Spring 1-1-2016

Quality Assurance Risk-Based Optimization for Departments of Transportation

Erick Frantz Oechler
University of Colorado at Boulder, erick.oechler@colorado.edu

Recommended Citation

Oechler, Erick Frantz, "Quality Assurance Risk-Based Optimization for Departments of Transportation" (2016). *Civil Engineering Graduate Theses & Dissertations*. 56.
https://scholar.colorado.edu/cven_gradetds/56

Quality Assurance Risk-Based Optimization for Departments of Transportation

by

Erick F. Oechler

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of
Master of Science
Department of Construction Engineering Management
University of Colorado at Boulder

2016

This thesis entitled:

Quality Assurance Risk-Based Optimization for Departments of Transportation

written by Erick F. Oechler

has been approved for the Department Construction Engineering Management

Keith R. Molenaar

Matthew R. Hallowell

August 2016

The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
Of scholarly work in the above mentioned discipline.

Abstract

Oechler, Erick Frantz (M.S. in Civil and Architectural Engineering)
Quality Assurance Risk-Based Optimization for Departments of Transportation
Thesis directed by
Professor Keith Molenaar and Associate Professor Matthew R. Hallowell

The quality assurance (QA) environment for highway construction has been changing rapidly over the past years pushed by budget reductions, new testing methods and the use of alternative project delivery methods. The objective of this research effort is to define the state-of-practice for risk-based QA optimization practices in departments of transportation (DOTs) and to propose a framework to help QA resource allocation decision making.

The context for this objective is construction projects across their full range of type, size, complexity and project-delivery method. The authors conducted a comprehensive literature review, national survey, interviews with eight DOTs and a Delphi process to achieve the research's objective.

The first results of this research is discovery that DOTs optimize their QA approach depending on a material's variability or project's characteristics. However, DOTs are currently inconsistent in how they optimize practices QA for alternative delivery methods. The results are shown in a framework that provides five levels of

QA practices across a spectrum of visual inspection, material certification, and sampling and testing.

Secondly, the framework revealed that the optimization model structure is sound and that the theoretical modeling techniques originating in economics (e.g., Kirkpartick 1974) have practical application to infrastructure construction. The Delphi process showed that the total cost of quality (CoQ) was optimized when the highest level of QA effort was selected.

Acknowledgements

This research was based on the NCHRP Project 10-92 with the guidance and help of Keith Molenaar PhD, Matthew Hallowell PhD, Sidney Scott III, P.E, and Linda Konrath. Special thanks to Cecil Jones, John D'Angelo, PhD, P.E., Gerald Huber, Jo Sias Daniel PhD, P.E., and also indebted to the many DOT representatives who gave their time to participate in the survey, interviews, and Delphi to share their experience and identify their needs and best practices related to materials quality assurance.

Contents

List of Figures

List of Tables

Chapter I. Introduction

Background

Project variability is one of the main differences between the construction industry and the other industries such as the manufacturing or pharmaceutical. In the highway sector, a project's characteristics such as size, location, and contracting method make every project unique. In order to achieve expected performance in highway infrastructure, Departments of Transportation (DOTs) developed specifications describing the construction methods and materials needed. DOTs later moved towards a statistically based materials Quality Assurance (QA) procedures.

The manufacturing and defense industries have been using risk-based QA approach to ensure performance for more than 70 years. Even so, the implementation of QA throughout DOTs has been inconsistent and what is accepted for some projects may be considered non-conforming in others.

Research Problem

In order to optimize the resources used in infrastructure design and construction, the Federal Highway Administration as well as some DOTs have been pushing to use more of the contractor's test results for acceptance. However, there is a dearth of data allowing DOTs to take risk-based approaches to QA management. The impact of a change in DOTs' current QA approach could be very significant given that materials represent 50% of Federal aid construction dollars. Additionally, DOT's resources have been shrinking in budget as well as in qualified workforce. Thus, there is a need to effectively allocate resources without compromising the quality or performance of a product.

Research Objective

The objective of this research is to develop a method to optimize materials QA programs and provide recommendations for appropriate QA resource allocation across their full range of type, size, complexity, and project-delivery method. The essential research questions are:

- How can we optimize Quality Assurance (QA) investment with a risk-based approach?
- What factors influence Departments of Transportation's (DOT) QA approach?
- How does QA spending impact the cost of quality?

Methods

In order to develop a model that could be used to optimize a DOTs QA approach, we developed a methodology that consists of two phases (***Figure I-I Methodology***).

The objective of the first phase was to understand materials QA current state of practice for various DOTs by using three different research methodologies.

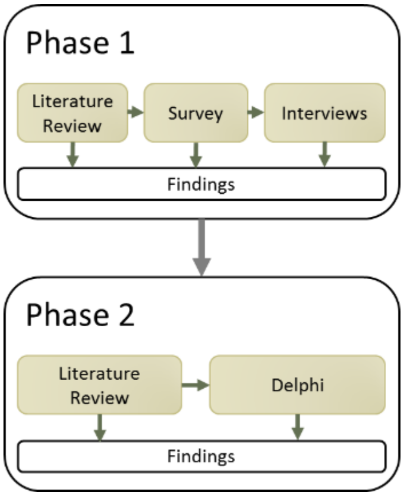

Figure I-I Methodology

- Literature review: Analyze relevant papers, manuals, schedules and reports to assess the current QA approach.
- Survey: Identify practitioners that could be interviewed and the factors that could modify a DOT's QA approach.
- Interviews: Understand DOT's personnel existing day-to-day work on QA as well as risk based procedures.

In Phase 2, through a literature review in quality models, risk, and with the information collected from Phase 1 we could develop a model to be validated or tried through a Delphi process.

Organization of the Thesis

The thesis is arranged into two independent articles that relate directly to the Phase 1 and Phase 2. Chapter 2 presents a state of practice of DOTs approach toward QA with special emphasis on how are they optimizing their resources. Chapter 1 shows the need for a risk based optimization model that is presented in Chapter 3.

Chapter 3 details the methodology to conduct the Delphi as well as the results for Hot Mix Asphalt optimization curves. It also, describes the impact of a projects factors regarding QA and the consensus or polarization reached during the Delphi. The possible applications and further research needed are stated at the end of this chapter.

Chapter 4 summarizes the results and lets the reader know the nuances of this research. It is a helpful chapter for anyone that would continue this line of inquiry. The research questions presented in Chapter 1 are answered in this chapter as well.

Chapter II. State-of-Practice for Risk-Based Quality Assurance in State Departments of Transportation

INTRODUCTION

In response to shrinking budgets and reductions in both the number and experience level of inspectors and engineers, US state departments of transportation (DOTs) are seeking ways to improve and optimize their processes (Murphy et al. 2011). The ultimate goal is to achieve efficiencies of resource allocation in project and program delivery. A burgeoning area for process improvement is materials quality assurance (QA) – a critical, though resource-intensive, component of project delivery.

The importance of materials QA is without question. Materials represent approximately 50% of Federal-aid construction dollars (Federal Highway Administration 2013). When QA programs are well designed, they can provide confidence that project materials and workmanship will be in reasonable conformance with plans and specifications (Federal Highway Administration 2014). Conversely, an inadequate QA plan can increase the risk of short and long-term failure, leading to reduced design life, increased maintenance costs and possible safety concerns (Hughes 2005; Murphy et al. 2011). Logically, more comprehensive and robust QA programs will result in less risk. However, an overly rigorous QA plan can result in unnecessary project costs; an outcome that DOTs can ill afford in this time of flat or declining resources.

The objective of this research effort is to define the state-of-practice for risk-based materials QA optimization practices in DOTs. We explore this objective by considering the full range of project type, size, complexity, and project-delivery method. Ultimately, the knowledge gained through this comprehensive state-of-practice survey will enable DOTs to better benchmark practices, identify advanced practices, and to develop context for new, risk-based approaches.

APPROACH

To achieve the research objective we began with a review of relevant academic research, regulatory requirements, and guidance manuals published by state DOTs. We included any resource that included methods of material QA and risk management for transportation construction projects. This literature review effort was supplemented by survey of state DOTs to identify specific approaches and differences in approaches to materials QA. Although all DOTs have construction manuals, specification handbooks, or QA guides, there is tacit knowledge that is not captured within these documents. Thus, the process ended with interviews of experienced DOT representatives. This section describes the details of each research step.

Literature Review

The goals of the literature review were to document the breadth of materials QA methods across the US and to benchmark current procedures. To this end, we collected and reviewed construction and materials manuals and related QA documents. These included quality assurance program guidelines, standard specifications, minimum sampling and testing requirements, materials control and acceptance guides and forms, and others. We purposefully sampled from a geographically diverse set of highway agencies, including Arizona, Colorado, Florida, Illinois, New Hampshire, Texas, Virginia, Washington, Wisconsin and Wyoming. These documents were found primarily from searches of DOT websites.

An additional goal of the literature review, was to identify any advanced risk-based material QA practices in construction, manufacturing, or other industries that might be applicable to transportation. We conducted literature searches using general internet search engines, academic and research search engines, research institutions including the Transportation Research Board, and societies with journal and conference publications. Particular emphasis was placed on obtaining any documents that would support the development of a QA plan for a highway construction project that optimizes risk.

Survey

To confirm and expand upon the findings from the literature review, we developed an on-line survey and distributed it through email invitations to a list of almost 200 transportation professionals. These individuals were drawn primarily from two Association of American State Highway Transportation Officials (AASHTO) Subcommittees: Materials and Construction. To ensure the survey reached the intended audience, we asked recipients to identify additional individuals from within or outside their organizations who had appropriate knowledge in the topic. Our goal was to distribute the survey broadly.

We designed the survey questions to identify and assess a wide range of topics. First, we aimed to assess the extent to which different project factors (e.g., project type, facility type, material quantities, project delivery method, funding source, material criticality, etc.) affect materials acceptance procedures and protocols. Second, we aimed to identify any trends related to materials QA and the use of statistically-based specifications, contractor quality control (QC) data in the acceptance decision, and alternative project delivery methods, such as design-build, maintenance contracts and warranties. Finally, we aimed to document any use of tiered or risk-based materials acceptance programs.

To minimize the time and effort of respondents and help ensure an adequate response rate, we incorporated the following best practices into the design and deployment of the survey: (1) use of clear, relatively short, non-leading survey questions that asked respondents to rate, rank and/or select the best response(s) from a list of provided choices as well as the option to provide additional comments in open-ended dialog boxes; (2) invitations for the respondents to self-select for further participation in the research and to share examples of their QA documents; and (3) inclusion of an endorsement letter from the chairman of the AASHTO

Interviews

Based on the survey data, we chose to interview representatives from eight highway agencies in an effort to better understand why differences were observed across to represent a variety of different materials management and evaluation systems. We targeted California, Florida, Ohio, Maryland, New Jersey, Texas, Virginia and Washington. Specific criteria for selecting DOTs for interviews included the following:

- DOT geography relative to materials QA;
- Range of materials management systems;
- Materials qualification and certification practices;
- Experience with alternative delivery and warranty/guarantee provisions;

- Structured approach within their DOT to material QA/acceptance based on material type (e.g., project-produced, plant-produced and standard manufactured products), project types and other risk factors; and
- Availability of previous FHWA or internal QA process reviews or audits from which we could draw.

We asked DOTs to involve their most experiences materials or QA engineers in these interviews. In order to guide the interview discussions, we developed a comprehensive structured interview protocol that addressed the following key topic areas:

- Characterization of major materials (categories) for consideration in the model (e.g. project-produced, specialty fabricated materials/products and standard manufactured products);
- Materials QA protocols (i.e. sampling and testing, certification and inspection) for major materials and how they vary based on project type, size, quantity, project delivery method or other criteria;
- Internal and external QA costs related to sampling and testing, certification or inspection for verification and acceptance, including how to track or account for these costs;
- Use of contractor QC test data for acceptance, including how use of such data affects DOT resources; and

- Identification of significant materials/product risks and likelihood and consequences (e.g., cost) of non-compliance with specification requirements for major materials.

