Case Study

Risk-Managed Lifecycle Costing for Asphalt Road Construction and Maintenance Projects under Performance-Based Contracts

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Abstract: To date, few contractors have been involved in performance-based contracts (PBCs) for road construction and maintenance projects where they have to use lifecycle cost (LCC). The main drawback for using the LCC approach is the LCC assumptions used to address projects under high risk for contractors such as PBCs where the contractors are more than likely to be responsible for both the construction and maintenance of the road for a certain warranty period. This research was conducted to enhance LCC assumptions by introducing a risk management tool. Hence, the LCC will be based on more accurate and probable assumptions, and accordingly the results of the LCC estimate will be more reliable in the future for such risky projects. The research adopted a five step methodology through (1) identification of the risks, (2) quantification of the hot mix asphalt (HMA) costs through a cost breakdown structure (CBS), (3) comparative LCC calculations, (4) Monte Carlo scenario analysis, and (5) a demonstrative case study. The results of the analysis indicated that the introduction of a risk management tool can provide contractors with a better understanding of the most probable sensitive risks that they may encounter during the construction and maintenance phases with the emphasis on the ranges of risks they can take or the contingencies they need. A sample project in Colorado was estimated comparing traditional LCC estimation methods to risk-managed LCC. The risk-managed LCC showed about 2.5–6.5% increase in cost, which could be quite significant on large projects that traditionally have low profit margins, which could expose the contractors and the project to unforeseen cost overruns. **DOI: 10.1061/AJRUA6.0000888.**

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Introduction

Because performance-based contracts (PBCs) with warranties are required to be maintained for a considerably longer amount of time than any other contract, some contractors have found lifecycle cost (LCC) to be useful to address their estimates and budget concerns. The LCC is an economic assessment of a project that considers all significant costs over its economic life, expressed in terms of equivalent dollars (Kirk and Dell'Isola 1995). This is a logical tool for contractors to estimate the costs of the long-term commitment required under performance-based contracts.

Even though some contractors use LCC as a tool to predict future incurred costs and account for these risks with contingency and risk response plans, the use of LCC is limited primarily by the belief that "in some sense LCC estimates are inaccurate or based merely on guess-work" (Flanagan et al. 1987). Thus, the development of practices that address risk and uncertainty through risk management techniques will enhance the LCC. This can be done by improving the certainty of the assumptions on which the LCC is built and in turn improve the accuracy of cost estimates for construction and maintenance. Hence, under contracts of building and maintaining asphalt roadways, incorporating risk management techniques in LCC can increase a contractor's confidence by reducing the uncertainty caused by assumptions.

The purpose of this research is to develop a more accurate LCC model that uses risk management techniques to predict construction and maintenance contractor risk costs under contracts where the contractors build and maintain asphalt roadways.

The first objective of the research was to identify the most severe risks and their impact on road construction and maintenance contractors who build and maintain asphalt roadways, which was thoroughly explained, identified, and demonstrated in a previously published paper (Mehany and Guggemos 2015). The second objective encompassed in this paper is to enhance the LCC by incorporating risk management techniques to come up with risk-managed costs that will limit the chances of adverse future effects stemming from inaccurate assumptions. Finally, the impact of various assumptions will be quantified in a simple comparative case study using conventional and risk-managed LCC. The scope and application of this study is limited to the contractors for hot mix asphalt (HMA) road projects under performance-based contracts for construction and maintenance phases.

Literature Review

LCC

Lifecycle cost is a relatively new analysis tool in construction compared to other tools. It is mostly used by owners, especially in public and governmental agencies, for issues such as evaluating competing options in purchasing, forecasting costs and profits, and determining performance-cost tradeoffs (Boshoff et al. 2006). Among contractors, LCC is most often used in contracts where the contractor is responsible for building and maintaining the project

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such as performance-based contracts. The LCC is used under these types of contracts to enable contractors to consider alternatives and select options with the best value over the entire life of a project rather than focusing on initial construction costs. The resulting procurement of products that meet required and estimated lifetimes should lead to reduced maintenance budgets and greater financial stability going forward.

For road and highway projects, LCC analysis includes analyzing initial costs and discounted future costs such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs over the project lifecycle [Transportation Equity Act for the 21st Century (TEA-21 1998)]. It can help improve transportation investment decisions such as establishing funding levels, allocating resources among program areas, and prioritizing projects for selection (Walls and Smith 1998). However, the contractor use of LCC in road and highway projects is still minimal and limited to maintenance projects, primarily those with PBCs.

According to most sources, the primary barrier to wider adoption of LCC is the lack of good quality costs for use and performance data (e.g., Kirk and Dell'Isola 1995; Assaf et al. 2002). Additional limiters include management and cost problems and, as usual, the resistance to adopting any new technique. However, the main concern of many critics is that LCC is primarily based on assumptions, so the accuracy of its predictions is risky and doubtful (Flanagan et al. 1987).

