |
| | Provide a proactive operations system to avoid delay in maintenance causing disruption of end users daily activities | [30] |
| | Provide effective pavement inspection schedule | [31], [32] |
| | Provide quick conditional scenarios for time-constraint pavement issues based on available funds, available human resources and equipment | [33] |
| | Identify pavement treatment timing | [34] |
| | Avoid consequences of delaying or accelerating a pavement treatment | [35] |
| | Monitor outcomes to evaluate whether the results are consistent with what was expected | [36] |
| Innovation and Operational Perspective | Provide criteria for minimum serviceability, minimum skid, maximum distress, minimum structural adequacy | [37] |
| | Provide construction quality control | [38] |
| | Encourage innovation in managing the pavement operations to improve the process of management | [39], [40] |
| | Provide instruments to measure performance and predict failures, materials for construction and repair | [70] |
| | Allow the use of information systems and models to locate problems, and making in situ repairs and tests | [41], [42] |
| | Provide objectively based priority program to provide justification for budget requests | [43], [44] |
| | Provide precise inventory database design and operation | [45], [46] |
| | Monitor the efficiency and effectiveness of the works carried out | [23], [47] |
| | Provide a more systematic approach to identifying current and future road conditions and needs | [48] |
| | Provide data to communicate agency decision impacts on pavement condition | [49], [50] |
| | Determine main causes of deterioration for each road | [51], [52] |

This is achieved in this study with the help of the BSC and QFD. By combining both, an essential strategic tool is obtained. As a likewise usage, the different factors of a SWOT (strength, weakness, opportunities, and threats) matrix were used by Lee and SainOnko [64] as the four main perspectives of a BSC, allowing them to develop a new strategic management system which is systematic and holistic. They have used the QFD to define the objectives of the four BSC SWOT perspectives in the e-business field.

This study modifies the existing BSC method and introduces the financial, public authorities, scheduling, and innovation and operational perspective. These four perspectives are critical components of a pavement management system. They will set the base for the long-term goals for the pavement management performance. To achieve these long-term goals, these modified perspectives are integrated with QFD to track and quantify the long-term goals of the pavement management system. The literature has defined some of the pavement factors that will help in determining the significant perspectives and objectives of organizations working in the pavement sector. The technical and non-technical factors related to pavement management, relevant objectives were defined for each one of the four pavement perspectives in the modified BSC scheme. Then, these objectives and targets are quantified and transferred to long-term goals and ''Fishbone Diagram and Cause-Effect Analysis'' with the help of QFD. It was found that the QFD and BSC tools are relatively new concepts in the pavement management subject. This will help in understanding the requirements and allocation of the required funds for the top priority objectives.

With the application of the QFD and modified BSC, the industry professionals in the pavement management would be able to combine short term and long-term strategies on financial, scheduling, public authorities, innovation, and operational perspectives. QFD and modified BSC are two powerful tools to capture these needs.

## III. BALANCED SCORECARD TOOL

Developed by Kaplan and Norton [65], the BSC suggests that the organization is viewed from four different perspectives so that the development metrics could be improved, data could be collected, and the growth of the organization or the project could be analyzed based on these perspectives. Rather than focusing on only short-term goals, the BSC is a framework used to translate the vision and strategies of an organization and clarify its policy through the selected objectives.

The BSC perspectives have been modified in this study to serve the goals of this study (Figure 1). The financial aspect is considered as the main one since it is the most critical perspective for pavement management. The customer perspective is changed with the ''public authorities'' perspective because they are the primary customer for organizations working in the pavement sector. The internal business process perspective is altered with the scheduling perspective being the central pavement management perspective; effective pavement scheduling keeps projects on tracks.

