QUALICON: Computer-Based System for Construction Quality Management

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Abstract: This paper describes a computer-based system for construction quality management. The system tasks are derived from the elements of ISO 9001 standard and designed to integrate with other computer-aided project management functions. They 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 was defined for representing the information used in the system tasks. The central role of the inspection and test plan representation was exploited to associate to construction components and processes, relevant inspections/tests, requirements/criteria, actual results, and nonconformance analyses. Templates were devised to enable the reuse of predefined packages of information, which recur from project to project. The developed system will render the assisted quality management tasks more effective. Its use was tested on data from different construction domains.

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Introduction

The life performance of constructed facilities is an indicator of the quality level specified in the design/planning and achieved in the construction. In construction, quality is defined as conformance to established requirements (CII 1989) and is a critical factor in determining project acceptance and resultant contractual payment levels. Based on relationships between material/construction characteristics (e.g., layer thickness, density, compaction) and performance (Chamberlin 1995), deviations from design and construction requirements can adversely impact the service life of the finished project in which distresses can occur (cracking).

During construction, nonconformance occurs when the finished state of a project and/or its parts deviates from established requirements and necessitates decisions to be made regarding their acceptance and rectification. Nonconformance stands in the project time frame between antecedent anomalies (poor compaction) and future distresses of the finished work (i.e., performance problems). To the contractor, nonconformance can yield penalties, cost, and time burdens for rework and can result in productivity loss (Battikha 2000b). To the owner and/or user, nonconformance can translate into problems related to safety (structural failure), service (functional underperformance), and economy (maintenance costs). In 1988, expenditures for the United States highways, including outlays and maintenance, reached $68 billion at all government levels (Roberts et al. 1996). In 1997, the estimated cost of correcting all current deficiencies of the Canadian National Highway System was $17.4 billion (Transport Canada 1998). In essence, quality-related problems need to be eliminated and preferably prevented at early stages, prior to nonconforming occurrences and consequent distresses.

Properly implemented, formal quality systems provide a vehicle for achieving conformance to established requirements (i.e., quality). ISO 9000 series standards furnish conceptual guidelines with which to structure and implement the elements of a quality system (Arnold 1994). Achieving conformance to established requirements consists of a series of quality management activities during the various phases of a project. In the design phase, quality requirements for the end products and/or their performance are specified to meet the user's needs. Depending on whether the specifications are method-type, end-result, or performance-related, construction methods and materials are specified by the owner's agent or defined later by the contractor to permit achievement of these requirements. In addition, quality management procedures are developed to ensure compliance with the specifications. During construction, nonconformance in terms of end products (the finished state of the constructed product), output products of activities (the states through which the end product passes during its construction), and/or in-process characteristics may be detected. Appropriate actions must then be taken to rectify nonconforming situations and, if possible, diagnosis of the reasons causing nonconformance, followed by the elimination of the causes to prevent recurrence during the remainder of the project and on future projects. These activities require the analysis of vast amounts of data, and fast, expert-based decisions about actions to be taken.

Antecedent Work

Various computerized applications have been developed for the documentation and analysis of quality-related information (No-

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Table 1. Elements of ISO 9001:1994 Standard Selected for Computerized Support

ISO 9001 Element	Requirements
Quality system (4.2)	Development and maintenance of a documented quality system as a means of ensuring conformance to specified requirements.
Design control (4.4)	Development of procedures for the control and verification of the design of the product to meet user specified requirements; identification of design activities; definition of user/customer specifications (design input); expression of design output in terms of requirements and its verification in meeting the user specifications; and, control of design changes.
Process control (4.9)	Identification, planning, monitoring and control of operations.
Inspection and testing (4.10)	Performing inspection and testing to verify conformance to specifications, for in-process production and completed products; planning and documenting inspections and tests including inspection and authority, nature and amount of inspection.
Inspection and test status (4.12)	Identification of inspection status and whether a product is conforming or nonconforming.
Control of nonconforming product (4.13)	Identification, segregation, disposition and documentation of nonconforming products; and describing type and extent of the nonconformance and denoting condition for potential repair/disposal.
Corrective and preventive action (4.14)	Investigation into the root cause of the nonconformance and the specification of appropriate corrective or preventive action, favoring a proactive approach.
Quality records (4.16)	Documentation of all quality-related information, including inspection and test plans, inspection forms, test reports, audit reports, quality costs, nonconformance reports, corrective action requests, etc.
Statistical techniques (4.20)	Application of adequate techniques to control process capabilities and product characteristics, ranging from defect analysis to statistical sampling.

vokshchenov and Allum 1992; Chu et al. 1995). The U.S. Department of Transportation at the Federal Highway Administration offers a quality assurance software package that provides guidance on the use of adequate quality assurance procedures for highway construction projects, and allows the user to analyze test results with the use of statistical techniques, for the purpose of deriving conclusions about these techniques and incorporating them into effective specifications (FHWA 1996). A hybrid knowledge-based expert system has been provided to deal with the quality assurance of concrete (Khajuria 1994). Expert systems in combination with database management systems have been employed in supporting maintenance tasks, including problem identification, diagnosis of causes, and suggestion of corrective actions (Foo and Akhras 1994; Shen and Grivas 1996). An expert critiquing system has also been developed for the assistance of both designers and reviewers in preventing errors, detecting them, and providing critiques and suggestions (Fu et al. 1997).

Efforts to date in the construction domain have not been directed towards exploiting information technology as an environment for integrating and supporting the totality of the quality management function and its association with other project management functions (Battikha and Russell 1998a). Rather, they have been narrowly focused on a particular aspect of quality management or a specific product, and have not considered the role of formal quality systems and their structure as derived from ISO 9001 standard (ISO 1994). Further, they do not handle the definition of design, construction, and quality management requirements, and the development of inspection and test plans. In addition, they are unable to detect nonconformance and its causes and effects on the life performance of the facility. Existing diagnostic tools are not applicable to nonconforming situations during construction, do not address the link between design/construction problems and performance, and do not have enough flexibility to handle different types of construction. Additionally, most of the work has focused on reactive as opposed to proactive or preventive quality management, which is the preferred strategy for dealing with quality-related issues.