LCC and Risk Management

After extensive literature review, it was clear that estimated costs for HMA performance-based contracts could be improved with the incorporation of risk management techniques into LCC. Risk management can offer a firm ground in practical application of LCC (Boussabaine and Kirkham 2003). Therefore, by including risk analysis and management in the LCC evaluation process, future costs can be analyzed using standard present worth analysis and probabilistic ranges over the asset life (Hamilton and Brink 2012)

Basically, most risk management tools and techniques that address risk and uncertainty are suited to support the decision maker with clear and comprehensive information (Flanagan et al. 1987). Accordingly, it is possible and clear that by incorporating risk management techniques, LCC can be enhanced by improving the assumptions on which it is based. This makes a risk-managed LCC approach a better tool, which is the focal point of this paper.

Methodology and Data Sources

The full research methodology adopted is a mixed "quantitative and qualitative" method (Mehany and Guggemos 2015). However, this paper's research design is solely a quantitative approach that includes: (1) the quantification of the HMA costs through a cost breakdown structure (CBS); (2) comparative LCC calculations; and (3) a correlation matrix for creating scenario analysis by drawing the correlation relationships between the different severe risks.

The research design is illustrated in the methodology framework (Fig. 1). The most severe risks as identified by Mehany and Guggemos (2015) in Fig. 2 are a major risk management input for two major components in this research. First, the most severe risks are introduced into a risk correlation matrix analysis to create the scenario analysis required as an input in the LCC model. Second, it is combined with the CBS to demonstrate the dollar value of the risk costs that will be a second input in the risk-managed LCC model. Finally, the results of the two comparative LCC models will be generated based on different inputs. The conventional LCC is solely based on the CBS, whereas the risk-managed LCC will be based on the risk-managed costs and the scenario analysis combined. The following sections illustrate the methodology and the details of every component in this research design.

HMA Construction and Maintenance Costs Using CBS

The cost breakdown structure is a breakdown of the costs of the various processes during the construction phase to come up with the most appropriate unit price. The CBS was used to identify the HMA construction and maintenance costs. In the construction phase, the costs were calculated according to the stage of construction, which is divided into four main stages: (1) material and production; (2) trucking and transportation; (3) paving; and (4) compaction. Those stage costs are totaled as a unit cost ($/ton). In the maintenance phase, the costs were mainly allocated to two different types of maintenance, crack fill, and overlay. These two maintenance techniques were selected because they are the most widely adopted by most department of transportation agencies (DOTs) and specifically Colorado Department

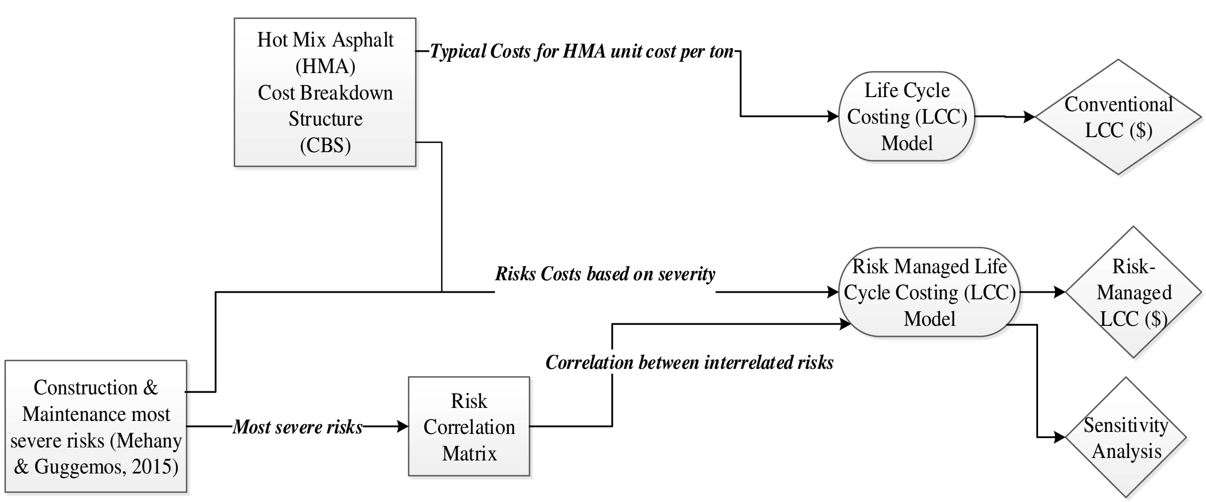

Fig. 1. Research design and methodology framework

Construction Risks	Maintenance Risks
Risk of investment in innovations	Weather changes
Prices Fluctuation	Infrastructure deterioration
Bonding Capacity	Nonporous HMA surface
Delayed Owner payments	Excess or high viscosity rejuvenators
Weather changes	Cleanness of cover aggregate
Emergency Repairs	Binder & cover aggregate. Quant. Calibration
Changing Mixes	Cleaning procedure
Voids Control	Excessive aggregate application
Long-term storage	Insufficient Compaction
Segregation at dumping	Roughness components consideration
MTV - Availability	Leveling courses overruns
Stoppage time	
Paving Speed	
Screed Adjustments	
% of crushed Aggregate Mass	
Compaction Speed	
Distance to Paver	
"Go/no go" Approach	

Fig. 2. Most severe risks in construction and maintenance phases (reprinted from Mehany and Guggemos 2015, reprinted by permission of the Associated Schools of Construction, http://www.ascjournal.ascweb.org)

of Transportation (CDOT), where they dominate most of their bills of quantities (BOQs) for maintenance projects.

