A General Performance Model for Design-Build Highway Pavement

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A General Performance Model for Design-Build Highway Pavement Warranty Decisions

By

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Written by Spencer J. Won
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Abstract

New challenges are revealed as more projects are delivered and contracted through innovative methods such as design-build project delivery and performance-based specifications. One challenge from the owner's perspective is lack of control, especially over design decisions and construction procedures. Due to this problem, highway agencies have adopted various additional contractual provisions, of which one is warranty. Warranty is intended to be a method of protecting the owner from possible quality defects and also of improving the initial and long-term performance of the facility.

The research question is how warranty characteristics (i.e., warranty period) and other project characteristics impact the performance of highway pavement projects. To answer this question, a decision model was developed to simulate warranty impacts on project performance. Also, simulations were run to estimate the outcomes of projects with varying scope, contracting, and delivery methods in order to examine the impact of project characteristics on warranty decisions and project outcomes.

A probabilistic decision-modeling technique, General Performance Model (GPM), is adopted for this warranty decision model. GPM is one method that is being used widely and has been proven to work for both alternative comparison and selection decision. Since GPM has been developed specifically for the purpose of comparing probable performance

outcomes for various decision alternatives, it fits the purpose of this research.

According to the simulation results, the contract price tends to increase as the warranty period becomes longer and higher-level performance is required. On the other hand, the agency's expected maintenance and repair costs tend to become less with longer and stricter warranty. Where the life-cycle cost (LCC) of a facility is concerned, the simulation shows that warranty is more beneficial for projects with certain characteristics such as sufficient contractor control, innovation opportunity, design-build delivery method, and performance-based specifications. The results of sensitivity analysis show that warranty period and required-performance level influence project outcomes significantly. Among intermediate factors, amount of warranty risk, motivation for quality improvement, and innovation effort were found to be more sensitive than others.

A model is constructed to represent some aspects of the dynamic behavior of a real system. Therefore, a properly developed model can serve as a tool for investigating the behavior of the system and predict future outcomes with reasonable enough accuracy. In order to check the validity of the model, the process of requisite-model validation was applied, and a number of checkpoints were examined through expert interviews.

Because of the representative nature of the model, a few assumptions had to be made. Also, the model has some limitations due to its method and scope. First, the project outcomes are measured in the form of life-cycle-cost (LCC) only. The performance measures other than LCC are not considered in the model. Also, the timing of warranty decision is limited to after-project development and prior bidding. Warranty decisions at different times, such as warranty option, which is practiced after construction, are not considered in this model. Finally, the model is limited to asphalt highway pavement projects. Although warranties are often used in other types of projects, such as concrete pavement, bridges, and ITS, they were not considered in this research. The model could be expanded to cover a wider range of project types, decision timing and performance measures in future research.

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CHAPTER 1: INTRODUCTION

1.1 Background and Scope

As more projects are delivered and contracted through innovative methods such as design-build project delivery and performance-based specifications, challenges are revealed. One of them, from the owner's perspective, is lack of control, especially over design decisions and construction procedure (Design-Build Institute of America 1994). Because the contractor is responsible for design and construction decisions, the owner may have doubts about the quality of the product. To address this issue, highway agencies have adopted various additional contractual provisions such as quality assurance and quality control (QA/QC), plan submittal requirements, incentives/disincentives, and warranty provisions in order to protect themselves from quality defects and ensure long-term performance. Among these methods, the use of warranty provisions is the focus of this research.

A warranty is a contractual agreement which obligates the contractor to rebate or rectify the product that has failed within predetermined period or usage (Hancher 1994; Yeh and Lo 2000; Yun 1997). With a warranty, the owner can protect himself against early-defect risk because it is transferred to the contractor. Also, the use of a warranty can motivate the contractor to strive for better initial quality and long-term performance of the product, as the warranty provision obligates the contractor for future repair cost. For these reasons the use of warranty encourages life-cycle-cost based design and construction (Won 2003).

However beneficial it may be to the owner, the inclusion of a warranty also tends to increase contracting price (Ferragut 2003). Hence, the contracting agency must consider carefully what provisions are to be included in a warranty. Also, as more highway projects are contracted with warranties, there is increased need for research on its various implications for cost and performance. Agencies would benefit greatly from a decision framework to assist in critical decisions affecting cost and quality.

The effort to find an optimal warranty policy such as warranty period and other optional requirements began as early as 1963 (Singpurwalla and Wilson 1993) in manufacturing. Abundant information is available for various products and conditions, but for construction no comprehensive decision model has yet been introduced. Do date, the research on construction warranties has been limited to general guidelines (Thompson et al. 2002) and surveys of current practice (Bayrakat et al. 2004).

Only recently has research on warranty cost estimation been performed (Damnjanovic and Zhang 2005; Oh et al. 2005). However, these studies have focused on mathematical analysis methods. The use of these methods is limited under the current circumstances because sufficient amounts of data have not yet been accumulated, and reliable input data for quantitative analysis are not yet available. Another shortcoming of previously developed models is that their use has been limited to projects being delivered through traditional design-bid-build methods. Other innovative methods used in conjunction with warranties can be beneficial (Ferragut 2003). The last shortcoming of previous models is the omission of external factors such as owner's preference and market condition. In addition to finding the optimal warranty strategy for maximizing benefit and minimizing cost, other factors also influence warranty decision. For example, a contracting agency may prefer a longer-term warranty due to a staff shortage and be willing to pay extra for it. Previous studies have not considered such factors.

Because of all the shortcomings of previous studies, the need still remains for a new tool which does not requires data, overviews the whole decision process and takes into account various factors such as delivery method, contract type, market condition, and contractors' risk attitude. Hence, this study focuses on providing a comprehensive overview of the decision attributes, project characteristics, and external factors which practitioners can reference in making their warranty decisions.

In order to investigate variation in the performance of projects with different warranty alternatives and project characteristics, a project-performance forecast model was developed. This study employed the general performance model (GPM) as the primary analytical method. GPM was developed and has been used for analyzing various alternatives such as long-term strategy selection (Venegas and Alarcon 1997) and contractor selection (Alarcon and Mourgues 2002). As supplements to GPM, other concepts such as life-cycle cost (LCC), structured interviews, and requisite model validation were also used. The life-cycle cost concept was used primarily as a measurement of project performance. Structured interviews and questionnaires were used to assess impact ratings that were required for GPM. Finally, the concept of requisite model validation was applied to ensure that the results were defensible. Figure 1.1 is a graphical representation of the topical domain and methodological scope of this research.

1.2 Question and Objective

Given the background and scope of this research the following question was developed to guide this study.

How do warranty characteristics and project characteristics impact the performance of highway pavement projects?

To answer this question, the research has the following objectives:

- Examine various internal and external factors and determine the important factors in making warranty decisions.
- Develop a decision model that simulates warranty impacts on project performance indicators.
- Run simulations of projects with varying scopes and processes in order to examine the impacts of warranty characteristics (e.g., decision variables of warranty period, limited liability characteristics) and project characteristics on project performance.

1.3 Methodology

The methods employed in this study were applied in eight phases: 1) literature review; 2) research question and objectives; 3) model structure development; 4) model structure validation; 5) model assessment; 6) model validation; 7) model simulation and results; and 8) findings and contribution. Organization of these phases is shown in Figure 1-2. In the figure the phases are organized in a horseshoe-shaped curve (Kunz and Fischer 2008) starting sequentially from the top-left corner and proceeding clockwise to the bottom-left corner. The boxes represent phases, and the solid arrows direction of sequence flow. The dotted arrow represents a comparison-and-feedback process.

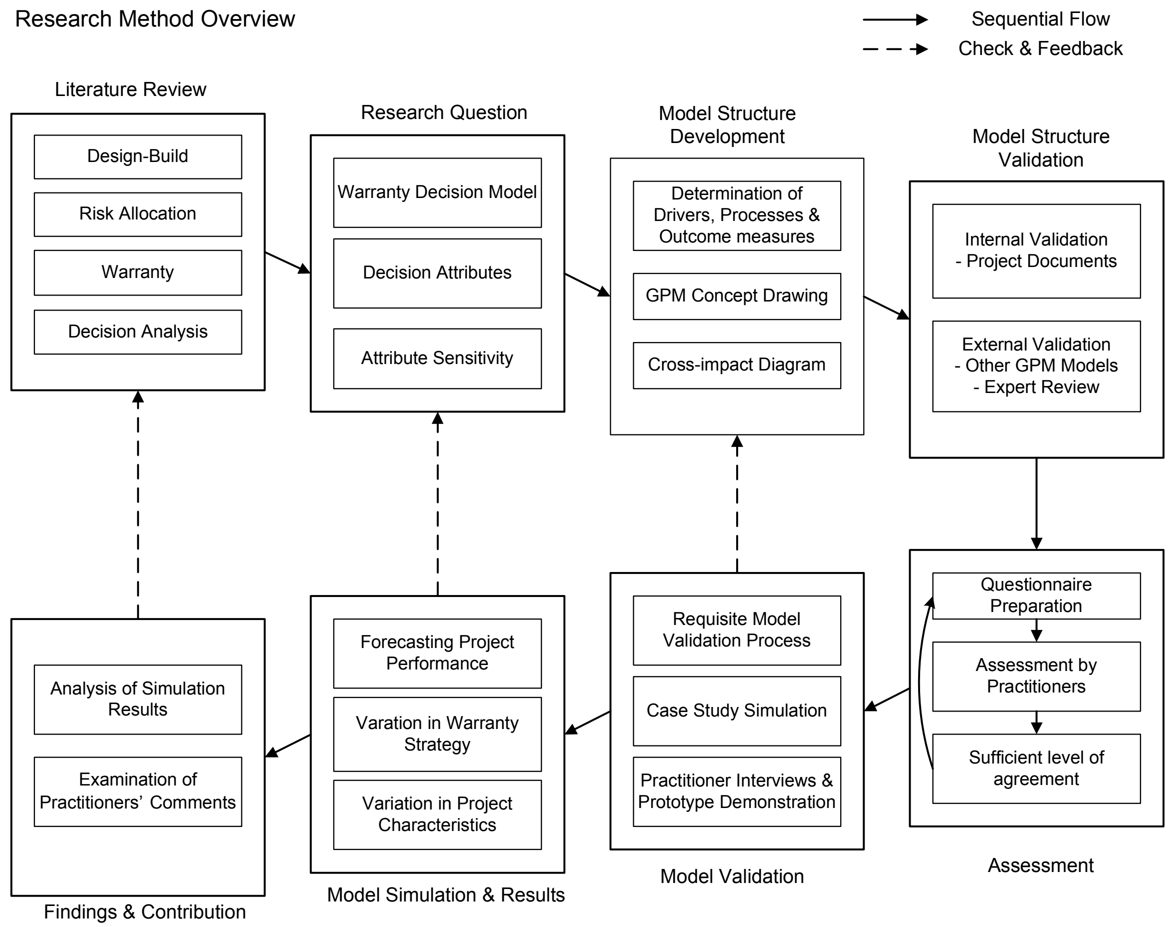

Figure 1-1: Methodology Overview

First, a comprehensive literature review was performed of four relevant topics – warranty, design-build, and risk allocation and decision analysis. In the warranty review, general characteristics, types, current state-of-practice, and state-of-research are the main areas of focus. In the review of the design-build process, unique characteristics of design-build in comparison with traditional methods are thoroughly examined. Some key topics of the design-build review are basis of contract, procurement process, contracting methods and risk-allocation principles. Finally, various decision-analysis methods are reviewed to determine the best-fit method for answering the research question.

The research objective is to decide upon the proper warranty characteristics such as period, bond amount, and liability limitations for projects. According to the literature, several decision models have been developed to solve the problem in both manufacturing and construction (Blischke and Murthy 1994; Damnjanovic and Zhang 2005; DeCroix 1999; Oh et al. 2005; Yeh and Lo 2000; Yun 1997). However, previous models do not make possible the complete achievement of the research objective, because 1) current models were designed specifically for traditional design-bid-build systems and are not applicable for innovative systems such as design-build; 2) sufficient amounts of reliable data are not available for optimization models; and 3) existing models do not take into account external factors such as market conditions, bidding environment, and contractors' motivational factors.

Therefore in this study the warranty decision is considered as an alternative selection question, and the objective is to find the most suitable period and strategies for a given project. Each warranty period and strategy set is considered an alternative, and the decision is the selection of the one that best fits the given project. GPM is one method that has been proven to work for both alternative comparison and selection. Since GPM has been developed specifically for the purpose of comparing not only costs but also likely performance results for various decision alternatives, it fits the warranty decision in construction well where project outcome is measured in terms of quality as well as cost. Therefore, the GPM method – with some modifications – is selected as the main method of decision modeling for this study.

The development of the warranty-decision model in this study consists of two steps: 1) decision attributes identification; and 2) model structure (framework) development. In the development stage, various factors relevant to warranty decisions and project performance were determined from literature review and discussions with warranty practitioners. Once all the decision attributes were identified, they were organized and structured in accordance with GPM theory (i.e., five model components -- decisions, drivers, processes, outcomes and external variables).

The developed model framework was validated prior to data collection, as shown in Figure 1-2. This process is called model-structure validation and is done by document review and expert consultation.

The values of variables such as initial probability and cross-impact rating of each pair of events were decided through questionnaire and structured-interview methods. These methods were selected because they require smaller sample size, and each sample provides more information. Since there are only a few practitioners with sufficient warranty experience for these assessments, and it would be difficult to satisfy the sample-size requirement of a survey, a questionnaire and interview process were chosen for this study.

Finally, the model was validated using a requisite model-validation process. The process requires checkpoints of interaction with practitioners, validation of model form and content, and clearly defined limitations. In order to achieve these checkpoints, structured interviews were performed. The validation interview consisted of a prototype demonstration of the model, presentation of simulation results, and semi-structured, open-ended discussions. In this process, the model was tested by practitioners, and their feedback was reviewed in order to refine, calibrate and validate the model. Another validation method used in this research was extreme-case simulation. In this method, hypothetical cases with extreme input values are applied to the model and simulated outcomes are compared to obvious outcomes.

The last two phases of the study were the presentation of results and evaluation of the study's contribution. The developed model was simulated using actual and assumed input data (hypothetical projects derived from actual case projects) to produce results and findings. One finding relates to the key attributes of warranty decision, which were found by sensitivity analysis using the developed model. Also, performance forecast for various warranty-decision strategies and project characteristic provided valuable information. Finally, the research process, resulting model, simulation results, and findings were evaluated and compared to the initial objectives of the study.

1.4 Contributions

The concept for this study was derived from the idea that current models are deficient in some aspects and intended to provide a better model. Therefore, the research process and resulting products must return a contribution to both the industry and academia.

The final model is a result of a decision process that adds formalism and minimizes the influence of personal opinion and bias in decision making. Through the use of the GPM process, this study deviates from detail-oriented numerical analyses and brings a broader perspective into the decision. For example, the study introduces decision attributes beyond project parameters such as market and contractor characteristics. Finally, the resulting model reflects characteristics of alternative delivery and contracting systems such as design-build and performance-based specifications.

1.5 Dissertation Outline

The following is an outline of the remainder of this dissertation

Chapter 2 – Background

This chapter prresents a review of literature on four topical areas -- design-build delivery method, risk-allocation, warranty contracting, and fundamental decision theories including general performance modeling (GPM), cross-impact analysis (CIA), and life-cycle cost analysis (LCCA).

Chapter 3 – Methodology

This chapter describes the sequence of the research and justifies its appropriateness to the research question and objectives. GPM and CIA methods are introduced in comparison to conventional influence-diagramming and decision-tree methods.

Chapter 4 – Model development

Each sequence of the GPM-framework development and model-component determination process are described. Detailed descriptions of each GPM element (i.e., decision alternatives, drivers, processes, and outcomes) are presented. A GPM conceptual drawing, influence diagram, and cross-impact matrix of the model are constructed and presented.

Chapter 5 – Assessment

The method and process for assessing impact ratings among variables are described.

Impact ratings are assessed from structured interview with practitioners. The assessment was an iterative process in which multiple rounds of interviews were conducted until a satisfactory level of consensus was achieved. The level of consensus was measured by standard deviation of individual assessments and Kendall's W.

Chapter 6 – Simulation and Results

A total of five hypothetical case projects with various project characteristics were simulated to measure the impact of various warranty strategies and project characteristics on performance outcomes. Sensitivity analysis of decisions, drivers, and processes were conducted to determine the importance of each factor to the overall project outcome. Finally, the results of the simulation were used for model validation. Two hypothetical projects were designed as extreme cases, and the simulation results from these cases provided insights as to the model's validity.

Chapter 7 – Model Validation

The model was validated through a requisite model-validation process which differs from general model validation in that it focuses on interaction with practitioners. Therefore, structured interviews were held with practitioners of various professions (agencies, contractors, consultants).

Chapter 8 – Findings and Conclusion

The last chapter presents findings derived from simulation results and practitioner interviews. These findings were compared to the research questions and objectives in order to check the completeness of the product. Also, discussions of research contributions to both academia and industry are included. Finally, shortcomings of the developed model and the research are discussed along with suggestions for further improvement to the current model and prospects for future research.

CHAPTER 2: BACKGROUND

This chapter provides fundamental background information on the subjects that are closely relevant to this research. The information presented in this chapter is the foundation of the research and it is referenced throughout this documents. As this research examines risk allocation decision making in highway design-build projects, a brief definition, history, and characteristics of design-build are first introduced. Second, the concept of risk allocation is introduced. Thirdly, warranty contracting method is discussed with a focus on decision making. Finally, various previously researched and published studies relevant to warranty method are introduced. Also, based on the current status of warranty research, the point of departure of this research is introduced.

2.1 Design-Build Delivery and Contracting Method

Highway agencies have traditionally awarded most of their projects to the lowest bidders at a lump-sum contract price after the designs are completed and approved. However, this design-bid-build approach has encountered problems. While traditional design-bid-build delivery produces a transparent set of checks and balances between design integrity and construction cost, it also results in slow product delivery and often in adversarial relationships. Furthermore, frequent cost growth through change order and litigation cost due to disputes have even reduced clarity in scope definition and weakened fixed cost guarantee. Also, focusing on low bids leaves too little emphasis on product quality, time, and factors that affect long-term performance (Carpenter et al. 2003). In order to alleviate such problems, various innovative delivery and contracting methods have been developed and introduced to the transportation industry. Design-build is one of these alternative project delivery methods. Design-build combines both project design and construction under one contract. In design-build, the owner contracts with one firm or team to complete a project in its entirety.

Section 2.1.1 starts by defining what delivery and contracting are and introduces some of delivery and contracting methods. Then the discussion continues with the history and characteristics of design-build with special emphasis on its uniqueness in terms of risk allocation.

2.1.1 Concept of Delivery and Contracting

Delivery is the process of acquiring and providing service to the project owner to bring about the product in need. The delivery service may include either design or construction or both. In earlier eras, when there was less social interaction among individuals or families and only simpler construction was performed, most construction has was by the person who had the need – the owner. In other words, almost all the construction projects were self-delivered. As the world has become more socialized and works professionalized, construction is more often done by the professionals who provide design and construction service in exchange for an appropriate fee. These professionals are referred to as builders, or more widely contractors.

A contract is a written or verbal agreement between two persons or parties. As more constructions were performed by entities not project owners, the need for formal agreements between parties became apparent. Such agreements are made through contracts. A contract specifies what work ought to be performed by the contractor and the amount of the fee the owner is obligated to pay the contractor for the work. As the construction process and social interaction among people have become more complex, the importance of contracts has grown significantly.

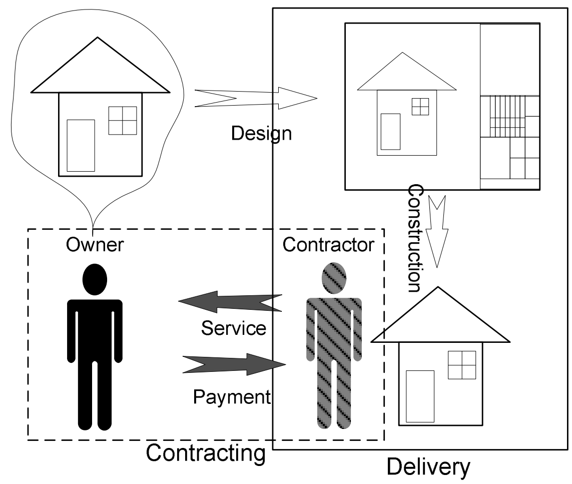

Figure 2-1: Concept of Delivery and Contracting

Figure 2-1 above describes the concept of delivery and contracting. When the owner has a need, he may acquire services from a contractor who is a professional designer, builder, or both. The service can include advising, designing, administrating, constructing, etc. The process by which the professional offers service to the owner is called project delivery. The written or verbal agreement between the owner and the person who delivers the project is contract.

Conditionally according to the owner's preference and project characteristics, the owner may choose to hire a single entity to perform all the tasks of design and construction. Sometimes, the owner may hire different entities to perform each task of design and constructing. Some inexperienced owners may also want to hire consultants as representatives to administrate the project. There can be various ways to get the project done. The way the tasks in a project are assigned and the parties organized and contracted is a delivery system or method.