In an attempt to bridge this gap, a set of quality management tasks has been identified for potential computerized support and is listed in Table 1. These tasks represent the formal construction quality management function as derived from the elements of the ISO 9001:1994 standard (ISO 1994) and are directed towards a preventive role in addition to a reactive one. They relate to (1) defining design, construction, and quality management requirements; (2) performing construction process control and relevant inspection and testing; (3) identifying and predicting process and product related nonconformance; (4) evaluating the type and extent of nonconformance; (5) investigating its root cause(s); (6) specifying remedial, corrective, and/or preventive actions; (7) using appropriate statistical techniques for analyses; (8) documenting the learning experience for future use; and (9) providing relevant reports. These tasks can benefit from the use of information technology because they are highly repetitive and involve ill-structured decision-making processes that require deductions to be drawn from masses of quantitative and qualitative information.

Research Objectives

The main purpose for conducting this research was to develop a computer-based system to support quality management in construction (QUALICON), to assist quality management teams in the construction industry, to deal with information and consequent decision-making processes pertaining to nonconformance/distresses 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

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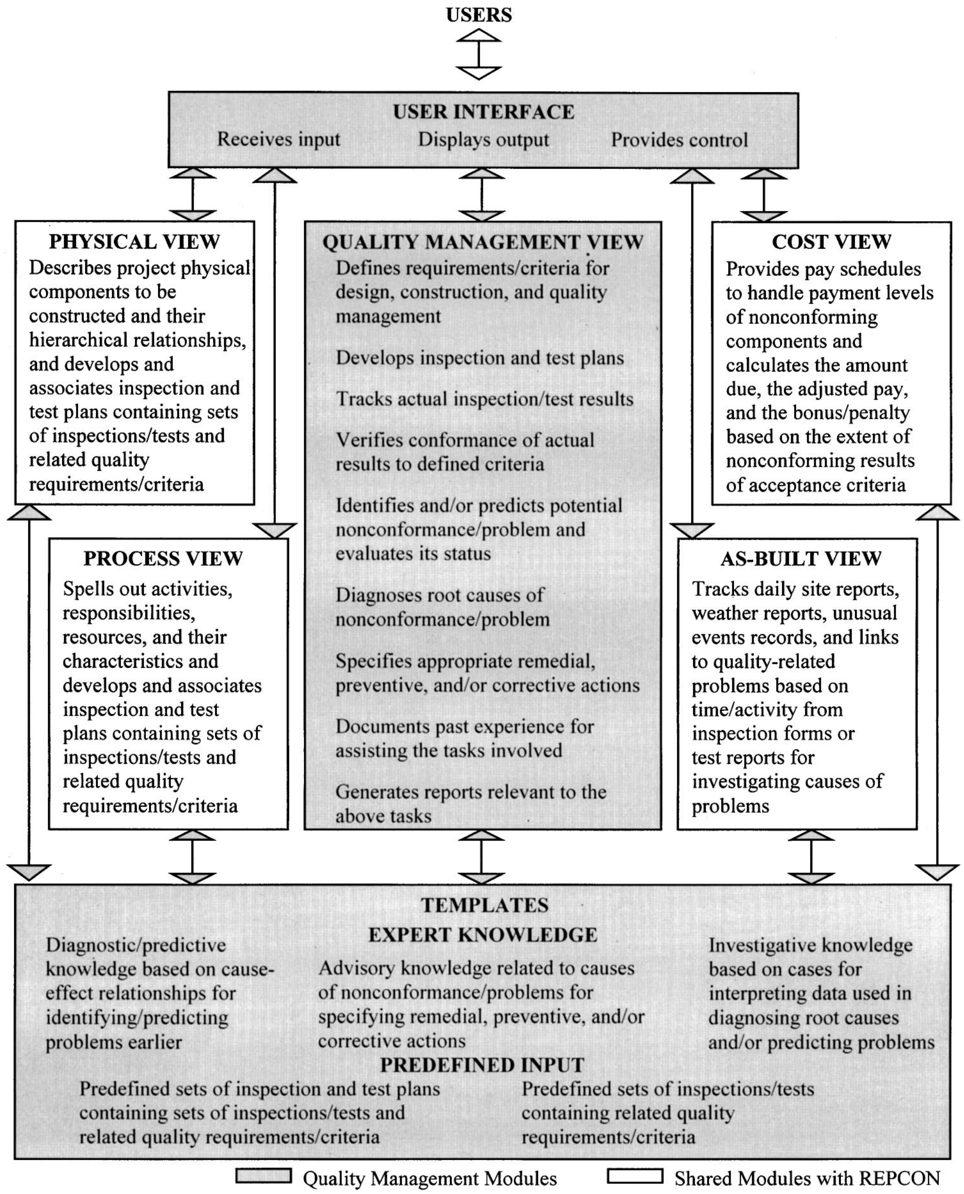

Fig. 1. System architecture

and/or preventive actions. This paper presents an overview of the system design and reports on the first phase of its realization, which is confined to (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. The focus of the second phase of the system realization includes applications of expert systems reasoning technologies for the identification and/or prediction of problems, the diagnosis of their causes, and the specification of appropriate actions. Except for the statistical applications (given the availability of statistical software packages on the market) and the reasoning tasks, the system development described in this paper has considered the core functions of the selected ISO elements identified in Table 1.