The cost data were collected from several HMA contractors and public agencies including Larimer County, CDOT, and other anonymous contractors. Most of the CDOT costs were publicly available on the CDOT web database (CDOT 2013). The data collection focused on the government agencies (specifically the Colorado Department of Transportation and Larimer County) for the unit prices of the asphalt layer and repairs, private contractors, and subcontractors for other cost data.

Most Severe Risks

The most severe risks were the results from a previous study (Mehany and Guggemos 2015), which represent the most severe risks at each phase along with their severity scores. Those risks will be the input for the correlation matrix to create a scenario analysis that accounts for the association between the risk occurrences on a project. The same risks will be used in combination with the CBS to create the dollar value, which will represent the risk costs during each phase according to their severity.

Risk Correlation Matrix

A risk correlation matrix was created using the *Statistical Package for the Social Sciences* (*SPSS*) program (using the Pearson correlation method). The *SPSS* was used in this research to determine the relation between different risks in terms of their correlation and association with each other. This correlation relationship is needed to have a matrix (correlation matrix) of the correlation coefficients for the different variables (risks) linking their association with each other. This matrix is fed to a Monte Carlo simulation to create scenarios of the risk occurrence in the project during the construction and maintenance phases.

Risk Costs Estimation

The risk severity scores and the standard deviation (Mehany and Guggemos 2015) were interpreted into dollar values and calculated by multiplying the cost of each construction process by the severity score and another by SD to get the dollar value for each of them. These are the same dollar values that will be used in the LCC models in the next step of this research.

LCC Models Using Monte Carlo Simulation

The LCC model used in this research adopted a Monte Carlo probability analysis simulation technique. The probability analysis was chosen at this stage of the research to provide a range of potential cost outcomes with multiple confidence levels (PMBOK 2013). This research project uses probability analysis, specifically the Monte Carlo analysis, which is a computer simulation that is used to solve many uncertainty problems in various scientific disciplines. Monte Carlo analysis is "the discipline of designing a model of an actual or theoretical physical system, executing the model on a digital computer, and analyzing the execution output" (Fishwick 1995). It is originated as computational algorithms that rely on repeated random sampling to compute their results and is considered one of the most useful modeling techniques for project risk management. It is effective because it determines potential outcomes by simulating a project, including risk scenarios, multiple times.

The Monte Carlo simulation program used in this study is named *Crystal Ball*. *Crystal Ball* is one of many types of Monte Carlo simulation software available. It is a user-friendly software that works as an add-on to Microsoft *Excel*, which makes it easier for the user to deal with the program through a familiar spreadsheet. Basically, *Crystal Ball* works through very simple steps. First, the user assigns the simulation assumptions and their distribution. Second, the user should define the forecasted cells (total cost cells) that will be the simulation results based on the probability analyzed assumptions. The final step (optional in *Crystal Ball*) is creating scenario analysis by developing a correlation matrix that can be defined in the same assumption window to identify the correlation between the different assumptions, creating a scenario-based simulation run. This simulation technique will run for thousands of times/iterations to provide a good accuracy through its probability analysis of the different scenarios.

Comparative Case Study—Conventional LCC versus Risk-Managed LCC Models

Finally, two LCC models based on those *Crystal Ball* Monte Carlo simulation models were created using the same CBS, one with standard lifecycle costs using only the CBS components and the other including the risk-impacted lifecycle costs. Both models were applied to the same case study parameters and analyzed with a Monte Carlo simulation program after using correlation statistical analysis to create the scenario analysis and the association between the risks involved. The comparison between the two model results will be concluded and represented in the results section to compare the difference.

Sensitivity Analysis

As one of the contributions of this research, a sensitivity analysis was done to show the most sensitive risks that can affect the overall cost of the LCC. The sensitivity analysis is a way to determine which of the risks have the most potential impact on the project and examine the extent to which the uncertainty of each project element affects the project objectives examined when all other uncertain elements are held at their baseline values (PMBOK 2013).

Data Collection and Analysis

HMA Construction and Maintenance Costs

For the unit cost of HMA during the construction phase, a cost breakdown structure (CBS) was created to ensure that the data collected includes all the factors that could affect the cost for the contractor to construct and maintain the asphalt layer.

These CBS components are based on the data collected from the agencies and contractors for a standard hot mix asphalt crew for highway paving with an assumed production rate of 150 ton/hr. The crew is an eight-person crew for laying down, paving, and compaction operations along with the truck drivers and the laborers during the transportation, and the HMA facility processing, as noted in Table 1. Table 1 includes the main components of the HMA construction costs divided in phases that begin with the materials and the HMA production and ending with the compaction phase. During the calculation of the HMA unit cost, the rolling resistance (RR) rating and caterpillar (CAT) performance charts were used for speed (mph) determination/calculation (Peurifoy and Schexnayder 2002).