We distributed the questions in advance of the interviews to provide participants with the opportunity to assemble any necessary information, data or subject matter experts prior to the interviews. Interview responsibility was divided among the authors, with at least two authors participating in each interview to help ensure adequate documentation of responses.

RESULTS

The level of detail in the results increased from literature review, to survey and interviews. The survey and interviews confirmed the information obtained through the literature review and increased our understanding of the DOTs QA practices. In line with previous research (Federal Highway Administration 2007, 2013, 2014; Hughes 2005), these practices were found to vary among DOTs and, in some cases, even varied within districts of the same state.

Table 1 provides a sample of our results and methodology to illustrate typical high-level findings. Findings were divided into two main categories: QA optimization and risk-based QA optimization. This division emphasizes that DOTs use both risk-based and other methods of optimization, depending on a material's variability. It also shows the three methods that we used to acquire information. Table 1 is not intended to be comprehensive; rather it is intended to illustrate the structure and type of data collected, which is further described below.

Table II-I - Overview of research methods and results

Research Methodology	Source of Information	QA Optimization	Risk based QA Optimization
Literature review	More than 60 relevant papers, manuals, schedules and reports.	Create levels of acceptance based on what is required for each material. Certify or use approved products. Acceptance selection based on material variability, criticality of a material and/or project characteristics. No clear message on the rationale behind decision-making. Informal guidelines for prioritizing inspection.	Agencies are incorporating both qualitative and quantitative risk-based approaches to QA.
Survey	Responses from 58 people out of 37 DOTs and other Highway Agencies.	Acceptance depends on project characteristics and material classification according to 82% of the respondents. Only 44% of the respondents say project delivery method and funding sources have an impact on QA approach. Some agencies applied the same QA process regardless of project characteristics.	More than 45% have a risk-based approach in their QA program. 90% modified sampling and testing based on risk. 75% modified inspection based on risk.
Interview	Maryland Washington Ohio California New Jersey Texas Virginia Florida	Reduced frequency of testing for small quantities or large volumes of project produced materials under control Local agency streamlining Criticality of materials Qualification criteria Alternative contracting criteria	Some DOTs have developed processes to incorporate risk considerations in their materials QA practices. QA based on the criticality of materials (e.g., risk rating materials)

Categories and Levels of Materials QA Practices

A comprehensive QA program should consist of the following core elements: QC acceptance; independent assurance; dispute resolution; personnel qualification; and laboratory accreditation/qualification (Federal Highway Administration 2002). Apart from sharing these fundamental components, material QA practices vary widely among DOTs. What constitutes an appropriate acceptance method, or simply an acceptable product, for one DOT may not be acceptable to another (Federal Highway Administration 2007, 2013, 2014; Hughes 2005).

We found that a DOT materials QA practices are generally based on methods that have historically produced satisfactory results. These legacy practices, however, may fail to take advantage of more recent developments such as a new understanding of materials behavior, the use of more performance-based quality measures, the use of non-destructive testing technologies that provide for continuous sampling and data collection and/or an increasing use of performance specifications and alternative delivery methods that shift more responsibility for quality management to industry (Hughes 2005).

Despite the differences in how DOTs manage the acceptance of materials and manufactured products, all DOTs generally include a combination of sampling, testing, certification, inspection and evaluation processes. **Error! Reference ource not found.** summarizes current acceptance programs obtained from the literature review and survey. These programs intend to assure that the materials, products and workmanship in a project are in reasonably close conformity to the plans and specifications. The check marks in Table 2 represent that the DOT identified uses the specific materials QA acceptance methods listed.

Table II-II – Highway materials acceptance practices

Categories	Arizona	Florida	Virginia	Illinois	New Hampshire	Colorado	Texas QAP DB	Washington	Wisconsin	Wyoming
Sampling and Testing										
Field Statistical (PWL or other)	✓	✓				✓	✓	✓	✓	
Field – non- statistical	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Plant	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Central Lab Verification	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Source of supply	✓	✓	✓	✓	✓	✓		✓	✓	✓
Small Quantities	✓	✓		✓	✓			✓	✓	
High Volume (Reduced Frequency)		✓							✓	
Other	✓		✓			✓		✓	✓	
Materials Certification										
Manufactured Products from Certified Suppliers	✓	✓	✓	✓	✓	✓		✓	✓	✓
Certified sources of supply	✓	✓	✓	✓	✓	✓		✓	✓	✓
Qualified/Certified Products NTPEP DOT	✓	✓	✓	✓	✓	✓			✓	✓
Tiered Certification (criticality of products)	✓		✓			✓				
Statements of Compliance	✓					✓		✓	✓	✓
Inspection										
Shop or source inspection		✓	✓	✓	✓	✓		✓	✓	✓
Desktop									✓	✓
Diary Documentation									✓	
Visual field inspection		✓	✓	✓	✓	✓		✓	✓	✓

A closer look into DOT acceptance practices suggests the existence of an informal hierarchy based loosely on the following materials types: project-produced, fabricated, and standard manufactured item. DOT manuals describe the practices and how the material is to be used on a project depending on the quantities involved. (Arizona Department of Transportation 2005; Baker et al. 2010; California Department of Transportation 2013; Colorado Department of Transportation 2014; Florida Department of Transportation 2015; Goulias and Sahand 2013; Illinois Department of Transportation 2012; Texas Department of Transportation 2010; Washington State Department of Transportation 2013a; Wyoming Department of

Transportation 2015) The hierarchy is included in Table 3 and is further described below.

Table II-III - Levels of DOT QA effort

	Categories of Materials QA		
QA Level	**Inspection**	**Certification**	**Sampling and Testing**
Level 1	One time inspection of manufacture and field delivery/placement	Review certification and verify that certification complies with contract requirements or that materials is on the qualified products list	N/A
Level 2	Randomly inspect manufacture and field delivery/placement	Review certification data and back-up test data from vendor (i.e. mill test or other test attached to cert) for compliance with contract requirements	Perform random verification testing
Level 3	Intermittently inspect manufacture and placement (e.g., or system-based plant inspection)	Review certification data and back-up test data from vendor (e.g., mill test or other test attached to cert) for compliance with contract requirements.	Perform intermittent verification sampling and testing (or verification testing at a reduced frequency).
Level 4	Continuously inspect manufacturer and placement (e.g., system-based plant inspection and field inspection).	N/A	In conjunction with use of contractor test data for acceptance, perform verification sampling and testing at a specified frequency and compares it to the contractor's results. Also responsible for independent assurance.
Level 5	Continuously inspect (i.e. plant inspection and field inspection).	N/A	Performs sampling and testing and accepts materials using DOT results. Also responsible for independent assurance.

As one can see from Table 3, the categories of QA methods include inspection, certification, and sampling and testing. The specific practices within each of these general methods define the levels of QA effort in the table. The first general category consists of inspection, ranging from plant or source to desktop and visual. Inspection can span from one time inspection of manufacture or field produced materials once they are placed to a continuous plant or field inspection. The use of inspection for any kind of acceptance with a combination of other levels of QA is widespread among DOTs.

The second category of materials QA is material acceptance through material certification. This procedure is commonly used on manufactured materials or products. Certifications vary from specific sources, such as a mill test report for a specific lot of material (issued by the fabricator or producer of the raw materials), to general (such as a contractor's certification that the materials were obtained from a reputable source of supply). The certification might apply to pre-approved materials through the National Transportation Product Evaluation Program (NTPEP) (Federal Highway Administration 2013), materials on a qualified products list, or from pre-approved sources (California Department of Transportation 2013; Illinois Department of Transportation 2009; New York State Department of Transportation 2005). Certifications can be issued by DOTs or by the contractor or supplier using a statement of compliance to assure that the materials meet certain criteria.

The most advanced category of materials QA, sampling and testing, involves a range of testing options, including statistical and non-statistical methods and possibly the use of contractor QC results in the acceptance decision. The type and frequency of tests vary depending on the location where the samples are taken, the test method, the quantity or variability of materials and project type. Quality assurance of project-produced materials generally entails some level of sampling and testing.

Use of Contractor QC Data for Acceptance

DOTs express that they are experiencing pressure to operate more efficiently due to budget constraints. They have downsized, outsourced, and assigned more responsibilities to the contractor in response. One of the approaches to improve efficiency and leverage statistically-based specifications and alternative delivery methods, entails the use of contractor QC test results in DOT acceptance decisions (Anderson and Russell 2001; Kopac 1997). In fact, it is now quite common, even under a design-bid-build contract, for agencies to include contractor QC test results even for critical quality characteristics in their acceptance decisions (California Department of Transportation 2013; Federal Highway Administration 2004, 2014; Florida Department of Transportation 2015; Hughes 2005; Illinois Department of Transportation 2012; Texas Department of Transportation 2010; Washington State Department of Transportation 2013b; Wyoming Department of Transportation 2015). As shown in Figure 4 and according to a 2013 FHWA program evaluation report, at least 31 DOTs out of 52 DOTs use contractor test results in acceptance decisions (Federal Highway Administration 2013). Our survey confirmed this trend, showing that 79% of the respondents use contractor data in their acceptance decision and 29% of those always use contractor's QC data for their QA process. Nevertheless, the use of this approach still requires independent verification testing by the DOT, or an agent acting on behalf of the DOT (Federal Highway Administration 2002). Similarly, for projects with short-term warranties, where the warranty will not cover the anticipated life of the warranted product, DOTs will generally perform some level of initial acceptance testing at the end of construction (Anderson and Russell 2001).

Impact of Project Characteristics on QA Practices

According to our survey, the majority of DOTs (82%) reported that they use alternatives to design-bid-build project delivery, with design-build being the predominant alternative. Results also showed that warranties or maintenance contracts are used on a variety of materials, but most often on pavements or pavement elements. Likewise, contract documents (e.g., Florida Department of Transportation 2014) suggest that use of alternative contracting methods (e.g., design-build) may change the traditional approach to materials QA by shifting greater responsibility for quality to industry. Interestingly, 44% of the survey respondents indicated that use of alternative contracting methods did not affect the selection of methods used for materials QA. In fact, a few respondents were unsure of how delivery methods affect materials QA in any respect. This perspective suggests that alternative contracting methods do not necessarily or consistently affect materials QA practices.

DOT preferences, variations in interpretation of federal QA requirements, and maturity of local industry can all influence QA decision-making (Kraft and Molenaar 2014). However, trends suggest that as agencies gain more experience with alternative delivery, they gradually implement policies through pilot or demonstration programs that shift greater responsibility for materials management to industry (Kraft and Molenaar 2014; Molenaar et al. 2008).

Trends in QA Optimization

Highway agencies optimize their materials QA practices to some extent by modifying their standard sampling and testing schedule based on material criticality, quantities, type/size of project, and project delivery method. This approach to optimization was a key finding from the literature review that was confirmed through the survey (Ashley et al. 2006; Baker et al. 2010; California Department of Transportation 2007; Federal Highway Administration 2004; Goulias and Sahand 2013; Molenaar et al. 2008; Murphy et al. 2011; Texas Department of Transportation 2008, 2011). We found there were no noteworthy differences in the types of optimization strategies associated with a DOT's size, geographic location, or other demographic factors. This suggests that optimization strategies could be universally applied. However, we did find that the QA process depends on the criticality and the variability of a material or product, suggesting that the optimization process is more strongly related to the material, its properties, and the characteristics of the project.