System Architecture

Fig. 1 displays the basic modules that form the system architecture (Battikha 2000a). The different views of a project shown in this figure (i.e., physical, process, cost, and as-built) represent categories of management functions that can be supported with computer applications (REPCON 1998), and whose information is essential to the quality management function. A view is a representation of project information specific to a certain domain of project development or management. The physical and environmental view describes what is to be built in terms of geometry, topology, physical systems, materials, besides the physical, economic, and sociopolitical environment in which the project will be developed. The process view portrays how the project will be constructed, who is responsible for the different work disciplines, when it will be executed, and where. The cost view deals with cost estimations and tracking during construction from the per-

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spectives of the owner, contractor, and subcontractor. The as-built view captures what happened, why, and what actions were taken with emphasis on analysis. A fifth project view, that of the quality management function, provides the tasks of the system targeted to support construction quality management, as shown in Fig. 1. This view interacts with the other four project views to accomplish its main processes and relies on expert knowledge to perform the reasoning inherent in these processes. The integration of the quality management view with other project views enables the quality management function to share much of the same data and tasks used in other project management functions. The quality management view also provides predefined sets of input, in the form of standard templates, to assist the user in defining a large amount of input information that usually recurs from project to project.

With respect to the quality management function, the physical view provides a gateway to specifying, as defined in project specifications at the design stage, quality requirements/criteria of end products (e.g., pavement density, smoothness, thickness) and their corresponding required quality levels (target values) and tolerances. Requirements to which inspection/test results must conform are referred to as criteria (i.e., criteria upon which an inspection/test passes or fails). The physical view also provides the flexibility for defining the remaining requirements/criteria (and their quality levels) of materials and/or other output products of construction activities (e.g., mix), in case the type of specification does include their definition. End-result specifications can limit the given description to the contractor to end products, while method-type specifications stipulate materials and construction methods. Performance-related specifications focus on predicting project performance (e.g., durability) and performance specifications describe performance requirements. Similarly, the process view provides for the quality management function a gateway to specifying requirements/criteria related to construction activities such as construction equipment and methods (i.e., method-type specifications).

Inspection and test plans (ITPs) for each physical component (e.g., asphalt surface layer of a pavement), and the associated activities that shaped it, are defined in the quality management view. They are also defined in the physical and the process views to facilitate their association to the physical component and to the activities involved in its construction, respectively. These plans include the physical requirements/criteria (associated to the physical components), the process requirements/criteria (associated to the activities), and the responsibility, timing, frequency, scope, and method of inspection/testing. ITPs and nonconformance reports are related to the cost view to release or withhold payments for an assigned status and a defined payment level based on pay schedules, in case of nonconformance. The system captures results from inspection and test activities and allows them to be verified against specified criteria. When nonconformance (e.g., low density of asphalt surface layer) is identified or predicted, the system assists management to diagnose the root cause(s) of the nonconformance with the use of as-built records, including site reports that document prevailing site conditions, etc.. In addition, the system evaluates the nonconformance status regarding its extent and type in order to be assigned a priority for action, and specifies appropriate remedial, preventive, and/or corrective actions. These reasoning processes exploit the various aspects of the expert knowledge. Much of the encoded expertise, referred to in Fig. 1, is based on expert knowledge deduced from the literature and on feedback from actual projects documented in the post-construction phase (Battikha 2000a).

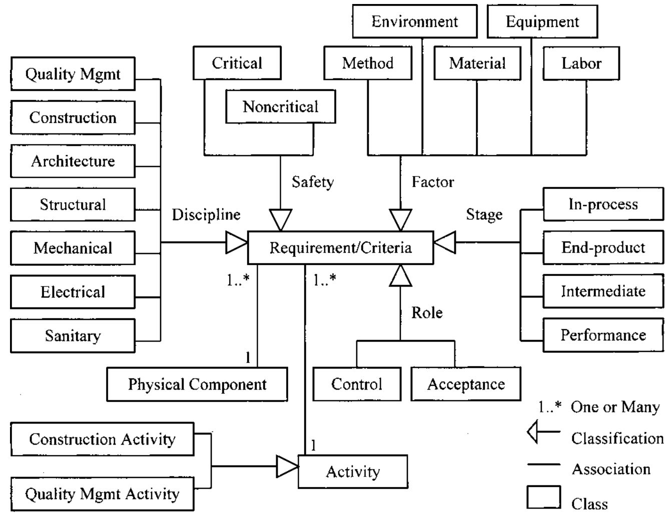

Fig. 2. Requirement/criteria subclasses

Information Representation

The core of the system is centered on representations of physical (construction output products) and process (activities) requirements/criteria which are capable of capturing the essential constructs for reasoning about construction quality-related problems while sharing, as appropriate, information and tasks with other project management functions. Integration includes provision of requirement definition for project components and activities, including construction and quality activities (e.g., specifying density target values, providing inspection and test plan requirements), scheduling quality management activities, tracking as-built results, calculating payment levels, etc..

A physical component (e.g., asphalt surface layer, hot mix asphalt) undergoes different transformations due to activities until it reaches the finished state—end product (Battikha and Russell 1998b). An activity is influenced by many factors concerning labor, equipment, method, environment, and material (including its input), while producing an output product. As shown in Fig. 2, a *requirement/criteria* class represents a descriptor (quality characteristic) for physical components and activities, including construction and quality management activities. Hence, any requirement/criterion can become a candidate for conformance verification and reasoning about it, in case of nonconformance. However, in the scope of the present research, only criteria are considered for the conformance verification task. Requirements/criteria can be of different subclasses relating to *discipline, safety, factor, stage, and role*. The *role* subclasses indicate whether the requirement/criterion is considered for acceptance or for control. The *stage* refers to the stage at which the requirement/criterion is tracked with reference to the construction process. An *in-process* requirement/criterion relates to an activity; an *end-product* requirement/criterion relates to a finished state of a product; an *intermediate* requirement/criterion relates to an output product that is still undergoing construction transformations (e.g., mix); a *performance* requirement/criterion relates to the operation state of the product. For example, a quality characteristic (density) about a physical component (asphalt surface layer) is represented by a criterion with the following subclasses: *structure*, *critical*, *material*, *end-product*, and *acceptance*. This denotes that density is a structural characteristic of critical importance in terms of safety, of a material type factor affecting a process (in case it becomes an