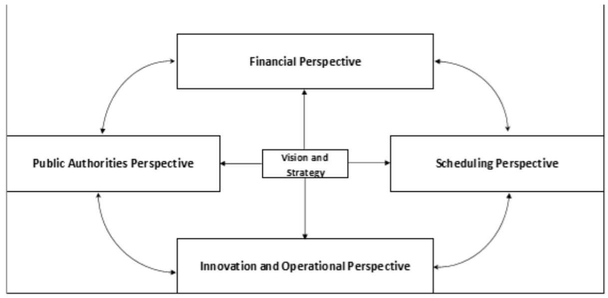



**FIGURE 1.** Modified balanced scorecard.

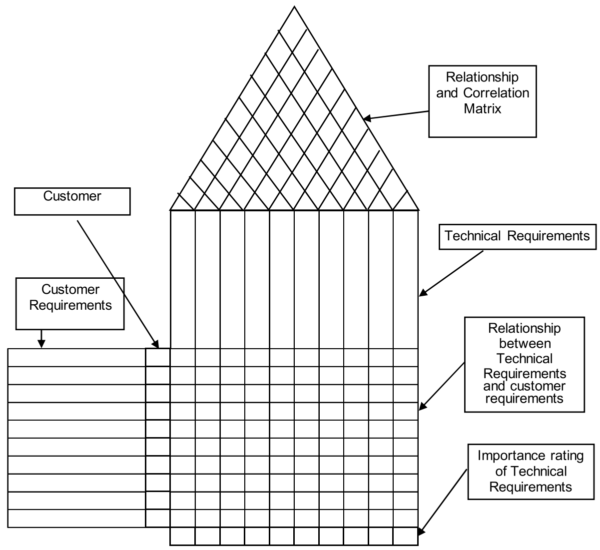



**FIGURE 2.** The house of quality.

The learning and growth perspective is changed with the innovation and operational perspective because this change will allow the researcher to relate primary operational objectives to the financial ones. These newly revised perspectives were selected based on expert opinions in the pavement management field.

## IV. QUALITY FUNCTION DEPLOYMENT TOOL

QFD was developed for the transformation of customers' voices into the engineering characteristics of the product. It is done by identifying the various perspectives in a QFD House of Quality (Figure 2).

In a QFD diagram, the customer requirements are transformed into product know-hows as the technical design requirements or the voice of the organization. Through the BSC, it is possible to cover all the perspectives of pavement management. Still, there is no proper mechanism that could be used for building and maintaining the relevance of the defined objectives. At this level, four perspectives of the modified BSC would be adapted by the QFD, allowing a powerful tool to measure and track the long-term goals of the pavement management system. After an excessive literature review on technical and non-technical factors related to pavement management, relevant objectives were defined for each one of the four pavement perspectives in the modified

**TABLE 2.** Score calculation for objective "reduce life cycle cost of pavement".

| In pavement management, the reduction of pavement life-cycle cost is: | | | | |
|---|---|---|---|---|
| **Answer Options** | **Response Percent** | **Response Count** | **Scale** | **Average Score** |
| Very Important | 48.7% | 37 | 7 | |
| Important | 31.6% | 24 | 5 | |
| Moderately Important | 15.8% | 12 | 3 | 5.47 |
| Slightly Important | 1.3% | 1 | 1 | |
| Not Important | 2.6% | 2 | 0 | |

BSC scheme. These objectives will be discussed in the following section.

## V. CONTRIBUTION TO BODY OF KNOWLEDGE AND APPLICATION OF STUDY

This study is the first one that uses the QFD and BSC tools together to achieve short and long-term strategies on the pavement management industry. The combination of QFD and BSC was targeted to increase the short and long-term performance of the pavement management industry. The study is for the pavement industry and getting the perspective of all stakeholders in one system. While client satisfaction is a vital tool, contractor performance is precious. QFD and Balance Scorecard covers both aspects for the benefit of the pavement industry. The combined tool of QFD and BSC serves the clients and contractors and all relevant stakeholders in the industry. The study is quantitative in terms of measuring and tracking the long-term goals of the pavement management system by the QFD and the contribution of pavement management experts through the questionnaire. In this way, the pavement management industry will discover the relative importance of each factor on a quantitative basis. Later on, these rankings were transferred to a fishbone diagram, which clearly shows that the improvement of a specific objective would lead to the advancement of the pavement management system. The reason for selecting the top-ranked goals is that sometimes the industry may not have enough resources to improve all objectives at a time. This ranking would lead the pavement management industry to define the most critical items to get started. Otherwise, the industry would use all factors at the same time. Then, by setting the relationship between factors, the industry would apply a Cause-Effect Analysis to lead to better pavement management performance. This study is the first study in the literature defining the relationships for each category and linking them through a strategical performance improvement system to enhance pavement management for the industry. The industry professionals would use Cause-Effect Analysis to define a simple yet powerful management system.