Table 2 represents the breakdown of the HMA unit cost based on the CBS calculation and the following assumptions. The hauling truck's empty weight is 22,260 kg (49,075 lb) and its rated payload is 26 t. The road grade to the site averages 1% with a RR of 60 kg/ton (120 lb/ton) hauling on an earthly poor maintained road conditions with a distance to the site of 8 km (5 mi.). The loading and unloading time is 15 min. Finally, the cost of the HMA at the mix facility is $55/ton including all material and equipment involved.

Table 1. Cost Components in the CBS

Stage	Cost component
Materials and production	Aggregates
	Asphalt binders
	Modifiers and additives
	HMA facility operations
	Drivers and operators
Transportation	Transportation (hauling) trucks
	Transportation (hauling) truck drivers
Paving	Pavers
	MTVs
	(8-person crew) foreman
	(8-person crew) paver operator
	(8-person crew) 2 screed operators
Compaction	Steel and pneumatic tire roller (PTR) compactors
	(8-person crew) 3 compactors and rollers operators
	(8-person crew) 2 laborers for miscellaneous work
Maintenance	Fog seals/slurry seals/chip seals
	Rejuvenators
	Crack sealing

Table 2. HMA CBS Based on the Calculations According to the Construction Procedure

Stage	Cost ($/ton)
Material and production	55
Trucking and transportation	5
Paving	2.1
Compaction	2.4
Total HMA unit cost	64.5

The cost was broken down in the same manner of the cost components where it is divided by phases from the HMA facility production to the compaction phase as shown in Table 1. These costs are specific to this case study with the aforementioned assumptions and can be adjusted according to other conditions (e.g., road conditions, grade, haul distances, and different market prices).

Risk Cost Estimation

The cost data for each risk were derived from the unit prices (Table 2). These costs were compared in reference to the cost data, which were collected from two main sources: (1) government agencies (specifically CDOT and Larimer County) for the unit prices of the asphalt layer and repairs and (2) private contractors and subcontractors for other cost data.

The risk severity scores and its standard deviation were interpreted into dollar values as in Table 3 where the risk is calculated by multiplying the cost of each construction process by the severity score and another by SD to get the dollar value for each risk. These are the same dollar values that were used in the LCC model shown in Fig. 3. Moreover, three construction risks will be excluded regardless of their severity scores due to reasons that will be explained further in the discussion and conclusion sections in addition to the fact that they are apparently out of the contractor's control. Those risks are risk of investment in innovations, price fluctuation,

Table 3. Simulation Dollar Value Cost Setup for Construction Risks

Risk	Level (milestone)	Stage cost	Severity (%)	Risk cost	SD (%)	SD cost
Risk of investment in innovations	Throughout the project	\$64.50	0.49	\$0.32	0.05	\$0.03
Prices fluctuation	Throughout the project	\$64.50	30.33	\$19.57	11.25	\$7.26
Bonding capacity	Throughout the project	\$64.50	3.17	\$2.04	0.10	\$0.07
Delayed owner payments	Throughout the project	\$64.50	1.33	\$0.86	0.89	\$0.57
Weather changes	Throughout the project	\$64.50	7.58	\$4.89	6.83	\$4.41
Emergency repairs	HMA facility	\$55.00	0.39	\$0.22	0.07	\$0.04
Changing mixes	HMA facility	\$55.00	0.98	\$0.54	0.91	\$0.50
Voids control	HMA facility	\$55.00	8.83	\$4.86	4.55	\$2.50
Long-term storage	HMA facility	\$55.00	0.96	\$0.53	0.95	\$0.52
Segregation at dumping	Transportation—truck loading	\$5.00	29.08	\$1.45	9.18	\$0.46
MTV—availability	Paving—MTV	\$2.10	0.37	\$0.01	0.38	\$0.01
Stoppage time	Paving—feeding pavers	\$2.10	8.17	\$0.17	2.86	\$0.06
Paving speed	Paving—laydown	\$2.10	8.33	\$0.18	4.04	\$0.08
Screed adjustments	Paving—laydown	\$2.10	8.33	\$0.18	4.04	\$0.08
% of crushed aggregate mass	Compaction	\$2.40	7.00	\$0.17	4.86	\$0.12
Compaction speed	Compaction	\$2.40	8.21	\$0.20	5.15	\$0.12
Distance to paver	Compaction	\$2.40	5.75	\$0.14	5.65	\$0.14
Go/no go approach	Handing over—PBC end result specs	\$64.50	1.88	\$1.21	1.83	\$1.18

Unit Cost at Construction stage:							
Cost Break down by stage:							
Material & Mixing process (HMA Facility) :							
Cost of material & mixing operation =		\$ 55.00	/ ton				
Cost of transportation including all its procedures:							
Trucking Transportation cost =		\$ 5.00	/ ton				
Laydown - Paving operation including Labor & Equipment:							
Labor & Equioment crews cost =		\$ 4.50	/ ton				
		Most Severe Risks Associated at this stage					
Item	Cost	Emergency repairs	Change in mixes	Voids control	Long term storage		
Material & Mixing operation	\$ 55.00	\$ 0.22	\$ 0.54	\$ 4.86	\$ 0.53		
		Segregation at Dumping					
Transportation & Trucking	\$ 5.00	\$ 1.45					
		MTV availability	Stoppage time	paving speed	screed Adjustment		
Paving opertaion	\$ 2.10	\$ 0.01	\$ 0.17	\$ 0.18	\$ 0.18		
		% of crushed Aggr. Mass	compaction speed	Distance to paver			
compaction operation	\$ 2.40	\$ 0.17	\$ 0.20	\$ 0.14			
		Risk of innovation invest.	Prices Fluctuation	Bonding capacity	Weather	Go no go approach	Delayed owner payments
Through the Whole construction operation	\$ 64.50			\$ 2.04		\$ 1.21	\$ 0.86
Total Risk accounting Cost =	\$ 77.26						