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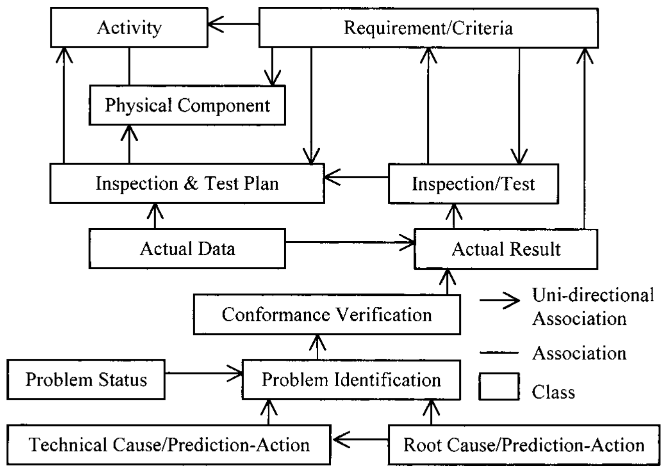

Fig. 3. Main domain class diagram

input), tracked at a finished state of a product, and is considered for acceptance in quality management. An equipment speed (related to a construction activity) is represented with a different set of subclasses: *construction*, *noncritical*, *equipment*, *in-process*, and *control*. An inspection frequency (related to a quality management activity) is represented with the following: *quality management, noncritical, method, in-process*, and *acceptance*. These classifications furnish a consistent input environment for versatile specification handling and provide information for the system functionality, including the reasoning process in the case of nonconforming construction results. They define directions for (1) action priority and decision responsibility (e.g., a nonconformance in a *critical* characteristic is assigned a priority for action provision, and a structural designer will deal with the decision if it concerns *structure*); (2) present and/or future problem stage (e.g., a problem in an *in-process* characteristic can be a predictive condition for a potential nonconformance); (3) payment dues (e.g., a nonconformance in a characteristic considered for *acceptance* necessitates payment considerations); and (4) effective retrieval and reasoning procedures with reliance on knowledge documentation and artificial intelligence technologies (e.g., a problem in a *method* type characteristic allows the search into *method* type conditions from the stored organized knowledge (Battikha and Russell 1999; Battikha 2000a).

The main domain model of the system is presented in Fig. 3 (Battikha 2000a). A requirement/criterion, which describes a physical component or an activity, is assigned one or more inspection/test activities, which together form an inspection and test plan, for a certain number of physical components and/or activities. The actual result of the inspection or test activity of the criteria has a conformance verification and, if it is nonconforming, will have a problem identification that will have a problem status, a technical cause (and prediction if applicable) and action, and a root cause (and prediction if applicable) and action. The inspection and test plan representation has a central role that links to physical components and activities relevant inspections/tests, requirements/criteria, actual results, and nonconformance analyses. The classes forming the templates, in which predefined sets of information are stored, consist of the *inspection and test plan* and *actual data*, the *inspection/test*, and the *requirement/criteria*.

System Usage Description

The first realized phase of the system has been tested and validated using data from highway pavement and concrete structure construction domains. Two types of construction domains have been used to evaluate the system flexibility as a generic tool. The developed system forms an integral module of an existing software package (REPCON 1998), which is capable of defining project components, activities, resources, pay items, scheduling, and tracking as-built records through aspects of the four previously mentioned views (physical, process, cost, and as-built). The programming task has been performed by a programmer using the C++ programming language (Microsoft 1998). In this paper, some interfaces are illustrated to describe the system functionality, and use is made of a test case, along with data acquired from industry standards and practice pertaining to the highway pavement construction domain. The test case consists of a segment from a pavement lane forming part of a highway project whose physical components at the different transformation states are represented in the physical view. These products and their related processes form the basis upon which inspections/tests have been selected and ITPs composed. In the standard templates, data has been acquired to relate to the asphalt surface layer end product and associated products/processes, given that in this test case, the asphalt surface layer is subject to density tests after being compacted. The density specification to which the conformance of test results are verified, refers to individual values falling between 90 and 98% of the established voidless density. In this case, most of the actual test results of each individual measurement fell outside the specified range (86.8). Each result is compared to the specification range and an output is provided by the system concerning the *conformance verification* (nonconforming).

System Standard Templates for Quality Management

The standard aspect of the system, involves inspection/test and ITP templates, populated with a set of reusable inspections/tests and ITPs that can be copied as appropriate to a project file. These templates are devised to allow the user to store in, and recycle predefined sets of inspections/tests and ITPs, which are usually used on a recurring basis from project to project.

Inspections/tests are fundamental units with which ITPs are composed to form the central core of the quality management view. The inspection/test standard template embodies a set of standard-defined inspections/tests, such as the ones published in ASTM (1991) or AASHTO standards. They are collected under a user-defined classification that segregates them into useful sets. ITP standard templates can also be classified by the user into useful sets, which contain standard inspections/tests as well as specific (i.e., nonstandard; particular to a project) inspections or tests as they relate to a type of construction product/process (e.g., asphalt surface layer component, aggregate component, laying activity, compacting activity, etc.). In addition, ITP templates embody management requirements as they relate to quality (e.g., quality management procedures, inspection/test frequencies, etc.). The inspections/tests can be copied, where appropriate, to the set of inspections/tests forming the ITP template or to a project file. Examples illustrating and validating the usage of these two templates and their design features are provided in the following subsections.