## VI. DATA COLLECTION AND ANALYSIS

A detailed review has been done to determine relevant objectives for four different pavement perspectives in the modified BSC scheme. The study ended up with seven different goals for the financial aspect, ten for the public authorities' attitude, seven for the scheduling perspective, and eleven for the innovation and operational perspective. These objectives can be seen in Table 1.

A survey was prepared to collect data for the QFD approach. It was distributed to various experts in the pavement field worldwide. A total of 76 completed surveys have been received from professionals working in the pavement field. A Likert scale is a rating scale, usually employed on survey forms, that measures how people think about something by collecting responses to particular questions or groups of related statements [73]. The Likert scale assessed the strength of the relationship among perspectives in this study. A Likert scale from 0 to 7 was used to specify the importance of the financial objectives, which are the first dimension of the QFD. Each objective listed under the "Financial Requirements" section was rated by the respondents. In Table 2, as an example, the rating of the objective "Reduce life cycle cost of pavement" is presented.

The average score was calculated by the weighted average of response counts and corresponding rating by the respondents, as shown below.

$$\{(37^*7)+(24^*5)+(12^*3)+(1^*1)+(2^*0)\}/76 = 5.47$$

As can be seen from the above equation, 37 respondents gave a score of 7 for the financial objective "Reduce life cycle cost of pavement." The number of responses for scores 5, 3, 1, and 0 is 24, 12, 1, and 2, respectively. The rest of the objectives average score calculations are presented in Table 3. The percent of importance is calculated by dividing each average score by the summation of all average scores. For example, for the objective "Reduce life cycle cost of pavement," the percent of importance was calculated by dividing 5.47 by the summation of all scores, namely 33.

The average score calculation above was similarly used to determine the relationship between the financial objectives and the objectives of three other perspectives listed on the horizontal part of the QFD. A Likert scale from 0 to 3 was used to determine the importance between the first dimension of the QFD and the other three pavement

**TABLE 3.** Average score equation for financial objectives.

| # | Ranking of Financial Objectives | Calculated Average Score | Percent (%) of Importance |
|---|---|---|---|
| 1 | Reduce life cycle cost of pavement | 5.47 | 16.6 |
| 2 | Reduce resources consumption | 5.43 | 16.5 |
| 3 | Reduce overall costs for maintaining and rehabilitating the road network | 5.28 | 16.0 |
| 4 | Reduce or Eliminate end users' lawsuits due to safety issues | 4.87 | 14.8 |
| 5 | Work out the Least Cost Solutions Considering Different Alternatives | 4.20 | 12.7 |
| 6 | Reduce vehicles operating costs | 4.05 | 12.2 |
| 7 | Reduce cost of data collection | 3.70 | 11.2 |
| # | Total | 33.00 | 100 |

**TABLE 4.** Relationship between a financial objective "reduce consumption of resources" and "provide clear inventory of country road network".

Kindly specify relationship between financial objectives (columns) and public authorities' objectives (rows) please insert (1, 3 or 5) where ("1" weak, "3" medium and "5" strong relation). Important Note: if you leave the answer blank it means there is no relation.

| **Reduce consumption of resources** | | | | |
|---|---|---|---|---|
| **Answer Options** | **1** | **3** | **5** | **Response Count** |
| Provide clear inventory of country road network | 9 | 26 | 21 | **56** |
| **Unanswered question (rating=0)** | | | | **9** |
| **Total number of responses to this question** | | | | **65** |

perspectives. Different Likert scales were used to cover the broad relationship between views in this study. As an example of the calculation, the objective "provide clear inventory of country road network" and its relation to one of the financial goals "reduce consumption of resources" are given in Table 4.