Fig. 3. Snapshot of Monte Carlo (*Crystal Ball*) simulation for the construction cost including construction risk

and weather. For the maintenance risks, the same as the construction phase, all the risks were identified, ranked, and assessed according to their severity in order to be simulated as a dollar value for the maintenance costs using the LCC model with different scenario analysis.

The risk probability analysis was done using the Monte Carlo simulation where all the severe risks encountered in the construction phase were located in the assumptions cells (for every risk) of the LCC model as shown in Fig. 3. However, a scenario analysis had to be created and incorporated to represent the risk interdependencies and associations before running the LCC model. This was accomplished using a risk correlation matrix that is explained thoroughly in the following section.

Risk Correlation Matrix

A Pearson correlation statistical analysis was done after a descriptive statistics was conducted for each variable representing the risks. The correlation matrix from the *SPSS* results shown in Fig. 4 was loaded in the Monte Carlo simulation program to create

Load the matrix	Voids control (Construction (M.C))	Stoppage time (Construction (M.C))	paving speed (Construction (M.C))	screed Adjustment (Construction (M.C))	% of crushed Aggr. Mass (Construction (M.C))	compaction speed (Construction (M.C))	Distance to paver (Construction (M.C))
Voids control (Construction (M.C))	1.000	0.840	0.840	0.840	0.890		
Stoppage time (Construction (M.C))		1.000	1.000	1.000			
paving speed (Construction (M.C))			1.000	1.000			
screed Adjustment (Construction (M.C))				1.000			
% of crushed Aggr. Mass (Construction (M.C))					1.000		
compaction speed (Construction (M.C))						1.000	1.000
Distance to paver (Construction (M.C))							1.000

Fig. 4. Correlation matrix used in simulation

a scenario analysis through the association of the risks with each other. This matrix is based on the most significant correlation scores appeared in the correlation analysis relationships.

LCC and LCC Risk-Managed Models

The simulation model *Crystal Ball* was set up, the correlation matrix loaded, and the assumption and forecast cells identified as in Fig. 5 and as a shown in Fig. 3 for the construction phase.

For the maintenance phase, the assumptions and cost calculations shown in the LCC model Fig. 6 are accounting for the two major maintenance procedures for road maintenance. These procedures are crack-filling maintenance for every three years and HMA overlay every six years, both during responsible maintenance/warranty period of 10 years. As shown in Fig. 6, every periodic maintenance future value was calculated along the 10 year contract duration after construction. The assumption cells for the maintenance risks will only include the overlay risks because they are the most severe and the most common maintenance associated with HMA roads. The forecasts calculated based on these assumptions are the total HMA risk accounting cost, overlay maintenance risk accounting cost, and the HMA LCC, all measured per ton.

Assumptions	*Forecasts*
Emergency repairs	Total Construction Risk accounting Cost
Change in mixes	Total Maintenance Risk accounting Cost
Voids control	Total HMA Risk Accounting LCC
Long term storage	
Segregation at Dumping	
MTV availability	
Stoppage time	
Paving speed	
screed Adjustment	
% of crushed Aggr. Mass	
Compaction speed	
Distance to paver	
Bonding capacity	
Go/no go approach	
Delayed owner payments	
Leveling courses overrun	
Roughness component consideration	
Discount rate	
Inflation rate	

Fig. 5. Assumptions and forecasts in the model sheets

Results and Findings

The basic results from the simulation models are as shown in Figs. 7–9. Also, Table 4 shows the comparison between the conventional and the risk-managed simulated LCC models. The calculation were made as in the following:

HMA total risk accounting construction cost (mean value) = $\$77.23 \pm 3.2$/ton.

HMA overlay cost for the section studied = $(12{,}877 \pm 471.04)/445$ t = $\$28.93 \pm°\ 1.06$/ton.

Total LCC/HMA ton for the assumed 10 years as performance period = $\$133.27 \pm 5.17$/ton.