Standard Inspection/Test Template

An inspection/test template is a set of standard inspections/tests classified under a user-defined type. An example of a defined standard quality management template containing a set of ASTM inspections/tests classified under bituminous mixtures is shown in Fig. 4. The set of inspections/tests stored in a template, as shown in this example, provides a flexible approach to the user to select

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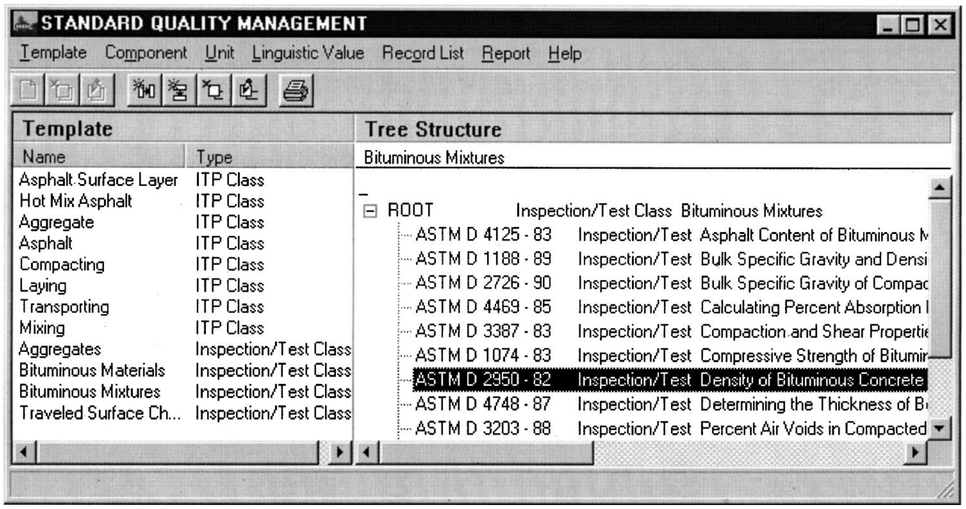

Fig. 4. Selecting an inspection/test from bituminous mixtures inspection/test class

appropriate inspections/tests from a variety of pertinent choices to compose an ITP in an ITP template or in a project file. The different inspection/test and ITP templates defined and populated for asphalt pavement construction are shown in Fig. 4. The *component* command allows one to *add/delete/edit* the highlighted component from the tree to *add* at the same level or sublevel of a component, and to *copy* from another standard template at the same level or sublevel of a component. The foregoing system capabilities allow one to efficiently compose ITPs and organize pertinent information using modular pieces of information.

The basic unit of the inspection/test template is the inspection/test. The folders contained in the inspection/test, selected as an example from the list of bituminous mixtures template, are shown in Fig. 5. They denote the five main items of information that the user can define (input) in an inspection/test standard template. The *requirements* are designated for the description of the inspection/test requirements (i.e., describe how the inspection/test is to be conducted). They include the inspection/test method, equipment, or any other condition pertinent to its successful execution. Examples on these requirements are extracted from ASTM (1991) standards and are illustrated in Fig. 6. In this screen, the user can input the test reference and its name (i.e., density test). The *reference*, defined as ASTM D 2950-82, refers to the corresponding ASTM standard test designation. The listed test requirements in this figure can be controlled with the *add/delete/edit* command buttons. In addition, during the activation of the *add* command button, the user can select whether a *single* or a *context unit* type of information is going to be input. If it is *single*, the user has to specify whether it is *quantitative*, *linguistic*, or *boolean*, so that the appropriate interface can be provided by the system.

The *criteria* to be inspected/tested are defined in their respective folder, and their definition follows exactly in the same manner the inspection/test *requirements* definition. Fig. 6 illustrates the density criterion definition to be tested. This density specification captures two quantitative values (for the mean and the individual measures) for a criterion of an end-product material whose test result is of critical importance and considered for acceptance (as represented in the screens). The value ASTM 2041, shown in this screen under the *reference* of the criteria, refers to