Using the same average score equation, the score of the relation between "provide clear inventory of country road network" from the "Public Authorities" vertical perspective with "Reduce consumption of resources" from the horizontal Financial Perspectives was calculated as per the following calculation (Please note that the total number of responses to this specific question was 65):

$$\{(0^*9) + (1^*9) + (3^*26) + (5 \times 21)\}/65 = 2.95$$

The rest of the relation between each vertical objective and each horizontal objective can be calculated accordingly based on the total number of responses. The scores between "provide clear inventory of country road network" and each financial objective are shown in Figure 3.

In Figure 3, the score for ranking of requirements is calculated by the weighted average of financial requirement scores and each vertical objective score. For example, the score

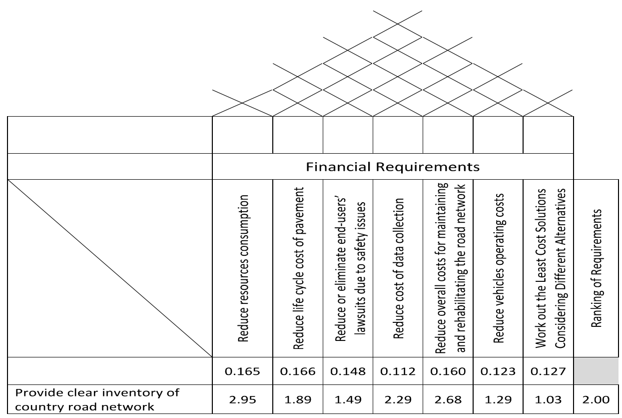
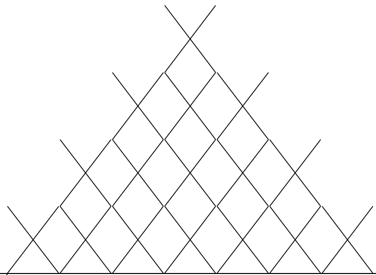



**FIGURE 3.** Scores for "provide clear inventory of country road network".

for "provide clear inventory of country road network" is calculated as:

$$\{(2.95^*0.165) + (1.89^*0.166) + (1.49^*0.148) \\ +(2.29^*0.112) + (2.68^*0.160) + (1.29^*0.123) \\ +(1.03^*0.127)\} = 2$$

This process is repeated for each vertical objective, and the ranking of scores is also normalized so that the total