Table 4 shows the results from the conventional and risk-managed simulated LCC. The costs calculated in the risk-managed LCC simulation model forecasting cells and the costs calculated using conventional LCC differed little arithmetically (2.5–6.5% for total LCC) as shown in Table 4. However, a great advantage of the risk management probability analysis is introduced for contractors to use. This advantage is demonstrated in the capability of the observation of the range, confidence levels, and certainty of the estimate through the simulation frequency charts as shown in Fig. 10. The LCC certainty level can be adjusted through the simulation model, providing the contractors with the range of risk that

Maintenance Costs:							
Cost Assumptions and calculations:							
Average Crack Fill cost =	$ 0.50	/ square feet					
based on the previous tonnage Q.S section dimensions (500'x 24') :							
Overlay thickness =	1.5	inches					
HMA quantity =	445	tons - previously estimated					
course Overruns % =	10%						
Crackfill cost = 500 ft x 24 ft x 1$/sq.ft =		$ 6,000.00				***Most Severe Risks Associated at this stage***	
					Cost	***Levelling courses overrun***	***Roughness component consideration***
Overlay quantity = 74.07 tons / 1" x 1.5" x 10% course overrun =			122.2155	HMA tons =	$ 12,877.37	$ 1,979.00	$ 1,456.00
Crackfill unit cost = Crackfill cost / Total construction tonnage =			$ 13.48	/ ton			
Assumed Maintenance Periods:							
Year 3			Year 6				
Crack fill maintenance =	$6,000.0		HMA overlay =	$ 12,877.37			
Inflation factor =	1.124864		Inflation factor =	1.265319018			
FV =	$6,749.2		FV =	$ 16,293.98			
	$ 15.17	/ construction ton		$ 36.62	/ construction ton		
Year 9							
Crack fill maintenance =	$6,000.0						
Inflation factor =	1.423312						
FV =	$8,539.9						
	$ 19.19	/ construction ton					

Fig. 6. Snapshot of Monte Carlo (*Crystal Ball*) simulation for the maintenance cost including maintenance risks

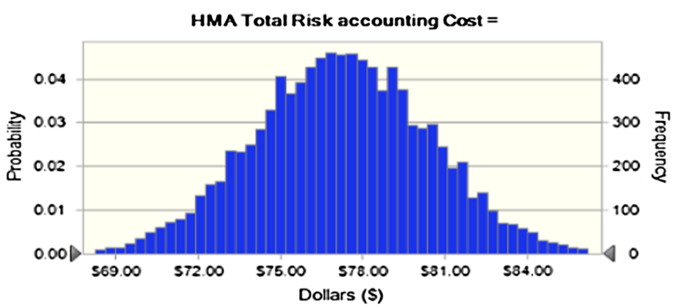

Fig. 7. Cost simulation probability for HMA total risk accounting cost per ton

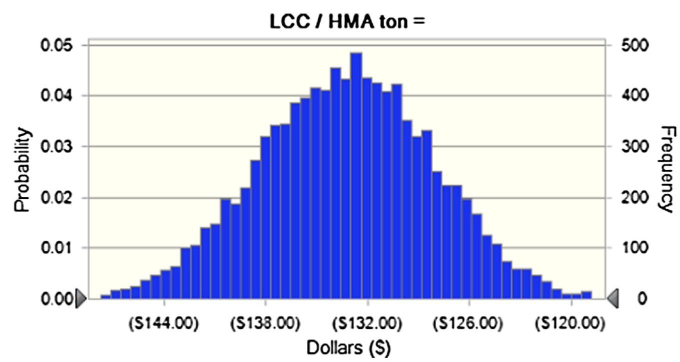

Fig. 9. Simulation model result showing LCC/HMA ton

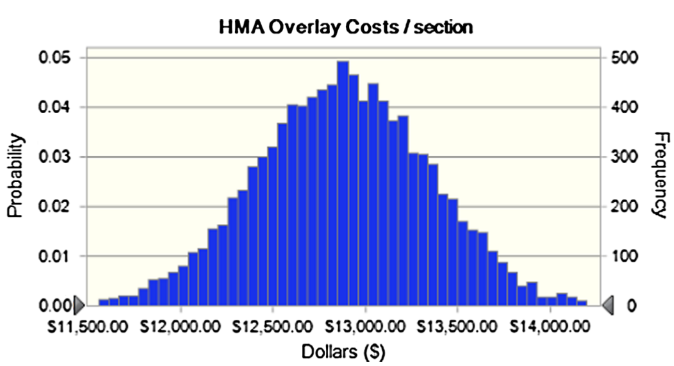

Fig. 8. Simulation model results showing HMA overlay costs per section

Table 4. Results from the Conventional and Risk-Managed Simulated LCC/HMA Ton

Risk-managed versus conventional LCC costs	Conventional LCC	Risk-managed simulated LCC
Construction costs	\$77.26/ton	$\$77.23 \pm 3.2$/ton
Maintenance costs	\$28.94/ton	$\$28.93 \pm 1.06$/ton
LCC	\$130.06/ton	$\$133.27 \pm 5.17$/ton

they can take and the contingency that they can distribute. This is a great advantage because it is virtually impossible for contractors to win bids for jobs with no-risk *100% certainty costs*, yet they can manipulate the certainty and confidence levels through the simulation results of the Monte Carlo simulation in general.