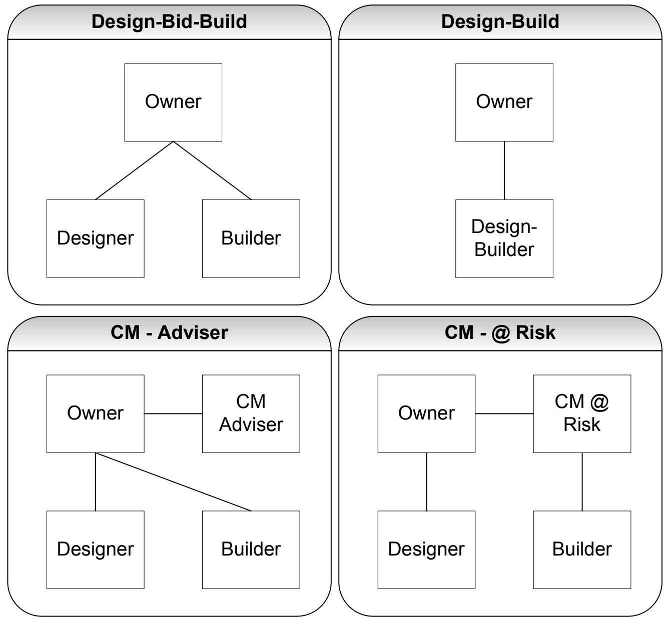

Figure 2-2: Various Delivery Methods

Figure 2-2 above shows four of most common delivery methods. The most common delivery method is design-bid-build (DBB). The owner contracts with two different entities for design and construction service. In design-build (DB), the owner contracts with a single entity for both design and construction service. A construction Manager (CM) is another party who may be involved in the project. CM acts as the owner's representative in case the owner lacks construction experience. There are two different CM delivery methods. One is that of CM adviser. In this case, the CM plays an advising role and does not contractually relate to either designer or builder. In CM- at risk, the CM takes the full responsibility and has contractual relationship to design, builder and all other parties involved in the project.

At this point, all the players who can be involved in the project are introduced. As the next step, the project owner wants to select and contract with the adviser, designer, builder who has the best ability at the lowest possible price through appropriate competition. The process of selecting the person or organization that will provide work and service for the project owner is called procurement. More discussion of the unique characteristics of design-build in terms of the roles and responsibilities of each player, procurement, contracting methods are presented in a later section.

2.1.2 History of Design-Build in Highway Construction

Although design-bid-build has been the dominant delivery method, especially in the highway industry, for the past several decades, design-build is not a new concept because master-builders could be considered a form of design-build.

In ancient Mesopotamia, the Code of Hammurabi (1800 BC) fixed absolute accountability upon master builders for both design and construction. This code references a single source of responsibility for the design and construction of structures which shows much similarity to modern design-build (Beard et al. 2001). The process of construction supervised by a master-builder has been the major delivery method that has been used for thousands of years before the separation of design and construction.

During the Renaissance era, as buildings became larger and more complex, and the designs became much more complicated, the traditional design-bid-build project delivery method was formed (Twomey 1989). Since then, DBB has been the most widely used delivery method throughout the modern era. However, in the 1960s, the significant cost-overrun problem with DBB led owners to search for innovative delivery methods. Design-build was introduced as one of them. The formal use of design-build in the public sector dates back to 1968 (Design-Build Institute of America 1994).

At first, design-build was used more frequently in the private sector. The reason for this was that the fear of corruption in the selection process and the sense that lowest price was no longer guaranteed held public agents back from choosing design-build. It was not until the mid-1980s that public owners and agencies began to utilize design-build. As traditional design-bid-build began to show systematic deficiencies such as frequent legal claims and relatively long delivery time, public agents strove to find different methods, one of which was design-build. Ever since its acceptance for transportation projects in the mid 1990s, the use of design-build in the public sector has been steadily increasing. Currently, design-build is in use on a wide variety of highway projects, from bridges to automated traffic management systems, and from new freeways to reconstruction of decaying roads.

The expansion of design-build in highway construction accelerated even further with the passage of the Transportation Equity Act for the 21st Century (TEA-21) and Special Experimental Projects No. 14 (SEP 14). As of December 2002, 304 design-build projects had been approved for federal funding (FHWA 2002).

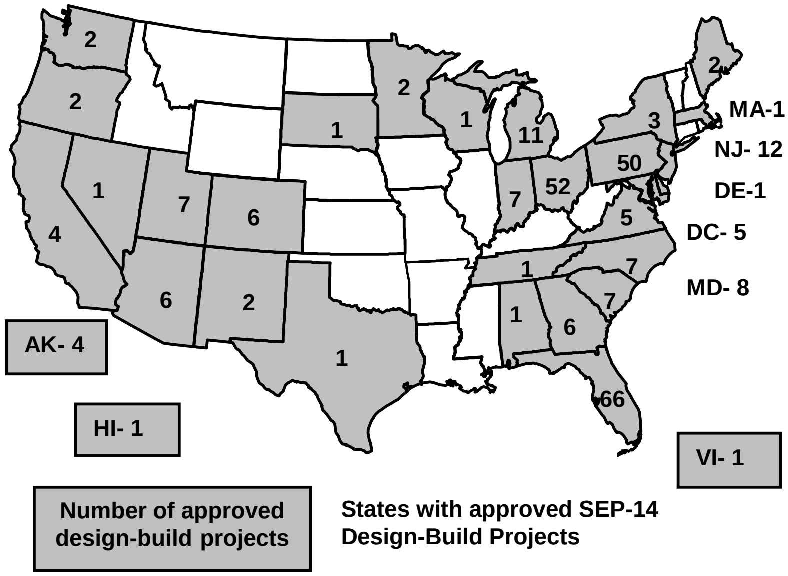

Figure 2-3: Map of States with Approved SEP-14 DB Projects (2003)

As of January 2003, more than 30 states had used or were considering the use of design-build project delivery on federally aided highway construction projects. However, design-build is not yet widely known among all the highway agencies. Its use is concentrated in a few states as shown in Fig. 2-3. Only three of these states, Florida, Ohio, and Pennsylvania, have applied the method more than 50 projects. Conversely, seventeen states have applied to less than five projects as shown.

2.1.3 Characteristics of Design-Build

Design-build is an alternative project delivery method that combines both project design and construction under one contract. Design-build projects can vary significantly in the amount of design included in the RFP, risks allocated to the design-builder, and procurement methods, but the key element in each project is a single source of responsibility to the agency through one contract for both design and construction.

In design-build, the owner contracts with one firm or jointed team to complete a project in its entirety. Although the difference between DBB and DB may sound as simple as the difference between having separate contracts for design and construction or one contract for both, this difference is so fundamental that it impacts almost every aspect of a construction project such, including the attitude of participants and the way decisions are made, and the project procured, and executed. Among various aspects, the differences in procurement, risk allocation, and contracting are examined below.

2.1.3.1 Timing and method of procurement

The two significant differences are in timing and method of procurement. Procurement is the process of selecting the contractor (builder) for a project. Traditionally in DBB, highway agencies define the scope and requirements of a construction project by fully completing design documents (within the agency or with the assistance of design consultants) and then hiring construction contractors to build the project though a low-bid process. In design-build project delivery, agencies define the project scope and requirements through initial design documentation and then procure both the final design and construction through an evaluation of technical proposals and price.

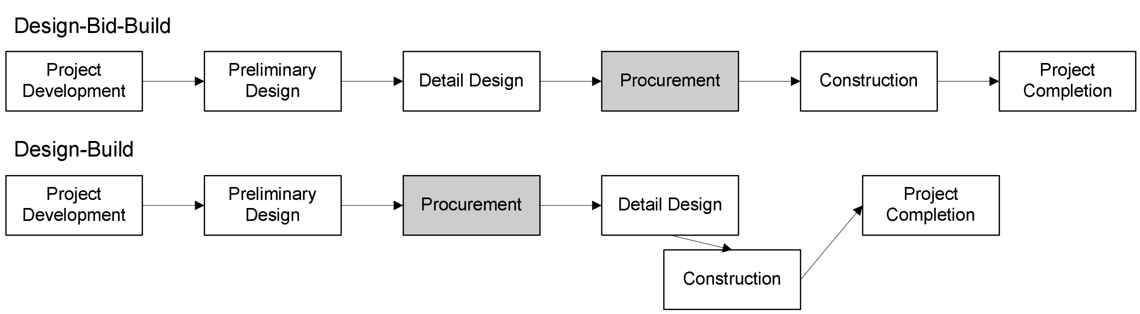

Figure 2-4: Activity Sequence in DBB and DB

Figure 2-4 shows the difference in timing of procurement. The procurement occurs after the detailed design in DBB and before detailed design in DBB. This difference leads to a few unique characteristics of DB. The most significant one is that it enables overlapping of design and construction activities and yields shorter schedules. As seen in Figure 2-4, design-bid-build project delivery is very linear, while design-build allows for concurrent activities yielding shorter overall schedules. Also the contractor is involved in the project at an earlier stage and has greater opportunity for innovative input into the design. In contrast, procuring a project before design completion can create more uncertainty in the project in terms of cost, scope, quality, etc.

The method of procurement is another significant distinction of design-build. Traditionally highways agencies have selected and procured most of their projects on low-bid basis. Since the project is procured after the final design is completed, all the bidders completes over the price of the same design. However, this low-bid procurement method is not appropriate for design-build and does not fully utilize its strength. Therefore, for design-build projects, the best-value procurement method is highly recommended (NCHRP 2005).

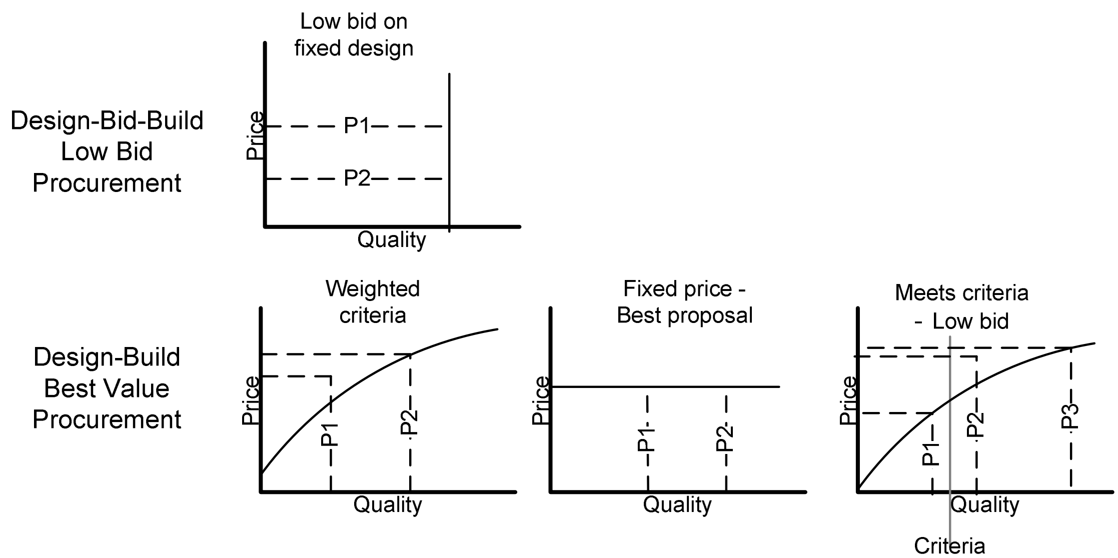

Figure 2-5: Graphical Representation of Low-bid and Best-value Procurement

Figure 2-5 shows how the contractor is selected in low-bid and best-value mechanisms. In low-bid procurement of DBB, all the bidders ought to bid on the same completed design and the bidder with the lowest price is selected. The key difference between best-value procurement and low-bid procurement is the variation of quality (design) of the proposals (bids). While the quality is fixed in the low-bid mechanism, the quality varies among proposals as competitors propose different designs (different quality level) as well as the prices.

As shown in Figure 2-5, there are three basic categories of best-value method: weighted criteria, fixed price / best proposal, and meets-criteria / low-bid methods. All of the methods show flexibility on quality which enhances the strength of design-build in terms of flexibility and innovation.

Proposal 2 (P2) is the winner in all the cases shown in the figure. P2 has the lowest price in low-bid procurement as well as better value and meets the criteria in best-value procurement.

2.1.3.2 *Basis of contract*

Figure 2-6 presents a comparison of the design-bid-build and design-build methods of delivery by depicting the basis of a contract between an agency and a contractor/design-builder.

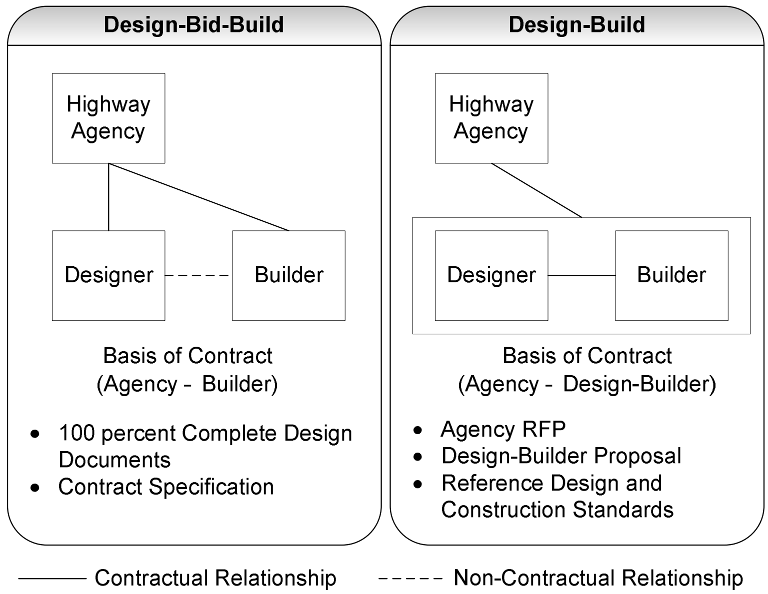

Figure 2-6: Contractual Relationship and Basis of Contract in DBB and DB

As seen in Figure 2-6, the basis of a design-build contract (between owner and contractor) is different from that of design-bid-build. The agency passes on responsibilities for final design to the design-builder and takes a design-oversight role during the final design development. In the same manner, the design-builder assumes responsibility for the final design and also the responsibility for the coordination of construction within the design. This relationship significantly changes the basis of the contract between the agency and the entity performing construction. No longer are 100 percent complete plans and specifications the technical basis of the construction contract. In design-build, an agency's request for proposal (RFP) and the design-builder proposal are the technical basis for the contract. The 100 percent complete plans and specifications become a deliverable of the contract – they are no longer the basis of the contract.

The difference in contractual basis, along with timing of procurement, plays an important role in risk/responsibility allocation and consequent contracting methods such as warranty, which is one of principal subjects of this research. Because the agency does not provide 100 percent design and allows the design-builder to do most of the designing, the agency can be free of design responsibility, thus it is easier to transfer design-defect risks. Also, the agency may also choose to delegate certain aspects of quality control and/or quality assurance, third party coordination, and construction oversight, but they must carefully consider the possible risks and associated costs of allocating these aspects of the project. The next section presents a more detailed discussion of risk allocation in design-build.

2.1.4 Risk Allocation in Design-Build

Appropriate allocation of risks is one of the most critical and difficult aspects of any construction project, including one using design-build method. In recently years, many owners have chosen to use the design-build method of project delivery to manage their risk better. One reason for that is the fact that the design-build system provides more flexibility in risk allocation. Many risks that were traditionally borne by the contracting agency can be transferred to the contractor in the design-build system. This is attributable mostly to the single point of responsibility and earlier procurement characteristics of design-build. However, this flexibility should not result in shifting all possible risks to the contractor which would eventually lead to high bids, excessive changes and disputes.

Therefore, decisions in regard to risk allocation should be made through appropriate analysis and decision-making process. The flexibility can be beneficial only upon proper allocation of the risks.

2.2 Warranty Contracting

Although the historic introduction of warranty concept dates back to 1654 (Singpurwalla and Wilson 1993), its usage was mostly in manufacturing. The first historical usage in construction was in 1889, when George W. Bartholomew proposed the first Portland cement concrete pavement to the city of Bellefontaine, Ohio (Portland Cement Association 1991). Similarly to its historic usage, the research on warranty was done mostly from a manufacturing perspective. Recently, in an effort to improve quality in construction products, warranty began to gain popularity as an innovative contracting method. In 1987, the Transportation Research Board, with Federal Highway Administration (FHWA) cooperation, initiated a task force effort to identify innovative contracting practices. The FHWA subsequently approved Special Experiment Project No. 14 (SEP 14). As a result, along with design-build and other innovative contracting methods, the use of warranty contracting in public highway construction was approved.

In this section, the definition, type, and characteristics of warranty contracting are examined first. Second, some characteristics and types of warranty that are used specifically in road construction are introduced. In this section, performance based warranty contracting is examined in comparison to workmanship warranty. Also, the differences in basic and extended warranty are described. Finally, advantages and disadvantages of warranty are examined.

2.2.1 General Definition and Types of Warranty

Warranty is a type of contractual agreement, made along with the of purchasing agreement between the manufacturer and the consumer, which obligates the manufacturer to rebate or rectify a product that has failed within a predetermined period, usage, or both. The rectification can be accomplished through repair or replacement, and the associated cost is fully or partially borne by the manufacturer of the product depending on the type and coverage.

A warranty can be categorized by types as shown in Table 2-1. This categorization is based on an earlier study (Blischke and Murthy 1994).

Table 2-1: Warranty Types (General)

<table>
<tr><td colspan="2">Rebate</td><td colspan="2">Replace</td><td colspan="2">Repair</td></tr>
<tr><td colspan="3">Free-rectification</td><td colspan="3">Pro-rata</td></tr>
<tr><td colspan="3">Renewing</td><td colspan="3">Non-renewing</td></tr>
<tr><td colspan="3">Unit (specified period, usage, etc)</td><td colspan="3">Perpetual (Life-cycle)</td></tr>
<tr><td colspan="3">One dimensional</td><td colspan="3">Two dimensional</td></tr>
<tr><td colspan="3">Basic</td><td colspan="3">Extended</td></tr>
</table>

First, warranty can be categorized by the compensation method to be used for the failed product. Sometimes the contract specifies the method that is to be used, but it is usually left as optional to the manufacturer to rebate, replace (completely rectify), repair (partially rectify) the product. The decision is usually made for each case based on the type of the product, degree of failure, cost for each method, etc. For a smaller and less expensive product, it is usually a better to replace it with new one. For relatively larger and expensive ones, repair is the better option. Rebate can be an option preferable from a marketing perspective, as people would prefer refund over time-consuming replacement or repair.

In free-rectification warranty, the cost of rectification (either replacement or repair) is borne completely by the manufacturer. In pro-rata, it is borne jointly by the manufacturer and the consumer. It appears that free-rectification is more preferable to the consumer than pro-rata, but not always because pro-rata can lower the initial price of the product, as the warranty premium (incorporated in the price) is lower in the pro-rata type of warranty. One other warranty method, similar to pro-rata but different in some aspects, is limited liability. It is the same as pro-rata in terms of sharing risk, but also different as it requires the provider to cover the risk only up to a pre-determined amount of cost. Any cost exceeding the fixed amount is left to the owner. Limited liability warranty is often used for very expensive products where the risk is too big and full warranty likely results in excessive risk premium.

In renewing a warranty, the warranty period or usage is renewed each time the product is rectified. Contrarily, in non-renewing warranty, the warranty period counts down from the day of purchase no matter what happens during the warranty period. The renewing characteristic of a warranty is usually specified in its provisions.

The majority of warranty contracts pertain only to the warranty period or the life of the unit sold. This is called unit warranty. In contrast, the perpetual warranty guarantees product performance (through continuous monitoring, repairing, replacing) until the consumer ends the relationship or the contract expires. In return, the provider collects service fee. One example that shows the difference between unit warranty and perpetual warranty is a personal computer (PC) versus computer network system in a large corporation. A PC usually has a unit warranty which covers failures for a specific period of life span of the unit. However, for a large network system, upon the purchase of the system or agreement for service, the manufacturer guarantees continuous and perpetual repair, replacement, and updating of the system. In perpetual warranty, the provider guarantees certain performance of the system, and it is up to the provider to take any necessary action including replacement of units.

In unit warranty, the warranty coverage ends as the age or usage amount of the unit reaches the pre-determined limit. A warranty that is delimited only by age is called a one-dimensional warranty. Most unit warranty falls into this category. For some products, the warranty period ends when either of two dimensions, age or usage, reaches the limit. One representative example of this type is automobile warranty as it has two dimensions of elapsed time from purchase and mileage.

2.2.2 Warranty in road construction: types and characteristics

Warranty concept was first introduced and developed mostly in the manufacturing. As characteristics of construction (especially road construction) are much different from those of manufacturing, the types and methods of warranty contracting are also different from those used in manufacturing.

Due to the uniqueness of road construction, the type of warranty used is limited to repair, free-rectification, non-renewing, unit, one dimensional (time), basic (constructor provided). In terms of coverage, the type of warranty in construction is usually the material & workmanship warranty. Usage of performance warranty is usually limited to design-build projects due to allocation of design responsibility. The warranty period in most cases ranges from six months to ten years (Bayrakat et al. 2004). The table below summarizes the type, coverage, and period of warranties that are usually used in the construction industry which also is the focus of this research.

Table 2-2: Warranty Types (Construction)

<table>
<tr><td>Rectification Method</td><td>Rebate</td><td colspan="2">Replace</td><td>Repair</td></tr>
<tr><td>Cost of Rectification</td><td colspan="2">Free-rectification</td><td colspan="2">Pro-rata</td></tr>
<tr><td>Renewing</td><td colspan="2">Renewing</td><td colspan="2">Non-renewing</td></tr>
<tr><td>Unit</td><td colspan="2">Unit (specified period, usage, etc)</td><td colspan="2">Perpetual (Life-cycle)</td></tr>
<tr><td>Measurement</td><td colspan="2">One dimensional</td><td colspan="2">Two dimensional</td></tr>
<tr><td>Provider</td><td colspan="2">Basic</td><td colspan="2">Extended (Service Contract)</td></tr>
<tr><td>Work type</td><td>Material</td><td colspan="2">Workmanship</td><td>Performance</td></tr>
<tr><td>Period</td><td colspan="4">0.5 to 10 years</td></tr>
</table>

2.2.2.1 By work type (material, workmanship and performance)

The distinction of warranty type by work type is unique to construction and is not found in any other industry. This distinction is made due to the fact that, in construction, the design and the construction can be done by different entities while they are always done by one party in manufacturing. In other words, in design-bid-build, the owner designs and responsible for any faults in the process. In such a system, it is hard to legally bind the builder for faults over which he had no control. If the owner wants the builder to be responsible for any defect either caused by design or construction, it would be too expensive, as it would cause excessive risk for the builder. Therefore, it is reasonable to set limits to the warranty's responsibility, so the builder is responsible for the defects that are caused by mistakes in construction only. This type of warranty is called a material and workmanship warranty.