| | | Financial Perspective | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Reduce resources consumption | Reduce life cycle cost of pavement | Reduce or Eliminate end users' lawsuits due to safety issues | Reduce cost of data collection | Reduce overall costs for maintaining and rehabilitating the road network | Reduce vehicles operating costs | Work out the Least Cost Solutions Considering Different Alternatives | Ranking of Requirements | % of Ranking | Overall ranking |
| | | *0.165* | *0.166* | *0.148* | *0.112* | *0.160* | *0.123* | *0.127* | | | |
| Public Authorities Perspective | Provide clear inventory of country road network | 2.95 | 1.89 | 1.49 | 2.29 | 2.68 | 1.29 | 1.03 | 2.00 | 3.60 | 14 |
| | Provide proactive maintenance schedule | 2.74 | 2.72 | 1.49 | 1.58 | 3.46 | 1.40 | 1.03 | 2.16 | 3.89 | 2 |
| | Provide Pavement scoring system to rate condition of pavement | 2.46 | 2.52 | 1.34 | 1.80 | 2.97 | 0.94 | 0.89 | 1.93 | 3.48 | 19 |
| | Comply with environmental and safety laws and requirements and improve their procedures | 2.40 | 1.60 | 3.45 | 1.23 | 2.12 | 0.95 | 0.95 | 1.88 | 3.40 | 21 |
| | Provide accurate decision-making techniques for pavement operations | 2.94 | 2.35 | 1.60 | 1.68 | 2.71 | 1.40 | 1.11 | 2.04 | 3.69 | 10 |
| | Monitor the efficiency and effectiveness of the paved roads | 2.68 | 2.42 | 1.80 | 1.75 | 2.89 | 1.31 | 1.03 | 2.06 | 3.71 | 9 |
| | Evaluate the consequences of delaying or postponing maintenance on future budget needs | 2.52 | 2.42 | 1.58 | 1.42 | 3.38 | 1.12 | 0.85 | 2.00 | 3.60 | 13 |
| | Provide a sound basis for resource allocation and optimal use of funds | 3.00 | 2.12 | 1.08 | 1.52 | 2.38 | 1.02 | 1.35 | 1.85 | 3.34 | 24 |
| | Increase the effectiveness of management and provide savings in expenditure | 3.05 | 2.32 | 1.54 | 1.72 | 2.46 | 1.51 | 1.77 | 2.11 | 3.81 | 4 |
| | Reduce road congestion specially at peak periods | 2.51 | 2.11 | 1.68 | 1.23 | 2.45 | 2.34 | 1.09 | 1.97 | 3.55 | 16 |
| Scheduling Perspective | Provide on-time future schedule for maintenance activities based on pavement type and condition. | 3.24 | 2.37 | 1.37 | 1.65 | 3.39 | 1.18 | 0.74 | 2.09 | 3.78 | 6 |
| | Provide a proactive operations system to avoid delay in maintenance causing disruption of end users daily activities | 2.76 | 1.90 | 1.52 | 1.18 | 2.84 | 1.50 | 0.82 | 1.87 | 3.37 | 22 |
| | Provide effective pavement inspection schedule | 2.68 | 1.92 | 1.66 | 1.94 | 2.97 | 1.03 | 0.90 | 1.94 | 3.50 | 18 |
| | Provide quick conditional scenarios for time-constraint pavement issues based on available funds, available human resources and equipment | 2.94 | 1.56 | 1.18 | 1.76 | 2.29 | 1.02 | 0.95 | 1.73 | 3.11 | 27 |
| | Identify pavement treatment timing | 2.58 | 1.76 | 1.44 | 1.63 | 3.18 | 1.11 | 1.05 | 1.89 | 3.41 | 20 |
| | Avoid consequences of delaying or accelerating a pavement treatment | 2.32 | 1.89 | 2.15 | 1.31 | 2.97 | 0.98 | 0.79 | 1.85 | 3.35 | 23 |
| | Monitor outcomes to evaluate whether the results are consistent with what was expected | 2.65 | 1.73 | 0.97 | 1.69 | 2.29 | 0.98 | 1.11 | 1.68 | 3.04 | 28 |
| Innovation and Operational Perspective | Provide Criteria for minimum serviceability, minimum skid, maximum distress, minimum structural adequacy | 3.16 | 2.30 | 1.12 | 1.46 | 3.63 | 0.98 | 0.88 | 2.04 | 3.69 | 11 |
| | Provide construction quality control | 3.47 | 2.04 | 2.12 | 1.37 | 3.04 | 0.88 | 0.91 | 2.09 | 3.76 | 7 |
| | Encourage innovation in managing the pavement operations to improve the process of management | 3.28 | 1.98 | 1.04 | 1.79 | 2.93 | 1.21 | 1.18 | 1.99 | 3.59 | 15 |
| | Provide instruments to measure performance and predict failures, materials for construction and repair | 3.25 | 2.25 | 1.58 | 1.86 | 3.42 | 0.98 | 0.89 | 2.13 | 3.84 | 3 |
| | Allow the use of information systems and models to locate problems, and making in situ repairs and tests | 3.25 | 2.30 | 1.23 | 1.58 | 3.30 | 1.33 | 0.88 | 2.08 | 3.75 | 8 |
| | Provide objectively based priority program to provide justification for budget requests | 3.47 | 1.98 | 0.84 | 1.68 | 2.60 | 0.89 | 0.79 | 1.84 | 3.32 | 26 |
| | Provide precise inventory database design and operation | 3.39 | 1.95 | 1.30 | 1.77 | 2.86 | 0.98 | 0.89 | 1.96 | 3.54 | 17 |
| | Monitor the efficiency and effectiveness of the works carried out | 3.16 | 1.89 | 1.56 | 1.77 | 3.12 | 0.98 | 1.04 | 2.01 | 3.64 | 12 |
| | Provide a more systematic approach to identifying current and future road conditions and needs | 3.28 | 2.16 | 1.56 | 1.74 | 3.18 | 1.09 | 1.11 | 2.10 | 3.80 | 5 |
| | Provide data to communicate agency decision impacts on pavement condition | 2.98 | 1.75 | 1.42 | 1.82 | 2.67 | 0.84 | 0.98 | 1.85 | 3.34 | 25 |
| | Determine main causes of deterioration for each road | 3.56 | 2.40 | 1.53 | 1.75 | 3.61 | 1.21 | 1.21 | 2.29 | 4.13 | 1 |
| **Sum of Scores** | | | | | | | | | 55.4 | 100.00 | |