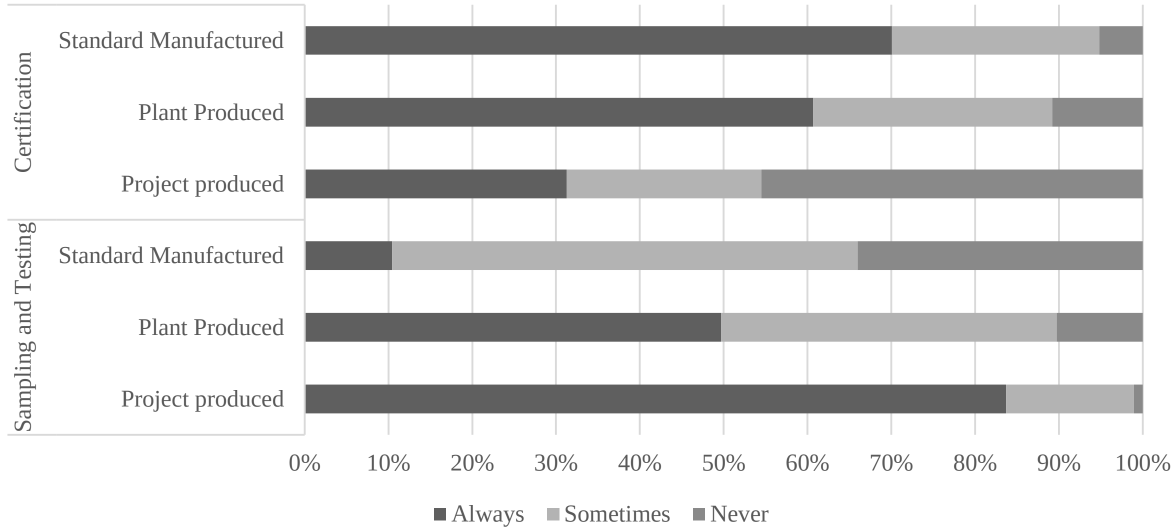

Figure II-I - DOT QA approach to high profile projects

As one can see from Figure 4, more than 80% of the survey respondents stated that they perform sampling and testing - often in combination with inspection - for project-produced materials such as earthwork, base courses, pavements, and cast-in-place structures. However, they rely on certification and inspection for fabricated or standard manufactured products such as paints and coatings, which are produced in more controlled environments. This finding was consistent for both high-profile projects (i.e., large, urban, or high volume roadways) and low-profile projects.

In addition to material classification (i.e., project produced vs. plant produced vs. standard manufactured items), respondents also indicated that the quantity of materials involved (80%), the criticality of materials (65%), and project type (65%) also affect acceptance practices. In contrast, project delivery type, facility type (interstate, primary road, secondary road, etc.), and funding source were reported as having less influence on acceptance procedures (45%, 41% and 22% respectively). At the extreme, some DOTs commented that they apply the same QA process regardless of project characteristics.

In summary, the rationale for selecting a particular acceptance method, from inspection to continuous, statistically-based sampling and testing, are currently based on:

- Material variability and level of control required for materials to meet specifications (e.g. prefabricated products or structural elements are less variable and typically require less field control than pavement materials or soils);
- Criticality of specific materials or products from the perspective of difficulty to repair or replace, safety, maintenance cost or cost of rework; and
- Project characteristics, such as type, size and complexity

The ultimate approach to select a QA method for a particular project remains qualitative and informal with much discretion left to project engineers to modify rates or protocols based on engineering judgment. Further, as observed by Hughes (2005), the risks associated with adequate contractor sampling and testing are still not well understood.

Trends in Risk-Based QA Optimization

One of the goals of our study was to document any risk-based approached to QA method selection and optimization. Some DOTs have, indeed, developed processes to consider components of risk, although no DOT has developed and implemented a complete risk analysis for materials QA. For example, Caltrans developed a draft Construction QA Program Manual (California Department of Transportation 2015) that includes an approach to materials specifications based on the consequence of failure of each material property. For example, Level 1 items are considered to have the greatest consequence of failure while Level 4 items have the least consequence. Several DOTs developed similar risk-based approaches such as Texas (Texas Department of Transportation 2011), South Dakota (South Dakota DOT 2008), Washington (Baker et al. 2010), Indiana (Mostafavi and Abraham 2012), and New York (New York State Department of Transportation 2005).

In the survey, 45% of the respondents reported that risk is a factor in their optimization process. For those DOTs that include risk components (i.e., either probability or impact of failure), the majority (90%) reported that they modified sampling and testing rates based on risk and 75% reported that inspection procedures were altered based on risk. Eighteen respondents provided additional commentary to clarify their answers, noting that the frequency of sampling is decreased for materials that they perceive have lower risk or a short design life.

All of the reponses share the general theme of ad hoc assessments typically governed by the perception of a material's criticality. This is exemplified well by one respondent's quote, which noted, *"Nothing is a written specification, but our managers can increase/decrease frequency of tests if needed."* This, and similar comments, imply that the processes that respondents reported as risk-based were mostly qualitative and informal, with discretion left to project engineers to modify rates or protocols based on engineering judgment. Nevertheless, the findings suggest that a foundation exists for developing and implementing a more in-depth process for optimizing the costs and risks of materials QA.

CONCLUSIONS

The triangulation of the literature review, survey, and interview results provided a richer understanding of the state-of-practice for risk-based QA methods in DOTs and opportunities for future development. Three general statements can be made to summarize the results:

- DOT QA approaches vary between states in terms of acceptance, optimization, and material specifications;
- The large majority of DOTs consider risk in QA practices through engineering judgement, but only a few have formalized risk-based policies and/or guidance; and
- The use of alternative delivery methods on DOT impacts QA practices, but these impacts are not consistent between DOTs.

We identified three main factors that currently impact a DOT's QA approach. First, project-produced materials have a higher variability and, therefore, DOTs spend more resources to ensure their quality. We found this factor to have a consistent impact across all DOTs. Second, the criticality, or quantity, of a material impacts the QA approach, with materials that are perceived to be more critical having grater investments in QA effort. Third, DOTs have qualitative approaches to consider the impact of a material failure and they can change the specifications depending on the perceived risk. Fourth, DOTs vary the resources allocated to a project's QA depending characteristics such as size, location, or complexity. Fifth, the demographics of the DOT (e.g., geography and size) appear to have little or no influence on the selection of QA methods, suggesting that the same optimization approaches may apply broadly. Finally, we found that 45% of the survey respondents did not vary their QA approach on different project delivery methods. This perception contradicts the findings from previous research efforts (Gransberg and Molenaar 2004; Kraft and Molenaar 2014) and the guidance in alternative project delivery manuals (Florida Department of Transportation 2014; New York State Department of Transportation 2005; Texas Department of Transportation 2011).

Although some DOTs employ QA method selection approaches that consider components of risk, we recommend research into formal and comprehensive risk-based approaches. Typically, the impact component of risk is accounted for in the consideration of material criticality in the selection of a materials QA strategy for a project. However, the likelihood of material nonconformance or material failure associated with each level of QA effort is not explicitly considered. Quantitatively modeling such data may enable the use of objective, risk-based approaches that are not subject to judgement-based bias. From a practical perspective, DOTs should consider the development of a standardized approach to QA optimization, ideally involving empirical data and objective approaches tied directly to observable project outcomes.

REFERENCES

Anderson, S. D., and Russell, J. S. (2001). “NCHRP Report 451: Guidelines for Warranty, Multi-Parameter, and Best Value Contracting.” National Cooperative Highway Research Program, National Academy Press Washington D.C.

Arizona Department of Transportation. (2005). “Construction Manual - Chapter 10 Materials.” Arizona Department of Transportation, Phoenix, AZ.

Ashley, D. B., Diekmann, J. E., Molenaar, K. R. and American Trade Initiatives Inc. (2006). “Guide to Risk Assessment and Allocation for Highway Construction Management.” Publication No. FHWA-PL-06-032, U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Baker, T. E., Molohon, R. J., and McIntyre, R. W. (2010). “Materials Risk Analysis.” WA-RD 745.1, Washington State Department of Transportation Research Report, WSDOT Office of Research & Library Services, Olympia, WA.

California Department of Transportation. (2007). “Project Risk Management Handbook: Threats and Opportunities” Second Edition, Office of Statewide Project Management Improvement Sacramento, CA.

California Department of Transportation. (2013). “Construction Manual.” California Department of Transportation, State of California Department of Transportation Division of Construction, Sacramento, CA.

California Department of Transportation. (2015). “Chapter 2: Construction Quality Assurance Roadmap.” California Department of Transportation, Sacramento, CA.

Colorado Department of Transportation. (2015). “2015 Field Materials Manual, Quality Assurance Procedures for Construction and Materials Sampling and Testing.” Colorado Department of Transportation, Denver, CO.

Federal Highway Administration. (2002). “Title 23: Code of Federal Regulations: Chapter I. Subpart B–Quality Assurance Procedures for Construction.” Electronic Code of Federal Regulations

Federal Highway Administration. (2004). “Technical Advisories Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks.” Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks, <http://www.fhwa.dot.gov/construction/t61203.cfm> (Mar. 25, 2015).

Federal Highway Administration. (2007). “Quality Assurance in Materials and Construction.” FHWA/HPC-10, Office of Professional and Corporate Development Program Improvement Team, Washington, D.C.

Federal Highway Administration. (2013). “Quality Assurance Stewardship Review Summary Report for Fiscal Years 2009 through 2012.” U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Federal Highway Administration. (2014). “Construction Quality Assurance for Design-Build Highway Projects.” FHWA-HRT-12-039, U.S. Department of Transportation Federal Highway Administration, McLean, VA.

Florida Department of Transportation. (2014). “I-4 Ultimate Project, Volume I – Concession Agreement” Contract # E5W13, Financial Management #432193-1-52-01, Florida Department of Transportation, Deland, FL.

Florida Department of Transportation. (2015). “FDOT: State Materials Manual.” FDOT: State Materials Manual, <http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/materialsmanual/index.shtm> (Mar. 25, 2015).

Goulias, D., and Sahand, K. (2013). “Material Quality Assurance Risk Assessment.” Project No. SP909B4K, Maryland State Highway Administration Baltimore, MD.

Gransberg, D. D., and Molenaar, K. (2004). “Analysis of Owner’s Design and Construction Quality Management Approaches in Design/Build Projects.” Journal of Management in Engineering, 20(4), 162–169.

Hughes, C. S. (2005). “NCHRP Synthesis 346: State construction quality assurance programs: A Synthesis of Highway Practice” Transportation Research Board of National Academies, Washington, D.C.

Illinois Department of Transportation. (2009). “Project Procedures Guide; Sampling Frequencies for Materials Testing and Inspection.” Illinois Department of Transportation Bureau of Materials and Physical Research, Springfield, IL.

Illinois Department of Transportation. (2012). “Standard Specifications for Road and Bridge Construction.” PRT3519235-20,000-07-2011, Illinois Department of Transportation Departmental Policies, Springfield, IL.

Kirkpatrick, E. G. (1970). Quality Control for Managers and Engineers. John Wiley & Sons, Inc. USA.

Kopac, P. (1997). “Contract Management Techniques for Improving Construction Quality.” FHWA-RD-97-067, U.S. Department of Transportation Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean VA.

Kraft, E., and Molenaar, K. R. (2014). “Quality Assurance Organization Selection Factors for Highway Design and Construction Projects.” Journal of Management in Engineering, 04014069-1 to 04014069-9.

Molenaar, K., Gransberg, D., and Datin, J. (2008). “NCHRP Synthesis 376: Quality Assurance in Design-Build Projects.” National Cooperative Highway Research Program, Transportation Research Board of National Academies, Washington D.C.

Mostafavi, A., and Abraham, D. (2012). “INDOT Construction Inspection Priorities.” Publication FHWA/IN/JTRP-2012/09, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN.

Murphy, T. R., Taccola, L. J., and Murphyao, A. (2011). “Proceedings of the Material Quality Testing Risk Assessment and Multi-State Peer Exchange Meeting.” Illinois Center for Transportation, Springfield, IL.

New York State Department of Transportation. (2005). “Quality Assurance Procedure for Standard Specifications, Construction and Materials Section 700-Materials and Manufacturing.” NYDOT Materials Bureau Albany, NY.

South Dakota Department of Transportation. (2008). “SDDOT Construction Manual Project Management Section Chapter 3 - Materials.” South Dakota Department of Transportation, Pierre, SD.