In a material and workmanship warranty, the contractor is only responsible for any defects in materials and any misconduct in installation. Therefore he is not responsible for any design defects. This type of warranty fits well with the traditional design-bid-build delivery system and has been widely used in construction. However, the difficulty of distinguishing design defects from construction defects often leads to disputes.

A performance warranty is same as product warranty in which the contractor is fully responsible for any early defects which prevent the product from performing as promised or expected.

The following is a list of the characteristics of material/workmanship and performance warranties;

- Material/Workmanship vs. Performance
    - Material/workmanship is often used in DBB project
    - A material/workmanship warranty obligates the contractor for non-design defects only
    - Often it is hard to distinguish design defects from construction defects
- Performance warranty
    - As with product warranty in manufacturing, the contractor is fully responsible for any defect
    - Often used in design-build projects

2.2.2.2 By provider (basic and extended)

In manufacturing, the warranty is distinguished by the provider as either basic or extended (service contract). Usually the manufacturer of the product provides a relatively short-term basic (often called manufacturer's) warranty and the retailer or third party provides an extended warranty usually for additional cost. Therefore, the terms "basic" and “extended” are used mainly to indicate the provider. This distinction is important because it differentiate many aspects of the warranty to which the buyer should pay attention.

In construction, the use of the terms “basic” and “extended” is different. People often refer to a “basic warranty” as one which is politically driven, enforced by law or regulation. For the U.S. federal government requires all road constructions funded by the federal government to have one year basic warranties. Therefore, if a project is fully or partially funded by the federal government, it must have at least one year of warranty, and it is not an option for either the procuring agency or the contractor. The basic warranty is mandatory for either party and it does not need to be specified on the contract, the contractor cannot be exempt from liability in any case. Similarly, some states have their own laws or regulations which require certain types of warranty on their projects. Most states require basic warranties of one to three years, and most of them are material and workmanship warranty.

In contrast, an “extended warranty” is one which the procuring agency decides to use on a project in extension (or replacement) of the basic warranty. When the procuring agent feels the need for a longer warranty to ensure the quality of the product, the agent may extend the warranty to a much longer period and specify contract. When the agency and the contractor agree on the contract, it becomes a legal agreement between two parties and is in effect. The extended warranty can be either material and workmanship or performance.

In addition to the apparent distinction between basic and extended, the purpose of a warranty is often different between two types. The basic warranty which is usually short-term and has a limited level of liability is used to protecting the owner from early and initial defects. The extended warranty, which may be much longer-term, is used to allocate the risk and responsibility of future defects that may be caused by insufficient durability and natural wearing out. The figure below shows this difference in graphical fashion.

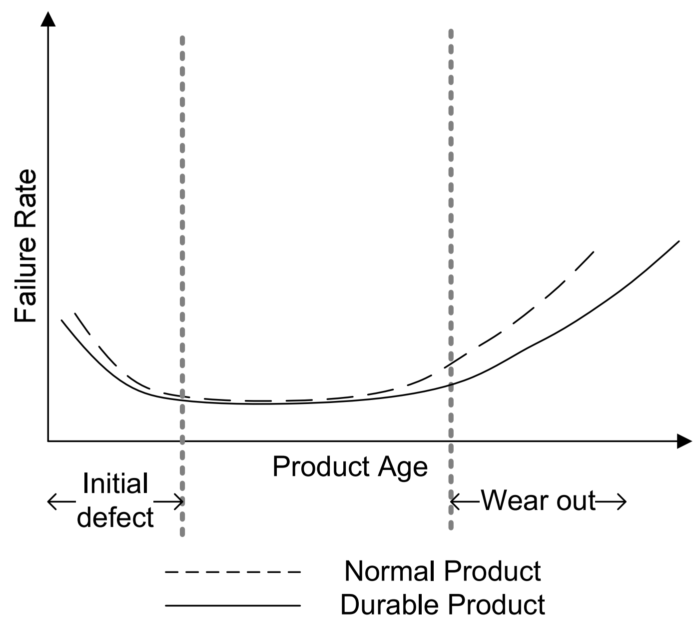

Figure 2-7: Failure Rate vs. Age for Typical Products (Nattrella 2003)

The figure above (Figure 2-8), often referred to as a bathtub curve, shows change in failure rate of a product as the product ages. In the initial stage, a product usually has significantly higher rate of failure, which is mostly caused by initial defects. An initial defect means the product does not function as expected from the beginning due to mistakes made in the installation or manufacturing process. In manufacturing, these defective products are picked out by quality inspection and testing. In construction, the basic warranty allocates the responsibility of inspecting and repairing initial defects to the contractor.

As the product ages, its reliability decreases (failure rate increase) due to natural wear which is not caused by mistakes in manufacturing. This is natural and expected. This is where the difference between a well-designed durable product (solid line) and less-durable product (dotted line) become apparent. A more durable product has a longer life, wears out slowly, and has a lower failure rate increase and costs less to repair. In contrast, it cost more to repair a less durable product. When the agency chooses to have a longer-term extended warranty and requires the contractor to be responsible for wear out defects, the contactor is motivated to design the product with better quality.

- Basic vs. Extended
    - Basic warranty – the period that the law or regulation require for every project (usually 1-2 years)
    - Extended warranty – long term warranty that is significantly long enough to change design decision (3+ years)

2.2.2.3 Other types used in construction

First, warranties in road construction are mostly of the one-dimensional expiration type. The warranty in road construction has always been one-dimensional but there is some movement toward changing to a multi-dimensional type which includes factors such as traffic volume, traffic type, etc. In a one dimensional warranty, the contractor accepts the risk of unexpected high volume of traffic and high percentage of heavy vehicles, which can significantly shorten the life of pavement. The automobile industry has been using multi-dimensional warranties which include limits on mileage in addition to time, and has been successful. Hence, the contracting agency may consider multi-dimensional warranties in the future in order to avoid high risk-premium.

Second, the usual warranty in road construction is unit warranty rather than perpetual. Each warranted item has its own warranty period, and as it expires the contractor becomes free of responsibility for that item. However, the use of perpetual warranty may also be tested in the future as the industry moves to more to long-term, performance, and life-time warranties. The design-build-maintenance contract is similar to perpetual long-term warranty.

In road construction, there have been some projects carried out with renewable warranties. Most such warranties have been on electronic equipment such as Intelligent Transportation System (ITS) and Signal Systems. In renewable warranty, as the contractor replaces an item, the warranty period restarts and the contractor held responsible for the item for an additional time period. The renewing-warranty concept is currently being used widely, but its impact on overall construction warranty usage is very limited since electronic equipment is usually warranted by the manufacturer and the contractor is merely a middleman who takes the responsibility and transfers it to the manufacturers of the equipment.

Almost all construction warranties are free-rectification type, which means the contractor has full responsibility for any cost associated with repair. Although it never had been tested, a pro-rata warranty may be a way of decreasing warranty cost. Also, there are some state agencies who utilize a warranty type which is similar to pro-rata warranty. This is usually called a maximum liability warranty. In maximum liability, there is maximum repair cost which the contract specifies for repair and the owner holds risk for cost beyond the amount.

2.2.3 Advantages and Disadvantages in the Use of Warranty

The use of warranty presents advantage and disadvantage to both the owner and the contractor. When contracting agents decide on the type and period of warranties to be used, they should consider and weight all the advantages and disadvantages. The following is a list of benefits and costs of warranty use.

- Advantages
  - Transfers risk of early (or unexpected) defect to the contractor
  - Motivates the contractor (or design-builder) to perform better (or choose better design) which improves quality and life cycle cost
  - Saves cost of inspection, future maintenance
- Disadvantages
  - Limited number of bidders – lower competition level
  - Small contractors cannot participate
  - Additional Cost
    - Possible price increase due to higher design quality
    - Expected repair cost (during warranty period)
    - Warranty bond cost
    - Profit and risk premium

2.2.4 Warranty Decision

One of the keys to success in warranty usage is making the right decision on warranty policy. Warranty decision can be a simple question of yes/no. Also, it can be a series of many sub-decisions on warranty type, coverage, period and other strategic options. In this section, the warranty-decision process is briefly introduced. The focuses of this discussion are

- The differences between the decision on legislative level and project-level warranty decision
- Ways in which the decision process differs by delivery method (DBB and DB)

For public projects, warranty decisions are usually made at two different levels. One is the legislative decision, which sets laws and regulations that governs all projects performed, administered, or funded by the government. This decision sets the minimum warranty period and coverage, which often referred to as the basic warranty. This decision considers trend, conditions of the industry in general. These warranty use regulations sets the minimum and maximum boundaries but usually leaves some flexibility for individual projects. The legislative-level warranty decision has some characteristics such as

- It only sets very minimum warranty period, coverage which is vital for the public
- It should consider not only the benefit of the public but also conditions of the industry
- It should be flexible, as each project is unique

Because the scope of this research is limited to project-level decision, no more discussion on legislative level decision is presented.

Unlike legislative decision, the warranty policy decision at project level is made based on the various specific factors such as project, owner, proposer, and current market characteristics. It is important that the decision should not be biased by the contracting agencies' past experience (either bad or good) and avoids control by one individual over the decision. The agency must consider all the factors that may influence the outcome of the warranty. The typical items that must be considered in making warranty decision are shown in the tables below.

Table 2-3: Project Characteristics

Project Type	Degree of technical difficulty
	Type and number of labor, equipment, and supervisor
	Degree of subcontracting
Project Size	Cash flow requirement
	Workforce required
Contract & procurement method	Completeness of drawing
	Bidding method
Construction Period & Timing	Inflation & seasonal factor
Project Environment	Weather condition
	Workforce & sub availability
	government and bank
Usage	Traffic Volume
	Traffic Type
Performance Prediction	Material lab & historic date
	Future cost prediction

Table 2-4: Proposers Characteristics

Expertise	Project experience
	Past project performance
	Possession of qualified staff, etc
	Reputation
Financial stability	Firm capacity
	Financial Strength
	Relationship with bank
Overhead	General offices¡¯overhead
	Expected rate of return
Partnership	Type and strength of partnership
Firm condition	Share of the firm in the market
	Current work load
	Need for work
	Staff utilization
Other company goal	Reputation promotion, expansion

Table 2-5: Market Characteristics

Bonding availability	Warranty bond amount and period
	Bonding market condition
	Surety's policy
Current Market condition	Level of competition
	Fluctuation of resource cost
	Availability labor in market
	Existence of similar project
Future market condition	Condition of economy
	Discount rate

The process of making a warranty decision is different for each type of project delivery method. The warranty policy decision in a traditional design-bid-build project is made based on the various attributes plus any pre-determined design. Since, design is completed and available prior to the warranty decision, the decision can be made based on mathematical analysis such as cost/benefit and life-cycle cost analysis. The Figure 2-9 shows the decision process in traditional design-bid-build method. The bolded rectangular box represents the decision of balancing between level of quality and cost. In this process, the agency determines the level of quality and likely cost, in other words the quality level and cost are the owner's controllable variables. The warranty decision is made based on the final design, known failure-rate curve, and other available data.

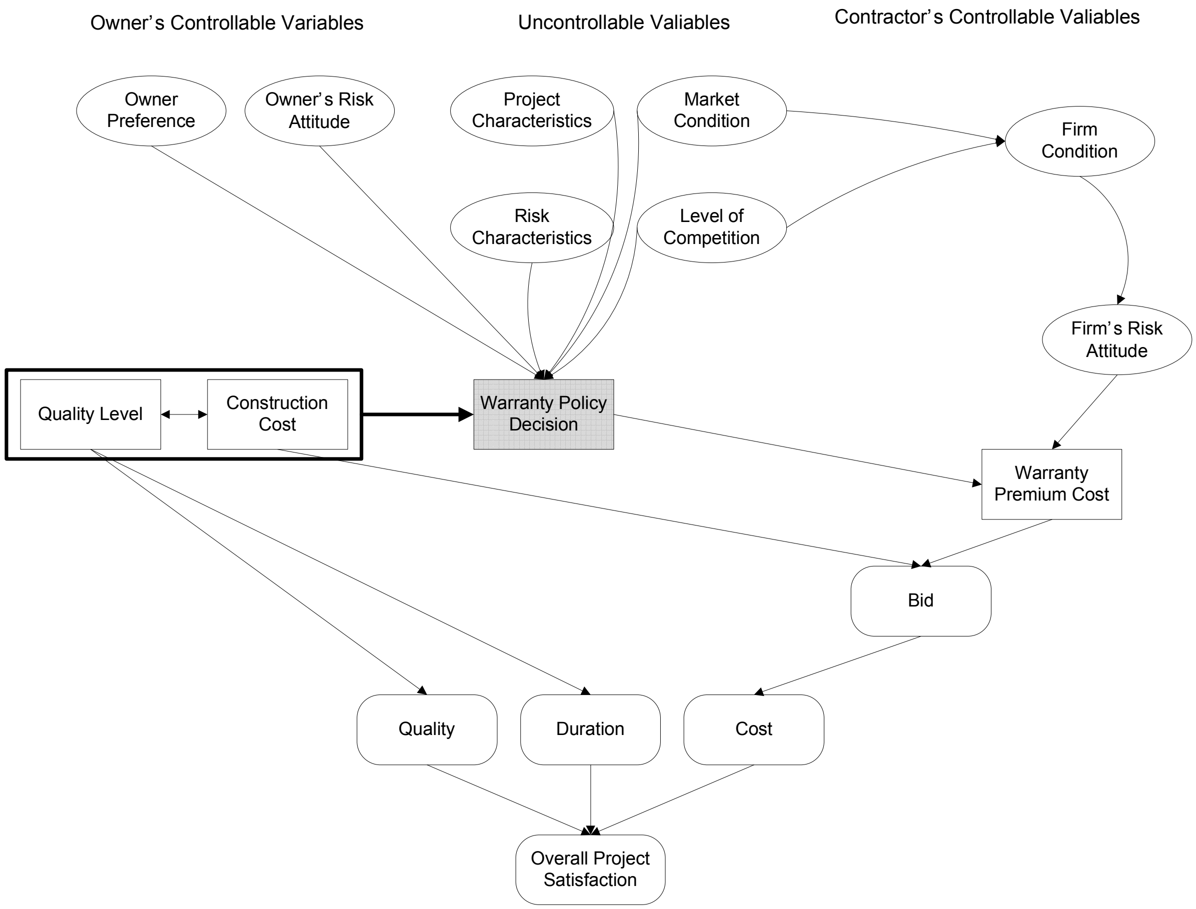

Figure 2-8: Warranty Decision Influence Diagram (DBB)

In design-build, the process shows two unique conditions. One is the timing of the warranty decision, which is made prior to the final design. Because the decision is made without completed design, mathematical analysis is often not possible. Also, the design decision is made by the design-builder not by the owner. In design-build, the quality/cost tradeoff decision is now the design-builder's controllable variable. This difference made the decision harder and more critical as the warranty provision is the sole method of owner control on the quality/cost decision

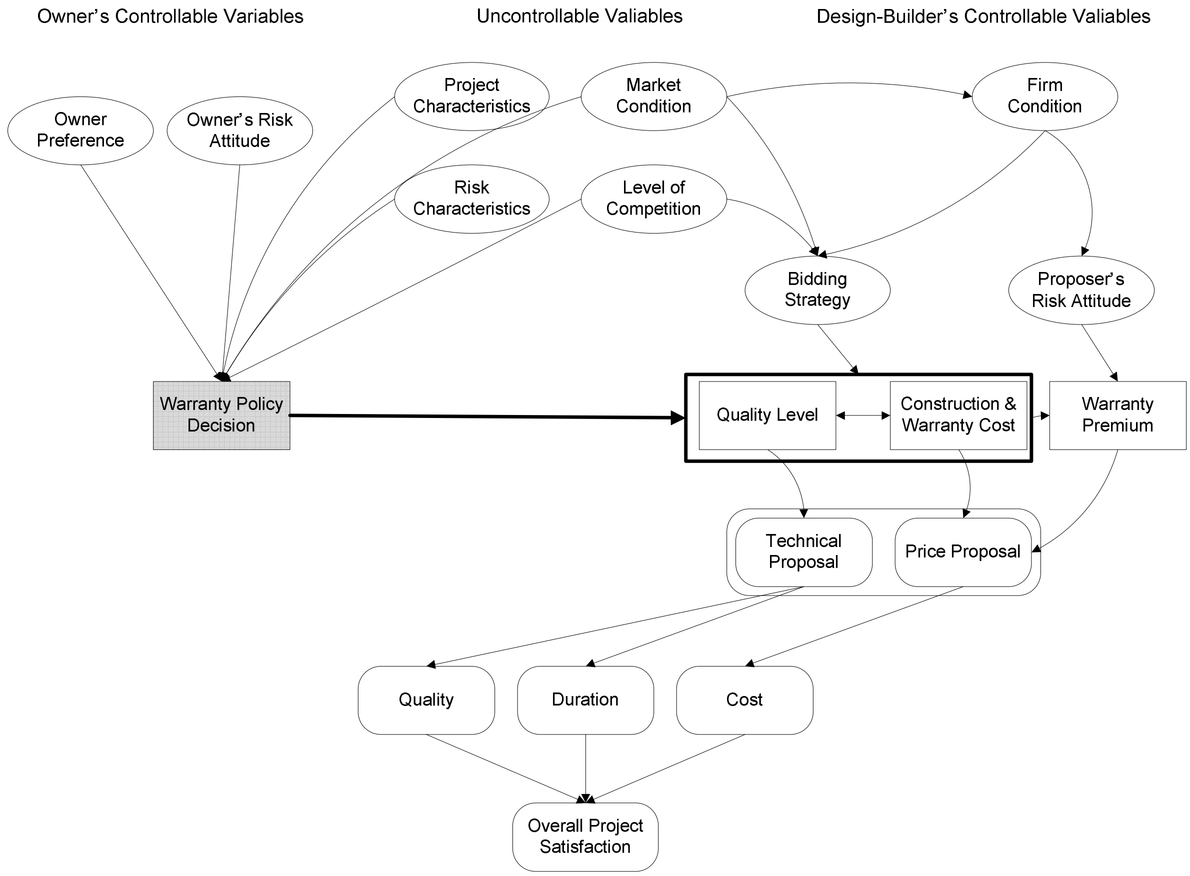

Figure 2-9: Warranty Decision Influence Diagram (DB)

2.3 Point of Departure

As shown in the literature review on design-build, risk-allocation, and warranty contracting, there is a need for research on warranty decision. The design-build procurement system allows the owner to transfer design responsibility to the design-builder and to choose to transfer any post-construction risk through the warranty contracting method. As a warranty transfers significant risk to the contractor, it is obvious that there should be some increase in the price of initial construction to compensate for expected and unexpected future cost. Also, warranty contracting offers benefits such as savings from possible future maintenance cost reduction and quality improvement. Therefore, the warranty policy decision which includes the warranty period is a key decision the owner has to make to minimize both owner's present and future costs and maintain satisfactory quality throughout the lifetime of the facility.

In this section, various studies of warranty decision and closely relevant topics are summarized. This process clarifies what has been done so far and what remains to be done. This literature review and analysis process sets the starting and ending point of this study.

2.3.1 Previous Warranty Studies and Decision Models

As warranty contracting is relatively new concept in construction, few studies have been completed; those which have been are reviewed and listed in Table 2-6. Along with studies of construction, some key studies in manufacturing are reviewed for the purpose of comparison. In the table, the research objectives and methods of each study are listed.

Table 2-6: Previous Studies on Warranty

		Won (2008)	Bayraktar et al. (2006)	Damnjanovic et al. (2005)	Oh et al. (2005)	Bayraktar et al. (2004)	Cui et al. (2004)	Thompson et al. (2002)	Lin et al. (2007)	Ben-Daya et al. (2006)	Huang et al. (2006)	Yeh (2000)	DeCroix (1999)	Singpurwalla et al. (1993)
Industry Domain	Manufacturing								√	√	√	√	√	√
	Construction	√	√	√	√	√	√	√						
Research Objective	State of Practice				√	√		√						
	Warranty Bond	√	√											
	Warranty Cost & Value						√					√		
	Warranty Period Decision	√		√					√		√		√	√
	Preventive Maintenance	√								√				
	Design-build	√												
Research Method	Optimization & Reliability			√						√	√		√	
	Survey & Interview	√	√		√	√		√						
	Real Option						√							
	Game Theory										√		√	√
	Fuzzy & Risk Analysis	√							√			√		

The first apparent difference between studies in construction and manufacturing is the length of history. While the effort to determine an optimal warranty policy began as early as 1963 in manufacturing (Singpurwalla and Wilson 1993), similar research in construction began only recently, and thus the deficiency in research experience.

Another difference between studies in the two industries is in research objectives and study domains. So far, research in construction warranty has been limited to general guidelines (Thompson, et al. 2002) and survey of current practice (Bayrakat et al. 2004). Only one study has been conducted of warranty bonds. However, that study was limited to interviewing surety companies to point out a few key factors that determine bond cost. Only recently has warranty cost estimation research been introduced (Damnjanovic and Zhang 2005; Oh et al. 2005). This study falls short of fulfilling the objectives outlined in the proposal. Also, it relied on lab data instead of more reliable historic data. In contrast, studies of warranty in manufacturing were done on various topics such as warranty decision, estimation of warranty cost, and value of maintenance. Because a survey of status of practice is the initial stage for further, more in-depth studies, it is obvious that there is a need for advancement in the science of highway construction. This *[?] can be further justified when compared to the amount of research completed in manufacturing.