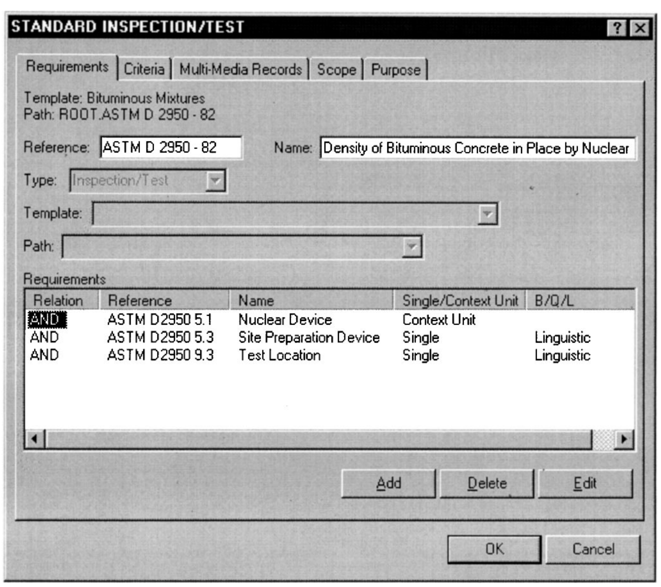

Fig. 5. List of requirements for the selected density test

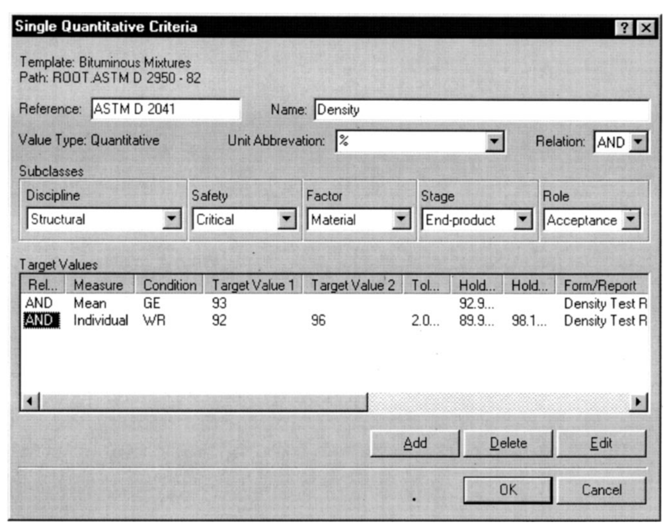

Fig. 6. Input criterion

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the designation of the corresponding ASTM standard density specification. Fig. 6 also denotes the subclasses of the density criterion, the defined unit of its target value(s), and lists its target values, tolerances, and hold points for both the mean (mean of a number of measurements) and the individual measures. The hold points indicate the values at which the work should be held, if attained by the test result. It is noted that *requirements* and *criteria* are represented by the same class (as referred to in the system design in Fig. 3) but with different nomenclature of the class title. *Criteria* are simply the requirements of the project/component (or activity) that the inspection/test result(s) must meet (i.e., they are measured/monitored characteristics). Product/process requirements become criteria when coupled with the inspection/test, because they are requirements upon which the inspection/test can pass or fail. Inspection/test requirements can become criteria, in case they are coupled with an audit activity, which in turn examines the compliance of a quality activity (inspection/test) to its defined requirements. Currently, no conformance verification has been included in this regard (this falls outside the scope of the present research, because it concerns auditing). The *multimedia records* extend the possibility for the user to view different records in multimedia environments. Scanned documents (e.g., complete standards), videos, pictures, etc. can be accommodated to facilitate and/or complete the information representations. The scope and purpose of an inspection/test can be defined in the *scope* and *purpose* folders, respectively. A multitude of design features characterizes the inspection/test standard template and provides its functionality with flexibility and efficiency. These features and their implications are summarized below.

- Classifying the inspections/tests (e.g., aggregates, bituminous materials) allows the speedy set up of an ITP by selecting and copying an inspection/test to compose ITPs in an ITP template or in a project file.
- Coupling the inspection/test with the criteria to be inspected/tested reflects the practice processes of design and specification definition. It provides an efficient way to handle the design criteria in association with appropriate inspection/test requirements.
- Allowing the user to select the subclasses regarding the discipline, the stage, the role and the factor permits the definition of diverse types of requirements related to any area of design/planning at any stage of the project development/operation, and for any quality management strategy, in a flexible and consistent environment. The subclass regarding safety extends the setting for the system reasoning mechanism.
- Providing the *context unit* as a capability, in addition to *single* to represent requirements/criteria allows the user to group, under a certain context, multiple requirements/criteria. The context unit definition can extend into other context units as much as the user needs. However, values are assigned as the *single* choice is selected. The context unit feature allows the representation of complex hierarchical structures of information.
- Assigning the requirements/criteria *subclasses* is devised for the *single* requirements/criterion to consider the possibility that in a context unit, multiple requirements/criteria can have different subclasses (e.g., critical/noncritical). Similarly, defining the *form/report* is provided for the *single* requirements/criteria given that each one can be reported on separate forms/reports. Such definitions to the *single* requirement/criterion provide greater flexibility to the user for managing information.
- Selecting the nomenclature of the data fields/headings from the practiced quality management domain provides the user with more familiarity and efficiency in the user-system interaction (e.g., requirements, criteria, test, target value, tolerance, hold point). However, flexibility and generality are taken into consideration. A generic aspect is preserved for fields, which can describe different classes (e.g., name, reference). It allows one to define and adopt in a flexible way, for example, a vocabulary that can be used in the system to reflect reality (e.g., tests are stored in the standard template by their name and their ASTM reference number). It also serves for defining various fields whose corresponding values are also defined respectively (e.g., a requirement name can be temperature, speed).

Standard ITP Template

An ITP template is a collection of planned inspection/test activities related to the criteria of a physical component and/or a construction activity to be inspected/tested. Each ITP template is classified under a user-defined type to be considered independently for each physical component or activity. This provides an efficient way to associate ITPs to the appropriate physical components and/or activities in a project file. An ITP of a project is the collection of all ITPs about the physical components (and their activities) constituting the project, in addition to the ITPs associated at that project level. An ITP can be named after the physical component or activity to which it relates. The inspection/test activity can be named after the characteristic to which it is associated (e.g., temperature inspection), or as defined in industry standards (e.g., ASTM) using the flexible and generic characteristics of fields. However, such nomenclatures are not enforced. Several ITPs can be under one class. These can denote the multistates into which the component can undergo, or else, the multiple tasks of an activity. Furthermore, they can be the grouping of both kinds (ITPs for components at different transformation states and activities). However, this remains flexible for the user to act upon.

An ITP template has two levels namely the ITP and the inspection/test. The ITP has a series of folders to describe it. The *actual data* folder provides the user with a flexible format to input information about the ITP definition (e.g., responsibility, location). The *requirements* folder is similar to the inspection/test *requirements* folder, but dedicated to the ITP requirements in terms of its definition as a quality activity. At a higher level of abstraction of quality management guidelines, the *QM procedures* folder allows the user to define quality management procedures regarding the ITP definition. The *QMS requirements* folder is also similar to other requirements folders, but in the present context, is dedicated to the quality management system requirements of the organization for that activity. As provided, the folder of the *actual data* of the ITP displays the actual information about an ITP in association with the planned information defined in the folders of the *requirements*, the *QM procedures*, and the *QMS requirements* of that ITP. Finally, the *multimedia records* permit the documentation of different forms of information about an ITP.

