# Reasoning Mechanism for Construction Nonconformance Root-Cause Analysis

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**Abstract:** This paper describes how problem patterns can be identified and analyzed for diagnosing and/or predicting nonconformance of constructed facilities. This will enable appropriate actions to be taken for eradicating the causes of nonconformance and preventing their recurrence and/or their occurrence. A structure has been defined for representing construction projects information and organizing knowledge extracted from past experience to facilitate the analyses. Pattern analyses have been directed at deriving root cause classes of problems including (1) design, which relates to the assigned specifications, methods, and/or procedures; (2) execution, which involves errors or the inability to execute tasks; and (3) external, which includes unforeseen events or accidents. Highway pavement construction has been selected as an application and illustrative domain. Expert knowledge related to low density and roughness of constructed pavements has been assembled and organized to support the analyses. The approach provides a generic mechanism to carry out integrated root cause analyses with design/planning, construction, and quality management information. Its application has been demonstrated and validated using case studies from different construction domains.

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## Introduction

Poor performance of civil infrastructure systems and built facilities can adversely impact the safety of the public, the services provided, and the economy of the nation. Inadequate specifications and/or nonconformance to design and construction requirements can affect the service life of the finished project in which distresses can occur (Chamberlin 1995). Departures from quality requirements can surface at different stages of the project life. This includes problems during the construction process; at the intermediate products (outputs of construction activities that have not yet become end products) and end products (finished products); and during the operating life of the project (distresses). In construction, nonconformance occurs when the finished state of a project and/or its components deviates from established requirements and necessitates decisions to be made regarding their acceptance and/or rectification. To the contractor, nonconformance can yield penalties, cost, and time burdens for rework and can result in productivity loss (Battikha 2000b). To the owner or user, it can translate into problems related to safety (structural failure, environmental hazards), service (delays), and economy (maintenance and/or rehabilitation costs). In 2001, spending for building, maintaining, operating, and administering the United States transportation system by all government levels reached $176.2 billion (U.S. Bureau of Transportation Statistics 2005). In 1997, the estimated cost of correcting all current deficiencies of the Canadian National Highway System was $17.4 billion (Transport Canada 1998). Thus, problems of constructed facilities and civil infrastructure systems need to be eradicated, and preferably prevented at early stages, prior to nonconforming occurrences and consequent distresses. This paper focuses on developing an approach to identify and/or predict construction problems, and diagnose their root causes, in order to specify appropriate actions. This will help eliminate construction nonconformance, and prevent its recurrence and/or its occurrence.

Previous research work has been directed at developing a computer-based system to assist quality management teams in the construction industry to deal with information and consequent decision-making processes pertaining to nonconformance of construction projects, for (1) the detection of problems and/or their prediction; (2) the diagnosis of their root causes; and (3) the specification of appropriate remedial, corrective, and/or preventive actions. A set of quality management tasks has been identified for automation and the first phase of its realization achieved (Battikha 2006, 2005, 2002b, 2001a,b; 2000a, 1999; Battikha and Russell 1998b). These tasks are derived from the elements of ISO 9001:1994 standard (ISO 1994) and designed to integrate with other computer-aided project management functions. The realized phase can assist management in (1) the definition of requirements/criteria for design, construction, and quality management; (2) the development of inspection and test plans; (3) the tracking of actual inspection/test results; (4) the verification of their conformance to defined criteria; (5) the documentation of past experience in the form of standard templates for assisting the tasks involved; and (6) the generation of reports. A model has been defined for representing the information used in the system tasks, considering the management information integration of the design/planning, construction, and quality management processes. It reflects the transformation states of construction components during construction from raw materials to end products, and the connection of construction processes to these states. The model allows the

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classifications of the requirements/criteria describing these physical states and their respective processes in the design/planning phase, for analyzing their conformance status during the construction phase, as well as their potential performance during the operation phase. This consists of classifying product and process requirements/criteria into *material, equipment, method, environment*, or *labor*.

The second phase of the system realization focuses on developing reasoning technologies for (1) the identification and/or prediction of problems; (2) the diagnosis of their causes; and (3) the specification of appropriate actions. These reasoning tasks will be performed in response to nonconforming inspection/test results, which are obtained by the conformance verification task of the system realized phase. This paper reports in part on the development of the reasoning tasks. It describes a generic mechanism to carry out integrated root cause analyses with design/planning, construction, and quality management information. A structure for organizing knowledge extracted from past experience and representing information of construction projects to identify and analyze problem patterns for diagnosing and/or predicting nonconformance of constructed facilities is presented. This will enable appropriate actions to be taken for eradicating the root causes of nonconformance and preventing their recurrence and/or their occurrence. The patterns consist of a set of problems and/or classes of problems that recur/occur in conjunction with particular situations (Battikha 2002a). These problems are the nonconforming inspection/test results of the product or process criteria and carry an identical classification in their information representation (i.e., *material*, *equipment*, *method*, *environment*, or *labor*). Highway pavement construction has been selected as an application and illustrative domain. Expert knowledge related to low density and roughness of highway pavements has been assembled and organized to support the root cause analyses. An example case has been provided to demonstrate the approach, and case studies from different construction domains have been used to validate it.