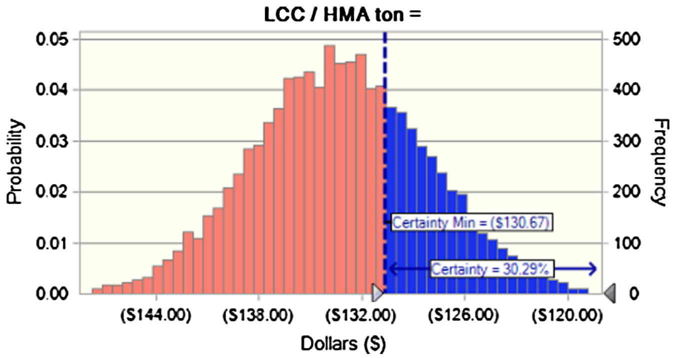

Fig. 10. Conventional LCC results confidence levels

Sensitivity Analysis

One of the main findings in the risk management simulation model presented in this research is the sensitivity analysis of the risks included in the study. This will not only affect the construction phase, but will also affect the LCC through the performance period of the estimated 10 years of the contract. These risks were found to be as shown in the sensitivity analysis as in Fig. 11.

From this sensitivity analysis presented in Fig. 11, one can see that the amount of the voids in the HMA mixture is probably the most important factor that affects the HMA mixture performance throughout the lifecycle of the pavement. This is a result of the voids being a directly proportional variable to the density of the HMA, which is the heart of the mixture endurance capability and it is dependent on all of the construction processes from the mix design until the compaction process. As a consequence, initial proper air void content represents a dense well-graded asphalt, allowing for good HMA performance, which would occur if the initial air void content limits were observed and suitable aggregate and asphalt cement were used. There, researchers stated the HMA mixture should be constructed with an initial air void content below approximately 8% and that the final air voids content after traffic should be above approximately 3% (Roberts et al. 1996). The percentage of crushed particles in an aggregate mass is also one of the most sensitive risks because is positively correlated with angle of internal friction. The higher it is, the more difficult to compact the HMA mixture, which in turn affects the density and void ratio and recalls all the problems previously mentioned for the void control issue.

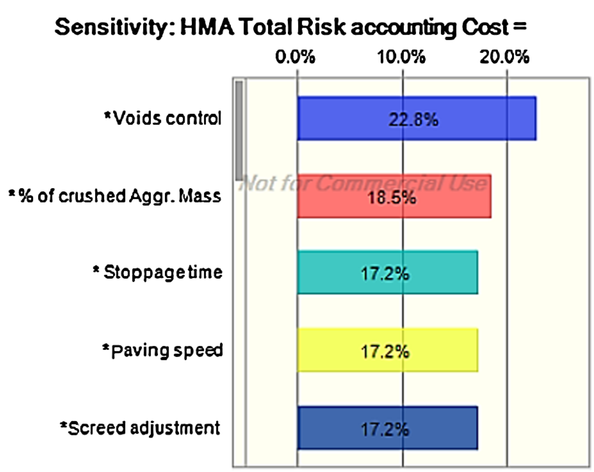

Fig. 11. Sensitivity analysis diagram based on the simulation model

Other important sensitivity variables are the stoppage time, paving speed, and screed adjustments. All three risks have the same sensitivity, which proves that the scenario analysis (by correlation matrices) through the simulation model paid off by determining the equivalent sensitive risks to the construction process. This is a major quality-control benefit for contractors to take advantage of during the controlling and monitoring process of a project. It facilitates this process by providing a link between different activities that must be controlled during the construction phase. The reason behind the link between the three risks is that, technically, when a paver stops, a new material loads arrives, so the force produced by the head of material in front of the screed can be different. This causes the screed to rise and fall several times to achieve a new condition of equilibrium, failing to produce the required leveling. Meanwhile, this stoppage time affects the distance to the paver, which will consequently affect the paving speed to compensate for that distance. During the paving operation, the material under the screed must be subjected to certain weight and compactive forces to maintain the required density and these interruptions will affect it as a result of any excessive screed or speed adjustments. Therefore, one can conclude there is an indisputable relationship between these three risks in the construction procedure. As a result, the contractor/builder should technically avoid these problems by maintaining paver stoppage quickly, but smoothly load it as quickly as possible [preferably using material transfer vehicles (MTVs)], accelerate to paving speed smoothly, and maintain a constant speed to avoid screed undulations caused by speed adjustments.

In the maintenance phase, the research has accounted for only two of the risks (not included in the sensitivity chart) encountered during the maintenance phase because they are the most common and most severe risks. The first was the roughness component consideration. The HMA overlay's main purpose is to reduce roughness, restore the skid resistance, and protect pavement deterioration, all in parallel. If not taken into account during the determination of the overlay thickness, a thin insufficient HMA overlay will be just another inefficient structural layer that will not help in the road improvement process the way it was intended to. The other risk in the HMA overlay is the leveling courses application. Overlays can cause major cost overruns for the contractor due to excess thickness in some sections caused by surface irregularities where the builders must apply more HMA tons than they could have estimated. The contractor can avoid or mitigate those risks by designing an overlay thickness that varies depending on the type of roughness components in the road profile. They can also use milling machines to mill the old road to a lane surface rather than using leveling courses.