Where research methods are concerned, studies in construction have been limited to surveys and interviews, with the exception of only a few. In the study of manufacturing, many researchers have utilized various sophisticated methods such as game theory, fuzzy set theory, and probabilistic risk analysis. More detailed discussion of method is presented in Chapter 3, where the methodology for this study is presented.

2.3.2 Research Needs

In several aspects this study intends to propose improvements to the current body of knowledge.

First, this study considers wider aspects of project environment such as market characteristics that may impact the warranty decision. The intention is to make the model more comprehensive than current material optimization models. The market characteristics that are considered in this study are listed in tables in Section 2.3.4.

Second, the analysis domain extends to pre-construction and post-construction stages of projects. As a warranty influences pre-construction activities such as contractor selection and design decision, any impact of such pre-construction process to warranty decision need to be considered. Similar to pre-construction, as a warranty definitely impacts post-construction activities and performance such as preventive maintenance, repair plan, and post-construction process should be included in the decision model.

Finally, characteristics of design-build project delivery and best-value procurement are examined. As the design-build process is unique among delivery systems, the warranty decision in design-build should differ from that in design-bid-build. Since all previous studies have been done in terms of design-bid-build systems, any findings and outcomes from this research would be unique for DB system useful additions to current literature.

2.3.3 Research Question and Objectives

The research question is, given project characteristics and other factors beyond project:

Given the background and scope of this research the following question was developed to guide this research.

How do warranty characteristics and project characteristics impact the performance of highway pavement projects?

To answer this question, the research has the following objectives:

- Examine various internal and external factors and determine the important factors in making warranty decisions.
- Develop a decision model that simulates warranty impacts on project performance indicators.
- Run simulations of projects with varying scopes and processes in order to examine impacts of warranty characteristics (e.g., decision variables of warranty period, limited liability characteristics, etc.) and project characteristics on project performance.

2.4 Chapter Summary

This chapter has defined the design-build delivery method in comparison to other methods. The unique characteristics of design-build such as difference in basis of contract, design responsibility transfer, and flexibility in risk allocation have been focuses of the discussion.

In the discussion of warranty contracting, two objectives of implementing warranties are presented. One objective is to transfer unexpected early defect to the design-builder and the other is to motivate the design-builder to strive for better initial quality.

In point of departure section, literature review on previous studies on warranty in both construction and manufacturing has revealed research need on warranty decision especially for design-build highway projects.

CHAPTER 3: METHODOLOGY

This chapter introduces the research and modeling methods used in this study. In the first section, an overview of the various methods and their organization is presented. A step-by-step process of model development and refinement process is organized in a horse-shoe shape. In the next section, the method-selection process is briefly described. The main methods of this research are the General Performance Modeling (GPM) and Cross-Impact Analysis (CIA) computing techniques. Some minor modeling and decision-making techniques are also applied. Finally, a more detailed description follows for each of the eight phases of the research process.

3.1 Overview

The process of this research has consisted of eight phases: 1) literature review; 2) research question; 3) model development; 4) model validation; 5) variable decision; 6) validation and verification; 7) model output and result; and 8) contribution. The phases are organized in the shape of a horseshoe (Kunz and Fischer 2008) as shown in Figure 3-1. Starting from the top-left corner and flowing clockwise to the bottom-left corner, the phases are organized sequentially. The boxes represent phases and the solid arrows direction of flow. The dotted arrows represent a check-and-feedback process.

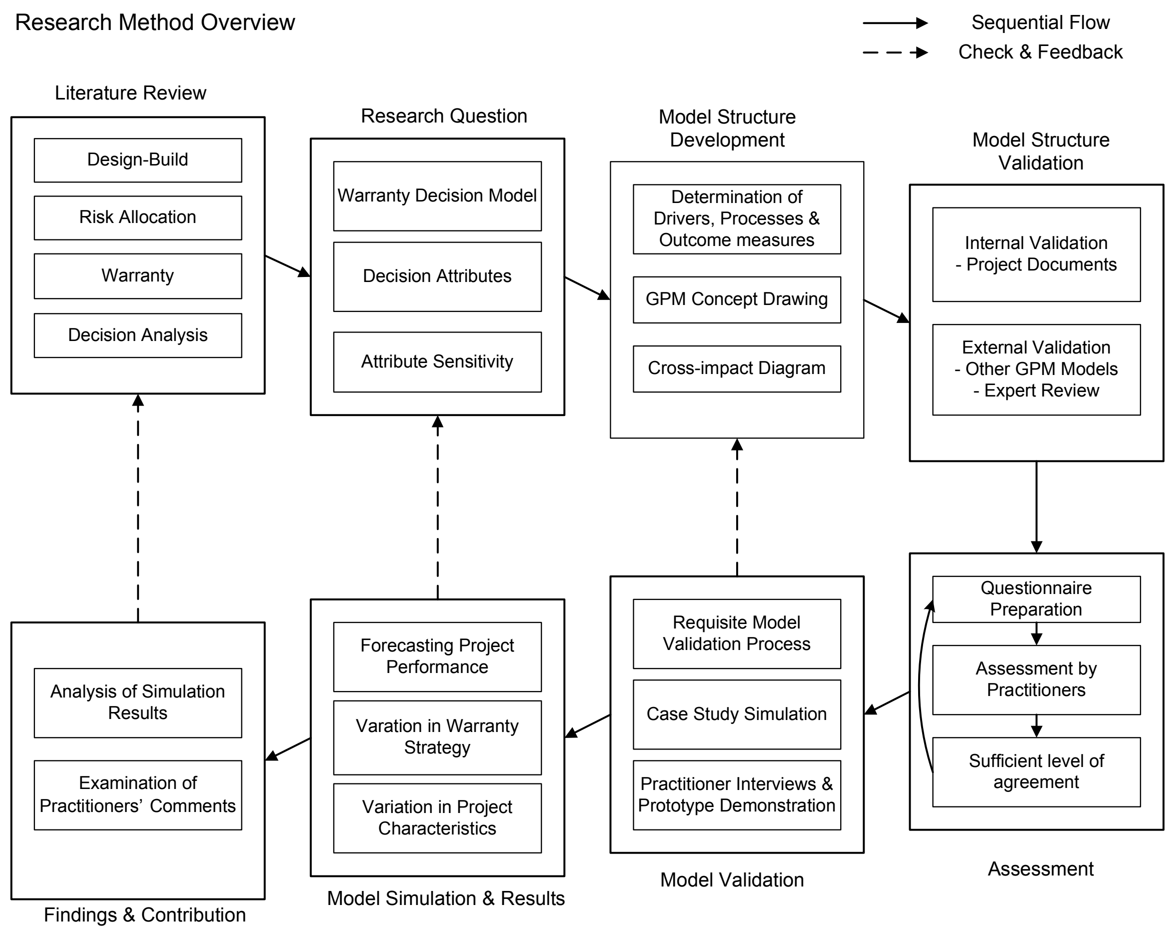

Figure 3-1: Methodology Overview

A comprehensive literature review is presented of three relevant topical areas – warranty, design-build, and risk allocation and decision analysis. In the review of warranty literature focuses on general characteristics, types, current state-of-practice, and state-of-research are main focuses. The review of design-build literature covers unique characteristics of design-build process in comparison with traditional methods. Some key topics of the design-build review are basis of contract, procurement process, contracting methods and risk-allocation principles. Finally, various methods of decision analysis are reviewed for the purpose of determining the method most suitable for the problem at hand.

From the review of current methods of warranty decision, the need for a new decision model is determined and the research question formulated. In order to answer the research question, a GPM model is developed in the model-structure development and variable value decision phases. In model-structure development, the GPM conceptual model is constructed. Prior to variable decision, the structure of the model is evaluated and refined through model structure validation. Once the model structure is validated, the necessary input values such as initial probability of occurrence and cross-impact rating are decided through practitioner interviews.

Once the model is developed completely, validation procedure of the newly developed model is performed. Findings from model validation are to be used for refinement of the model. After the model is developed and validated, decision simulation is performed, and the results should yield some new findings, which should answer the research question. Finally, the model-development process itself and output of the model (simulation results) should afford some contributions to both academia and industry.

More detailed description of each of process is provided in each of the later sections.

3.2 Decision Methods

In this section, some decision-analysis methods are reviewed that are closely relevant to the model in development. This review provides fundamental information about the model structure and illustrates the model-development process.

The model that is being developed through this study is a GPM, which was first developed and introduced by Alarcon and Ashley (1996; 1998). The GPM introduces a unique model-structuring mechanism designed for project-performance measurement that can be utilized for making various alternative decisions. In terms of decision analysis, the GPM utilizes a cross-impact analysis (CIA) method first introduced by Gordon and Hayward (1968) and applied to many future event prediction models. Along with GPM and CIA methods, more fundamental decision-analysis concepts such as influence diagramming and decision-tree methods are described in this section.

3.2.1 Influence Diagramming

An influence diagram is a compact graphical representation of a decision- making situation. It is a generalization of a decision network, in which decision- making problems are modeled and solved. The strength of this method is that it makes possible the compact representation of a problem, so that decision makers can oversee the decision problem on a piece of paper or single screen. One drawback of the method is that it makes it difficult to perform numerical analysis or probability computation directly from the diagram (Clemen 1996). Therefore, it is often used along with other means of modeling and analysis technique such as decision tree.

The following figure is an example of an influence diagram, which represents a simple decision to schedule a concrete pour.

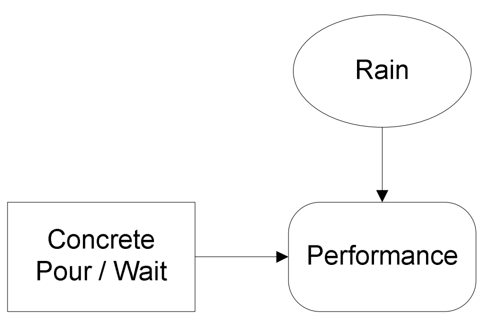

Figure 3-2: Influence Diagram Example I

The sample problem is deciding whether to schedule a concrete pour on a certain day. The decision is as simple as to pour or wait. In the case of deciding to wait, the construction will be delayed, and there will be some negative effect on project performance. However, in the case of waiting, it does not matter if it rains on that day. The other possible decision is to schedule a pour on that day. In this case, the performance outcome is dependent on the weather conditions. If it rains on that day, the poured concrete will not cure properly. The overall performance outcome in that case would be somewhat less satisfactory than in the waiting option.

As represented in the influence diagram above, there are two variables that influence the performance outcome. One is the decision the project scheduler is to make, and the other is the chance of rain. In order to make a quality decision, the decision maker should examine the chance of rain and consequences of rain for project performance. The influence diagram is clearly helpful to overview the problem at hand. However, as mentioned earlier, it is difficult to perform computation solely from the diagram. To illustrate the question better, the following assumed numbers are given.

Decision options: Pour concrete / Wait Chance of rain: P(Rain) = 0.2 Performance Rating Wait = 7 Pour (no rain) = 10 Pour (rain) = 1

Now all the information is given, but direct computation cannot be done easily from the influence diagram. Therefore, another decision-modeling technique is needed.

3.2.2 Decision Tree

The decision tree is another commonly used method which is superior for visualization of possible outcomes and computation of expected values. The following example is a decision tree for a concrete-pour decision.

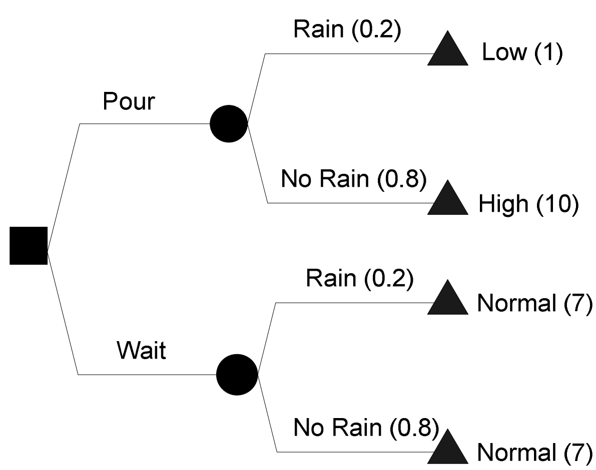

Figure 3-3: Decision Tree Example

As shown in the figure, there are four possible outcomes (2^2). Two outcomes in the wait branch are the same result as the normal performance outcome. In contrast, two possible outcomes in the pour branch are difference outcomes, high or low performance, which are dependent on the event of rain. Expected performance outcome values for each decision can be calculated with simple arithmetic. In the example above, the option of scheduling a concrete pour appears to be a better decision, as its expected value (8.2) is higher than that of the wait option (7).

Although decision tree is a great method for computation of simple problems, it is limited as to size, and its complexity grows exponentially as the problem involves more decision options and events. The following is an influence diagram of a problem that has an additional chance node – forecast. Now there are a decision option and two random variables. This means that there will be eight different outcomes (2^3), and the decision tree for this problem is twice as large as the previous one.

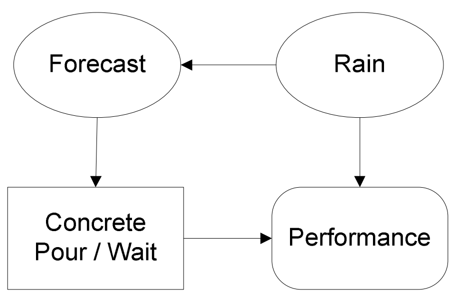

Figure 3-4: Influence Diagram Example II

The limitation of the decision tree method is obvious, as in real-world decisions there will be many decision attributes, and the decision tree will become unwieldy. Also, when there are multiple variables in a decision and their interaction must be considered, a decision tree may not work optimally. In Figure 3-4 above, the new variable, weather forecast, is certainly affected by the chance of rain (as it is ought to be). Also, the result of the forecast possibly changes the prediction of rain. If the forecast predicts rain, there will be a greater chance of rain than there will be if the forecast is indefinite. It is difficult to model such interaction among variables using the decision-tree method. When a decision becomes more complex, more sophisticated decision tools become necessary. One method which makes modeling of interaction possible is the cross-impact analysis method.

3.2.3 Cross-Impact Analysis (CIA)

The cross-impact method is an analytical approach to deciding the probabilities of a variable in relation to all other variables (Asan and Asan 2007). The probability of occurrence of an item can be adjusted from interactions among the variables. In other words, the outcome of one variable can influence the outcomes of other variables. In the concrete-pour decision problem, it is obvious there will be some interaction between weather forecast and actual weather outcome. Theoretically, those interactions can still be expressed in an influence diagram (as in Figure 3-4) and the probable outcome can be computed with a decision tree. However, the cross-impact method provides a more systematic computing mechanism which is simple as well as powerful. The next paragraph briefly summarizes the CIA mechanism as described by (Dalkey 1972).

The first step in CIA is to define the events to be included in the study. Some events have fixed value, while others have probabilistic characteristics. The initial set of events is usually determined from a literature search and interviews with experts in the field.

Once the event set is determined, the next step is to estimate the initial probability of each event. These probabilities indicate the likelihood of each event’s occurrence. At this stage, the initial probabilities are judged in isolation, which means that interactions among events are not considered at this phase. Similar to event-set determination, initial probabilities are often found through literature review and expert consultation. When the probability of an event is determined from expert input, it is important that the expert's judgment be unbiased, consistent, and accurate. Therefore, an additional inquiry method, such as Delphi, is often used along with CIA in order to improve accuracy level (Goldon and Hayward 1968).

The next step in the analysis is the consideration of interactions among events. In CIA, this is done through estimation of the conditional probabilities. Typically, impacts are estimated in response to the question, "If event *m* occurs, what is the new probability of event *n*?" If there is no interaction between events *m* and *n*, impact on *n* by *m* would be none, and the probability of occurrence of event *n* stays the same regardless of the outcome of *m*. When there is some interaction, the outcome of event *m* impacts event *n* in either a positive or negative direction. In addition, depending on the strength of interaction between events *m* and *n*, the magnitude of impact on *n* by *m* can be rated from 1 to 3. Combining direction (+, -) and magnitude (1 to 3), the cross-impact index of each pair of events is given one of seven ratings, -3 to 3 (-3, -2, -1, 0, 1, 2, 3) (Honton, et al. 1985).

Once the cross-impact rating is identified, the next step of CIA is finding the new (posterior) probability of an event. In the weather-forecast example, the outcome of the forecast has some impact on the probability of actual rain. Earlier, the initial chance of rain was found to be 0.2. This is the probability estimated input from the weather forecast. As more information (forecast) becomes available, the probability estimation can be updated. This updated probability is called posterior probability. The question is what would the posterior probability be when forecast predicts either rain or no rain.

Initial P_{Rain} = 0.2
Initial $P_{Forecast\text{-}Rain}$ = 0.3

Posterior P_{Rain} = P (Rain | Forecast-Rain) = ?

Posterior probability is conditional probability of rain, given that the weather forecast does predict rain. According to probability theory (Bay's Theory) and the influence-diagram computing method, posterior (conditional) probability can be calculated with known P_{Rain}, $P_{Forecast\text{-}Rain}$, and P (Forecast-Rain | Rain). However, P (Forecast-Rain | Rain) is not known. Therefore, either P (Forecast-Rain | Rain) or P (Rain | Forecast-Rain) has to be estimated.

One reason for using CIA is that it provides a systematic approach in estimating conditional probabilities. It can be difficult to estimate P (Rain | Forecast-Rain) directly. However, it may be easier if it is only a question of rating the weather forecast within -3 to 3 range. The following two questions illustrate the difference.

A. What is probability of rain if the forecast predicts rain?

B. How relevant is the forecast (in scale of -3 to 3) to actual rain?

Non-experts may have trouble answering question A, but find it a lot easier to answer question B, because almost everyone has some experience comparing weather forecasts and actual weather and may easily pick one of the seven rates. For example, if a cross-impact rating of +2 (forecast-rain impact the rain moderately in positive direction) is chosen, now with known cross-impact index, posterior P_{Rain} can be computed.

In their study, Honton et al. (1985) derived the following equation:

$$PosteriorPn = \frac{InitialPn \times C.V.}{1 - InitialPn + (InitialPn \times C.V.)}$$

Where C.V.(coefficient value) =
  │cross-impact index│+1 (if index ≥ 0)
  1 / │cross-impact index│ (if index ≤ 0)

With a known cross-impact index, the Posterior Probability can be found using Honton's equation.

Cross-impact index (forecast to rain) = +2
C.V. = │+2│+1 = 3
Posterior P_{Rain} = P (Rain | Forecast-Rain) $= \dfrac{0.2 \times 3}{1 - 0.2 + (0.2 \times 3)} = 0.43$

Therefore, when the forecast predicts rain, the probability of rain becomes 0.43, which is higher than what is estimated without forecast information. Likewise, all the posterior probabilities can be computed by the same procedure. As this example illustrates, the cross-impact method enables decision makers to address more complex problems.

3.2.4 General Performance Modeling (GPM)

General Performance Modeling (GPM) was developed on the basis of CIA. GPM features two strengths in comparison with the original CIA method.

3.2.4.1 Organization of variables

In real-world decisions, things get more complex when there is more than one decision (multiple, sequential decision), decision attribute, and outcome measure. Alarcon first introduced GPM to approach such decision making in a more systematic, organized fashion (Alarcon and Ashley 1996; 1998). This method can most easily be explained through an example. Figure 3-5 is an expanded influence diagram of the same concrete-pouring decision discussed earlier. The diagram is an example of a decision that is used only for the purpose of demonstration.

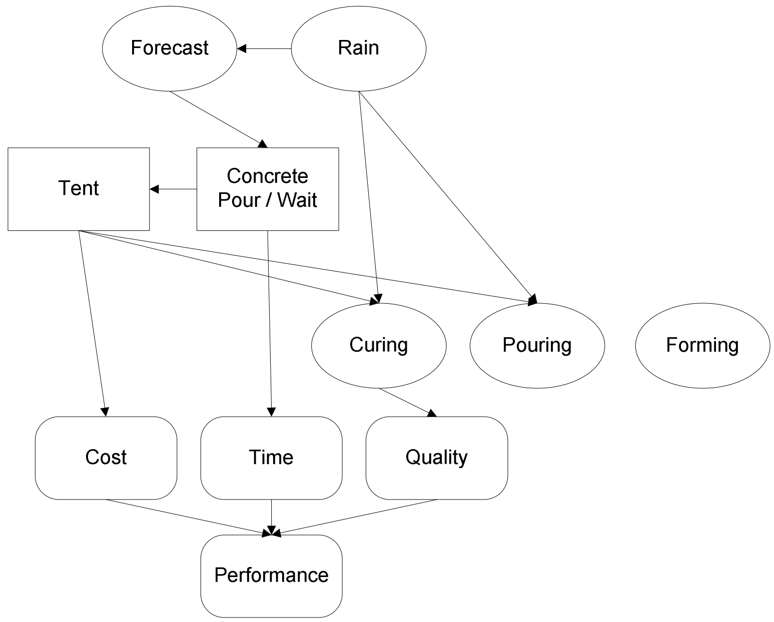

Figure 3-5: Influence Diagram Example III

Compared to the previous influence diagram (Figure 3-4), Figure 3-5 differs in two aspects. First, there are two decisions instead of one. In addition to the pour/wait decision, there is an optional decision to purchase a tent to protect the concrete during the pour. If the project manager decides to pour concrete, the work is influenced by the weather conditions. In this case, the project manager may make another decision about tent purchase. With a tent purchased, the potential damage in case of rain will be diminished, because a tent prevents rain from dropping onto the poured concrete, delaying curing, and protects workers from rain during the pour, but does involve additional cost. In GPM, these optional decisions are called strategies, and, combined with the main decision, they make up various decision alternatives.

In GPM, uncertain events that are initiated or influenced by the decision are defined as drivers, in this example, rain and forecast. The event of rain is a driver because it comes into in play only in cases of deciding to pour concrete, and the event of rain influences the project outcome. If the decision is to wait, the event of rain does not impact the project at all.