## Related Work

Knowledge can be extracted from various construction contexts and captured in different formats and/or used in various artificial intelligence technologies to assist in future problem-solving analyses and decision-making processes. For the purpose of providing quality improvement and picturing corrective and preventive measures, a quality cost matrix has been sought to capture nonconformance information on highway projects, including problem category, its specific nature, and root causes (Abdul-Rahman 1995). A hybrid knowledge-based expert system for quality assurance of concrete mix has been developed (Khajuria 1994). The system assists in revising the concrete mix; finding the reasons behind nonconformance and providing advice; and, estimating/predicting 28-day concrete strength, at an earlier age, using an artificial neural network. Example tables, which are easy to maintain and refine, are used to provide the association of causes and effects in the diagnostic process, and become part of their inductive modules. A set of rules of the expert system is derived from these tables using the method of induction (i.e., machine learning, by giving examples of experts' decision process rather than a general rule). This method has been adopted for knowledge acquisition to avoid (1) errors in interpreting expert information; (2) loss of fine points, which cannot be captured in the rule given by an expert; and (3) the inefficiency and slow procedure to build rules. Soibelman and Kim (2002) described the effectiveness and usefulness of knowledge discovery and data mining in identifying patterns for the analysis of construction problems and predicting trends using neural networks technology with application on causes of schedule delays. Their definition of a pattern is "an expression of describing facts in a subset of a set of facts." They presented several steps including problem identification, data preparation, data mining, data analysis, and refinement process, to implement their approach.

Knowledge organization and artificial intelligence technologies have also been effectively used in supporting diagnostic analyses and suggestions of appropriate actions of civil infrastructure systems. Shen and Grivas (1996) presented a system for civil infrastructure preservation and rehabilitation. The system is designed to assist in decision-making tasks performed in maintenance; namely, symptom observation, condition diagnosis, and treatment identification. It is comprised of relational databases and knowledge bases with cause-effect rules for organizing the heuristic structure. Elton (1989) developed an expert system to specifically diagnose the segregation of hot-mix asphalt. Acott and Dunmire (1987) organized causes of pavement roughness in table formats to aid in the diagnosis of these problems. Cheng et al. (1999) proposed an algorithm based on fuzzy logic to detect pavement cracking from very noisy pavement images. Efforts to date in the highway industry have identified quantitative models to predict pavement performance (Chamberlin 1995). These models are based on relationships between key materials and construction quality characteristics, and performance. They constitute an important element of performance-related specifications, and serve as a means to estimate from acceptance test results of the quality characteristics, enhanced or diminished service lives, and subsequent payment levels (Chamberlin 1995; Battikha 2003).

Existing problem identification and diagnostic tools (Abdul-Rahman 1995; Elton 1989; Shen and Grivas 1996; Acott and Dunmire 1987; Khajuria 1994; Cheng et al. 1999; Soibelman and Kim 2002) have been focused on a particular aspect of problem solving or a specific product. These tools are not applicable to nonconforming situations occurring during the different stages of the project, do not address the chronological interrelationships in their knowledge bases between design/construction problems and performance, do not have enough flexibility to handle different types of construction, and do not categorize the types of problems (e.g., *low density* is a *material* type problem of the *material* class criterion *density*) for further systemic quality management analyses. Additionally, most of the work has focused on reactive, as opposed to proactive or preventive problem solving, which is the preferred strategy for dealing with quality-related problems. The models used in performance-related specifications are quantitative. They capture relationships between factors leading to a performance indicator in the form of equations to quantify the result (Chamberlin 1995). Hence, no knowledge is represented for diagnostic purposes, and only the factors used in the equation are considered. Moreover, the interrelationships among those factors and/or between them and other factors, if they exist, remain hidden/implicit. The present research extends the literature by providing an approach to analyze root causes of construction quality-related problems using sets of patterns. Patterns are identified and analyzed, based on knowledge organization and information representation structures of construction projects for diagnosing and/or predicting nonconformance of constructed facilities.





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## Pattern Analysis

Three main root cause classes of quality-related problems have been identified including (1) design, which relates to the assigned specifications, methods, and/or procedures; (2) execution, which includes errors or the inability to execute tasks; and (3) external, which involves unforeseen events or accidents (Battikha 2000a; Battikha and Russell 1999, 1998a). This classification allows management to (1) focus and limit the diagnostic search rather than getting lost in a wide range of causes; (2) direct the appropriate nature of control for the kind of root cause in question as well as for its effects; and (3) understand the pattern of resulting effects of each root cause class on the affected entities, and consequently, enhance prediction for preventing nonconformance.