LCC Findings

The risk-managed LCC costs differ in the simulation model with a mean of \$133.27/HMA ton from the traditional/conventional calculated LCC of \$130.06/HMA ton. This difference seems to be a small one. However, practically it is a huge difference considering the tonnage required for highway roads construction. For example, if one considers a highway with the width of 7.3 m (24 ft) for only 96.6 km (60 mi.), it will include a tonnage of an estimate up to 281,952 t of HMA, which is equivalent to approximately \$1 million as shown in Fig. 12.

Again, considering the huge network of U.S. highway roads, this number can add up to billions of dollars over budget by precluding the risk management aspect behind the cost risk analysis of the LCC of roads. This research is conducted for the HMA layer only, and these numbers can escalate when considering all of the highway road structural components.

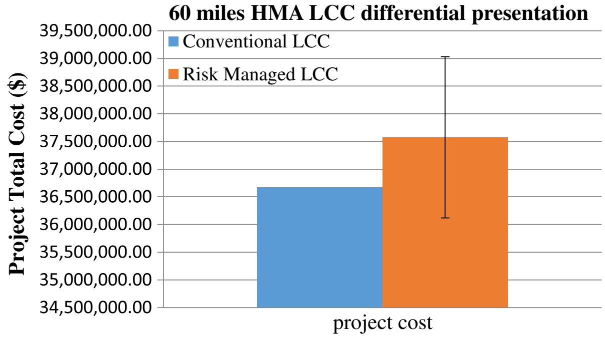

Fig. 12. Graphical representation of LCC for 96.6 km (60 mi.) highway

The main finding of this research/paper is that the introduction of the risk management modeling tool to the LCC will enhance the expected LCC by building its assumptions on risk-managed probability analysis. The result is a more reliable, more probable, and responsible LCC that can be used to assess the project budgets based on reliable cost risk analysis. The risk-managed LCC is more accurate and reliable because it is based on probabilistic scenarios taking into account the risk cost and variability during the long-term duration of the project along with the association of risk occurrence within these different scenarios. A risk-managed LCC should encourage contractors to expand their use of LCC. It should also lead to more research and innovative practices for improving the control and enforcement of quality standards, and can ultimately improve the overall road conditions and driver satisfaction.

Conclusions

The conclusion of this research can be described as threefold. First, according to the data gathered, the most sensitive contributing risks were discussed and demonstrated in the sensitivity analysis findings. It was demonstrated that voids control is one of the most sensitive risks during the construction phase. The percentage of crushed particles in an aggregate mass comes in as the second-most sensitive risk. The three other associated risks (stoppage time, paving speed, and screed adjustment) all coming in the third place were equal in their sensitivity due to their practical technical correlation on the construction site. In the maintenance phase, the two major risks were the roughness component consideration and the leveling course overruns, both in the HMA overlays application.

This research attempted to cover most of the risks that can occur during construction and maintenance. However, there were some risks excluded from the model, even though they are among the most severe risks. Those risks were the weather, risk of innovation investment, and price fluctuations. These risks were excluded for a variety of reasons. Weather and risk of innovation investment were excluded because they are very hard to predict or quantify. Also, contractors will not account for these risks in the bidding process, considering if they did include contingencies for these type of risks, they would be struggling to compete for any bids available. Another important reason is that some economic situations can force contractors to accept more risks. In some situations and during certain economic periods, contractors will bid for projects to break even or take a small amount of loss to keep their crews utilized/employed and to keep up with their overheads. Other risk types, such as the substantial risk of price fluctuations, can be mitigated and avoided through contract provisions and agreements between the contractor and the owner agency because price fluctuations and inflation are always pressing issues in today's economy. Most of the contracting agencies and the contract experts have developed many contract provisions and clauses to avoid these kinds of risks during construction because of their negative effect on both the owner and the contractor. Based on the previous discussion, a contractor should be primarily cautious of such contract language to avoid these uncontrollable risks.

Most of the risks covered can be considered long-term risks, which magnifies their effect under the performance-based contracts. Their effect will take place in the performance of the road and its condition, especially if there is a long warranty period included in the PBC. However, through the data-collection efforts, it was very noticeable that only a few contractors were involved or even willing to be involved in projects under performance-based contracts. This is because it is a new form of contract that is not yet fully experienced by many of the contractors or the industry expertise. It is also because PBCs carry a lot of risks and responsibilities that are allocated or shifted toward the contractor.

Second is the impact of those risks on the contractor's cost. The impacts on the contractor's cost as discussed in the findings are varied, but it can be always inflated by the warranty time period, and that is the reason behind the adoption of the risk-managed LCC during the involvement in long-term project commitment under those kinds of contracts. However, it was very obvious that the risk-managed LCC technique can be useful for any long-term contract. Not only contractors, but owners and the government and federal agencies can take advantage of this tool during their assessment and budgeting for their projects. They can also adjust their maintenance plans and asset improvement funds accordingly.

Third, how do contractors predict risk costs during road construction and maintenance phases? Again, this led to the focal point of the research/paper, which proves that a risk-managed LCC is more reliable than a conventional LCC that is based on mere assumptions. The risk-managed LCC can provide risk costs along with several scenarios, certainty, and confidence levels that help with the practical, unpredictable nature of the construction industry. This newly developed tool can be used for pricing PBC projects along with enhancing the risk management of the overall process of handling the estimating and managing of such projects.

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