Another deviation from the previous decision model is that there are specified construction procedures that are influenced by the decision and drivers. In this example, concrete pouring is subdivided into three separate processes of forming, pouring, and curing. As the diagram shows, the event of rain influences pouring and curing, but does not have much impact on forming. Rain will significantly influence the curing of concrete as it prevents drying, and may have some impact on pouring because it lowers productivity. However, the rain does not influence forming, which is done prior to the pouring date. With a breakdown of the procedure, it becomes clearer why and how an event influences the outcome.

Finally, instead of a single outcome, this model has multiple outcome measures – cost, quality, and time (schedule). Obviously a decision to wait will influence the schedule, but it will not do any damage to quality. On the contrary, a decision to schedule pouring influences quality, as it may rain, but does not influence schedule. The option of purchasing a tent will influence cost, but can prevent damage to the curing and pouring activities in case of rain. In GPM, these multiple measures are called outcomes, which are combined to make up the performance measure.

The following table summarizes the decision components as defined in GPM.

Table 3-1: GPM Decision Component Example

Alternatives / Strategies	Drivers	Processes	Outcomes
Pour / Wait	Rain	Forming	Cost
Purchase Tent	Forecast	Pouring	Quality
		Curing	Time

As explained above, with its more systemized and organized decision structuring mechanism, GPM provides a more comprehensive decision model which is more likely to lead to a quality decision.

3.2.4.2 Simplified (patterns) approach

Original CIA approach

A possible approach to the estimation of conditional probabilities is to estimate of the direction and strength of the "impact". Honton, et al. (1985) introduced a rating system to define strength and direction of impact. Table 3-2 summarizes six rating indices.

Table 3-2: Index Value for Strength and Direction (Honton et al. 1985)

Index value	Meaning
3	Significantly increases the probability
2	Moderately increases the probability
1	Slightly increases the probability
0	No effect on the probability
-1	Slightly increases the probability
-2	Moderately increases the probability
-3	Significantly increase the probability

Impact from occurrence of one event to the other can be defined using suggested index values. The impact ratings for pair each of events are determined from expert assessments. Table 3 shows across-impacts between two variables – design and repair cost (by contractor). This table summarizes index values, which are defined as the strength of direction of impact from column event to low event.

Table 3-3: Cross-Impact Matrix (Original method)

				Design				
	Events	Inc. Pro.	Adj. Pro.	PP	P	O	N	NN
Repair Cost (contractor)	PP	0.1	0.25	3	2	1	-3	-3
	P	0.2	0.19	2	1	0	-2	-2
	O	0.4	0.4	0	0	0	-1	0
	N	0.2	0.11	-1	-1	0	0	3
	NN	0.1	0.05	-2	-1	0	2	2

To construct the cross-impact matrix table above, each impact rating (i.e. design (PP) to repair (N)) is assessed by experts. Once the matrix is constructed, conditional (adjusted) probabilities of event set of repair cost given each outcome** event of design. For example, in a given Monte Carlo simulation run, outcome event for design is P. Then, adjusted probabilities can be found by use of the equations below (Honton, et al. 1985).

$$AdjustedP_n = \frac{InitialP_n \times C.V.}{1 - InitialP_n + (InitialP_n \times C.V.)}$$

Where C.V. (coefficient value) =

$|$ cross-impact index $|$ +1 (if index ≥ 0)
1 /($|$ cross-impact index $|$ +1) (if index < 0)

Adjusted P (Repair Cost)$_{PP}$ = $\frac{0.1 \times 3}{1 - 0.1 + (0.1 \times 3)} = 0.25$

Similarly, the rest of adjusted probabilities are found

Adjusted P (Repair Cost)$_{P}$ = 0.19

Adjusted P (Repair Cost)$_{O}$ = 0.40

Adjusted P (Repair Cost)$_N$ = 0.11

Adjusted P (Repair Cost)$_{NN}$ = 0.05

For each variable pair, probabilities can be adjusted by the same procedure. With all probabilities adjusted, the model will select event outcomes according to new probabilities.

Simplified (Assessment patterns) approach

The problem of original CIA method is apparent. It requires 25 assessments to find new probabilities for one pair of variables. With 19 variables, the number of required assessments exceeds nine thousand. In order to simplify the process and reduce number of assessments required, Alarcon and Ashley (1998) suggested an alternate method. Each set of assessments (25 in number) is replaced by a single assessment pattern, which can be determined relatively easily.

In order to compute adjusted probabilities, the simplified assessment is expanded to a matrix of 25 assessments according to predetermined patterns. In this method, the participating experts select one pattern that represents impact rating from one variable to the other. Types of patterns and a graphical description of this introduced-simplification method is shown in Figure 3-6 below.

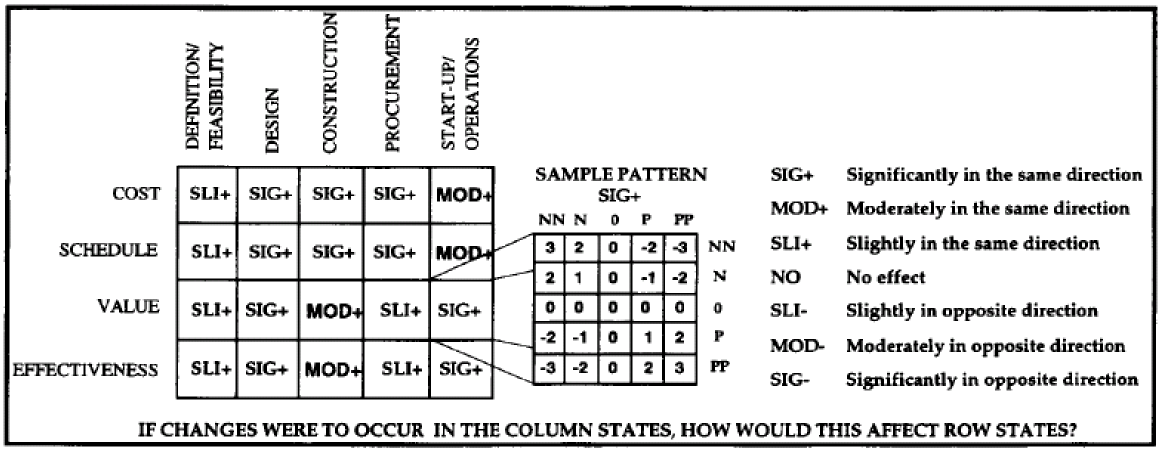

Figure 3-6: Simplified Cross-Impact Matrix with Pattern Types (Alarcon and Ashley 1998)

Table 3-4 below illustrates how simple and easy the assessment becomes when the simplified-pattern method is used. Functionally, Table 3-4 is the same as Table 3-3 presented previously. Once the cross-impact relation pattern is assessed in a single judgment, the full cross-impact matrix is estimated from the pattern. Table 3-5 is an example of cross-impact table estimated from a selected pattern. It is comparable to Table 3-3, and the resulting adjusted probabilities are close enough to those in that table. Table 3-6 presents seven patterns and interpretation as developed by Alarcon and Ashley.

Table 3-4: Cross-Impact Matrix (Simplified)

	Design
Repair Cost (contractor)	SIG +

Table 3-5: Cross-Impact Matrix (Estimated from pattern)

				Design				
	Events	Inc. Pro.	Adj. Pro.	PP	P	O	N	NN

Repair Cost (contractor)	PP	0.1	0.25	3	2	0	-2	-3
	P	0.2	0.20	2	1	0	-1	-2
	O	0.4	0.4	0	0	0	0	0
	N	0.2	0.11	-2	-1	0	1	2
	NN	0.1	0.04	-3	-2	0	2	3

Table 3-6: Cross-impact Index Symbols (Alarcon and Ashley 1996; Honton et al. 1985)

Symbol (Alarcon)	Interpretation
SIG +	Significant impact in the same direction
MOD +	Moderate impact in the same direction
SLI +	Slight impact in the same direction
NO	No impact
SLI –	Slight impact in the opposite direction
MOD –	Moderate impact in the opposite direction
SIG –	Significant impact in the opposite direction

3.3 Research Question and Method Selection

In the previous section, characteristics and strengths of the GPM method were introduced in comparison with conventional influence-diagramming, decision-tree and CIA methods. In this section, the research question is examined to show why GPM is the proper method for this study.

The research objective is to decide upon the proper type and period of warranty for a specific project. It appears that it is an optimization question and, in fact, some previous researches in both manufacturing and construction have attempted to solve the problem using various optimization methods (Blischke and Murthy 1994; Damnjanovic and Zhang 2005; DeCroix 1999; Oh et al. 2005; Yeh and Lo 2000; Yun 1997). However, it is clear that previous models cannot fulfill the needs of decision makers completely.

First, it can be assumed that few decision makers make warranty decisions on the sole basis of life-cycle-cost optimization. There are many other factors to be considered both within and outside of projects. Second, the delivery and contracting process of design-build is quite different from those of manufacturing and of design-bid-build. Unlike design-bid-build, in design-build, the contractor has some aspect of control over design selection, and it is up to the contractor to perform quality-cost tradeoff analysis to maximize his expected profit or achieve his other objectives. Therefore, warranty decision in design-build is not as straightforward as finding an optimum warranty that affords minimum life-cycle-cost and applying the findings in decisions about design and construction method. The warranty decision in a design-build project must be considered a factor that influences the contractor's cost-quality trade-off decision. Finally, one of the critical reasons for which a warranty decision cannot be made through optimization-modeling technique is lack of reliable data. Warranty use in U.S. highway construction has a relatively short history, and not much data is available as yet. Most of the optimization models listed above were developed in the manufacturing industry, where warranty has been used widely, and there are enough data to derive reliable results from numerical analysis. At this time, in the construction industry, there is not enough data to lead to reliable conclusions through the use of numerical life-cycle cost-optimization methods that were developed previously.

Hence, the warranty decision should be approached from a different direction. If a warranty decision is not quite an optimization question, or it is not feasible using conventional optimization models, it can also be considered an alternative- selection question or one of selecting the most suitable strategy for a given project. Each warranty period and type can be considered alternative and the decision is selecting the one that fits the given project.

As described earlier, GPM is one method that has been proven to work for alternative comparison and selection decision. Since GPM was developed specifically for the purpose of comparing not only costs but also likely performance results for various decision alternatives, it is suitable for warranty decision in construction, where project outcome is measured in terms of quality as well as cost. Therefore, the GPM method with some modifications is selected as the main method of decision modeling for this study.

3.4 Model Development

In this section, a GPM model is constructed for warranty decision in design-build highway projects. GPM is a modeling method that involves a unique way of structuring the question and process; therefore it is important to organize all the puzzle pieces their proper locations in order to have a complete GPM model which will eventually lead to reliable results.

3.4.1 Decision Alternatives

Decision alternatives are various decision options available to the decision maker. In this study the main decision alternatives have to do with warranty period. In addition to alternatives of period, there can be various strategies -- additional requirements and risk limitations which the project owner or agency may choose to include in the warranty (e.g., preventive maintenance during the warranty period, submission of warranty bond, limited liability, and pro-rata).

3.4.2 Drivers

Drivers are variables which are directly affected by the decision and conditional variables and which affect the process. It is important to think through what could be changed by the warranty alternatives and draw up a complete list of drivers. Such a list is presented in Section 4.1.3.

3.4.3 Processes

Construction processes are typically used to describe the functional characteristics of a construction project and are useful in identifying key information and resources. The processes are the project-related management and engineering processes that are required to execute the construction. They should be mutually exclusive and totally exhaustive of the construction process. In other words, there should not be any overlapping among processes, and the complete list of processes defined here should cover the whole construction process. A complete list of processes is presented in Section 4.1.4.

3.4.4 Outcomes

The outcome measures refer to methods of judging project performance. They can be cost item, quality measures, or other objectives that the owner wants to achieve in the project. The outcomes for the warranty model consist of various life-cycle costs. A complete list of outcomes is presented in Section 4.1.5.

3.5 Model Structure Validation

Once all the elements of the GPM model are identified and structured, prior to actual data collection and simulation, the model is validated for its content. The model structure validation process is intended to ensure that the newly developed model meets two criteria:

- Comprehends and identifies all the decision attributes in properly** organization,
- Fulfills its intended purpose and successfully reflects real cases

Two different validation methods are used for model structure validation. One is internal and performed within the model by the model developer. The other is external, performed utilizing outside sources such as other previously published GPM models and the advice of GPM experts.

3.5.1 Internal Validation

3.5.1.1 Project document review

Applicability to actual projects is tested through examination of actual project documents such as RFPs and contractor proposals. This test determines not only if the model is applicable but also if the model is comprehensive of all the factors considered in actual warranty decisions. For the purpose of model structure validation, procurement documents of three design-build projects in Washington State are used -- Thurston Way (2001), Everett (2005), and Kirkland (2005).

3.5.2 External Validation

External validation consists of two different tests. One is a comparison with other GPM and CIA models previously developed and published. The other is expert consultation.

3.5.2.1 Comparison to Other GPM Models

Although each GPM model is different in its questions, variables, and results, the overall structure and organization should be the same. Therefore, examination of a few GPM models should indicate whether the newly developed model is proper and complete. A comparison chart and summary table are to be constructed in this process.

3.5.2.2 Consultation

In this test, the model structure and framework are reviewed by experts who have sufficient experience with GPM or CIA modeling. The purpose of this step is to validate the model as a proper GPM model with rational selection and organization of variables -- decision alternatives, drivers, process, and outcomes. For the purpose of model framework validation which does not require any statistical validation, the model developer consults with four or five other people. He/she contacts several individuals who have studied and published GPM or CIA models and asks their opinions. Consulting with people who have experience developing a GPM or CIA models should be helpful in finding any defect in the model structure.

3.6 Variable Decision

Once the model is constructed, validated, and refined properly, the values of its variables must be decided. Some variables are fixed values, while others are in probabilistic-distribution form. Each variable is defined in its proper form. In this GPM model, there are three types of variables, which are condition variables, initial probability of events, and cross-impact ratings of pairs of events. In this model, variables are decided by user input, numerical analysis, and practitioners' input based on their knowledge and experience.

3.6.1 User Input

Since most conditional variables are project-specific and the model should remain generic, some conditional variables are left blank for user input. As the user inputs the values according to the project characteristics, the model takes them into the decision process along with other fixed variables, and utilizes them to make the decision. For the purpose of simulation and model validation, those user input variables are to be assumed by the developer. The following are examples of typical condition variables that are decided from user input.

Project Size: ________
Select one of followings
Large: >300 million dollars
Medium: 300 million dollars > > 30 million dollars
Small: < 30 million dollars

Funding Limitation: $________ Million
Input the contract price in million dollars

Allowed warranty length: ______ to _____ years
When there is no limitation, leave it blank

Figure 3-7: User Input Example

Some user input variables are of a selection type, just like the first example (project size). In this case, the user is asked to select one of the options provided. Some user input values are simple integer entry type. For clarification, brief instructions are provided and the process will be facilitated by the author.

3.6.2 Analytical Methods

In finding the initial probability of some events various analytical methods are used. This can be illustrated through the concrete-pour example. In finding the probability of rain, the appropriate method is analysis of historical data. For a given day of the year and location, there are data that provide a good idea of the probability of rain. As with finding the probability of rain using historical data, some initial probability of events can be found by analytical methods.

3.6.3 Questionnaire and Interview

Along with some initial probability decisions, most cross-impact ratings of pairs of events are decided through guided-questionnaire and interview methods of collecting information.

For finding the probability of rain, data is readily available, and the initial probability can be found from simple analysis. However, this is not the case for most events. Some initial probabilities cannot be found from analytical methods for various reasons, such as lack of reliable data. For such events, experts' experience can be especially useful information. People who have abundant experience in the subject area can provide reliable estimations. In order to collect information from experts, questionnaires and interviews are usually effective.

Questionnaire is one of the most widely used empirical research methods, which researchers use to identify and describe the hypothesis without scientific, logical, or analytical proof. In empirical research, data are collected directly or indirectly from experiments, experience, or observations (Chen and Goodman 1998; Khun 1962). In order to collect empirical data indirectly from other people, a questionnaire is often utilized. A questionnaire is a set of questions for gathering information from individuals. They can be administered by mail, telephone, or in face-to-face meetings (Department of Health and Human Services 2008).

For this model, some variable values are to be estimated from experts' experience through questionnaires. Questionnaire is selected as the method of information collection to estimate initial probability and cross-impact rating of events. In addition to questionnaire, each participant is interviewed for any additional comments.

The questionnaire-construction and interview procedures are performed as suggested by Lipinski (1990) in his paper on dynamic cross-impact modeling technique

(DYCIA). He suggested a method of determining strength of interaction among events from a workshop involving a group of experts. Because it is difficult to arrange a workshop and gather all the experts, such information can be gathered from questionnaires and phone interviews.

Participants in the expert panel were chosen based on their knowledge and experience on warranty. The model developer started contacting participants in a pavement-warranty symposium held in Grand Rapids, MI, in 2003 (Ferragut 2003). A total of fifty-seven people of various backgrounds (academia, contracting agent, contractor, surety) participated the symposium, of which the final includes a list of contact information. Other than those listed, authors of published warranty studies and contracting agents who have participated in projects with a warranties were asked to contribute information.

Once participants were decided, the information gathering and variable value decision making was performed as follows:

1. Instructing the participants

   Prior to questionnaire, the model developer described the CIA, GPM mechanism, information-gathering procedure and definition of each variable. This step was done by phone and e-mail. The questionnaire also included a brief introduction explaining the procedure, along with a definition of variables.

2. Ranking expertise

   The questionnaire began with self-evaluation questions in order to determine the level of expertise of each prospective participant. In Lipinski’s DYCIA method, judgment of each expert is weighted differently by the ranking of expertise. Based on self-evaluation criteria, each expert is ranked (1 to 5) and his/her judgment is weighted. Table 3-3 below is an example.

Table 3-7: Weighting of Expert's Judgment (Lipinski 1990)

Expert's Substantive Expertise Ranking	Relative Weight
1	1
2	2
3	4
4	8
5	16

3. Initial probability and cross-impact rating

   In this step, each participant is asked to answer the questionnaire, which included initial probability of each event and cross-impact matrix. In DYCIA, group discussion is conducted prior to any cross-impact rating decision; however, since this is done by questionnaire instead of workshop, discussion is replaced by questionnaire guidance and phone interview.

4. Encoding and processing the results

   Once participants' judgments are collected, the developer consolidates the data and draw initial conclusions about values. Participants' expertise ranking are to be applied in this step also. Prior to the next step, the input values are examined using a rule-of-triangle test (Section 3.7.1).

5. Feedback and second-round questionnaire

   Because this process utilizes questionnaire instead of workshop discussion as Lipinski suggested, feedback is examined and a second-round questionnaire conducted to eliminate personal bias and mistakes and improve the accuracy of information. The results of the first-round questionnaire are shared with participants, who are asked to reply to the same questionnaire. If any inconsistency is found by the rule-of-triangle test, it is also reported to the participants. With the results known and access to the other participants' opinions, participants should be able to provide more reliable information.

3.7 Model Validation

Model validation is an essential process in model development if the model is to be accepted and used to support decision making. Validation ensures that the model (Macal 2005):

1. Addresses the right problem
2. Meets intended requirements
3. Provides accurate representation of actual systems

To validate the developed model, two methods are used. Primarily, the model is validated through a requisite model-validation process. Then, as a secondary method, case simulation tests with extreme values are used to confirm the validity of the model.

3.7.1 Requisite Model Validation

For the purpose of validating the specific model developed in this research, the requisite model validation method is used as described by Phillips (1982; 1984). It is a people-based empirical approach often used in decision models in the social sciences.

The fundamental basis and also distinguishable characteristics of requisite model are that it has been developed and also validated in comparison to socially accepted knowledge pools rather than actual systems. As proposed by Phillips, requisite model is defined as a "simplified representation of social understanding whose form and content are sufficient to solve a particular problem" (1984). This definition is similar to the definition of any general model. The only significant difference is that the model does not directly represent any real system, but instead a social understanding of a real system.

This difference (between a requisite model and a general model) in model definition causes some differences in the approach to its validation. In order to validate a general model as representative of a real system, the model has to be compared to the mechanism, constitution, and results of the actual system. This direct-comparison requirement can be problematic when not much about the actual system is known. In a requisite model, the model is validated through comparison with social understanding of the system instead of the actual system. This concept not only makes the validation easier, but also more logically sensible, especially in the social sciences.

In his studies, Phillips proposes guidelines for validating a requisite model. In this research, the newly developed model is validated through this process. To be a valid requisite model, the model should be checked for various requirements. The following is a list of validation checkpoints proposed by Phillips (Phillips 1984).

1. Model form is sufficient
2. Model content is sufficient
3. Enough interaction between specialists & model developer
    A. Specialist input as to the form
    B. Specialist input as to the content
4. No new intuition emerges about the problem
    A. The model is exhaustive of social understanding of the problem
5. Social knowledge that is not included in the model

        A. Insignificant

        B. Too complex to be modeled

6. Defined limitation

        A. Conditional to problem, problem owner, time, environment

The main method of requisite model validation is practitioner interview, consisting of a structured interview and a questionnaire -- a set of questions that incorporate the checkpoints presented above.

3.7.2 Extreme Case Simulation

Once the variables are validated, the whole model is to be validated through simulation in various cases (projects). Case-study simulation is often used to validate both models and software (Sargent 1998). The model (software) is tested using actual or assumed variables, and the results are compared to known or obvious outcomes for the purpose of model-validity testing. There are two different types of cases that are used for this test.

1. A case with known outcomes
2. Extreme cases with obvious outcomes

In cases with known outcomes, the accuracy of the model can be easily validated, since the actual outcomes are known and can be compared to model output. If the simulation provides an answer close enough to actual outcome, the model can be considered validated. However, this is not the case most of the time. Often the real case outcomes (and all necessary variables) are not available. When there is no case with known outcomes, one alternative is to test the model with extreme input values. Usually outcomes with extreme input value are obvious and easy to predict. For example, if all the conditional variables are assumed to have values negative to warranty (high bond cost, high complexity, etc.), a valid model must suggest a minimum warranty. If not, something must be wrong with the model. If the model provides expected answers to all extreme cases, it is functioning as expected. In this study, case-study simulation is performed using hypothetical cases with extreme values.