Pattern analysis is directed to uncover whether a human (i.e., design or execution) or an accident/unforeseen event (i.e., external) is behind the root cause. Logically, a design problem can yield a repetitive effect, irrespective of who executes the task (in which the problem has occurred). An execution problem can yield different effects, where the same personnel (i.e., labor) are executing the task. Labor indicates the individual, team, and/or director of an activity accountable for the result of its execution, and is the decision maker of its know how. A sudden occurrence of a problem of an environmental type can be an indication of an external root cause. Variations of patterns can be confusing and careful analyses need to be carried out to confirm initial findings. Examples of patterns employed to determine the root cause class of a problem are provided and justified as follows:

(1) Design Root Cause Class: Three patterns are very likely to be indicative of a design problem including, but not limited to, the following:

Pattern I: problem type = method; problem 1 = problem 2; problem recurrence ≥1; and, labor 1 ≠ labor 2

The notation used in the previous pattern reads as follows, and its interpretation applies to the remaining patterns presented in this paper: *the problem type is method; the first problem is identical to the second problem; the problem recurrence is greater or equal to one; and the labor responsible for the first problem is different from the labor accountable for the second problem.*

Pattern II: problem type = equipment; problem 1 = problem 2; problem recurrence ≥ 1; and, labor 1 ≠ labor 2

Pattern III: problem type = material; problem 1 = problem 2; problem recurrence ≥ 1; labor 1 ≠ labor 2; equipment 1 ≠ equipment 2; and, method 1 ≠ method 2

From the previous patterns, an indication of a recurring problem is apparent, because problem 1 and problem 2 refer to two problems that have occurred in the same case. The problems in the first pattern are of a method type, and the personnel executing the work (i.e., labor) are different in at least two occurrences. Hence, the assigned method can be problematic, and is of a design class. In the second pattern, the problem is related to the equipment, and the personnel carrying out the work are different in at least two occurrences. This indicates that the assigned equipment-related requirement can be at the origin of the problem. The third pattern shows that the problem is of a material type and all other labor, equipment, and methods, are different in at least two occurrences. Such an indication points to a problem in the defined requirement of the material. It should be noted that the indication of different personnel does not eliminate, even if minimal, the chance of an execution root cause class.

(2) Execution Root Cause Class: Four patterns are very likely to be indicative of an execution problem including, but not limited to, the following:

Pattern I: problem type = method; problem recurrence ≥1; problem 1 ≠ problem 2; and, labor 1 = labor 2

Pattern II: problem type = equipment; problem recurrence ≥1; problem 1 ≠ problem 2; and, labor 1 = labor 2

Pattern III: problem type = material; problem recurrence ≥1; problem 1 ≠ problem 2; equipment 1 ≠ equipment 2; and, method 1 ≠ method 2; and, labor 1 = labor 2

Pattern IV: problem type = labor; problem recurrence ≥1; and, method 1 ≠ method 2

Irrespective of the problem itself, its type can be the indicator of an execution problem when combined with the fact that the personnel carrying out the work are the same, or when the problem is directly labor related. It should be noted that other patterns may interfere with the origin of the problem, and careful segregation of the root cause must be pursued (using additional analytical tools, observation, elimination, etc.). This is why problems need to be different in some situations (i.e., in the above first three patterns) in order to confirm the execution nature of the root cause.

(3) External Root Cause Class: The external problem can be tracked with the following pattern, which is a single occurrence of a problem that is outside human control:

Pattern I: Problem type = environment; and, problem recurrence = 0

For validation purposes, two case studies from building and bridge construction have been diagnosed using the proposed pattern analyses and the diagnosis resulted in the same classes of causes derived from the reasoning performed under regular analyses. Details on these case studies are provided in the following subsections.

### *Validation Case Study I: Building*

The case consists of a six-story reinforced concrete structure of a shopping mall in which one of the floor slabs collapsed. Experts from a rehabilitation center analyzed the case to diagnose the cause of the failure. Tests were performed on the slab section to detect how the aggregate sizes were spread across the section. The findings showed that the nonuniform spread of aggregate sizes is an indication of poor concrete placement. Further investigations revealed that columns and footings did not have structural steel ties between them. It was concluded that the personnel who were working on these activities did not have enough skill to adequately execute the work.

Using the pattern analyses, the poor concrete placement and the lack of steel ties between structures can be classified as method type problems. In this case, the identified pattern matches the following: *problem type = method*; *recurrence* ≥ 1; *problem 1 ≠ problem 2*; *and*, *labor 1 = labor 2*. The root cause of these problems is of an execution class where the same personnel have incorrectly executed two different construction methods, which confirms the experts' findings attributing the reason behind the poorly executed methods to the personnel low labor skill. It is presumed that in the past and on a small low-rise building, the personnel who install the rebar are responsible for the adequate spread of concrete around it.