**FIGURE 4.** **QFD scores for all objectives.**

sum of the ranking of requirements reaches 100 in total. The scores for all purposes are shown in Figure 4. In the next section, the scores will be interpreted for a better understanding of each objective score to pavement performance.

## VII. DISCUSSION OF RESULTS

The ranking of objectives for three perspectives (public authorities, scheduling, and innovation and operational) in line with the weighted averages scores considering financial goals are listed in Figure 3.

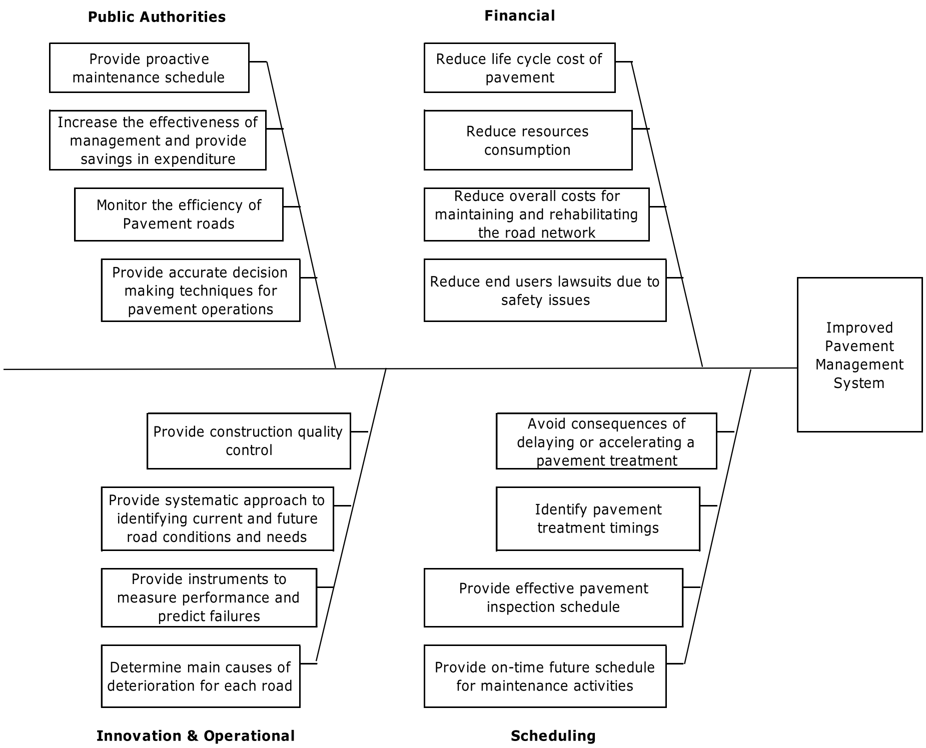



**FIGURE 5.** Fishbone diagram for top 4 objectives.

The above-ranked objectives would form the strategic objectives of the pavement management system. It can be seen from Figure 3 that the most important objectives (Ranked 1 to 3) are "to determine the main causes of deterioration for roads" [51], [52], [74], "provide proactive maintenance schedule" [16], [75] and "provide instruments to measure performance and predict failures, materials for construction and repair" [70], [72] with percentage rankings of 4.13%, 3.89%, and 3.84%, respectively. These factors belong to the "Innovation and Operational and Public Authorities" perspective of pavement management.