The folders of an inspection/test contained in the ITP are identical to the ones of the inspection/test template, with the addition of the *QM procedures* folder. In formulating an ITP, quality management comes into play and quality management procedures need to be defined for the inspection/test activity. Even though the inspection/test folders remain the same in both templates (i.e., inspection/test and ITP templates), the information defined by the user about an inspection/test belonging to an ITP is richer in terms of activity-related requirements. This inspection/test is now treated as a planned activity. Frequency, timing, responsibility,

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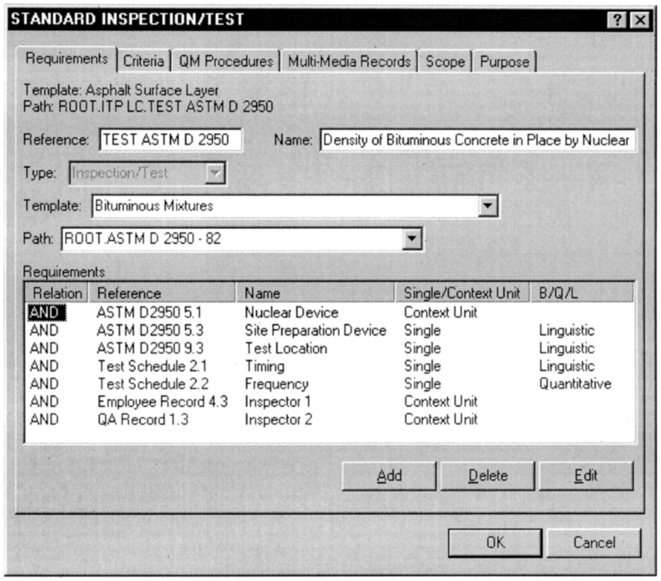

Fig. 7. Combined requirements of inspection/test for ITP

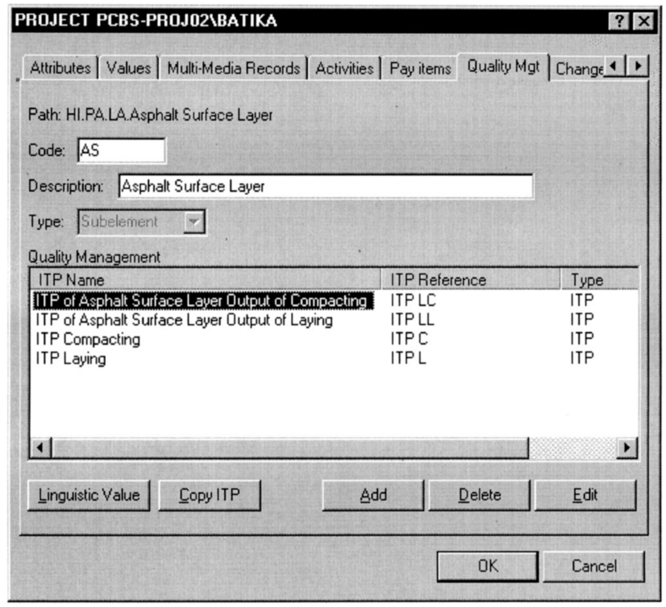

Fig. 8. ITPs associated to asphalt surface layer physical component

location, etc. of the inspection/test activity can be defined as needed, in addition to the inspection/test requirements, which can be copied from the inspection/test standard template. An example on this particular information that is pertinent to an ITP, as it relates to a density test in an ITP of an asphalt surface layer copied from an inspection/test template (i.e., density test from bituminous mixtures template), can be viewed in Fig. 7. The difference is that the *QM procedures* folder appears at this management level (i.e., ITP definition). In addition, the *template* and *path* fields appear in the inspection/test level of an ITP template to denote the inspection/test template from which the inspection/test has been copied. The *criteria*, as copied from the inspection/test template to the present ITP template, are identical to the inspection/test template. However, complete flexibility is available to the user to alter any change after copying the information from the initial template. The ITP template exhibits similar characteristics as the inspection/test template, because it includes an inspection/test unit, however, with the addition of the *QM procedures* folder. The following pinpoints its features and their respective benefits:

- Classifying the ITPs provides the user with greater flexibility to define the ITP class in addition to the ITPs falling under that class. These can be for a physical component, at different transformation states, and/or for an activity and/or its corresponding tasks. The ITPs defined for different transformation states of a physical component virtually carry this identified state to the associated inspections/tests and respective requirements/criteria; and
- Devising a folder for *actual data* to allow the user to input the responsibility, place, etc. in a flexible way permits the addition or omission of any field that the user would like to input, regarding the actual information of the ITP definition activity.

System Project File

In demonstrating the quality management tasks, from a project file, the test case is used, and the steps are described as follows. After a project name is defined, the existing physical view is selected to define the physical components breakdown structure and their location sets. At each location, a different requirement/criterion target value can be defined. When specifying these values, their associations with locations are assigned. For each physical component, from the physical view, a *quality management* folder is also devised for associating the physical view to the quality management view. Fig. 8 presents a list of ITPs for the asphalt surface layer physical component. The associated ITPs shown in this figure illustrate how the user can define the ITPs with complete flexibility for any state of a physical component (i.e., hot mix asphalt output of transporting, hot mix asphalt output of mixing, asphalt surface layer output of compacting, asphalt surface layer output of laying). This flexible feature also allows one to associate to the physical component the ITPs that are related to an activity whether or not a corresponding activity has been defined in the process view (e.g., ITP compacting, ITP laying). In this study, they are shown to demonstrate the flexibility offered to the user in selecting the mode of association and to reflect the centrality of the physical component representation. Although not implemented, given the identical approach in design/implementation, the process view is considered to house the activity-related ITPs. However, both associations are allowed, depending on the user's decision in handling associations.