### *Validation Case Study II: Bridge*

The bridge under analysis is comprised of four spans directed from west to east and measuring 144 m in total length. Eight girders, out of thirty-two installed prefabricated prestressed reinforced concrete (AASHTO type V) collapsed during the first



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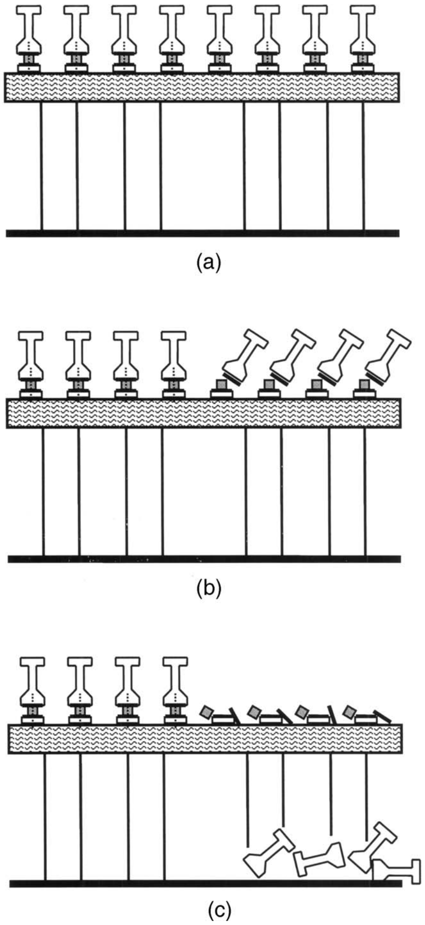


**Fig. 1.** Girders failure [adapted from MTQ (2000)]

phase of the bridge construction, causing one fatality and two injuries. The failure was analyzed by experts to diagnose its cause(s) and reported to the Ministry of Transportation of Quebec (MTQ 2000). It was concluded that the instability of the structural system during the construction stage has allowed the upper disks of the girders supporting devices to slide laterally to the south due to the inclination resulting from the rotation of the girders supporting devices caused by concrete temperature variations. Consequently, the girders also rotated, slid to the south, and fell on the ground. A schematic illustration of the rotation and sliding mechanisms is shown in Fig. 1.

The experts' diagnostic findings indicated that the bridge collapsed due to inadequate method design (lack of bracing of the structural system components during construction) that led to instability in the bridge structural system during construction manifested in two occurrences (displacement of the girders and their supporting devices) in which different construction/installation personnel were involved. This is consistent with the design cause class identified by the pattern analyses. In this case, the applicable pattern matches the following one: *problem type* = *material*; *problem 1* = *problem 2*; *recurrence* ≥1; *labor 1* ≠ *labor 2*; *equipment 1* ≠ *equipment 2*; *and*, *method 1* ≠ *method 2*. Further details on the application of the reasoning mechanism to the case under analysis, to detect systemic problems and enhance preventive decision making, can be found in Battikha (2004).

## Application Example Case

The example case involves the construction of two sections of a pavement lane forming part of a highway project. Each asphalt surface layer placed over the two sections (at two locations L1 and L2) weighs approximately 1,500 tons, and has a density specification as follows:

Each individual test value obtained within an acceptance section or lot shall be at least 87% of the established voidless density and shall not exceed 92% of voidless density. A lot with individual values above 92 or below 87 shall be removed and replaced to meet specification requirements.

The activities associated with the components that formed the asphalt surface layer during its transformation states include mixing, transporting, laying down, and compacting. Table 1 summarizes these activities and their respective input/output products (i.e., components). The asphalt surface layer at L1 is the end product for which density test results are collected and their conformance verified. The next subsections describe the identification of problems and how the reasoning can be performed facing the nonconforming test results indicating a low density problem.

**Table 1.** Activities and Respective Input and Output Components

| | Mixing | Transporting | Laying Down | Compacting |
|---|---|---|---|---|
| Input | Asphalt; aggregate | Mix | Mix | Asphalt surface layer |
| Output | Mix | Mix | Asphalt surface layer | Asphalt surface layer |

### Problem Identification

Upon completion of the end product construction (e.g., asphalt surface layer), density tests are performed and their results reported in the realized phase of the computer-based system to verify their conformance to the specified requirements (e.g., density target value between 87 and 92). In this example, most of the actual test results of each individual measurement are nonconforming because they fell outside the specified range (e.g., 86.8). Fig. 2 shows an output of the *conformance verification* task (i.e., nonconforming) and captures the density test result, location, date, time, and conformance verification of each of the five measurements. It also provides a suggestion on how the reasoning tasks to be computerized in the second phase of the system realization will be accessed in connection to nonconforming results (e.g., by activating the *problem* command button).