Texas Department of Transportation. (2008). “Quality Assurance Program for Design-Build Projects with an Optional 15-Year Capital Maintenance Agreement.” Texas Department of Transportation, Austin, TX

Texas Department of Transportation. (2010). “Guide Schedule of Sampling and Testing.” Texas Department of Transportation, Austin, TX

Texas Department of Transportation. (2011). “TxDOT Design-Build Quality Assurance Program- Implementation Guide.” Texas Department of Transportation, Austin, TX

Veen, B. (1974). “Quality Costs.” Proceeding of the second Eurpean Organization for Quality Control, EOQC, pages 55–59.

Washington State Department of Transportation. (2013a). “Materials Manual.” Washington State Department of Transportation Engineering and Regional Operations State Materials Laboratory, Olympia, WA.

Washington State Department of Transportation. (2013b). “Construction Manual.” Washington State Department of Transportation Engineering and Regional Operations State Construction Office, Olympia, WA.

Wyoming Department of Transportation. (2015). “Wyoming Transportation Department Materials Testing Manual” Wyoming Department of Transportation, Cheyenne, WY.

Chapter III. Risk-Based Quality Optimization of Infrastructure Materials using a Lifecycle Cost Approach

INTRODUCTION

Since 1970, there has been interest in optimizing the Cost of Quality (CoQ) in industrial settings (Kirkpatrick 1970; Plunkett and Dale 1988). Today, many industries define CoQ as the sum of the costs related non-conformance of materials and the costs of non-conformance prevention (Hylton Meier 1991; Morse 1993; Schiffauerova and Thomson 2006). The transportation sector is not different, as the Federal Transit Administration (FTA) groups quality costs into two broad categories: the price of conformance (i.e., defect detection costs) and the price of non-conformance (i.e., cost of defects or failures) (Federal Transit Administration and Urban Engineers 2012).

Due to shrinking budgets and reduction in the ratio of inspectors and engineers to work volume, Departments of Transportation (DOTs) have developed ways to improve the economic efficiency of their Quality Assurance (QA) processes (Murphy et al. 2011). Also, the Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP) have been promoting research on QA optimization in order to reduce waste and improve efficacy of existing programs (Federal Highway Administration 2004, 2013; Kraft and Molenaar 2014).

Existing approaches to QA optimization do not account for the full CoQ because resource allocation is directed by the price of non-conformance or criticality of a material and not on the balance between the risk of defect and the cost of prevention (Oechler, 2015). In order to address this practical limitation and the associated knowledge gap, this study aims to collect and analyze the requisite data for a risk-based CoQ optimization for highway construction for the first time. To demonstrate a complete risk-based CoQ optimization for asphalt construction, the following objectives were achieved: (1) identify levels of quality assurance effort for asphalt quality control and assurance; (2) quantify the risk reduced from implementing each QA level; (3) quantify the costs of each QA level; and, ultimately, (4) assemble these data in a risk-based optimization model. The focus of each objective was on lifecycle quality performance from the DOT perspective. This research builds upon the body of knowledge from industrial systems, optimization, transportation, engineering, and quality assurance.

BACKGROUND

Cost of Quality Optimization Models

In the construction industry, quality has been viewed as the degree to which the final product meets its specifications (Transportation Research Board 2005). By defining quality as conformance to specifications, the cost of quality becomes measurable (Davis et al. 1989). Given this definition of quality, the total CoQ is the sum of all costs associated *"with the prevention, measurement, and correction of problems arising from products, materials, or services that lack conformity to specifications"* (Hylton Meier 1991, p. 40). The Institute of Management Accountants classified these costs as prevention costs, appraisal costs, internal failure costs, and external failure costs (Morse et al. 1987).

Computing the total CoQ involves summing the cost of quality management activities (e.g., sampling, testing, certifications, and inspections) and expected value of the risk of material failure. Meier (1991) proposes an inverse relationship between these variables. That is, as the investment in prevention and appraisal costs increase, the expected value of nonconformance decreases and vice versa. The manufacturing industry formalized this concept into a theoretical CoQ optimization model (Kirkpatrick 1970; Plunkett and Dale 1988). This model, shown in Figure 1, represents CoQ as a function of QA costs and the cost of defective or nonconforming materials (Kirkpatrick 1970). Figure also uses percentage of budget as the vertical axis and quality of conformance (i.e., increased QA effort) on the horizontal axis. An increment of resources allocated to QA (i.e., QA cost) increases the quality of conformance but decreases the probability of defects. Thus, there is a theoretical optimum investment point that yields the lowest total cost to achieve the desired product, known as the lowest total CoQ.

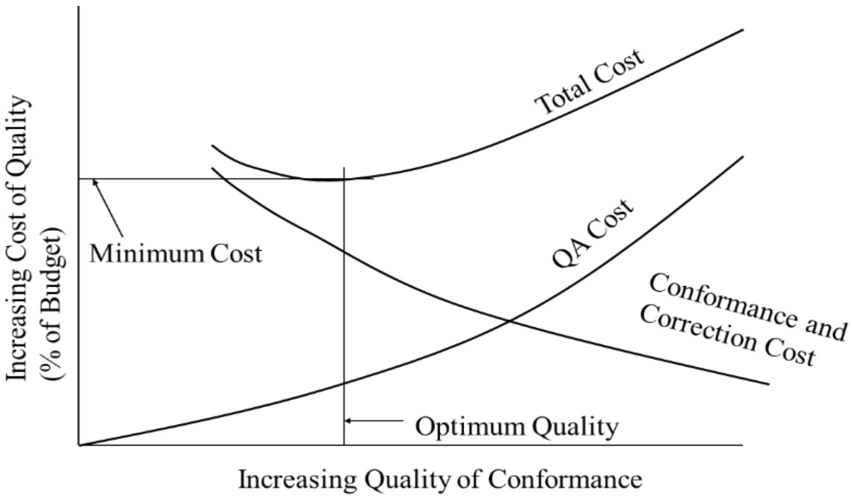

Figure III-I – General Economics of Quality Conformance Model (Adapted from Kirkpatrick, 1970)

Cost of Quality in the Construction Sector

In infrastructure construction researchers have identified, measured, and predicted the cost of rework (Love and Sing 2013). Also, researchers have attempted to quantify the CoQ by measuring the costs of correcting rework and the cost of quality management (Davis et al. 1989), the additional time and cost needed to correct defects (Abdul-Rahman 1995), and the overall cost of failure (Pheng Low and Yeo 1998). All of these studies have focused on CoQ from the contractor's perspective and consider the construction phase as the timeframe of interest. However, quality optimization is very different for a client (e.g., DOT) because they ultimately pay for the consequences of non-compliance and, thus, must adopt a lifecycle approach. This includes considering the long-term risk of material failure and all costs associated with QA efforts used to mitigate this risk. To date, the research community has yet to build data-driven lifecycle CoQ optimization models.

According to a recent state-of-practice review, DOTs incorporate or develop tools to optimize materials QA based on qualitative risk ratings (Kraft and Molenaar 2014). State DOT manuals describe methods that involve rating the criticality of a material or a project based on personal experience and do not take into account the cost of QA effort (Baker et al. 2010; Goulias and Sahand 2013; Murphy et al. 2011; Texas Department of Transportation 2008, 2011). Alternatively, the Federal Transit Administration provides a high level overview of cost of QA effort in their *Quality Management System Guidelines* (Federal Transit Administration and Urban Engineers 2012). This resource divides CoQ into two broad categories: price of conformance (i.e., defect detection costs) and the price of non-conformance (i.e., the cost of defects) and aligns with the aforementioned CoQ models. However, it remains theoretical and has yet to adopt a risk-based perspective or data. Thus, there is an opportunity to advance the sophistication of QA optimization from a DOT perspective through the creation of new risk-based knowledge.

POINT OF DEPARTURE

Current QA optimization approaches for infrastructure systems are directed by the price of non-conformance or the criticality of a material. Previous research in other industries, however, has enabled a more comprehensive approach that includes the balance between the risk of non-conformance and the cost of prevention. In this paper, these methods are adapted to optimize QA for infrastructure projects and the cost of QA efforts, cost of nonconformance, and probability of non-conformance are quantified for the first time. The resulting models demonstrate a new approach to CoQ optimization for the lifecycle of an infrastructure system.

MODEL DEVELOPMENT

A model was created by adapting Kirkpatrick's theory of CoQ optimization (Kirkpatrick 1970), including fixed increments from Veen (Veen 1974), and choosing variables proposed by Washington State DOT (Baker et al. 2010). Figure shows a theoretical example of the optimization model employed where:

- The "y" axis shows the percentage of the material cost and "x" axis presents the QA levels of effort (i.e., techniques applied to prevent non-conformance and to ensure expected lifecycle performance).
- Expected value (EV) of non-conformance, measured as the product of the probability of non-conformance and the impact of failure as a percentage of material cost.
- Cost of QA defined as the cost of performing a certain discrete levels of QA effort as a percentage of the material cost.
- Cost of Quality (CoQ) is the sum of the EV of non-conformance and the Cost of QA.

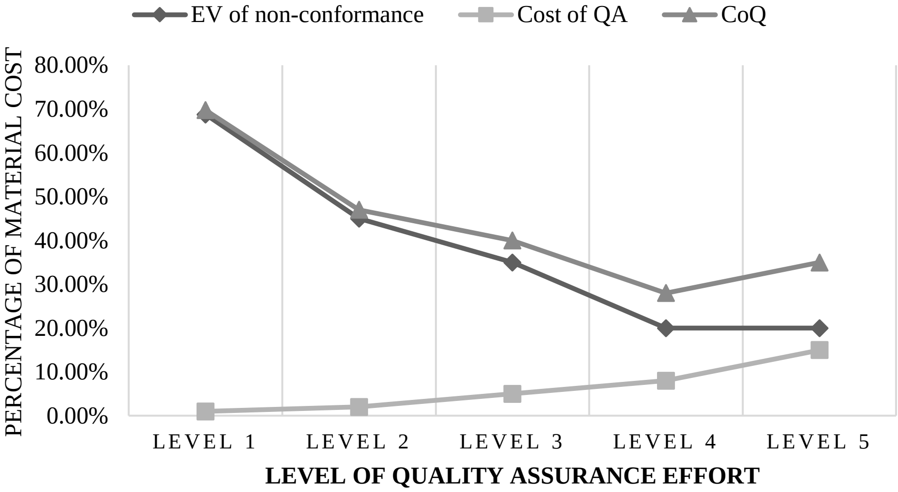

Figure III-II – Theoretical Cost of Quality (COQ) Optimization Curve for DOT Lifecycle Cost Optimization

The next section includes a description of a six-step methodology used to optimize the CoQ of hot mix asphalt (HMA) pavements from a lifecycle (i.e., DOT) perspective. The data required to optimize two different HMA material properties, four project scenarios, and five levels of QA effort are included.

RESEARCH METHODS

Risk-based optimization requires a series of data collection and analytical steps to produce the optimization curve depicted in Figure 2. A series of research steps were conducted in order to collect the contextual and quantitative data to perform a CoQ optimization. Contextual information was supplied in from Oecherl et al. (2015) and the quantitative data were obtained through a Delphi study.

Step 1: Selection of case material and properties for analysis

In order to select a material for analysis, two things should be taken into consideration: (1) the volume of data available for that specific material and (2) the importance of optimizing the material's CoQ in terms of the magnitude of its impact (i.e., criticality).

Because asphalt materials represent around 20% of the total roadway infrastructure budget, hot mix asphalt (HMA) was selected as the material of analysis for this study. About 95% of the paved roads are surfaced with asphalt and most are paved specifically with HMA (Anderson et al. 2000). To demonstrate the data collection, analysis, and optimization for asphalt we selected three of the most commonly used acceptance properties for HMA: density, asphalt content, and gradation (Hughes 2005). Although we used HMA to illustrate the CoQ lifecycle optimization methodology, we theorize that this methodology is transferrable to other materials and contexts.