It is imperative to investigate the causes of pavement distresses, which will lead to the failure of the pavement so that proper maintenance strategies could be applied to achieve a safe and most cost-effective solution by transportation agencies. Also, monitoring the pavement performance by taking field measurements regularly will be very useful to develop proactive maintenance schedules to increase the service life of roads and thus less use of resources. The following perspectives in this study consider the factors for the pavement structures, their past maintenance, and service life: "Provide clear inventory of country road network," "Provide effective pavement inspection schedule," "Identify pavement treatment timing," "Provide criteria for minimum serviceability, minimum skid, maximum distress, minimum structural adequacy," "Provide precise inventory database design and operation." As an example, the scores given to each perspective by the respondents contributed to the final ranking of the factors. These objectives should be the top priority for highway agencies to achieve their financial goals, such as reducing the life cycle cost, the overall cost of maintenance and rehabilitation, data collection, and end-users lawsuits. Focusing on improving and achieving the top objectives listed above, highway agencies will be able to achieve their financial goals by implementing correct strategies in their pavement management program. As a result, the agency will be able to set specific initiatives and possible measures of each objective to reach its financial goals. The organization will be able to allocate the required funds for pavement management on the right targets to achieve its short and long-term goals based on its importance ranking, which ultimately will lead to business growth and increased profit. In the subsequent sections, a Fishbone diagram and a Cause-Effect analysis will be introduced to represent how to achieve higher pavement management performance.

## VIII. FISHBONE DIAGRAM AND CAUSE-EFFECT ANALYSIS

A fishbone diagram is a tool for grouping the potential causes of a problem to identify the reasons behind them. The Fishbone diagram looks like a fish skeleton. The researcher needs to identify at least four "causes" that contribute to the problem and connect these four causes with arrows to the spine. These will create the first bones of the fish [66]. Many researchers used Fishbone diagrams to group causes of various problems in the construction industry [67]–[69]. Fishbone diagram helps one to see all reasons at the same time and is a successful illustration to present issues to stakeholders. The four most important objectives of the four pavement perspectives are shown in a fishbone diagram in Figure 5.