As low density is identified, the problems causing it are traced with reliance on a set of cause-effect relationships, in order to

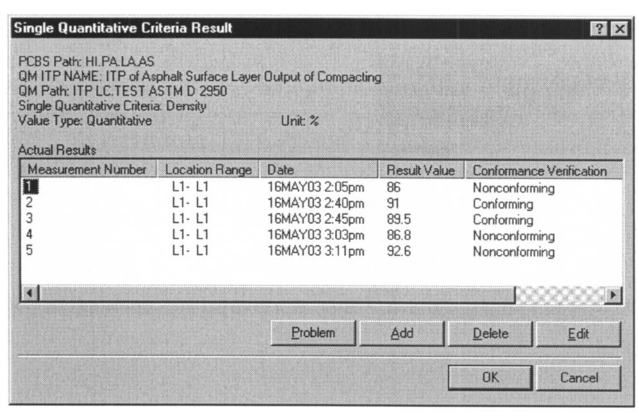


**Fig. 2.** Density tests results and conformance verifications [adapted from Battikha (1999)]



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**Table 2.** Cause Effect for Hot Mix Asphalt Segregation during Transportation (NAPA 1997; Elton 1989; Kennedy et al. 1987; Brock 1986)

| Knowledge identification | | | | | | |
|---|---|---|---|---|---|---|
| Project-based taxonomy | | | | Problem-based taxonomy | | |
| Project | End product | Component | Activity | Distress | Nonconformance | Effect |
| Highway | Asphalt surface layer | Hot mix asphalt | Transporting | Cracking | Low density | Segregation |

| Problem and advice | | |
|---|---|---|
| Condition | Type | Advice |
| Truck is loaded with one large deposit. | Method | Load truck with three small deposits, starting with front, then rear, and middle. |
| Slow dumping into paver. | Method | Deposit mix in the paver in a deluge. Raise the truck bed before opening the tailgate to enable the mix to move faster and help in deluging the paver hopper. |
| Piston that raises the truck bed intrudes upon the bed and creates a cavity. | Equipment | Block off the parts of the bed near the well to prevent cavity formation. Plywood or light gauge metal put across the bed front can solve the problem. |
| Truck beds are bumpy or rough. | Equipment | Keep truck beds clean and smooth. |

identify afterwards the root cause class. The cause-effect relationships consist of assembled knowledge, documented in formats, which allow the pattern analyses. Tables 2 and 3 show examples of how this knowledge is organized. The *component* heading, in these tables, represents the output of the indicated *activity*. The *end product* represents the finished state of that component. The *effect* is the component or activity-related problem, which is caused by one or many of the listed *conditions*. The *nonconformance* is the end product problem, while the *distress* represents its potential performance problem during its operating life. *Advice* is included to deal with the condition in question. This information representation and knowledge organization provides a structure to display the required reasoning and to match the problems occurring in the case under analysis with the appropriate documented knowledge. For reasoning purposes, the knowledge organization makes explicitly available the set of all the applicable factors causing a problem in interrelated cause-effect links. It also identifies the construction activities (e.g., mixing, transporting, laying down, compacting) in which they can occur (i.e., at the corresponding stages of construction). Factors and their effects are considered in relation to raw materials, intermediate output products, end products, and life performance. They are also designated with the type to which they belong (i.e., material, method, equipment, labor, or environment) and, as applicable, the nature of the problem is stated (i.e., condition, effect, nonconformance, distress).

## Root Cause Analysis of End Product Nonconformance

The analysis begins by identifying the problems that caused low density and the activity (e.g., transporting) in which each problem has occurred. This is performed with the aid of the cause-effect relationships and based on the identification of the project activities and their inputs/outputs. All detected problems and their respective type/class (i.e., method, equipment, environment, material, or labor), activity, chain, and recurrence are then gathered for the determination of the root cause class(es). The chain identification of the problems represents the path of graphically connected cause-effect relationships to which these problems belong. Several causes and effects can belong to multiple chains concurrently. If one chain is common between two problems, then they are linked (i.e., a cause and its effect). Fig. 3 depicts an example of cause-effect relationships with some chain identifications designed to support the analyses. For instance, *K.H.A.B.C.D.E.F.G* is assigned to *poor compaction* to designate a unique identity *K* and to denote that *segregation* with an allocated identification *H* (contained in *H.A.B.C.D.E.F.G*) affects compaction. This also points out that the segregation problem is caused by the conditions associated with the respective chains *A*, *B*, *C*, *D*, *E*, *F*, and *G*. With relevance to the present case, the chain *F* indicates a link between the condition *truck is loaded with one large deposit* and the nonconformance *low density*.