To supplement the case-study simulation, an additional test will be performed in order to validate the model's consistency project-to-project. In this process, the model is tested with projects of various type, size, and risk-level. Such project characteristics are decision attributes and may influence the decision outcome, but any of these project characteristics should not alter the model structure or decision process. Therefore, in this consistency test, the model is validated if it provides reliable information consistently for all projects with various characteristics. In this test, the model is applied to two different types of projects – new pavement and resurfacing. The reason for selecting new-pavement and resurfacing projects for comparison is that there would be design selection (especially pavement-base design) by the design-builder for a new-pavement project, but none for resurfacing. This comparison should show whether the warranty has any impact on the design-builder's design selection (to minimize future repair cost).

3.8 Model Output and Results

Once a GPM model is developed and validated, it is used to simulate performance outcomes with several actual and controlled hypothetical projects, and the outcomes are analyzed to reach conclusions and results.

This study provides a complete decision matrix, GPM model, and sensitivity analysis results. As the methodology overview diagram (Figure 3-1) indicates, the findings should fulfill the research objectives stated earlier:

- Provide a valid, comprehensive warranty decision model (GPM Model)
- Indentify warranty decision attributes (Decision Matrix)
- Prioritize decision attributes (Sensitivity Analysis)

The simulation results are compared to initial objectives. In case any of the objectives is not fulfilled, the model will be refined further.

3.9 Discussion of Research Contribution

This research was initiated from the idea that current models are deficient in some aspects and intended to provide a better model. Therefore, the research process and resulting products should be contributions to both industry and academia.

The model developer intends to develop a decision process which adds formalism and minimizes the influence of personal opinion and bias in decision making. Also with utilization of GPM, this study deviates from detail-oriented numerical analysis and incorporates a broader perspective in decision making. For example, it introduces decision attributes beyond project parameters such as market and proposer characteristics. Finally, the resulting model reflects characteristics of design-build projects such as less than 100% design completion at procurement, best-value procurement, and owner’s lack of control over design decision.

3.10 Chapter Summary

This chapter explains the research methodology. The process of identification of proper methods in order to answer the question and achieve objectives is briefly described. The selected analytical modeling methods (GPM and CIA) are described. As the method of data collection, the questionnaire method is selected and described. In order to validate the model, three tests of rule of triangle test, case study simulation, and prototype demonstration are proposed.

The proposed research methodology consists of eight phases -- 1) literature review; 2) research question; 3) model development; 4) model validation; 5) variable decision; 6) validation and verification; 7) model output and result; and 8) contribution. Each phase is described in detail in the next chapter.

CHAPTER 4: MODEL DEVELOPMENT

This chapter describes the process of model development and reports resulting model structure. Model development consists mainly of two stages, which are model structuring and variable value determination. In this chapter, the process and results of model structuring are presented, but variable characteristics such as probability of occurrence are left as blank to be filled in later once expert opinion is consulted.

This chapter consists of two sub-sections. In the first section, actual development of the new model is described in step-by-step fashion. The development process includes findings on various decision attributes, alternatives, strategies, drivers, and outcome measures. The process also includes organizing the items found to fit the GPM concept. A model for the warranty decision is constructed in a similar fashion to the GPM conceptual drawing in Figure 4-1. The figure is a sample GPM conceptual drawing that is borrowed from an earlier study done by Venegas and Alarcon on the topic of selecting long-term strategies for construction firms (Venegas and Alarcon 1997).

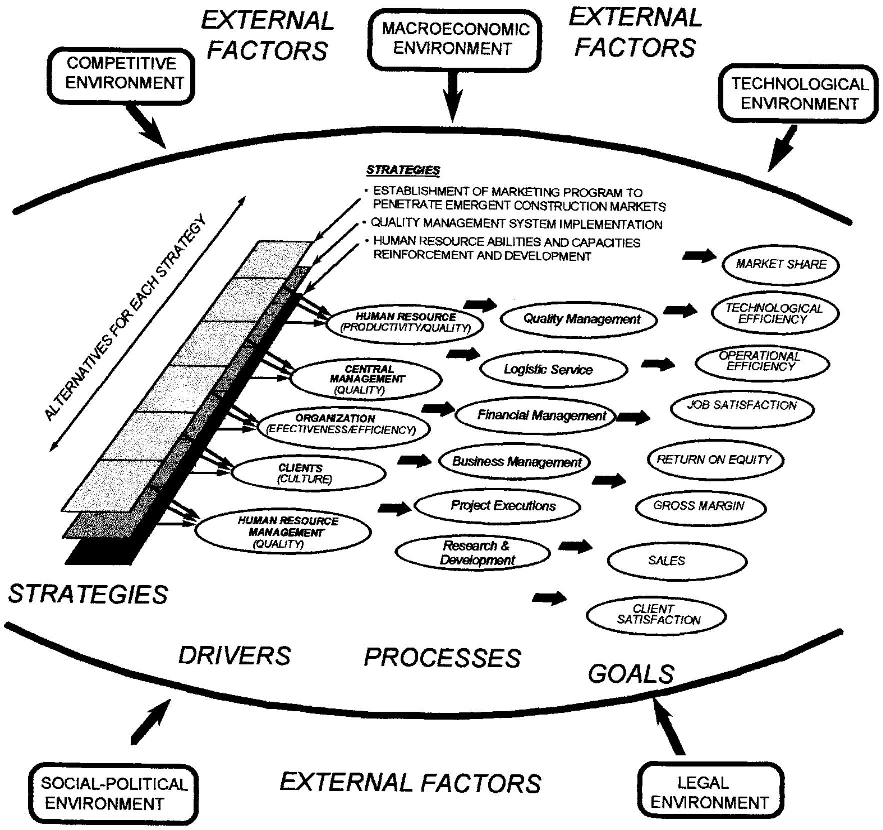

Figure 4-1: GPM Concept Drawing (Venegas and Alarcon 1997)

In the second section, the results of the model development process are presented. The results presented in this chapter are breakdown structures of decision and condition variables, breakdown structure of drivers, a GPM conceptual diagram, a simplified influence diagram, and a cross-impact matrix.

4.1 Model Structure

In this section, the warranty decision model is developed based on GPM structure. A typical GPM includes decision alternative & strategies, conditional variables, drivers, processes, and outcomes.

4.1.1 Decision Alternatives & Strategies

Decision alternatives are various decision options available to the decision maker. One of decision alternatives in this model is the warranty period. As discussed earlier, warranty in construction typically ranges from zero (no warranty) to ten years. Some construction items which have longer life spans such as bridges, structural components may have warranties longer than ten years. However, for the purpose of this model, warranties of zero, three, five, seven, and ten year period are considered as decision alternatives.

In addition to alternatives of period, there can be various strategies. The project owner or agency may choose to include additional service requirements such as preventive maintenance during the warranty period. Requirement of preventive maintenance is likely to improve performance of the item in the long term, but, most likely, there would be certain additional expense. Therefore, it is an optional strategy. The following is a list of possible decision alternatives and strategic options that are considered in this model development. The values in brackets are examples of possible options, and there can be replacements, additions, and substitutions as the development proceeds.

- Warranty period (None, 3, 5, 7, 10 years)

  Warranty period is the main decision in this model and typically ranges from none to 10 years. Alternatives that are applied to this model are none, 3, 5, 7, and 10 years

- Preventive Maintenance (None and yearly)

  Preventive maintenance is an optional strategy which may be included in the contract. The two options of no maintenance and yearly maintenance are considered in this model

- Warranty bond (None, 100% of reconstruction cost)

  A contracting agency may require submission of a warranty bond as insurance against contractor default on warranty work. A bond requirement may lead to cost additional to bid price. In most warranties, the owner requires a bond which guarantees 100% of reconstruction cost.

- Level of performance requirements (High, medium, low)

  In this decision, the level of performance requirements during warranty period are determined. Three decision options of high, medium, and low are assumed for this decision. These options are arbitrary levels which can be different for each agency and subject area.

- Limited liability (No limit, 10% of construction cost)

  With limited liability, the contractor is responsible for only a fixed maximum amount of repair cost. For anything beyond that amount the contractor is free from liability. This option decreases the risk to the contractor and result in lessening burden of paying for risk premium. However, this option may diminish the contractor's motivation for designing a durable product.

With five choices of warranty period (including no warranty) and four strategic options, the decision maker has total of 65 decision options (4 period options X 2^4 strategic option + no warranty). The table below summarizes some decision options that are considered in this model. Again, as the model development progresses, this list may change.

Table 4-1: Examples Warranty Decision Options

<table>
<tr><th></th><th>Period</th><th>Preventive Maintenance</th><th>Bond amount</th><th>Performance requirement</th><th>Limited liability</th></tr>
<tr><td rowspan="5">Decision Options</td><td colspan="5">No warranty</td></tr>
<tr><td>3 year</td><td rowspan="2">None</td><td rowspan="2">None</td><td>High</td><td rowspan="2">No limit</td></tr>
<tr><td>5 year</td><td>Medium</td></tr>
<tr><td>7 year</td><td rowspan="2">Yearly</td><td rowspan="2">100%</td><td>Low</td><td rowspan="2">10% of price</td></tr>
<tr><td>10 year</td><td></td></tr>
</table>

As shown in the table, the first option would be to have no warranty at all. In this case, there will be no further consideration of other strategic decisions such as maintenance, bond, pro-rata, and liability limit. There will be many other options with combinations of various strategies. For example, the owner may choose to have five year warranty with no preventive maintenance requirement, 100% bond, with high performance level and limited liability at 10% of contract price. Once the model is developed, and all the input variables are determined, the model simulates performance outcome for all the possible variations.

4.1.2 Condition Variables (External Factors)

Condition variables are conditions within and beyond the project that influence project performance in certain ways. Therefore, they have to be considered in warranty decision and are included in this study.

Conditional variables are sorted into the five categories of project, market, owner, proposer, and finally surety characteristics. In the warranty decision phase some of these characteristics are known to the decision maker and it can be applied by the model users. Others are not clearly known to the decision maker, so have to be a probabilistic form of random variables.

In this stage of model development, condition variables are determined by two methods of identification. One method involves brainstorming and simple information gathering techniques such as discussion with practitioners. It is obvious that government regulation in warranty is a limiting factor in warranty decision. Similarly, discussion with practitioners reveals that limits on available funds often set initial construction costs and prevent agencies from applying longer warranties. The second method that is used in condition variable identification is literature review. Literature on project performance and bid price decision is reviewed to find some warranty decision attributes. Various studies (Fayek 1998; Ioannou and Leu 1993; Oo et al. 2007) of proposers' markup (margin) decisions revealed that the margin of the project is consists of contractor's risk premium and profit. Also, those studies revealed that there are three major factors that influence the contractor's decision on margin – level of competition, contractor's need for work, and project's level of risk. As contractor's margin is important to the project cost performance, all three factors are included in the warranty decision attributes as condition variables. Similarly, a study of warranty bond (Bayraktar et al. 2006) identified some key factors that influence the cost of acquiring warranty bond. Some of the factors identified are project size, type, contractual method, contractor's reputation, and experience in similar project. All the condition variables identified by either brainstorming or literature review are listed in the figure below along with decision variables defined in the previous section.

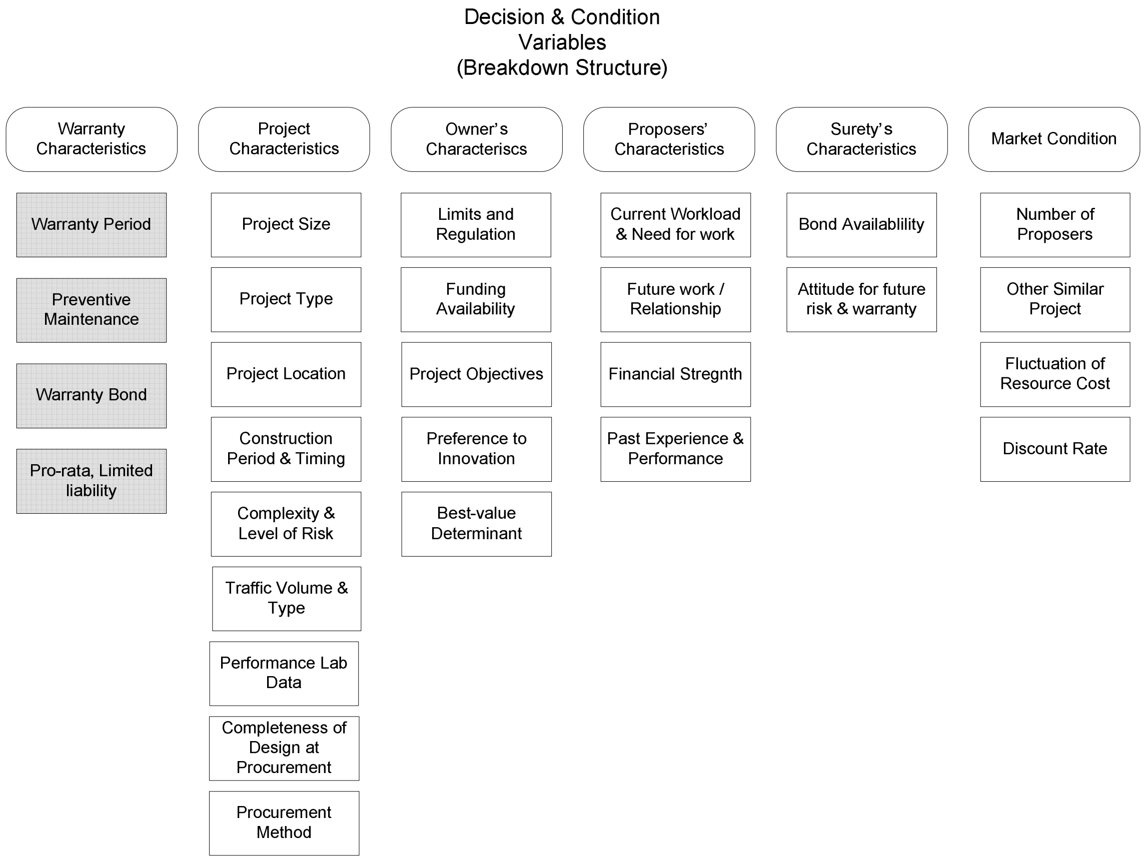

Figure 4-2: Breakdown Structure of Decisions & Condition Variables

Some conditions are boundary conditions (limitations) to the decision. Owner's limits and regulation on warranty may limit decision options. For example, some states have regulations on maximum or minimum warranty period that must be applied to any project. In that case, those regulations become boundary for warranty period decisions. Some conditions influence decision parameters such as drivers, processes, and outcomes. The characteristics of surety, such as bond availability, influence bond cost, which is one of the outcome measures.

4.1.3 Drivers

Drivers are variables which are directly affected by the decision and conditional variables and which affect the process. Drivers are affected not only by the decision, but also by the outcomes of other drivers. According to the GPM concept, drivers affect each construction process but do not directly influence project performance outcome. Considering the effects of warranty on various design-build processes, the following are found to be key drivers in warranty decision model.

- Additional risk to contractor

  It is certain that a warranty transfers much future risk to the contractor. The transferred risk often results in increased repair cost to contractors. This additional cost due to risk transfer is referred to as warranty cost (Damnjanovic and Zhang 2005).

- Increased contractor control

  A warranty may increase contractor control over some design and construction processes. With a warranty, the owner's involvement can be minimized, and the contractor should have more control and latitude in selecting materials, methods, and techniques than in a traditional project (Thompson et al. 2002).

- Increased opportunity for innovation

  Not only a warranty motivate innovation by the contractor, but with more control over design and construction process, the contractor can enjoy wider opportunities for innovation and improvement

- Contractor's motive to improve quality by design or construction procedure

  As more control over design (especially in design-build) is given to contractors with warranty and consequent liability, there will be more chance and motivation for them to choose designs that yield better quality and durability in exchange for higher initial cost. In consideration of future repair cost, the contractor or manufacturer often chooses higher quality despite higher initial cost (Huang et al. 2007; Lutz and Padmanabhan 1998).

- Increased importance of QA/QC plan and execution

  Warranty also leads the proposers to consider QA/QC more carefully and come up with better plans and execution.

- Need and willingness to perform post-construction maintenance

  Warranty extends contractor involvement in the project to years after project completion and requires them to maintenance up to the warranty's expiration.

For the purpose of numerical analysis, some drivers above can be broken down to more detailed levels. The following figure is a breakdown structure of drivers.

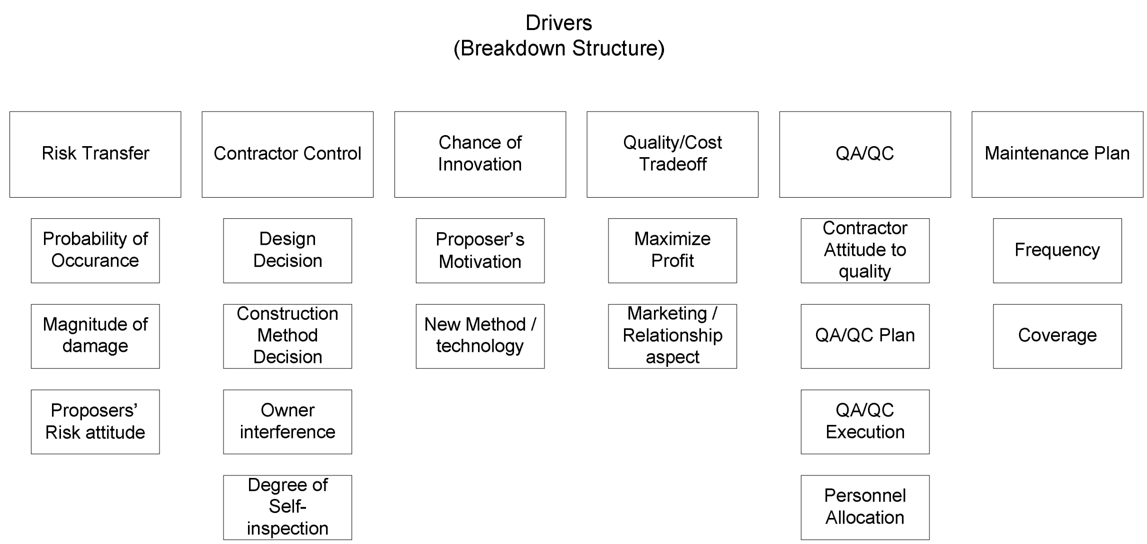

Figure 4-3: Breakdown Structure of Drivers

4.1.4 Processes

Construction processes are typically used to describe the functional characteristics of a construction project and are useful in identifying key information and resources. The processes are the project related management and engineering processes that are required to execute the construction.

Each of the drivers defined above influence one or more of processes in either a positive or negative direction. Each process influences one or more project performance outcomes, and as with drivers, there are interactions among processes. However, processes do not influence drivers.

According to the GPM concept, there are two points that should be considered when deciding upon processes. One is that the processes should be mutually exclusive and totally exhaustive. This means that there should not be any overlapping among processes and the defined processes should add up to constitute the whole project. The second point is the sequence of the processes. Each process defined should fit into an order in the actual construction, which means the design process should happen prior to construction, and so on. The following is a list of processes that are defined and used in this model.

- Procurement

  Procurement is a pre-construction process that includes all activities prior to the contractor's entry into the project. The procurement process often includes the owner's RFP preparation and issuance, the proposer's proposal preparation, bidding, contractor selection and contracting. This process is particularly important, as best-value procurement method is often used in design-build projects and the type of procurement method influences some contractor's decision on design and the construction methods which lead to project performance.

- Design

  Two key points of the design process are overlapping and control. Overlapping of design and construction is common in DB projects, which means that design and construction may not be mutually exclusive in some ways. Also, in design-build, the contractor has control over design decisions which is distinguishable from design-bid-build projects.

- Construction

  Construction is the physical installation of the selected material.

- Monitoring/Inspection

  In some sense, monitoring/inspection during construction can be part of construction process. However, in this study, monitoring/inspection is considered an independent process as it is particularly important to warranty decision and design-build process.

- Post-construction maintenance

  In a project without warranty, once the project is accepted, it is essentially finished. This means that, in projects without warranty, there is no maintenance/repair process. However, with warranty, the project is not totally completed until the warranty period expires. Therefore, with warranty, the contractor must remain involved in the project and perform necessary maintenance and repair. Depending on preventive maintenance options, the contractor can be obligated to perform mandatory maintenance during the warranty period.

4.1.5 Outcome Measures

The outcome measures of this study are unique from those of other GPMs' as it limits its measures to life-cycle-cost. The following are the outcome measures that are utilized in this model.

- Construction cost

  This refers to pure cost of performing construction, which includes labor and materials costs but is not same as bid price.

- Design cost (agency's)

  Design is usually done in two separate phases in design-build. The owner does the first phase of design (preliminary design) and the design-builder does the second phase (final design). Therefore, the cost of each phase of design should also be separated. Most of the owner's design cost comes from hiring designers and engineers to do site investigation and initial design that is to be included in the RFP.

- Design cost (contractor's)

  Similar to construction cost, contractor's design cost refers to the pure cost to the contractors of doing the design, such as the cost of utilizing their own design staff.

- Bond cost

  Bond cost refers to the warranty bond only, as this study focuses on warranty decisions. If warranty bond is not selected by the owner's decision, there will be no bond cost

- Maintenance Cost

  Maintenance cost refers to any cost to the agency for maintenance after construction to the end of the item's life.

- Repair cost (contractor)

  There are two different kinds of repair cost. One is cost of repair within warranty period, which is paid by the contractor, and the other is repair cost after the warranty expires. This cost item refers to the repair cost that the contractor is obligated to pay for.