Step 2: Assess project factors

DOTs change their QA approach depending on the characteristics of the project (Oechler et al. 2015). Unfortunately, there is no formal approach to determine the impact of project factors on QA optimization or to assess whether QA efforts are focused on the most important activities or materials (Mostafavi and Abraham

2012). Therefore, in order to properly characterize the risk of material nonconformance, a variety of project factors must be specified (Chapman 2001). Although there are many factors that may impact the risk and costs of QA, the following are consistently highlighted in literature (Oechler, et al 2015):

1. Industry experience: The confidence or reliability an owner has on the contractor and/or supplier.
2. Total material quantity: the planned quantity or volume of material to be used in a specific project.
3. Project delivery method: The system used by the owner for organizing and financing design, construction, operation, and maintenance services for this project.
4. Criticality: A project's size, location, complexity, or other factors that vary the impact of the project's performance either during construction or operation.

A dichotomous two-option method was selected for characterizing industry experience, material quantity, and criticality factors. Specifically, a score of low/high or small/large was used to define the factors for the case examples. For delivery strategy, Design Bid Build (DBB) or Design, Build, Operate, and Maintain (DBOM) were used as options. Although this was not a comprehensive manner of characterizing all potential projects, these characteristics are adequate to demonstrate the CoQ optimization methodology. Scenarios were created by exploring different combinations of these factors.

Even though there are 16 possible scenarios emanating from these four factors, scenarios that were not common (e.g. material with low criticality but high material quantity) or that were already reflected by another scenario (e.g., high industry experience and highly critical project is functionally similar to high industry experience and a large quantity project) were not modelled. The number of scenarios explored was limited because exponentially more data are needed to explore each additional scenario. In total, we collected data for the four scenarios in Table 1. The goal was to include scenarios that show both typical and extreme conditions of the model. The first scenario, which served as the benchmark, assumes high industry experience, high material quantities, a design-bid-build project delivery method, and a highly critical project.

Table III-I - Scenarios

	Scenario			
Factors	**1**	**2**	**3**	**4**
Industry Experience	High	Low	High	High
Material Quantity	Large	Large	Small	Large
Project delivery method	DBB	DBB	DBB	DBOM
Criticality/ Complexity	High	High	Low	High

Step 3: Define levels of quality assurance effort

A requisite component of the CoQ optimization model are the various levels of effort of QA (i.e., the x-axis of Figure 2). This QA effort is defined by the quantity of resources that an owner invests to monitor the material's conformance to the specifications as a percentage of material cost, which can range from 1% to 20%. It was assumed that more stringent controls correspond to higher effort and costs but lower risk of material failure.

The investment in QA is not continuous as Figure 1 would suggest. Rather, levels of effort fit into discrete categories or tiered approach. Based upon the tier approaches from various agencies (Baker et al. 2010, Oechler et al. 2015), the most common levels of QA effort were modeled. In total, we identified five discrete levels of QA effort for HMA that are commonly implemented in US DOTs and discussed in literature. These are summarized in Table 2***Table III-II. Levels of QA effort*** . For context, this table delineates the contractor and owner or DOT's responsibilities for each level. In subsequent analyses, these levels of effort were used as dependent variables and compared risk and QA costs between different project scenarios.

Table III-II. Levels of QA effort

QA Level	Description	Owner/DOT	Contractor/Vendor
Level 1	Visual Inspection	Visually inspects manufacture Visually inspects placement	Ensures fulfillment of contract requirements by internally controlling processes.
Level 2	Certification	Verify that certification complies with specification requirements.	Certifies materials and installation meet specifications Performs testing and maintain data to support certification
Level 3	Certification with backup data attached	Verification of data (audit certification data for compliance including option to perform additional tests)	Performs testing and submits backup data to support certification (i.e. mill test or other tests attached to certification)
Level 4	Reliance on contractor data for acceptance with DOT verification	Tests material on a reduced frequency and compares it to the contractor's results. Also responsible for IA.	Performs sampling and testing and provides results to owner
Level 5	Sampling and testing performed by DOTgency	Performs sampling and testing and accepts materials using their results. Also responsible for IA.	Ensures fulfillment of contract requirements by internally controlling processes.
Note: Inspection happens at all levels			

Step 4: Collect requisite data for model building

The data required for a risk-based QA optimization include the following: the cost of each level of QA effort, the probability of a non-conforming material at each level of QA effort, and the cost impact of a non-conforming material. These data are needed for each scenario in Table 1. Since these data are not available in existing literature and are not collected empirically by DOTs, the Delphi approach was used to collect all quantitative data. Because the value of currency fluctuated regularly, all costs were defined in terms as a percent of the material's total in-place cost. Additionally, the probability of a non-conforming material was estimated as the chance a material would not conform to specifications for each level of QA effort.

Data collection via the Delphi process

Research shows that Delphi is useful when the judgment of individuals must be combined to address an incomplete state of knowledge (Delbecq et al. 1975; Hallowell and Gambatese 2009). As was the case in this study, Delphi is also particularly useful when the research problem does not lend itself to precise analytical techniques but can benefit from subjective judgments on a collective basis; the individuals needed to contribute to the examination of a broad or complex problem have no history of adequate communication and may represent diverse backgrounds; time and cost constraints make frequent group meetings infeasible; more individuals are needed than can effectively interact in a face-to-face meeting; the heterogeneity of the participants must be preserved to assure the validity of the results (Linstone and Turoff 2002; Chapman 1998).

Expertise requirements

The success of a Delphi study largely rests on the combined expertise of the participants who constitute the expert panel (Powell 2003) and the extent to which cognitive biases are controlled or eliminated (Hallowell and Gambatese 2009). Panels must also have a sufficient size to ensure that the results are not biased by a particular participant's experience. A recommendation for panel size is five to 20 experts with diverse knowledge (Rowe and Wright 2001), which varies according to the scope of the problem and the resources available (Delbecq et al. 1975; Hallowell and Gambatese 2009). However, the collective expertise of the panel is far more important than the number of participants.

To select the expert panel participants were required to have more than 5 years of experience in HMA QA and at least 7 years of experience working for a DOT. Academic qualifications and professional registrations were not desired for this panel. A total of 8 experts participated on the Delphi panel, with an *average* of 30 years of experience each.

Number of survey rounds

Another important aspect of the Delphi technique is the number of survey rounds included in the data collection process. The iterative nature of the procedure generates new information for panelists in each round, allowing them to modify their assessments and project them beyond their own subjective opinions. It can represent the best forecast available from a consensus of experts (Corotis et al. 1981). Typically, three rounds of surveys are sent to a pre-selected expert panel, although the decision over the number of rounds is largely pragmatic (Hallowell and Gambatese 2009). The Delphi method requires a minimum of two rounds beyond which the number of rounds is disputed. In order to reduce variance in responses and improve the precision we conducted three survey rounds to reach consensus on questions related to materials QA.

For rounds two and three the experts were provided the median values from the previous rounds, comments from other panel members, and their own prior response. When providing data in subsequent rounds, participants were given the option to maintain their response from the prior round or change their response in light of the new information. In both cases, the participants were asked to explain their rational for either changing or maintaining their estimates.

Data collection instrument

In order to collect data from the panel, a survey tool was developed using Google Sheets, a web-based spreadsheet application, which allowed all panelists to enter their responses into the same document. The real-time anonymous collaboration feature streamlined and expedited the collection and processing of the expert opinions. With this tool, the moderator gained instant feedback on the expert's responses and streamlines the iterative process. Use of Google Sheets significantly reduced the overall data entry and lag time between rounds and allowed for anonymity while obtaining real-time responses.

Minimizing bias

As suggested by Hallowell and Gambatese (2009), a series of controls were implemented to minimize the potential effect of judgment bias. For example, results are reported as medians to reduce the impact of outliers who may be biased by recent or extreme past experiences. Also, experts remained anonymous to eliminate dominance bias and experts were asked to provide reasons for changing their responses to avoid the bandwagon effect and to reduce tendency toward conformity. These collective methods helped to reduce the potential for systematic errors in expert ratings.

Data obtained

The Delphi participants were asked to provide ratings of the following variables for each scenario:

- <u>Cost of QA</u> for each level of QA effort, each material property, and each scenario. In total, this involved 60 ratings per expert per round (i.e., 5 levels of QA effort x 4 scenarios x 3 material properties = 60 ratings).

- Probability of nonconformance for each level of QA effort, each material property, and each scenario. In total, this variable also required 60 ratings per expert per round.
- Cost of nonconformance for each material property and each scenario, requiring 12 ratings per expert per round. This variable required fewer ratings because the assumption in the model is that the cost of nonconformance is unaffected by the levels of QA. That is, the probability of nonconformance is affected by the levels of QA effort but the cost is not.

Step 5: Quantify Risk

Once the data were collected, the expected value of the risk of nonconformance was computed for each level of QA effort and for each scenario. The expected value of QA risk was quantified as the product of the probability of nonconformance and the cost of nonconformance (see equation 1). Since probability is unit-less, expected value is expressed as a percentage of material cost.

$$EV = I \times PNC \qquad \text{Equation 1}$$

Where, EV = Expected value of failure as a percentage of material cost (%); I = Impact of rework of material nonconformance measured as a percentage of material cost (%); PNC = Probability of nonconformance (%)

Step 6: Optimize the Cost of Quality

In order to optimize CoQ as shown in Figure 2, the cost of QA effort was added to the expected value of nonconforming materials. In essence, this is the sum of all costs related to reducing the probability of nonconformance and the risk of material nonconformance. This was done for every property, every level of QA effort, and all scenarios. For each property we were able to find the minimum CoQ for a given project scenario. The level of QA effort represents the independent variable in the lifecycle CoQ optimization. The goal is always to identify the level of QA effort that minimizes the total CoQ.

RESULTS

The raw median ratings provided by the Delphi experts are shown in Table 3. These are the critical data for the optimization. The first row includes the three properties (density, asphalt content, and gradation) followed by the four scenarios that correspond to Table 1 (S-1, S-2, S-3, and S-4). The table is organized into the three sections, corresponding to each optimization parameter of interest (probability of non-conforming material, cost of QA, and the impact of a non-conforming material or cost of rework). Note in Table 3 that the costs of nonconformance are over 100% because the total costs exceed the original budgeted cost, as expected.

The ratings provided by the experts in the first round were highly variable. This is potentially due to the fact that empirical data are not systematically collected by DOTs and are not published. Thus, the values are dependent only on the expert's past experiences. Fortunately, in subsequent rounds, the variability decreased significantly. Nevertheless, variability remained relatively high. Thus, the true values in Table 3 are likely to be within the range of +/- 5% of the reported values.

Although there was strong change in estimates between rounds one and two, there was negligible change in participant responses between rounds two and three. Although consensus was not achieved, stability in the ratings was observed after round three and the Delphi process was ended. Table 4 shows the standard deviation of the expert responses in each round for asphalt density. For brevity, we do not report the values for all three material properties; however, the results for the other material properties followed the same patterns in variability.