The detected problems, which can be of many types, are analyzed for any recurrence to identify a pattern such as the ones listed in earlier sections (e.g., in case another problem exists in the same activity; if it is of the same type; and, if it involves the same responsible personnel). Table 4 shows how problems are clustered. In the present example, the examination of the detected problems reveals the possible existence of the three root cause classes. Dealing with such a situation begins with the isolation of each possible class, the determination of the linkages between the problems, and the examination of their occurrence from a time perspective. The following summarize how the reasoning can be performed:

- The first step proceeds with gathering information about all occurring problems and their effects, as well as the related nonconformance, in clustered formats (e.g., problems in same activity; type of problems; and responsible personnel). The type of the problem (e.g., method) suggests that the problem is related to the assigned method, the firm/individual responsible for executing the method, and/or the external conditions under which the method was executed (i.e., either it is assigned, executed, or accidentally wrong). Knowing the activity in which the problem occurred (transporting) is also useful for investigation (Is there any other problem in this activity? Is it also a method type? Does it involve the same responsible personnel?).
- The second step requires the identification and analysis of patterns (e.g., repetitive problem(s), time of occurrence, etc.). The environmental condition has occurred once, which points to an external class. However, it has occurred in a compacting activity, which is performed after a transportation activity. Even though considered a root cause of low density, the other problems need to be analyzed, since they have occurred earlier, and the environmental problem could only have compounded the



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**Table 3.** Cause Effect for Asphalt Surface Layer Poor Compaction during Compacting (Chadbourn et al. 1996; Brakey 1993; NAPA 1993; Asphalt Institute 1989; Acott and Dunmire 1987)

| Knowledge identification | | | | | | |
|---|---|---|---|---|---|---|
| Project based | | | | Problem based | | |
| Project | End product | Component | Activity | Distress | Nonconformance | Effect |
| Highway | Asphalt surface layer | Asphalt surface layer | Compacting | Cracking | Low density | Poor compaction |

Problem and advice

| Condition | Type | Advice |
|---|---|---|
| Smooth surfaced aggregate causes low interparticle friction. | Material | Use light rollers or lower mix temperature. |
| Rough surfaced aggregate causes high interparticle friction. | Material | Use heavy rollers. |
| Unsound aggregate breaks under steel-wheeled rollers. | Material | Use sound aggregate or use pneumatic rollers. |
| Absorptive aggregate dries the mix, which becomes difficult to compact. | Material | Increase asphalt in mix. |
| Asphalt viscosity is high and restricts particle movement. | Material | Use heavy rollers or increase temperature. |
| Asphalt viscosity is low and allows the particles to move easily during compaction. | Material | Use light rollers or decrease temperature. |
| High asphalt content renders the mix unstable and plastic under roller. | Material | Decrease asphalt in mix. |
| Low asphalt content causes reduced lubrication and difficulty in compacting. | Material | Increase asphalt in mix or use heavy rollers. |
| Mix contains excess coarse aggregate and makes it harsh and difficult to compact. | Material | Use heavy rollers. |
| Mix is oversanded and becomes too workable and difficult to compact. | Material | Reduce sand in mix or use light rollers. |
| Mix contains too much filler and becomes stiff and difficult to compact. | Material | Reduce filler in mix or use heavy rollers. |
| Mix contains too little filler and exhibits low cohesion, mix may come apart. | Material | Increase filler in mix. |
| Mix temperature is high and renders it difficult to compact. Mix lacks cohesion. | Material | Decrease mixing temperature. |
| Mix temperature is low and renders it difficult to compact. Mix is too stiff | Material | Increase mixing temperature. |
| Lifts are thick and they hold heat and require more time to compact. | Material | Roll normally. |
| Lifts are thin and they lose heat and have less time to compact. | Material | Roll before mix cools or increase mix temperature. |
| Low air temperature, or high winds, or night construction causes rapid heat loss from mix, which leaves little time to compact the mix. | Environment | Control/increase mix temperature, or reduce the lag time between the paver and the roller. Or, increase lift thickness allowing the mix to retain heat longer. Or increase number of rollers, or reduce forward speed of paver, or use high energy/high density screed. Variables affecting compaction in cold weather include: Lift thickness, base temperature, mix temperature, air temperature, wind velocity, and solar radiation |
| Poorly graded surface of base course. | Material | Adopt proper base preparation. |
| Hydraulic screed lift not released. | Equipment | Release hydraulics and revise for improper or malfunction operation of hydraulics. |
| Vibrator not operating. | Equipment | Turn on vibrator. Revise electric or hydraulic system malfunction. |
| Rolling too fast. | Method | Slow down roller. Roll at or less than 3 mph so that particles are given time to move to make a denser mat. |
| Roller too light. | Equipment | Use heavier roller or increase roller ballast. |
| Inadequate rolling. | Method | Provide consistent rolling as specified. |
| Too few rollers. | Method | Increase number of rollers or reduce the speed of paver. |
| Segregation of mix. | Material | Revise segregation |