- Repair cost (Agency)

  This is cost to repair from the warranty expiration to the end of the item's life. Depending on the length of the warranty and initial durability of the product, the cost of repair varies.

- Contractor Margin

  In any bid price, there will be some contractors' margin as it is their business and it should bring them some profit. The amount of margin depends on various factors such as company condition, market condition, and contractor's risk perception. This is included in this study because warranty influences the amount of risk the contractor bears and has some impact on their margin decision.

4.2 Developed Model

This section presents some of the results from the developed model. The results include GPM conceptual drawing, influence diagram and cross-impact matrix.

4.2.1 GPM Conceptual drawing

Once all the decision attributes are decided, following GMP conceptual diagram is constructed. Compared to original GPM concept from Alarcon (Figure 4-1), the condition variables are substituted for the term of external factors because many factors that are considered in this study are both internal and external to the project. Other than this, the overall structure is similar to the original concept.

At this stage, only items on the first level of break-down-structure are included in the diagram for the sake of simplification.

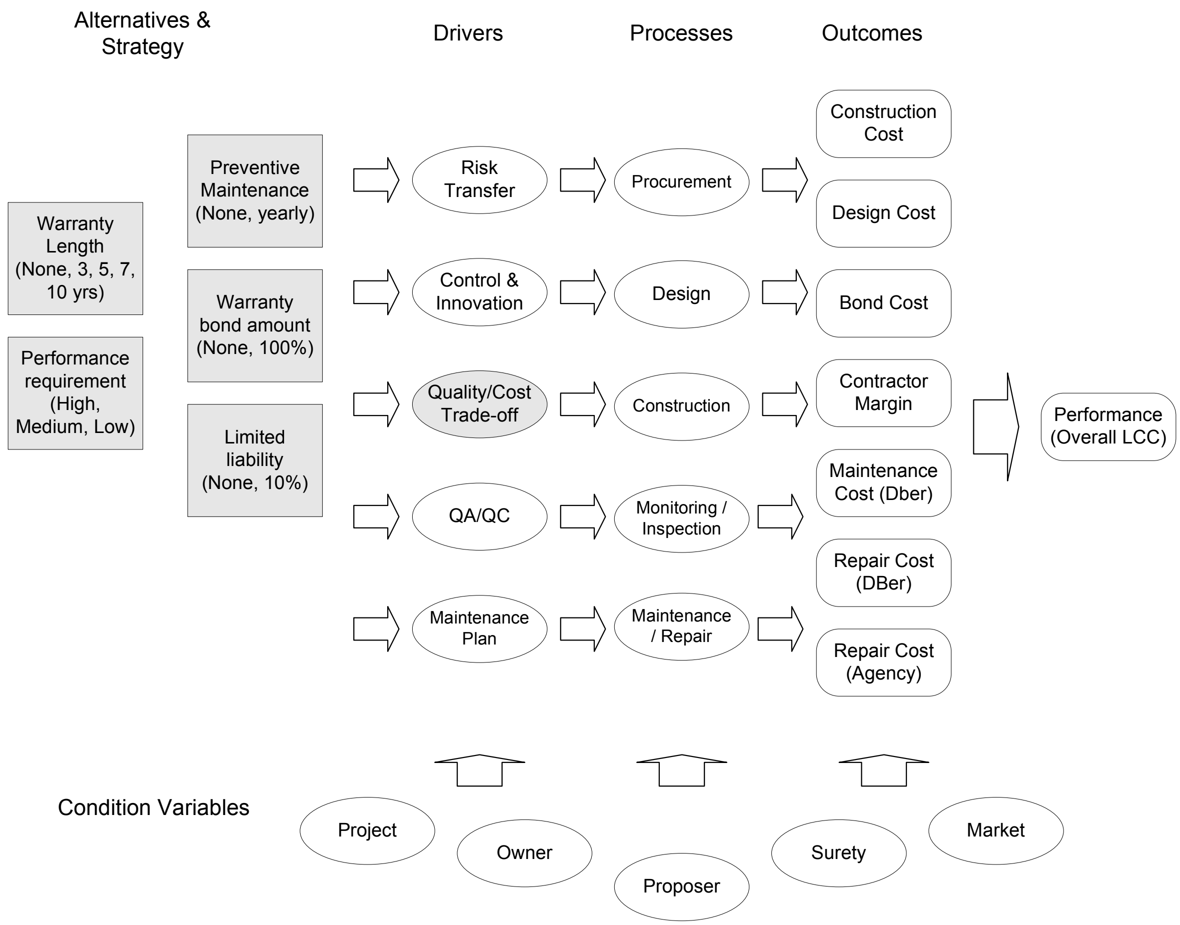

Figure 4-4: GPM Conceptual Drawing (Warranty Decision)

There are four decisions, five categories of condition variables, six drivers, six processes and seven outcomes. According to the GPM concept, influence characteristics are as follows.

- Decisions influence drivers
- Drivers influence processes
- Processes influence outcomes
- Outcomes add up to overall outcome
- Drivers influence one another
- Processes influence one another

Finally, there is one exception, which is condition variables, which may influence drivers, processes, and outcomes in any sequence. However, drivers, processes, and outcomes do not influence conditional variables, as they are either fixed or uncontrollable.

4.2.2 Cross-Impact Matrix

The cross-impact matrix is a table that summarizes the interactions among events and decisions. As defined in the GPM concept, the table includes drivers, processes, and outcomes. As shown in the table, drivers impact one another and also processes. Likewise, processes impact one another, but they do not impact drivers. Finally, processes impact outcomes, but drivers do not impact outcomes directly.

Table 4-2: Example of Cross-impact Matrix

		Transferred Risk	Innovation	Quality Improv.	QA / QC Plan	Maintenance	Procurement	Design	Construction	Inspection	Maintenance
Drivers	Transferred Risk		MOD+	SLI+	MOD-	SLI-					
	Innovation	MOD+		SLI+	NO	NO					
	Quality/Cost Tradeoff	MOD+	MOD+		NO	SLI+					
	QA/QC	MOD+	SLI+	MOD+		SLI+					
	Post Const. Maintenance	SLI+	NO	SLI+	SLI+						
Processes	Procurement	NO	SLI+	SLI+	NO	NO					
	Design	MOD+	MOD+	MOD+	NO	NO	MOD+				
	Construction	SIG+	SLI+	MOD+	MOD+	NO	SLI-	MOD+			
	Inspection	MOD+	SLI+	MOD+	MOD+	SLI-	NO	SLI+	SLI+		
	Maintenance	SLI+	SLI+	SLI+	SLI+	MOD+	NO	SLI+	NO	NO	
Outcomes	Construction Cost						MOD+	SIG-	MOD-	SLI-	NO
	Design (DBer) Cost						SLI-	MOD-	NO	NO	NO
	Warranty Bond Cost						NO	NO	NO	NO	NO
	Maintenance Cost						NO	SLI+	MOD+	MOD+	SLI+
	Repair (Agency) Cost						NO	MOD-	MOD-	SIG-	SLI-
	Repair (DBer) Cost						NO	SIG+	MOD+	SIG-	MOD+
	Contractor Margin						MOD-	SLI-	SLI-	SLI-	NO

For now, the table is filled up with assumed ratings just to show how it will be look like when the actual ratings are decided and inserted.

In the table, the cross-impact relationship is represented such that items in columns influence items in rows. The strength of impact is represented on a three scales of (Significant - SIG, Moderate - MOD and Slightly - SLI) and NO represents no impact. The direction of impact is represented in terms of + and – signs as positive and negative directions. For example, the boxes in the transfer-risk column and innovation row represent the impact of transfer risk on innovation. In this case, it is MOD +. This means that in the event of transfer risk the driver impacts the chance of innovation moderately in the same direction.

The table below summarizes symbols that are being used in this study. In previous studies, Alarcon used unique symbols such as SIG +, MOD -, etc. (Alarcon and Ashley 1998; Alarcon and Mourgues 2002). Table 4-3 presents Alarcon's symbols and interpretation.

Table 4-3: Cross-mpact Rating Symbols

Symbol (Alarcon)	Interpretation
SIG +	Significant impact in the same direction
MOD +	Moderate impact in the same direction
SLI +	Slight impact in the same direction
NO	No impact
SLI –	Slight impact in the opposite direction
MOD –	Moderate impact in the opposite direction
SIG –	Significant impact in the opposite direction

More details on Alarcon's impact rating system (pattern method) can be found in section 3.2.4.2

4.3 Chapter Conclusion

This chapter has described the process of model development and reported resulting model framework.

This chapter consists of two sections. In the first section, actual development of the GPM model was described in step-by-step fashion. GPM model consist five different elements of decision alternatives (strategies), condition variables (external variables), drivers, processes, and performance outcomes. Initial sets of these elements were developed and presented in this chapter. In the second section, the framework of developed model was presented. The framework developed and presented included GPM conceptual drawing, influence diagram and cross-impact matrix.

CHAPTER 5: ASSESSMENT

Once the model is constructed and properly refined, as the next step, the values of its variables must be determined. In this GPM model, there are three types of variables -- condition, initial probability of events, and cross-impact ratings of pairs of events. These variables can be assessed by user input, numerical analysis, historic data, and practitioners' input based on their knowledge and experience. In this chapter, the process of determining cross-impact ratings of variable pairs by practitioner assessment is described.

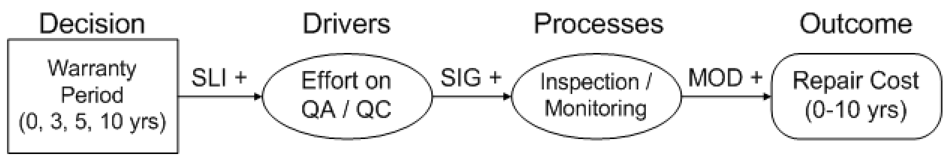

Figure 5-1: An example of variables and impact ratings

The key task in assessing variable values is determination of the cross-impact rating of each pair of decision attributes. In Figure 5-1, there are four variables, and it is assumed that the outcomes of some variables influence other variables (i.e., QA/QC effort impact performance of inspection/monitoring); impact relationships are indicated by arrows. Also, these impacts are rated as either significantly in the opposite direction (SIG-), moderately in the opposite direction (MOD-), slightly in the opposite direction (SLI-), no impact (NO), slightly in the same direction (SLI+), moderately in the same direction (MOD+) or significantly in the same direction (SIG+).

Impact ratings were collected from practitioner questionnaires and interviews. Selected participants were asked to assess the impact rating of each pair of events, and the final values were determined from those participants' opinions. The first step in the assessment process was to select interview participants from qualified practitioners around the country. Then, assessments were conducted in two steps -- initial and confirmation. In the initial step, participants were asked to fill out the questionnaires and assess impact ratings based on their warranty experience. For confirmation, the same participants were asked to reassess their ratings in order to confirm their judgments. The purpose of this two-step assessment was to minimize possible mistakes and misunderstanding of questions. A more detailed description of the assessment process and results is presented in the following sections.

5.1 Method

Cross-impact ratings of paired events are decided through guided questionnaire and interview methods of collecting information.

In finding some impact ratings, historical data or appropriate analytical methods are readily available, and ratings can be found from simple analysis. However, this is not the case with most events. It is difficult to determine some ratings by the use of analytical methods. For such events, experts' experience can provide useful information, such as reliable estimations. Questionnaire and interview methods may be used to collect information from experts,.

Questionnaire is one of the most widely used empirical research methods, which researchers use to identify and describe the hypothesis without scientific, logical, or analytical proof. In empirical research, data are collected directly or indirectly from experiments, experience, or observations (Chen and Goodman 1998; Khun 1962). In order to collect empirical data indirectly from other people, a questionnaire is often utilized.

One can administer questionnaires by mail, telephone, or in face-to-face interviews.

For this model, some variable values must be estimated from practitioners' experience through questionnaires due to the lack of quantifiable input needed for the model. A questionnaire was developed to estimate initial probability and cross-impact ratings of events. In addition to the questions relating to the initial probabilities, each expert was interviewed for any additional comments in open discussion.

5.1.1 Method Selection

In order to collect information from experts, some methods such as survey, interview, and workshop methods were examined for their suitability.

1. Survey

   Survey is a method of collecting information from the opinions of individuals. Since this method is more suitable for gauging public opinion (i.e. preferences), it may not be the most suitable method for research in which the goal is to gather factual information. Also, since a survey is always based on a sample of the population, and accuracy is heavily dependent on the number of participants (sample size), it also less suitable for this study because warranty is relatively new and has not been used widely, so not very many people have sufficient experience.

2. Interview

   Interview is a method of collecting information from conversations between two people. The interviewer asks questions of the interviewee to obtain desired information. The strength of interview method in comparison to survey is that interviewer can ask more in-depth questions while the interviewee can furnish additional information which was not anticipated by the interviewer. However, it also has some drawbacks, such as the influence of the interviewer, which can lead to cognitive bias (5.1.2.2).

3. Workshop

   Workshop is another method of collecting information in which groups of people are gathered to yield information and make decisions through discussion. Information sharing is one major benefit of the workshop method. However, at the same time group bias, misleading information, etc., may also disrupt the individual's own judgment and opinion.

Of the three methods above, the individual-interview method with a pre-determined set of questions (questionnaire) was selected for this study. The reasons for selection of the guided questionnaire and interview are as follows:

1. Limited number of practitioners with sufficient warranty experience – insufficient sample size for survey method.
2. Geographical and financial limitations -- workshop not feasible.
3. In order to minimize influence of interviewer on interviewees' individual judgment, a questionnaire was prepared.

5.1.2 Justification of Method

5.1.2.1 Limited number of interviews

One of most significant drawbacks of using interviews for cross-impact rating assessment is the limited sample size (number of interviews). In the end, only twelve practitioners were interviewed, a number far smaller than the minimum sample size required to be statistically meaningful. However, the limited number was unavoidable because warranty (especially performance warranty) has not been used widely yet, so not many practitioners were available. It was for this reason that the workshop setting assessment was initially examined. However, due to financial and time constraints of practitioners, a workshop could not be held. Instead, the researcher attempted to provide enough information to interviewees prior to and during interviews (guided interview) to simulate a workshop setting. Conducting guided interviews was the best option given the circumstances.

5.1.2.2 Cognitive bias

One other problem in affecting assessment rating through interviews is the influence of various cognitive biases. Although it is not possible to avoid all biases completely, since the ratings were to be determined from experience-based personal opinions, the following supplemental methods were adopted to minimize bias.

- Prior to interviews, interviewees were fully informed and given time to double check their responses. Also each interview was guided in accordance with the prepared questionnaire.
- Interviewees were given the chance to correct their ratings in a second-round assessment (conducted by e-mail) two months after the first-round. Prior to the second-round interviews, all interviewees were informed of the results of the first round in order to minimize cognitive bias or any simple misunderstanding of questions.

5.1.2.3 Level of confidence in the results

Because of the limited sample size, it was not possible to achieve a high level of confidence in the statistical analysis. Therefore, it was necessary to improve the confidence level in a different way. First, the assessment ratings suggested by various practitioners were examined as to level of consensus, i.e., the degree to which their opinions agree with one another (Section 5.5.1). To measure level of consensus, Kendall's *W* and standard deviation were computed and compared to other, similar findings. Standard deviation (absolute value of deviation) is used only for internal comparison (comparing results for the first-round assessment to those for the second-round assessment) to detect improvement in level of consensus. Second, the results for the first-round assessment were fed back to interviewees for correction. This process successfully eliminated some obvious mistakes and improved the level of confidence.

5.1.2.4 Selection of average (mean vs. median)

As described in later sections, the mean value of interviewees' assessment was selected as average. Median values were also calculated but not used. Although "mean" and "median" have distinctive meanings as statistical terms, mean value was selected and used as average because of the limited number of samples. A more detailed discussion is presented in section 5.3.4.

5.2 Process

The questionnaire construction and interview procedure were performed as outlined by Lipinski (1990) in his paper on dynamic cross-impact modeling technique (DYCIA).

However, due to differences in the assessment data, research characteristics and limitations, some modifications were made to the suggested process. Lipinski's method was devised for determining the strength of interaction among events in a workshop involving a group of experts. However, because it was not possible to arrange a workshop and gather all the experts from various regions of the country at the same place and time, information was gathered from questionnaires and telephone interviews. Also, in Lipinski’s DYCIA method, the judgment of each expert is weighted differently by expertise ranking. However, no system of ranking expertise was applied in this assessment process. Instead, participants were grouped by profession, and those in each group were asked to answer certain sets of questions related to their field of expertise.

With some modifications to Lipinski’s DYCIA process, the information gathering and variable-value decision making of this research were performed sequentially as in the flowchart below (Figure 5.2).

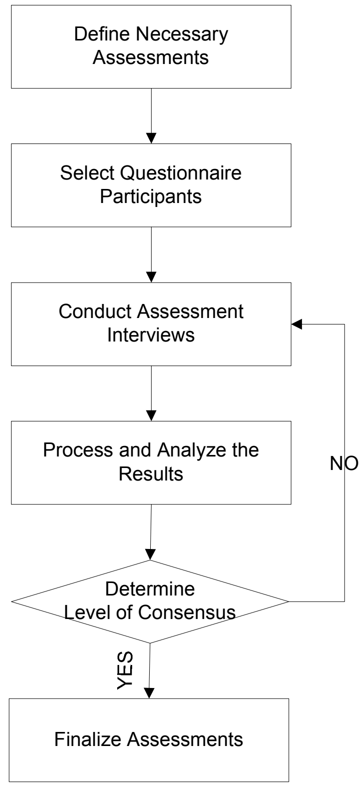

Figure 5-2: Impact-Rating Assessment Process

First, it was important to understand and clearly define the assessments that needed to be done. Therefore, all the necessary assessments were analyzed and organized. Second, assessment participants with appropriate expertise had to be selected. In the third step, "assessment interview", it was first necessary to inform the interview participants about the research, the model, and the assessment process. Then, assessment questions were provided for them to answer. Once all the interviews were completed and participants' responses collected, data analysis followed. The focus of this process was to determine the level of consensus in the opinions of the interview participants. If there is a low level of consensus, a second round of assessment interviews may be needed to confirm the initial assessments and calibrate participants' opinions in order to raise the level of consensus among participants. This process must be repeated until a satisfactory level is reached. The last step of this process is finalizing the assessments and moving on to the next step of data input and simulations. Each step of this process is described in detail in the following sub-sections.

5.2.1 Defining Necessary Assessments

The first step in the assessment process was defining what impact ratings were needed. Four different types (sets) of interactions were organized in a number of tables to facilitate assessment and analysis.

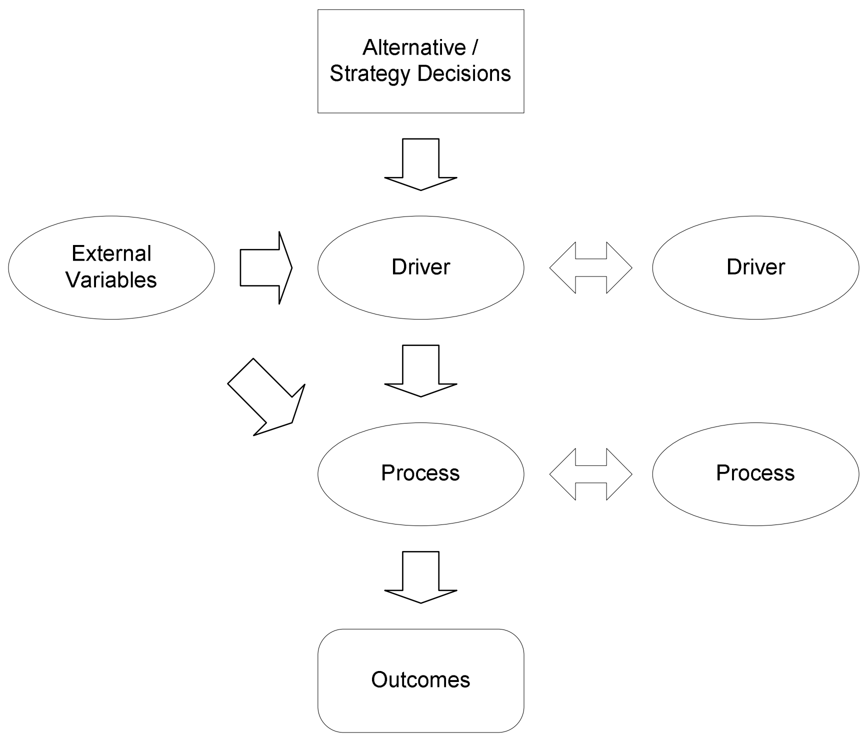

Figure 5-3: Influence Characteristics of GPM Variables

Figure 5-3 above shows different types of interaction among variable categories. These impact relationships are defined by GPM theory. By definition, decision variables impact only drivers. External variables impact both drivers and processes. Drivers impact one another as well as processes. Finally, processes impact one another and outcomes.

5.2.1.1 *Decision variable impact on drivers*

The first set of assessments required relates to the impact of decision variables (i.e., warranty period, preventive maintenance, warranty bond, required performance level, and limited liability) on drivers (i.e., risk transferred, innovation chance, quality/cost tradeoff decision, QA/QC plan, and maintenance plan). The decision variables may impact any of the GMP elements (i.e., driver, process, and outcome), but their impact will be mostly on drivers.

Each decision variable impacts drivers, and the magnitude of impact must be assessed by the experts. According to the GMP concept, drivers do not impact decision variables. Table 5-1 summarizes necessary assessments. The spaces in Table 5-1 represent impacts from column items (decision variables) to low items (drivers). In all 25 assessments need to be performed.