The role of standard templates comes into play in defining ITPs for each of the physical components. An ITP can be added, deleted, edited from a project file, or copied from an existing standard template to a project file. As shown in Fig. 8, the *copy ITP* command brings a list of ITPs belonging to previously defined ITP templates. Once the selected ITP is copied and listed, such as the highlighted ITP in Fig. 8, the *edit* command allows further definitions/alterations of ITPs and inspections/tests and their corresponding requirements/criteria. The density criterion, which has been defined during the design stage, is associated to its *results* at the construction stage. The *target values* of the criteria are defined at specific location ranges and the individual measure with corresponding target values and hold points falling within their respective ranges, are also specified.

With respect to the previous tasks, an identical path can be followed from the quality management view, after defining all the associated ITPs in the physical view. A list of the previously defined ITPs from the physical view is displayed in the quality

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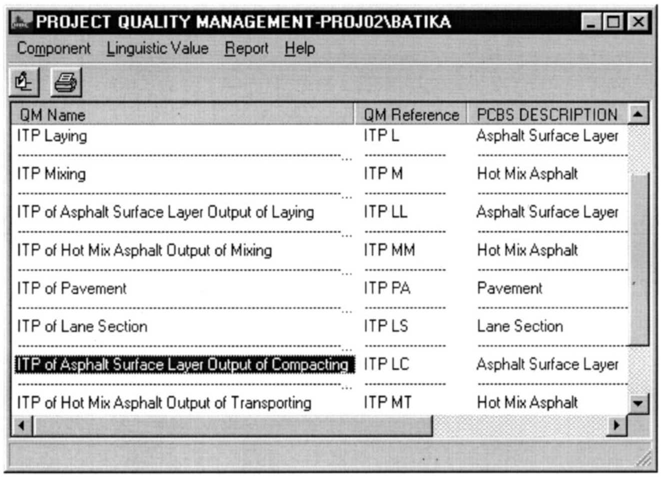

Fig. 9. Quality management view listing all ITPs

management view captured in Fig. 9. These ITPs, which relate to each physical component (and/or activity), form the core of the quality management view and a gateway from which quality-related information can be tracked (i.e., inspections/tests, requirements/criteria, actual results, etc.). Fig. 10 lists the *result value* of the *actual results* of each inspection/test activity (input by the user) and the *conformance verification* that is computed by the system for the different measurements at the corresponding location ranges. In case of a nonconforming result value, the *problem* command can be activated to identify the problem and perform the remaining reasoning tasks. This is left for the second phase of the system realization.

From a project file, the quality management module exhibits similar characteristics as the ITP template, because it includes ITPs containing their respective sets of inspections/tests; however, with the addition of the actual result and associated conformance verifications. The following describes the design features pertaining to the quality management module from a project file:

- Centralizing the ITP in the quality management view as a core for associating the inspections/tests, the corresponding criteria to be inspected/tested, their respective actual results, and pertaining nonconformance analyses, offers the benefit of organizing all related information in order to be handled from one source.

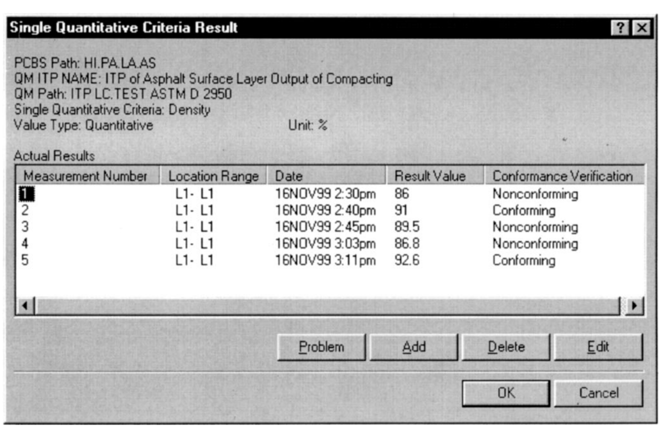

Fig. 10. Listed actual results and conformance verifications

- Associating ITPs to physical components and/or activities and then defining corresponding tests appropriately reflects the practical way that quality planners adopt and simplifies the process of recalling to which part of the product/process the ITP belongs. Devising a folder for *quality management* in the physical view is a flexible and efficient way for grouping all ITPs in association to the physical component for that view. Similarly, a folder for *quality management* in the process view will serve the process view in this regard.
- Enforcing the central role of the physical component, by allowing a flexible definition of ITPs corresponding to both physical components at different transformation states and activities that have transformed these components, provides a structured representation approach which stresses the centrality of a project physical components.

Conclusions

This paper has overviewed the design of a computer-based system for construction quality management and has described the first phase of its realization. The system functionality and flexibility has been tested and validated using data from different construction domains. The system can deal with a diverse range of information related to requirements/criteria, inspections/tests, actual results, and inspection and test plans and integrate them with the project physical aspect. The multiclassification of requirements/criteria for any product/process in a consistent input environment allows users to handle any type of requirement/criterion for any design/plan at any stage of the project development/operation. The inspection and test plan provides a central representation to associate to construction components and processes, relevant inspections/tests, requirements/criteria, actual results, and nonconformance analyses. The standard templates furnish a major facilitating functional feature that enables the reuse of predefined packages of information, which recur from project to project. Although effort is required to populate the standard templates for various types of projects, the developed system will benefit construction management by (1) providing an effective and efficient computerized environment for the assisted quality management tasks; (2) facilitating the implementation of formal quality systems pertinent to these tasks; and (3) extending and exploiting the data and tasks used in existing project management functions in an integrated fashion. The second phase of the system realization will treat the tasks pertaining to the problem identification and/or prediction, the diagnosis of their causes, and the specification of appropriate actions.

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