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**Table 3.** (*Continued.*)

| Knowledge identification | | | | | | |
|---|---|---|---|---|---|---|
| Project based | | | | Problem based | | |
| Project | End product | Component | Activity | Distress | Nonconformance | Effect |
| Highway | Asphalt surface layer | Asphalt surface layer | Compacting | Cracking | Low density | Poor compaction |

| Problem and advice | | |
|---|---|---|
| Condition | Type | Advice |
| Tire pressures too low on rubber-tired roller | Equipment | Adjust tire pressures to be correctly and uniformly inflated in order to fulfill the contact pressure of the roller, which affects compaction results. |
| Poor rolling pattern. | Method | Establish and keep a consistent rolling pattern. Determine the number of passes required to cover the width of the mat once, the number of repeat passes, the way to revise that the mix is compacted while it is within temperature limits, and the speed of rolling. The rolling pattern is better established on a test strip. It should not be varied unless the mix design is altered, the production rates have changed, weather conditions significantly became colder, or the underlayer condition has varied. |
| Yielding underlayer. | Material | When granular bases are paved, improve or modify and check density. Do not lay mix over a saturated base, revise drainage. When overlays are paved, cut out and patch weak spots. |
| Delayed rolling. | Method | Keep roller working as close to the paver as possible. |

problem (low density). Furthermore, one should examine if the problems are interlinked (i.e., if the environmental problem has been caused by one of the method type problems listed in Table 4) in order to know if they originate from the same root cause. This is not the case since the cause-effect relationships do not indicate any link (they do not have any common chain). Therefore, attention must be independently directed to the pattern(s) inherent in these two problems.

- The third step continues with the analysis to identify whether the root cause stems from a design, execution, and/or external source. Both problems (number 1 and number 2) are of a method type and have occurred in a transportation activity. The fact that the first problem has occurred three times in several transportation activities may be an indication of a design class. The simplest way to uncover this hypothesis is by examining if this method has been assigned as such, or to observe if it has been applied as such. Otherwise, the pattern analysis requires information (from records) about the personnel executing this task (i.e., labor). In case they are the same in the three occurrences, the execution class can be established.

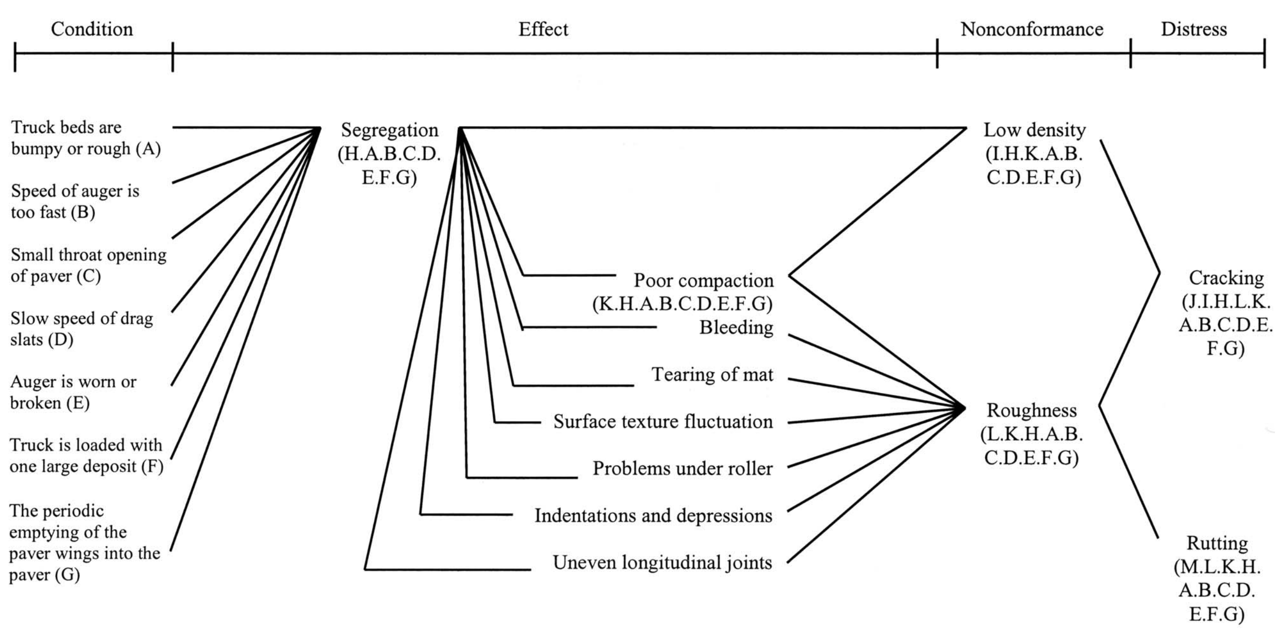


**Fig. 3.** Cause-effect relationships



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**Table 4.** Examples of Detected Problems for Pattern Analysis

| Number | Detected problem | Type | Activity | Chain | Recurrence |
|---|---|---|---|---|---|
| 1 | Truck is loaded with one large deposit. | Method | Transporting | F | 2 |
| 2 | Slow dumping into paver. | Method | Transporting | X | 1 |
| 3 | Low air temperature causes rapid heat loss from mix, which leaves little time to compact the mix | Environment | Compacting | Z | 0 |