Table III-III - Delphi results for optimization parameters

	Asphalt Density				**Asphalt Content**				**Gradation**			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
	Probability of a non-conforming material											
Level 1	65%	80%	65%	63%	65%	83%	65%	65%	65%	83%	65%	65%
Level 2	48%	58%	50%	45%	50%	65%	53%	45%	50%	63%	55%	53%
Level 3	43%	50%	43%	40%	45%	55%	45%	40%	40%	50%	40%	38%
Level 4	23%	30%	23%	18%	18%	23%	20%	14%	20%	28%	20%	18%
Level 5	10%	18%	10%	10%	10%	15%	10%	9%	10%	18%	10%	10%
	Cost of QA											
Level 1	1%	1%	4%	1%	2%	1%	4%	1%	2%	2%	4%	2%
Level 2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Level 3	2%	4%	3%	3%	2%	4%	3%	3%	2%	4%	3%	3%
Level 4	4%	5%	5%	4%	4%	5%	5%	4%	5%	5%	5%	4%
Level 5	6%	6%	7%	7%	6%	6%	7%	7%	7%	6%	7%	7%
	Impact of a non-conforming material											
Rework	118%	115%	113%	110%	125%	123%	118%	113%	110%	110%	110%	110%

S-1=Scenario 1; S-2=Scenario 2; S-3=Scenario 3; and S-4 Scenario 4

Table III-IV - Standard deviation for three rounds for asphalt density

Scenario 1				**Scenario 2**				**Scenario 3**				**Scenario 4**			
Level	**R-1**	**R-2**	**R-3**		**R-1**	**R-2**	**R-3**		**R-1**	**R-2**	**R-3**		**R-1**	**R-2**	**R-3**
Probability of a non-conforming material															
1	21%	21%	18%	**1**	24%	14%	13%	**1**	27%	21%	19%	**1**	22%	19%	16%
2	28%	26%	22%	**2**	29%	20%	19%	**2**	30%	23%	20%	**2**	32%	26%	23%
3	25%	22%	16%	**3**	29%	20%	17%	**3**	24%	20%	17%	**3**	27%	23%	20%
4	16%	16%	15%	**4**	28%	15%	15%	**4**	21%	14%	14%	**4**	14%	13%	13%
5	5%	4%	4%	**5**	13%	6%	6%	**5**	7%	8%	8%	**5**	7%	5%	6%
Cost of QA															
1	4%	3%	3%	**1**	4%	3%	3%	**1**	4%	3%	3%	**1**	5%	3%	3%
2	5%	3%	3%	**2**	5%	3%	3%	**2**	5%	3%	3%	**2**	5%	3%	3%
3	5%	3%	3%	**3**	5%	3%	3%	**3**	5%	3%	3%	**3**	5%	3%	3%
4	5%	4%	4%	**4**	5%	4%	4%	**4**	5%	4%	4%	**4**	5%	4%	4%
5	6%	3%	3%	**5**	15%	8%	8%	**5**	6%	5%	5%	**5**	6%	3%	3%
Impact of a non-conforming material															
	17%	17%	16%		21%	16%	14%		15%	15%	14%		14%	14%	14%

R-1=Round 1;R-2=Round 2; and R-3=Round 3

OPTIMIZATION RESULTS

The aim was to optimize total CoQ, which was computed by summing the expected value of non-conforming materials and the cost of QA. Since both values were measured as percentage of material cost, no data transformations were required. Consistent with past models (e.g., Kirkpatrick 1970), as DOTs increase QA effort the cost of QA increases and the expected value of non-conformance decreases.

Since 12 optimization curves were created (3 material properties x 4 scenarios), for brevity we highlight a representative curve in Figure 3. This figure shows a complete CoQ optimization for HMA density under scenario 4, including the constituent elements of the CoQ optimization. As one can see, the optimal investment point, corresponding to the minimal CoQ, occurs at Level 5 (sampling and testing performed by the DOT). A comparison of the optimization curves for all materials and scenarios reveals that project factors do affect the parameters but, interestingly, do not change the optimal choice (maximum QA effort). Figures 4 and 5 show comparisons for all 4 project scenarios for HMA density and asphalt content, respectively. To enable visual inspection these figures do not include these constituent variables.

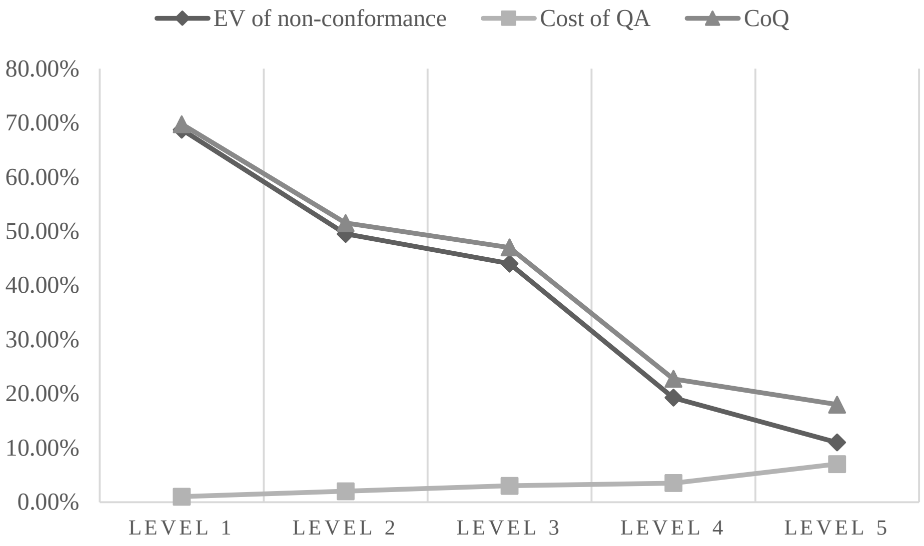

Figure III-III: Cost of Quality optimization for HMA density in Scenario 4

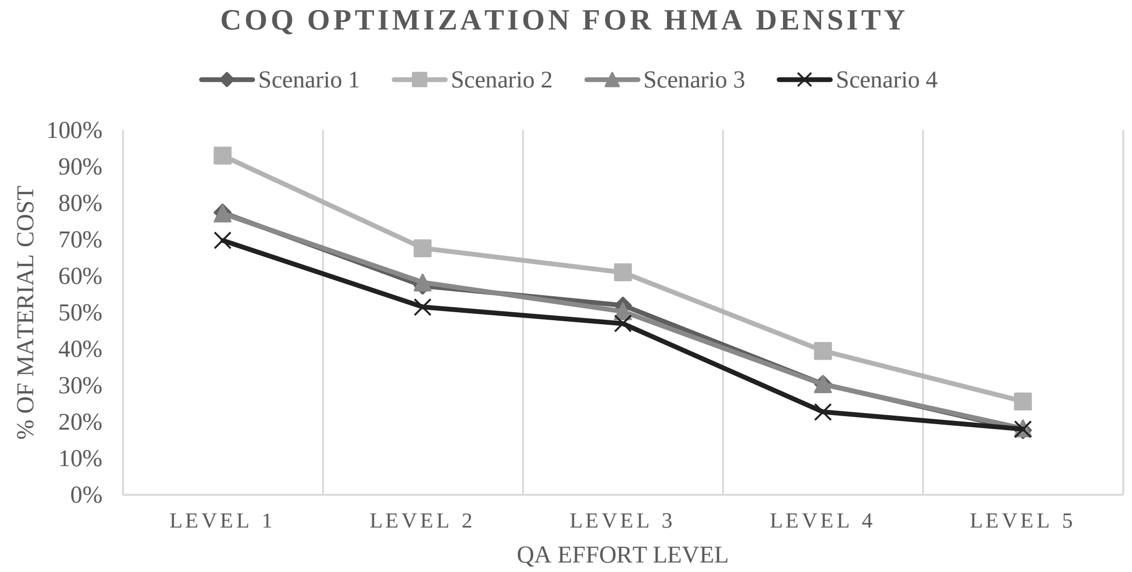

Figure III-IV: CoQ optimization for HMA density

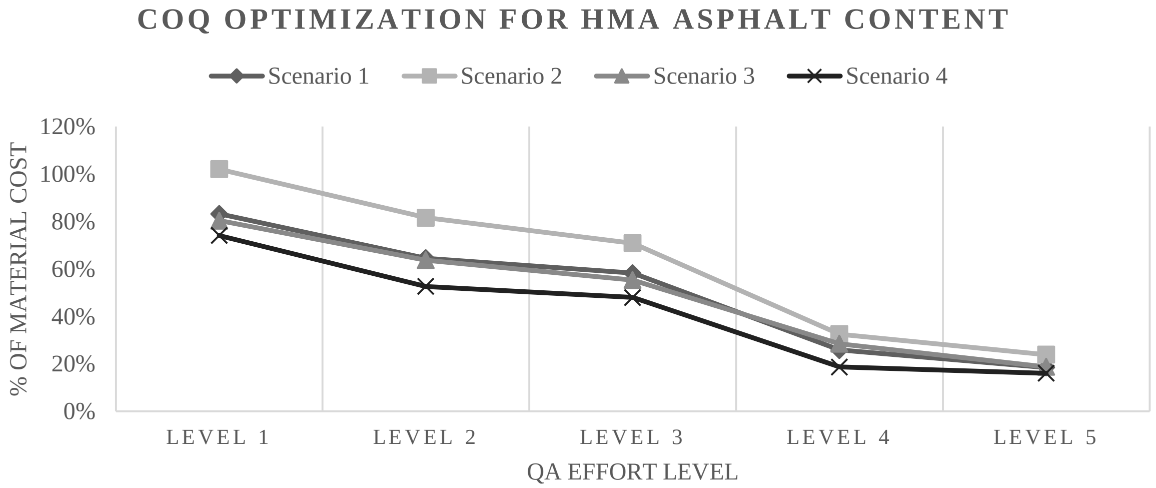

Figure III-V: CoQ optimization for HMA asphalt content

ANALYSIS AND DISCUSSION OF OPTIMIZATION RESULTS

The following discussion highlights interesting findings from the optimization results along with a discussion of the implications of these observations.

Optimization points were consistent across all materials and project scenarios. Perhaps the most surprising result was that all scenarios and all material properties returned the same optimal level of QA effort. Specifically, the lowest total CoQ was observed at the point of greatest QA effort for all cases. This investment point corresponds to the point of maximum risk mitigation and maximum QA expenditure. This finding has strong implications. The first implication is that DOTs should not rely solely on less sophisticated methods of QA such as visual inspection and reliance on contractor-supplied data, even for simple and small projects. These methods may be part of a more comprehensive program but, according to the optimization results, would not yield optimal CoQ. In all cases, the optimization suggests that additional resources should be expended for QA effort to balance the significant risk of material nonconformance. The second implication is that new levels of QA effort may be warranted that involve more frequent or more sophisticated testing. Without observing an inflection in the CoQ curve (i.e., the point where CoQ begins to rise as higher levels of QA effort are implemented), it is not possible to identify if new methods are warranted.

Scenario 2 was consistently shown to have the highest CoQ and Scenario 4 the lowest CoQ for all five levels of QA effort and for all properties. The results also indicate that contractor experience had an important impact on the probability of a material conformance to specification. Alternatively, Scenario 4, where the contractor is responsible for long-term quality (i.e., DBOM delivery method), had the lowest CoQ from the DOT perspective. Interestingly, one can infer that a DOTs can affect their CoQ by considering QA implications in the selection of the delivery method and contractors.

Experts returned similar risk perception across different material properties. When designing this study, the authors expected to observe significant differences in the risks of nonconformance across the project scenarios. However, an analysis of variance (ANOVA) test across the project scenarios revealed no statistically significant differences. A similar test to measure differences among material properties revealed that HMA gradation is less critical than density and asphalt content in terms of the cost of nonconformance ($p<0.05$). This finding is consistent with recent research that has found that density and asphalt content predict HMA pavement performance better than gradation (del Pilar Vivar and Haddock 2006; Prowell et al. 2005).

The costs of QA were stable across project scenarios for all levels of QA effort except for Level 5. The estimated costs of QA were mostly stable across the project scenarios. Although an ANOVA test revealed no statistically significant differences in the cost estimates for scenarios 1 to 4, there were comparatively large differences in cost of QA for level 5 (Sampling and testing performed by the DOT). This means that changing the characteristics of a project would have major impacts on the cost of QA when QA is performed fully by the DOT.

All expected assumptions of optimization behavior were confirmed. As discussed previously, we assumed that, as the levels of QA effort increased, the costs of QA increased and the probability of nonconformance decreased. We did not impose any restrictions or controls for these assumptions (i.e., experts were not informed of these assumptions and were free to enter data that refuted these assumptions). Still, the expert data confirmed the assumptions as can be seen in Figure 3. This finding is important to the overall validity of the risk-based cost optimization theory.

CONCLUSIONS

The purpose of this research was to develop a framework to optimize the lifecycle CoQ for a DOT using a risk-based model. A lifecycle approach was adopted because DOTs must pay for the quality-related efforts that occur prior to and during construction and pay for rework or reconstruction when a material fails during service. Prior research has focused on QA for contractors but no previous studies employed a risk-based approach nor focused on the DOT perspective.