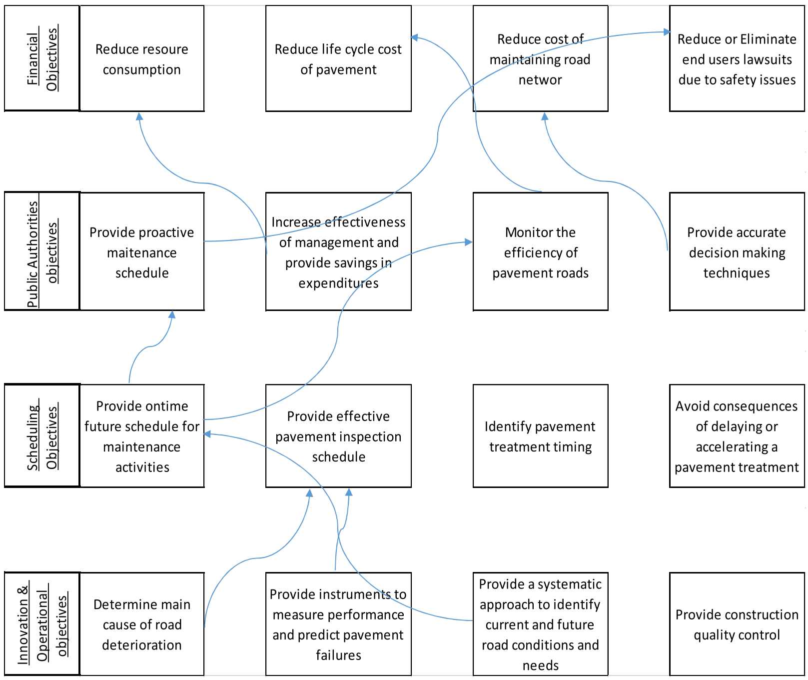



**FIGURE 6.** Cause-effect diagram showing relations between various objectives from different perspectives.

This diagram clearly shows that the improvement of a specific purpose would lead to the advancement of the pavement management system. The reason for selecting the top-ranked goals is that sometimes the company may not have enough resources to improve all objectives at a time.

This ranking would lead them to define the most critical items to get started. This fishbone diagram will not be only used to identify the best possible objectives for an improved pavement management system; it will be modified by the authors in such a way to show some of the cause-effect analysis in a positive way proving that improvement of one objective might lead to the advancement of a significant financial goal. A cause-effect analysis is also conducted after the Fishbone diagram that could clearly show the interrelated objectives. The Cause-Effect Analysis only considers the objectives in the Fishbone diagram; however, all objectives could be used if the organization has enough resources to cover all aspects. The cause-effect diagram clearly shows how the objectives are linked to each other. From this cause-effect linkages, the researcher can identify the future conditions needs and schedule for maintenance activities on time. It will also help to reduce the life cycle cost of pavements.

The linkage between objectives was determined based on the nature of the work. The accomplishment of one goal could lead to the achievement of one or more objectives. In this study, all the objectives and their links are connected up to the financial objectives as it is the ultimate goal to reduce the pavement management costs. A cause-effect diagram showing linkages between different objectives is shown in Figure 6.

This diagram shows how to reach the most important financial objectives through a path of interlinked objectives. With this analysis, a systematic approach to identify current and future maps in achieving the purpose of providing a reduced life cycle cost of pavement is presented. This can be studied in a detailed manner to make some eliminations in the objectives, but that is not part of this paper. It is also recommended that the company set milestones to accomplish the required objectives. This way, the progress of accomplishments may be tracked efficiently.

## IX. CONCLUSION

The objective of this paper was to develop a new analysis approach to be used in pavement management to prioritize different pavement management objectives of the four different perspectives, namely financial, public authorities, scheduling, innovation, and operational. It is the first research applying a modified BSC and QFD as a framework in pavement management to define various perspectives, objectives, and to rank them based on the most critical perspective goals. The perspectives were investigated in a survey along with their rankings to build a framework allowing the optimization of the multi-objectives in view of financial goals. It was found that the leading causes of deterioration for roads, proactive maintenance, and pavement field performance monitoring should be then taken into account as crucial objectives for highway agencies to achieve cost-effective pavement management.

The BSC and QFD, combined, can be used as a useful tool in pavement management to identify the objectives of each pavement perspective and rank different objectives based on the importance ranking of the financial ones. This will allow the organization to achieve better profit leading to business growth and a better focus on funds allocation. The tools of QFD and BSC were modified to meet the main objectives of this study.

The results of the research benefit the decision-makers working in the pavement management field, whether clients, contractors or consultants, by providing them with a detailed analysis allowing them to focus on particular objectives more than others, which will help them achieve their financial goals. This would lead to better profit and business growth. The cause-effect diagram can also be a powerful tool for the pavement management industry in finding the most critical objectives leading to better pavement management systems. As future research, more data could be collected to provide a better representation of the industry. Moreover, defining measures, targets, and initiatives to achieve the desired objectives would be studied. The same methodology developed in this paper could be used in other industries as well.

The proposed pavement management framework could be an appropriate successful tool for companies working in this field to be able to adequately define, select the perspectives and objectives of pavement management systems. This framework might also be the right tool in determining the initiative and performance measurements leading to achieving the most critical objectives.

## DATA AVAILABILITY

All data, models, and code generated or used during the study are available from the corresponding author by request.

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