This can be confirmed if another problem executed by the same personnel (i.e., labor) is of a method type. In case the personnel are different, then the design class can be established. A similar examination of the second problem is also required to determine whether the root cause is of an execution or design class. Moreover, verifying if the five occurrences (of both problems) of a method type problem is an indication of an execution class. This hypothesis can be proved if the personnel performing the tasks related to each of these two problems are the same. If so, then the root cause is of an execution class. Otherwise, it could be that there are two independent execution problems related to each of these two tasks, or one can be design and the other execution, or vice versa, or both of them can be design. This can be investigated in a similar fashion to the first problem. In case both are design, or both are execution, a systemic problem (e.g., higher level of management) may be the origin of the problem and can similarly be pursued.

- In dealing with the preventive/proactive mode, the cause-effect relationships are employed to predict potential nonconformance and/or future distress. Potential problems stemming from design, execution, or external sources can be identified by comparing the conditions of the case under analysis to the previously formulated patterns and matching them with compiled analyzed cases exhibiting similar patterns/problems. Prediction is viable when problems are detected during the early stages of construction because their effect is mainly on the finished product, which consequently impacts the operating life of the project, as represented in Fig. 3.

## Benefits and Application to Industry

Identifying and analyzing problem patterns for diagnosing and/or predicting nonconformance of constructed facilities will enable appropriate actions to be taken for eradicating the causes of nonconformance and preventing their recurrence and/or their occurrence. This will allow the construction industry to effectively manage quality, improve the performance of constructed facilities, and thus reduce their maintenance costs, and prevent potential safety and environmental hazards. Problems can be a bridge failure or a highway rutting, and need to be prevented/eliminated because they have a critical impact on the safety of the public, the service, and the economy of the nation. In addition, conducting integrated root cause analyses with design/planning, construction, and quality management information based on a classification of problems and their root causes, coupled with the application of commonality and clustering concepts, will enhance systemic quality management analyses and consequent proactive and reactive decision-making processes, which lead to organizational performance improvement.

## Summary and Conclusions

This paper has described how knowledge extracted from past experience can be organized to analyze root causes of construction quality-related problems of current projects. A structure for representing information of construction projects has been used to identify and analyze patterns based on a classification of root causes of problems. Three main root cause classes of quality-related problems have been identified including design, execution, and external. An example case has been provided to demonstrate the approach, and case studies from different construction domains have been used to validate it. Cause-effect expert knowledge related to low density and roughness of constructed pavements has been assembled and organized to support the reasoning mechanism. The approach is expected to render root cause analyses more effective and to facilitate their application in a computerized environment, which will be addressed in a future effort. The major conclusions of the present work are summarized as follows:

- While the proactive approach is the most preferred mechanism and its application is mostly beneficial when problems are detected at the early stages of construction to predict potential nonconformance and consequent distresses, the reactive approach helps build the knowledge with which predictions can be made on future stages or projects.
- The case studies show the importance of the root cause analyses and the need to prevent problems. They also demonstrate that the knowledge required for the analyses will be gathered in real situations to determine the causes of problems. Therefore, the rationale behind the approach is justified. Furthermore, when applicable, the proactive approach will render problem prevention possible and more effective.
- The flexibility of the proposed approach in detecting and analyzing patterns will allow the use of any type of knowledge assembled and organized for the particular analysis at hand, compared to the rigid traditional rule-based expert system, which relies on the interconnected rules of specific knowledge.
- The approach is not domain specific. Its generic nature is confirmed by its employment of patterns to identify classes of root causes of problems in search of systemic management problems, and its validation using case studies from different construction domains. The approach provides a mechanism responsive to the reasoning process about construction problems.

Future research should focus on automating the mechanism in connection to the first realized phase of the computer-based system for construction quality management. The pattern analyses would be more accurately validated and their effectiveness evaluated once incorporated in a computerized environment, and if suitable, appropriate statistical techniques applied. They would also be more reliable if they were accompanied by human expert



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reasoning, observations, and interpretations. This is based on the assumption that experts are impartial and have relevant knowledge in management, engineering, and construction. Limitations for the success of the approach include (1) the lack of recurring problems (or their types) in the case under examination, which may lead to inconclusive results; and (2) the unavailability of required information/knowledge to conduct the analyses. Case studies from the industry should be analyzed and compiled to assist in the analysis of root cause(s) of problems exhibiting similar patterns, and to capture best practices as a proactive measure to improve performance. Knowledge maintenance to accommodate novel developments should also be contemplated.

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