When building the optimization model, the levels of QA effort and the project characteristics that affect QA processes were identified via a literature review. Additionally, a material (hot mix asphalt) and three properties (density, gradation, and asphalt content) were selected as case examples. Once the context was established, data were collected for following optimization parameters: costs of each level of QA effort, probability of nonconformance for each level of QA effort, and the cost of nonconformance. The, these data were assembled into a CoQ optimization curve to establish the level of QA effort that minimizes CoQ.

The process revealed that the model structure is sound and that the theoretical modeling techniques originating in economics (e.g., Kirkpartick 1974) have practical application to infrastructure construction. The Delphi process returned interesting and unexpected results. First, for all project scenarios and all material properties, CoQ was optimized when the highest level of QA was selected. This means that future research and development may be warranted to explore more sophisticated and more costly methods of QA that further reduce the probability of nonconformance. Additionally, it appears as though the risks of nonconformance and the costs of QA were both stable across project scenarios, indicating that the type of project (e.g., size, complexity, delivery method, and contractor experience) has surprisingly little effect on the optimal QA approach. These joint findings indicate that DOTs may wish to consider more sophisticated QA approaches, even for smaller and less complex projects.

This study is not without its limitations. Perhaps most significant is the lack of available empirical data to perform the desired optimization. Although the underlying theory of risk-based lifecycle cost optimization remains sound, the input data drive the quality of the resulting optimizations and assessments. With no empirical data, a Delphi process was used as an alternative. Delphi offered a feasible approach to collect necessary data but is subject to the judgment-based biases of the experts. Various controls were taken in the design of the Delphi process; however, not all bias can be eliminated. Thus, the reader is cautioned that the values reported in this paper are likely to be within a reasonable range of actual values but are not necessarily precise. Future confirmatory research is suggested to validate the costs of QA, probability of nonconformance, and cost of nonconformance values. Further, DOTs are urged to begin collecting and tracking such data for future optimization needs.

A systematic bias that may have affected the results was the inclusion of experts who work for state DOTs. In particular, there may be a bias related to the estimations of the probability of nonconformance. Specifically, an “effect of a hidden agenda” (Mosleh et al. 1998) may have occurred towards increasing the probability of non-conformance if the DOT is not the one performing the sampling and testing. Unfortunately, there was no way to control for this bias and experts from DOTs were critical for the estimation of the costs of QA efforts and costs of nonconformance. No other professionals are capable of making such estimates. Again, validation of these findings with empirical data is essential.

REFERENCES

Abdul-Rahman, H. (1995). “The cost of non-conformance during a highway project: a case study.” Construction Management and Economics, 13, 23–32.

Anderson, D., Youtcheff, J., and Zupanick, M. (2000). “Asphalt Binders.” A2D01: Committee on Characteristics of Bituminous Materials Transportation in the New Millennium, Transportation Research Board of National Academies, Washington D.C.

Aoieong, R. T., Tang, S. L., and Ahmed, S. M. (2002). “A process approach in measuring quality costs of construction projects: model development.” Construction Management and Economics, 20(2), 179–192.

Ashley, D. B., Diekmann, J. E., Molenaar, K. R. and American Trade Initiatives Inc. (2006). “Guide to Risk Assessment and Allocation for Highway Construction Management.” Publication No. FHWA-PL-06-032, U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Baker, T. E., Molohon, R. J., and McIntyre, R. W. (2010). “Materials Risk Analysis.” WA-RD 745.1, Washington State Department of Transportation Research Report, WSDOT Office of Research & Library Services, Olympia, WA.

California Department of Transportation. (2007). “Project Risk Management Handbook: Threats and Opportunities” Second Edition, Office of Statewide Project Management Improvement Sacramento, CA.

Chapman, R. J. (1998). “The effectiveness of working group risk identification and assessment techniques.” International Journal of Project Management, 16(6), 333–343.

Chapman, R. J. (2001). “The controlling influences on effective risk identification and assessment for construction design management.” International Journal of Project Management, 19(3), 147 – 160.

Corotis, R. B., Harris, J. C., and Fox, R. R. (1981). “Delphi methods: theory and design load application.” Journal of the Structural Division, 107(6), 1095–1105.

Davis, K., Ledbetter, W. B., and Burati, J. L. (1989). “Measuring design and construction quality costs.” Journal of Construction Engineering and management, 115(3), 385–400.

Delbecq, A. L., Van de Ven, A. H., and Gustafson, D. H. (1975). “Group techniques for program planning: A guide to nominal group and Delphi processes.” Scott, Foresman Glenview, IL.

Federal Highway Administration. (2004). “Technical Advisories Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks.” Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks, <http://www.fhwa.dot.gov/construction/t61203.cfm> (Mar. 25, 2015).

Federal Highway Administration. (2013). “Quality Assurance Stewardship Review Summary Report for Fiscal Years 2009 through 2012.” U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Federal Transit Administration, and Urban Engineers. (2012). “Quality Management System Guidelines” FTA-PA-27-5194-12.1 U.S. Department of Transportation Federal Transit Administration, Washington, D.C.

Goulias, D., and Sahand, K. (2013). “Material Quality Assurance Risk Assessment.” Project No. SP909B4K, Maryland State Highway Administration Baltimore, MD.

Hallowell, M. R., and Gambatese, J. A. (2009). “Qualitative research: Application of the Delphi method to CEM research.” Journal of construction engineering and management, 136(1), 99–107.

Hughes, C. S. (2005). “NCHRP Synthesis 346: State construction quality assurance programs: A Synthesis of Highway Practice” Transportation Research Board of National Academies, Washington, D.C.

Hylton Meier, H. (1991). “A Control Model for Assessing Quality Costs.” Mid-American Journal of Business, 6(1), 40–44.

Kirkpatrick, E. G. (1970). Quality Control for Managers and Engineers. John Wiley & Sons, Inc. USA.

Kraft, E., and Molenaar, K. R. (2014). “Quality Assurance Organization Selection Factors for Highway Design and Construction Projects.” Journal of Management in Engineering, 04014069-1 to 04014069-9.

Linstone, H. A., and Turoff, M. (2002). “The Delphi Method: Techniques and applications.” ISBN 0-201-04294-0 Addison-Wesley Educational Publishers Inc; First Edition p53.

Love, P. E. D., and Sing, C.-P. (2013). “Determining the probability distribution of rework costs in construction and engineering projects.” Structure and Infrastructure Engineering, 9(11), 1136–1148.

Molenaar, K., Gransberg, D., and Datin, J. (2008). “NCHRP Synthesis 376: Quality Assurance in Design-Build Projects.” National Cooperative Highway Research Program, Transportation Research Board of National Academies, Washington D.C.

Morse, W. J. (1993). “Morse, A Handle on quality costs.pdf.” CMA Magazine, 67(1), 21.

Mosleh, A., Bier, V. M., and Apostolakis, G. (1998). “A Critique of current practice for the use of expert opinions in probabilistic risk assessment.” Reliability Engineering and System Safety, 20, 63–85.

Mostafavi, A., and Abraham, D. (2012). “INDOT Construction Inspection Priorities.” Publication FHWA/IN/JTRP-2012/09, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN.

Murphy, T. R., Taccola, L. J., and Murphyao, A. (2011). “Proceedings of the Material Quality Testing Risk Assessment and Multi-State Peer Exchange Meeting.” Illinois Center for Transportation, Springfield, IL.

Pheng Low, S., and Yeo, H. K. C. (1998). “A construction quality costs quantifying system for the building industry.” International Journal of Quality & Reliability Management, 15(3), 329–349.

Del Pilar Vivar, E., and Haddock, J. E. (2006). “HMA Pavement Performance and Durability.” FHWA/IN/JTRP-2005/14, Joint Transportation Research Program, Indiana Department of Transportation and U.S. Department of Transportation Federal Highway Administration, West Lafayette, IN.

Plunkett, J. J., and Dale, B. G. (1988). “Quality costs: a critique of some ‘economic cost of quality’ models.” International Journal of Production Research, 26(11), 1713.

Powell, C. (2003). “The Delphi technique: myths and realities.” Journal of advanced nursing, 41(4), 376–382.

Prowell, B. D., Zhang, J., and Brown, E. R. (2005). Aggregate properties and the performance of Superpave-designed hot mix asphalt. NCHRP report, Transportation Research Board, Washington, D.C.

Rowe, G., and Wright, G. (2001). “Expert opinions in forecasting: the role of the Delphi technique.” Principles of forecasting, Ed. J.S. Armstong, Springer, 125–144.

Schiffauerova, A., and Thomson, V. (2006). “A review of research on cost of quality models and best practices.” International Journal of Quality & Reliability Management, 23(6), 647–669.

Texas Department of Transportation. (2008). "Quality Assurance Program for Design-Build Projects with an Optional 15-Year Capital Maintenance Agreement." Texas Department of Transportation, Austin, TX.

Texas Department of Transportation. (2011). "TxDOT Design-Build Quality Assurance Program- Implementation Guide." Texas Department of Transportation, Austin, TX

Transportation Research Board Management of Quality Assurance Committee. (2005). "Transportation Research Circular Number E-C074: Glossary of Highway Quality Assurance Terms." Third Update, Transportation Research Board of National Academies, Washington, D.C.

Veen, B. (1974). "Quality Costs." Proceeding of the second Eurpean Organization for Quality Control, EOQC, pages 55–59.

Chapter IV. Conclusions

Research questions

This study answered the three research questions stated in Chapter 1. The answers below are a summary of the detailed findings from Chapters 2 and 3.

- How can we optimize QA investment with a risk-based approach?

We developed a framework and a computer-based tool that can be used to optimize a DOT's approach to materials QA. The framework helps adjust QA resource allocation by relating a certain QA approach to a risk of non-conformance. It will aid DOTs to better understanding of the relationship between QA effort and the risk of non-conforming materials, therefore facilitating resource allocation decisions for QA approaches. This framework can be used in combination with other risk based optimization methods currently applied by Washington's (Baker, et al, 2010), Texas' (Texas Department of Transportation, 2010), and New York's DOTs (New York State Department of Transportation, 2005).

- What factors influence DOT QA approach?

Four factors, industry experience, material quantity, criticality and complexity, and project delivery method did have a consistent impact on the DOTs' QA approach.

In Chapter 3 we went further and used scenarios to explore the level of impact of each factor in the total cost of quality. We found that by changing the characteristics within those factors can help DOTs' resource allocation in materials

QA. For example, by changing the project's delivery method towards a private-public partnership, in which the contractor or supplier is responsible for the highway for more than 15 years, the total cost of quality for a project can be potential reduced by 20% to 70% as compared to a project with an uncertified contractor and a traditional design-bid-build delivery method.

- How does QA spending impact the cost of quality?

For HMA, we found an inverse relationship between the resources allocated by DOTs and the expected total cost of quality. The risk of removing and replacing a material that is not conforming to specifications proved to be higher than pursuing the highest level of QA effort. For example, currently state DOTs are trying to cut spending and QA has been one important target but the results show that actually in order to save money in the long term, DOTs should continue allocating resources in QA. This result is specific of HMA and would probably vary in some way among different materials as discussed in future research section.

Limitations

Chapter III focuses on HMA and should not be extrapolated to other materials because of the nature of the material's production variability and the specific properties we asked experts to assess. Other materials that are either plant produced or standard manufactured might have a completely different behavior.

Even other project produced materials have different levels of predictability and process controls.

Another limitation of this research was the number of experts that participated in the Delphi process. Additional experts could potentially provide more accurate results or more knowledge in their answers. The experts' capacity to express the problem solution in terms of probabilities was also an issue. For example, when experts thought of a situation that had a great impact on CoQ, they may have biased the probability of it happening and therefore magnifying the risk. On top of that, our methodology asked experts to assess the impact of a worst-case scenario in which a material had to be removed and replaced. As a consequence we had very high risks of failure and low cost of QA effort.

The Delphi methodology intends to drive experts towards consensus. However in this research, two experts maintained their answers throughout the process regardless of what their peers said. A larger number of experts might have had minimized the impact of outliers in the results.

Applications

The methodology developed in this research process has plenty of room for application whenever there is need to optimize resource allocation in quality, safety, or any investment made in order to reduce the probability of an outcome. This framework can be used to aid decision making where the outcome of the investment has to be understood through a life cycle point of view.

As previously stated in the limitations section, this research focused on optimizing DOT QA approach for HMA. Applying the same framework to a variety of materials or even to a different industry would shed light on the model's validity and applicability.

Further research

One limitation of this research was the number of experts that participated in the Delphi process. To have a more robust HMA optimization model, a subsequent Delphi could be run. This could help identify if the number of experts, their background or bias, had an impact in the results of the research. Many of the limitations of this research could be avoided if the framework presented on Chapter III was applied to a different set of experts.

Further research could include understanding the impact of the expert's capacity to accurately express in terms of probability. Some experts would change the probability of the event occurring if the impact was catastrophic. Within the Dephi process further research is needed to correct those deviations. Researchers could profit from understanding the experts optimistic or pessimistic bias beforehand in order to correct their probability assessments.

Other materials and other kinds of projects could help validate and understand the behavior of the total cost of quality as the QA effort varies. This further research should use the same steps shown in this framework. Empirical data should be favored if available, but any indirect method such as the Delphi used in Chapter III can be used as well.

Finally, the next step in this research would be to validate the model with empirical data. Now that the inputs needed to populate the model are clear, we know which data to start collecting. After collecting enough HMA data we could verify if the model behaves similarly as the actual projects.

Bibliography

Abdul-Rahman, H. (1995). “The cost of non-conformance during a highway project: a case study.” Construction Management and Economics, 13, 23–32.

Anderson, S. D., and Russell, J. S. (2001). “NCHRP Report 451: Guidelines for Warranty, Multi-Parameter, and Best Value Contracting.” National Cooperative Highway Research Program, National Academy Press Washington D.C.

Anderson, D., Youtcheff, J., and Zupanick, M. (2000). “Asphalt Binders.” A2D01: Committee on Characteristics of Bituminous Materials Transportation in the New Millennium, Transportation Research Board of National Academies, Washington D.C.

Aoieong, R. T., Tang, S. L., and Ahmed, S. M. (2002). “A process approach in measuring quality costs of construction projects: model development.” Construction Management and Economics, 20(2), 179–192.

Arizona Department of Transportation. (2005). “Construction Manual - Chapter 10 Materials.” Arizona Department of Transportation, Phoenix, AZ.

Ashley, D. B., Diekmann, J. E., Molenaar, K. R. and American Trade Initiatives Inc. (2006). “Guide to Risk Assessment and Allocation for Highway Construction Management.” Publication No. FHWA-PL-06-032, U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Baker, T. E., Molohon, R. J., and McIntyre, R. W. (2010). “Materials Risk Analysis.” WA-RD 745.1, Washington State Department of Transportation Research Report, WSDOT Office of Research & Library Services, Olympia, WA.

California Department of Transportation. (2007). “Project Risk Management Handbook: Threats and Opportunities” Second Edition, Office of Statewide Project Management Improvement Sacramento, CA.

California Department of Transportation. (2013). “Construction Manual.” California Department of Transportation, State of California Department of Transportation Division of Construction, Sacramento, CA.

California Department of Transportation. (2015). “Chapter 2: Construction Quality Assurance Roadmap.” California Department of Transportation, Sacramento, CA.

Chapman, R. J. (1998). “The effectiveness of working group risk identification and assessment techniques.” International Journal of Project Management, 16(6), 333–343.

Chapman, R. J. (2001). “The controlling influences on effective risk identification and assessment for construction design management.” International Journal of Project Management, 19(3), 147 – 160.

Corotis, R. B., Harris, J. C., and Fox, R. R. (1981). “Delphi methods: theory and design load application.” Journal of the Structural Division, 107(6), 1095–1105.

Colorado Department of Transportation. (2015). “2015 Field Materials Manual, Quality Assurance Procedures for Construction and Materials Sampling and Testing.” Colorado Department of Transportation, Denver, CO.

Davis, K., Ledbetter, W. B., and Burati, J. L. (1989). “Measuring design and construction quality costs.” Journal of Construction Engineering and management, 115(3), 385–400.

Delbecq, A. L., Van de Ven, A. H., and Gustafson, D. H. (1975). “Group techniques for program planning: A guide to nominal group and Delphi processes.” Scott, Foresman Glenview, IL.

Federal Highway Administration. (2002). “Title 23: Code of Federal Regulations: Chapter I. Subpart B–Quality Assurance Procedures for Construction.” Electronic Code of Federal Regulations

Federal Highway Administration. (2004). “Technical Advisories Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks.” Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks, <http://www.fhwa.dot.gov/construction/t61203.cfm> (Mar. 25, 2015).

Federal Highway Administration. (2007). “Quality Assurance in Materials and Construction.” FHWA/HPC-10, Office of Professional and Corporate Development Program Improvement Team, Washington, D.C.

Federal Highway Administration. (2013). “Quality Assurance Stewardship Review Summary Report for Fiscal Years 2009 through 2012.” U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Federal Highway Administration. (2014). “Construction Quality Assurance for Design-Build Highway Projects.” FHWA-HRT-12-039, U.S. Department of Transportation Federal Highway Administration, McLean, VA.

Federal Transit Administration, and Urban Engineers. (2012). “Quality Management System Guidelines” FTA-PA-27-5194-12.1 U.S. Department of Transportation Federal Transit Administration, Washington, D.C.

Florida Department of Transportation. (2014). “I-4 Ultimate Project, Volume I – Concession Agreement” Contract # E5W13, Financial Management #432193-1-52-01, Florida Department of Transportation, Deland, FL.

Florida Department of Transportation. (2015). “FDOT: State Materials Manual.” FDOT: State Materials Manual, <http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/materialsmanual/index.shtm> (Mar. 25, 2015).

Goulias, D., and Sahand, K. (2013). “Material Quality Assurance Risk Assessment.” Project No. SP909B4K, Maryland State Highway Administration Baltimore, MD.

Gransberg, D. D., and Molenaar, K. (2004). “Analysis of Owner’s Design and Construction Quality Management Approaches in Design/Build Projects.” Journal of Management in Engineering, 20(4), 162–169.

Hallowell, M. R., and Gambatese, J. A. (2009). “Qualitative research: Application of the Delphi method to CEM research.” Journal of construction engineering and management, 136(1), 99–107.

Hughes, C. S. (2005). “NCHRP Synthesis 346: State construction quality assurance programs: A Synthesis of Highway Practice” Transportation Research Board of National Academies, Washington, D.C.

Hylton Meier, H. (1991). “A Control Model for Assessing Quality Costs.” Mid-American Journal of Business, 6(1), 40–44.

Illinois Department of Transportation. (2009). “Project Procedures Guide; Sampling Frequencies for Materials Testing and Inspection.” Illinois Department of Transportation Bureau of Materials and Physical Research, Springfield, IL.

Illinois Department of Transportation. (2012). “Standard Specifications for Road and Bridge Construction.” PRT3519235-20,000-07-2011, Illinois Department of Transportation Departmental Policies, Springfield, IL.

Kirkpatrick, E. G. (1970). Quality Control for Managers and Engineers. John Wiley & Sons, Inc. USA.

Kopac, P. (1997). “Contract Management Techniques for Improving Construction Quality.” FHWA-RD-97-067, U.S. Department of Transportation Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean VA.

Kraft, E., and Molenaar, K. R. (2014). “Quality Assurance Organization Selection Factors for Highway Design and Construction Projects.” Journal of Management in Engineering, 04014069-1 to 04014069-9.

Linstone, H. A., and Turoff, M. (2002). “The Delphi Method: Techniques and applications.” ISBN 0-201-04294-0 Addison-Wesley Educational Publishers Inc; First Edition p53.

Love, P. E. D., and Sing, C.-P. (2013). “Determining the probability distribution of rework costs in construction and engineering projects.” Structure and Infrastructure Engineering, 9(11), 1136–1148.

Molenaar, K., Gransberg, D., and Datin, J. (2008). “NCHRP Synthesis 376: Quality Assurance in Design-Build Projects.” National Cooperative Highway Research Program, Transportation Research Board of National Academies, Washington D.C.

Morse, W. J. (1993). “Morse, A Handle on quality costs.pdf.” CMA Magazine, 67(1), 21.

Mosleh, A., Bier, V. M., and Apostolakis, G. (1998). “A Critique of current practice for the use of expert opinions in probabilistic risk assessment.” Reliability Engineering and System Safety, 20, 63–85.

Mostafavi, A., and Abraham, D. (2012). “INDOT Construction Inspection Priorities.” Publication FHWA/IN/JTRP-2012/09, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN.

Murphy, T. R., Taccola, L. J., and Murphyao, A. (2011). “Proceedings of the Material Quality Testing Risk Assessment and Multi-State Peer Exchange Meeting.” Illinois Center for Transportation, Springfield, IL.

New York State Department of Transportation. (2005). “Quality Assurance Procedure for Standard Specifications, Construction and Materials Section 700-Materials and Manufacturing.” NYDOT Materials Bureau Albany, NY.

Pheng Low, S., and Yeo, H. K. C. (1998). “A construction quality costs quantifying system for the building industry.” International Journal of Quality & Reliability Management, 15(3), 329–349.

Del Pilar Vivar, E., and Haddock, J. E. (2006). “HMA Pavement Performance and Durability.” FHWA/IN/JTRP-2005/14, Joint Transportation Research Program, Indiana Department of Transportation and U.S. Department of Transportation Federal Highway Administration, West Lafayette, IN.

Plunkett, J. J., and Dale, B. G. (1988). “Quality costs: a critique of some ‘economic cost of quality’ models.” International Journal of Production Research, 26(11), 1713.

Powell, C. (2003). “The Delphi technique: myths and realities.” Journal of advanced nursing, 41(4), 376–382.

Prowell, B. D., Zhang, J., and Brown, E. R. (2005). Aggregate properties and the performance of Superpave-designed hot mix asphalt. NCHRP report, Transportation Research Board, Washington, D.C.

Rowe, G., and Wright, G. (2001). “Expert opinions in forecasting: the role of the Delphi technique.” Principles of forecasting, Ed. J.S. Armstong, Springer, 125–144.

Schiffauerova, A., and Thomson, V. (2006). “A review of research on cost of quality models and best practices.” International Journal of Quality & Reliability Management, 23(6), 647–669.

South Dakota Department of Transportation. (2008). “SDDOT Construction Manual Project Management Section Chapter 3 - Materials.” South Dakota Department of Transportation, Pierre, SD.

Texas Department of Transportation. (2008). “Quality Assurance Program for Design-Build Projects with an Optional 15-Year Capital Maintenance Agreement.” Texas Department of Transportation, Austin, TX

Texas Department of Transportation. (2010). “Guide Schedule of Sampling and Testing.” Texas Department of Transportation, Austin, TX

Texas Department of Transportation. (2011). “TxDOT Design-Build Quality Assurance Program- Implementation Guide.” Texas Department of Transportation, Austin, TX

Transportation Research Board Management of Quality Assurance Committee. (2005). “Transportation Research Circular Number E-C074: Glossary of Highway Quality Assurance Terms.” Third Update, Transportation Research Board of National Academies, Washington, D.C.

Veen, B. (1974). “Quality Costs.” Proceeding of the second Eurpean Organization for Quality Control, EOQC, pages 55–59.

Washington State Department of Transportation. (2013a). “Materials Manual.” Washington State Department of Transportation Engineering and Regional Operations State Materials Laboratory, Olympia, WA.

Washington State Department of Transportation. (2013b). “Construction Manual.” Washington State Department of Transportation Engineering and Regional Operations State Construction Office, Olympia, WA.

Wyoming Department of Transportation. (2015). “Wyoming Transportation Department Materials Testing Manual” Wyoming Department of Transportation, Cheyenne, WY.