Table 5-1: An Impact-Rating Table (from Decision Variables to Drivers - Pattern Method Applied)

		Decision variables				
		Warranty Period	Performance Level	Warranty Bond	Preventive Maintenance	Limited Liability
Drivers	Risk Transferred					
	Motive for Innovation					
	Quality/Cost Tradeoff					
	Importance of QA/QC					
	Maintenance Plan					

Impacts between each pair of decisions are to be rated using one of seven ratings –

SIG+, MOD+, SLI+, NO, SLI-, MOD-, and SIG- (See Cross-impact rating system – Chapter 2). Also, the degree of impact from decision outcomes to drivers needs to be assessed. Table 5-2 is a sample assessment table. In this particular case, participants are asked to rate the impact of 0-, 3-, 5-, and 10-year warranties on five different drivers.

Table 5-2: Impact-Rating (from Decision Options to Drivers)

	Decision Options				Drivers				
	No Warranty	3 Years	5 Years	10 Years	Amount of Risk	Innovation Chance	Quality improvement	QA/QC	Post-const. Maintenance
Scenarios	√								
		√							
			√						
				√					

The decision impact on drivers is assessed as one of five ratings – very positive (PP), positive (P), no effect (O), negative (N), and very negative (NN). These ratings are from original CIA methods (3.2.4.2).

5.2.1.2 External variable impact on drivers and processes

External variables are defined as any characteristics of the project, owner, proposal, surety or market that may influence project outcome or other GPM factors that may influence the warranty decision. Unlike decision variables, external variables may impact both drivers and processes. Table 5-3 below presents some external-variable impacts on drivers and processes. Impacts of external variables on drivers are to be rated using the cross-impact ratings, SIG+, MOD+, SLI+, NO, SLI-, MOD-, and SIG-.

Table 5-3: An Impact-Rating Table (from External Variables to Drivers and Processes)

		External Variables							
		Project Size	Project Complexity	Delivery Type	Specification Type	Preference to Innovation	Level of Competition	Past Experience	Financial Strength
Drivers	Risk Transfer								
	Motive for Innovation								
	Quality/Cost Tradeoff								
	Importance of QA/QC								
	Maintenance Plan								
Processes	Procurement								
	Design								
	Construction								
	Inspection								
	Maintenance								

Among the external variables listed Table 5-3, some are project characteristics, such as project size and complexity, while others are owner, proposer, and market characteristics (i.e. level of competition, proposer's financial strength).

5.2.1.3 Cross-impact matrix of Drivers and Processes

A cross-impact matrix defines interactions among variables (i.e., drivers and processes). The cross-impact rating for each pair variable must be assessed by the interview participants with appropriate expertise. Table 5-4 is a sample cross-impact assessment from this research. In Table 5-4, the cross-impact relationship is presented such that items in columns impacts items in rows.

Table 5-4: A Cross-Impact Table among Drivers and Processes

		Transferred Risk	Motive for Innovation	Quality/Cost Trade-off	QA / QC Plan	Maintenance	Procurement	Design	Construction	Inspection	Maintenance
Drivers	Amount of Transferred Risk	X	__	__	__	__	X	X	X	X	X
	Motive for Innovation	__	X	__	__	__	X	X	X	X	X
	Quality/Cost Tradeoff Decision	__	__	X	__	__	X	X	X	X	X
	QA/QC Plan and Execution	__	__	__	X	__	X	X	X	X	X
	Post Construction Maintenance	__	__	__	__	X	X	X	X	X	X
Processes	Procurement	__	__	__	__	__	X	NO	NO	NO	NO
	Design	__	__	__	__	__	__	X	NO	NO	NO
	Construction	__	__	__	__	__	__	__	X	NO	NO
	Inspection	__	__	__	__	__	__	__	__	X	NO
	Maintenance	__	__	__	__	__	__	__	__	__	X

Some assessment results are obvious and can be omitted from the assessment process. For example, since the processes of the model are sequential, it can be assumed that results of latter processes cannot impact former processes (i.e., impact from construction to design). Therefore, as shown Table 5-4, some results are predetermined and not assessed.

5.2.1.4 Process impact on outcomes

The last impact type is that of process on project outcomes. The performance of each construction process is assumed to have some impact on one or more project outcomes, and these interactions must be assessed. The table below shows the impacts of processes on outcomes.

Table 5-5: An Impact-Rating Table (from Processes to Outcomes)

		Processes					
		Procurement	Design	Construction	Inspection	Acceptance	Maintenance
Outcomes	Construction Cost						
	Design Cost						
	Warranty Bond Cost						
	Post-Construction maintenance						
	Repair (Agency) Cost						
	Repair (Contractor) Cost						
	Contractor Margin						

5.2.2 Participant Selection

Participants in an expert panel must be chosen on the basis of their knowledge and experience with asphalt pavement warranties. The criteria for selecting interview participants were as follows:

- Construction experience
- Research experience
- Warranty/non-warranty project experience.

First, the interview participants' general experience in construction is considered. For the assessment task, the researcher sets a threshold value for construction experience at a minimum of five years of experience in project administration or contract management. Similarly, participants' experience in research, especially related to warranty, is considered. Finally, the most important principal of measuring participants' level of expertise is their experience in both warranted and non-warranted projects. This is particularly important, since the focus of the assessment is to measure warranty impact on project performance, and, in order to do so, the participant should have experience in both warranted and non-warranted projects and understand the differences between them. For the purpose of this task, the minimum number of projects with and without warranty is set at four (preferably a minimum of two with warranty and two without).

5.2.3 Grouping by Profession

For reliable impact-rating assessments, the questionnaire participants must possess adequate levels of expertise. Therefore, the model developer must determine whether the person assessing values possesses enough knowledge and experience. However, it is difficult to determine someone's level of expertise unless enough resources and time are used to test each participant thoroughly.

One idea about measuring the level of expertise of the person being assessed is using his/her profession as an indicator of the probable level of expertise. Under the assumption that people within the same profession have similar kinds and levels of expertise, individuals can be grouped by their profession and given to appropriate ratings.

Four professions were selected and their likely expertise types anticipated, as shown in Table 5-6. The table summarizes four selected professions and their probable fields of expertise.

Table 5-6: Various Professions and their Probable Expertise

Professions	**Expertise Types**
Contractor	Business Decision
	Cost estimating
	Supplying (Material)
	Construction methods
Designer/Engineers	Contracting and Procurement
	New Technology
	Design decision
	Designing
Surety	Firm evaluation
	Bond price decision
Contracting agent	Warranty Policy
	Project Funding
	Initial project development
	Monitoring and Inspection

Contractors possess expertise in business decision making (i.e., taking risks, bidding), cost estimation, construction methods, staff utilization, etc. Similarly, expertise in designing, surety, contracting is anticipated, as shown in Table 5-6 – Various Professions and their Probable Expertise.

The next step is to examine each assessment and decide which professionals are more likely to be knowledgeable in each subject. The assignment for each profession is shown in the Table 5-7. Each assessment is noted with a letter symbol, which represents one of the professions. The letter C represents the "Contractor" profession. Likewise D is "Designer"; S is "Surety"; and A is "Government Agency". Table 5-7 is an example of grouping questions that are more suitable for each profession.

Table 5-7: Assessments and Appropriate Profession Groups

		Transferred Risk	Motive for Innovation	Quality/Cost Trade-off	QA / QC Plan	Maintenance	Procurement	Design	Construction	Inspection	Maintenance
Drivers	Amount of Transferred Risk		C	C	C	C					
	Motive for Innovation	C		C	C	C					
	Quality/Cost Tradeoff Decision	D/C	D/C		D/C	D/C					
	QA/QC Plan and Execution	C	C	C		C					
	Post Construction Maintenance	C	C	C	C						
Processes	Procurement	A	A	A	A	A					
	Design	D/A	D/A	D/A	D/A	D/A	D/A				
	Construction	C	C	C	C	C	C	C			
	Inspection	A	A	A	A	A	A	A	A		
	Maintenance	C	C	C	C	C	C	C	C	C	

For example, contracting agents are more likely have good understanding of procurement performance because they have procured many projects. Therefore, it would be more reasonable to ask contracting agents to assess impact ratings from drivers to procurement. Similarly, it is more likely that designer is the proper profession for assessing impacts on design performance, and contractor is on construction. In some cases, there is more than one profession who may be capable to answer the question. For these questions, more than one profession is assigned (i.e., Quality decision, design performance).

5.2.4 Instructing the participants

Prior to administering the questionnaire, the model developer must describe the CIA, GPM mechanism, information gathering procedure and definition of each variable. The questionnaire also includes a brief introduction of the research, an explanation of the procedure, and definitions of variables. The actual participant guidelines and definitions of variables to be provided to the interview participants can be found in Appendix 1 – Assessment Questionnaire Packet.

5.2.5 Cross-impact rating decision

In this step, each participant is asked to answer the questionnaire, which includes single and cross-impact matrices. In DYCIA, group discussion is conducted prior to cross-impact rating decision; however, since this is done by questionnaire instead of workshop, the discussion process is substituted for by questionnaire guidance and interview either by phone or in-person. However, the research must be cautious not to bias the participant with any of their guidance.

5.2.6 Processing assessment results

Once participants' judgments are collected, the developer consolidates the questionnaire and makes initial decisions on values. In this step, the assessments of all participants are collected and their average values decided. In addition, variations among participant opinions are examined to determine the level of agreement. If the level of agreement is not satisfactory, another round of assessment interviews may be necessary.

5.2.7 Feedback and second-round questionnaire

Because this process utilizes questionnaire instead of workshop discussion as Lipinski suggested (Lipinski 1990), feedback and a second-round questionnaire is conducted to eliminate mistakes, achieve consensus, and improve the accuracy of information. Participants are informed of the results of the first-round questionnaire and are asked to fill out the same questionnaire again. If any inconsistency or a low level of agreement among participants' opinions is found, it is also reported to the participants. With access to first-round assessment results and other participants' opinions, participants are able to provide more reliable information.

5.3 Initial Assessment

In this section, the actual process and results of the initial assessment are described. Most of the interviews and assessment processes were conducted as planned, but in some instances modifications to the original plan were necessary. Overall, the initial assessment process was completed successfully, but there were a few shortcomings found in the analysis results, which were accounted for in the second round of assessments. Details of the processes and results are presented in the following sub-sections.

5.3.1 Participants

In order to find assessment interview participants with adequate expertise in warranty, the model developer contacted participants in the pavement warranty symposium held in 2003 in Grand Rapids, MI. A total of 57 people with various backgrounds (i.e., academia, contracting agent, contractor, surety) participated the symposium, and the final report of the symposium includes a list of their contact information (Ferragut 2003). Other than those in the list, authors of published warranty studies and contracting agents (i.e., state department of transportation) who have participated in projects with a warranty were asked to participate in the information gathering.

As a result, a total of twelve people with warranty expertise were selected and agreed to participate in the assessment interview. Table 5-8 is a list of participants and their qualifications.

Table 5-8: Qualification of Assessment Interview Participants

Participant	Profession	Construction Experience	Warranty Experience
A	Agency	• 15 years in DOT • Administered over 30 projects	• 10+ projects with warranty
B	Agency	• 5 years in DOT and 2 years in construction company • Administered many projects	• Recent projects (10 to 20 projects) had short-term warranty • Many projects prior to warranty implementation
C	Agency	• 12 years in DOT	• 5-6 projects with warranty (pilot studies) • 2 Reports on effectiveness of warranty
D	Agency	• 10+ years in a Federal contracting agency	• Warranty policies guidelines
E	Contractor	• 20 years in construction business	• About 10 projects with warranty • 20+ Projects without warranty
F	Contractor	• 10+ years in construction • Have constructed numerous highway and road projects	• A few projects with short-term and long-term warranty • Most projects (more than 20) were without warranty
G	Contractor	• 5+ years in construction • Have participated about 10 projects	• Two projects with warranty (one long-term performance warranty) • 5-6 projects without warranty
H	Agency	• 23 years in DOT	• Most of projects in the state had mandatory warranty
I	Contractor	• Many years as both contractor and paving contractors' association	• 4-5 recent government pavement projects had warranty • Many other projects without warranty
J	Contractor	• 10+ years as the president of a small paving company • Numerous paving projects	• Some of recent projects had 3 year warranty (about 3 or 4)
K	Agency	• 15+ years in DOT • Administrated many projects	• 3-4 projects with material and workmanship warranty for short period (2-3 years)

As shown in Table 5-8, only people from two professions – agency and contractors – participated in the interview. The plan was to interview people of four different professions. However it was found that the participants from the agencies had enough knowledge of design and bonding issues that they were able to answer most of questions.

5.3.2 Process

Assessments were collected from structured interviews, which means that the model developer explained the research, the model, and the assessment process, and provided guidance to the participants while they filled out the questionnaire. The model developer's guidance ensured that the participants were well-informed and fully understood the process. However, the model developer was careful not to bias or influence the respondents with the guidance.

The interviews were conducted individually by phone or in-person. There was no discussion among participants, and the interviewer did not provide any information about others' assessments and opinions in this initial assessment interview.

5.3.3 Questionnaire Packet

Prior to the interview, a questionnaire packet was provided to participants. The questionnaire had two purposes. One was to provide information needed by the participants prior to the interview, so they understood the objective and process of the assessment. The other purpose was to provide the set of questions to be answered. The questionnaire consists following sections.

Participant Information

This section included questions to the participants about themselves such as profession, title, construction and warranty experience.

Project Information

This section asked about participants' previous projects with warranties.

Assessment Guideline

This section explained the basic concept of the GPM model and the process of impact-rating assessment. For clarity, this section included an example of an impact-relationship diagram and a corresponding rating-assessment table. The example was designed in such as way that it is not directly relevant to any actual question (to avoid bias) but similar in format and organization. Figure 5-4 and Table 5-9 are the examples provided to the participants. Figure 5-4 is an influence diagram and Table 5-9 is a cross-impact matrix that corresponds to the figure.

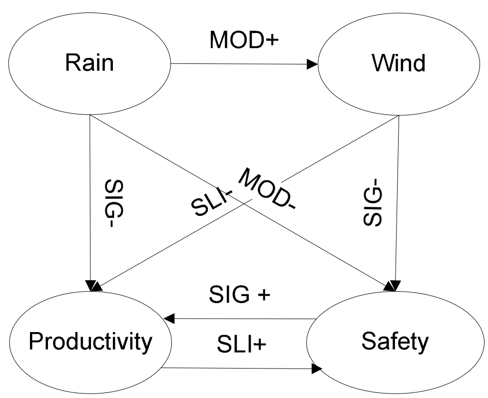

Figure 5-4: An Example of Impact Relationship and Ratings (Questionnaire Packet)

Table 5-9: An Example Table of Impact Ratings

		Rain	Wind	Safety	Productivity
Condition	Rain	X	NO	NO	NO
	Wind	MOD+	X	NO	NO
Outcome	Safety	MOD-	SIG-	X	SLI+
	Productivity	SIG -	SLI-	SIG+	X

Variable Definitions

This section listed definitions for all the variables in the model. This is critical that the participants understand what each variable means before assessing impact ratings, so a table of definitions was provided. Table 5-10 is part of the definition table that was provided to the participants. In the table, definitions of drivers are provided along with influence directions – Positive and Negative.

Table 5-10: Definitions of Variables (Drivers)

Drivers	Risk Transfer	This is a measure of amount of risk transferred to the design-builder from the owner due to the use of a warranty contract. Examples include cost to repair post-construction defects, rework, etc. *Positive – More risk* *Negative – Less risk*
	Control and Innovation	This is measure of level of contractor control and chance of innovation. Control and chance of innovation can be applied to both design and construction. *Positive – More control and chance of innovation* *Negative – Less control and chance of innovation*
	Quality/Cost Tradeoff Decision	This refers to the likelihood of the design-builder selecting higher quality design (or construction method) over the design that yields lower cost due to the use of a warranty contract. *Positive – More likely to choose higher quality over lower cost* *Negative – Less likely to choose higher quality over lower cost*
	QA/QC Plan and Execution	This measures contractor's involvement and level of effort in planning and performing QA/QC during construction. This measure includes various efforts such as developing more rigorous QA/QC plans assigning more and more qualified personnel for QA/QC monitoring. *Positive – More effort in QA/QC* *Negative – Less effort in QA/QC*
	Post Construction Maintenance	This measures design-builder's motivation or desire for planning and performing post construction maintenance to maintain high quality level during warranty period. *Positive – More effort in post construction maintenance* *Negative – Less effort in post construction maintenance*

Assessment Tables

A number of assessment tables were included in the questionnaire for the participants to fill out. These were the main data input for the interviews. The participants were asked to fill out the assessment tables using GPM cross-impact ratings (i.e. SIG+, MOD-). Table 5-11 is an example of an assessment table.

Table 5-11: An Assessment Table as Presented to Interviewees

		External Variables (Project Characteristics)				
		Project Size	Project Complexity	Specification Type	Procurement Method	Load uncertainty
Drivers	Risk Transfer					
	Control & Innovation					
	Quality/Cost Tradeoff					
	Importance of QA/QC					
	Post-Const. Maintenance					

For more details of the interview questionnaire, the whole initial assessment questionnaire packet is presented in Appendix 1.

5.3.4 Results

Once all the interviews were complete, assessments were collected and input into Excel for data analysis. For the purpose of analyzing convenience, impact ratings were converted to numerical symbols (Table 5-12).

Table 5-12: Impact Ratings and numerical symbols

Rating	Numeric Symbol	Interpretation
SIG +	+3	Significant impact in the same direction
MOD +	+2	Moderate impact in the same direction
SLI +	+1	Slight impact in the same direction
NO	0	No impact
SLI –	–1	Slight impact in the opposite direction
MOD –	–2	Moderate impact in the opposite direction
SIG –	–3	Significant impact in the opposite direction

Table 5-13 is a part of a data sheet and shows assessments by eleven participants of five items (ratings). At the end of each column, the mean and median values are included.

Table 5-13: A Sample of Assessment Result Data Sheet

	Item 11	Item 12	Item 13	Item 14	Item 15
A	3	0	2	2	
B	3	3	3	2	2
C	3	3	2	2	2
D	3	2	2	1	
E	2	2	2	3	1
F	3	2	1	3	2
G	3	-1	2	3	1
H	3	2	2	2	1
I	3	2	2	2	1
J	3	1	2	2	1
K	2	0	0	2	0
Mean	2.82	1.45	1.82	2.18	1.22
Median	3.00	2.00	2.00	2.00	1.00
Rating	SIG+	SLI+	MOD+	MOD+	SLI+

For final value for each rating item, the averages of participants' assessments were found. There are two possible values that can be selected as average – mean and median.

Mean is an arithmetic average which is found from the sum of all numbers divided by the number of data. Median is defined as the number separating the higher half of data from the lower half. The median of a finite list of numbers can be found by arranging all the observations from lowest value to highest value and picking the middle one. If there is an even number of observations, the median is not unique, so one often takes the mean of the two middle values or one of the middle one is selected.

The median (i.e., a central tendency measure) indicates the degree of support from the participants for each item. Unlike to arithmetic mean, the median offers the advantage of being affected less by extreme values and possible errors. However, when there is not a large enough number of data (i.e., due to the small sample size), using the median could be problematic. Using median as average when the sample size is relatively small may end up ignoring minority opinions. Therefore, in this assessment process, the arithmetic mean value is selected as the average. Since the rating should be an integer, the mean values were rounded up or down.

The resulting mean, median and average ratings are shown in Table 5-13 (last three lows).

5.3.5 Issues in the Initial Assessment

Analysis of the assessments shows that there were a few issues, or problems, in the initial assessment values. First, for some ratings, the sample sizes were simply not large enough because participants did not assess all items. Participants we asked to assess only those items with which they had experience and, therefore, not all variables had 11 assessments. It is reasonable if these omissions were due to lack of confidence in their experience. However, in many cases, some assessments were skipped due to time constraints. Therefore there was a need to get back to them and ask them to complete the assessments.

The second issue with first assessments was the low level of consensus among participants' opinions. Details of this analysis is not discussed here (find details in the discussion of level of consensus in Section 5.4.2), but the level of consensus in the initial assessments was not satisfactory. The final problem was obvious mistakes that were recognized by the model developer either during the interviews or the data analysis process.

Many mistakes were caused by confusion about direction of influence. Due to the nature of the rating system, participants were easily confused about influence direction (+, -) and ended up miss-assessing some items.

5.3.6 Need for Confirmation Assessment

Due to the issues with the initial assessments listed previously, it was determined that another round of assessment interviews was required. The purposes of this second-round assessment were: 1) to increasing sample size; 2) to confirm mistakes and correct; and 3) to communicate among participants' by feeding back the results of initial assessment.

5.4 Confirmation and Calibration Assessment

In order to confirm and calibrate participants' opinions, another round of assessments were conducted. The purpose of this round of interviews was to verify the assessments of the first round (i.e., eliminate mistakes) and check for possible changes in opinion.

5.4.1 Process

The participants in the first round were contacted and asked to participate again. As a result, the response rate was good. Ten out of eleven first round participants were able to participate in the second round. Only participant D could not participate in the second round. For participant D, who did not participate in the second round, assessments from first round were carried over to second round without any change. It should be noted that there were no apparent mistakes in first round assessments of participant D.

The second-round participants were provided with a new assessment table. This time, the assessment table included information from the results of the first round assessments. The information includes the participant's own assessment in the first round and the average value of all the assessments (from other participants) from the first round. Table 5-14 was provided to the second-round participants.

Table 5-14: A Sample of 2nd Round Assessment Table

Participant C		**Performance level impact to drivers**			
		1st Assessment	Average	2nd Assessment (If different)	Comments
Drivers	Risk Transferred	SIG +	SIG +		
	Control & Innovation	MOD –	MOD +	MOD +	Direction Error
	Quality/Cost Tradeoff	SIG +	MOD +		
	Importance of QA/QC	SIG +	SIL +	MOD +	Changed opinion
	Post-Const. Maintenance	SIG +	SIL +		

This table includes four columns – first-round assessment, average, second-round assessment, and comments. In the first column, each participant's first-round assessment value is provided in comparison to the average of all participants' opinion in second column. If the participants found that their first-round assessment was mistaken or wanted to change their opinion based on the average responses, they wrote their new opinion in the third column. Finally, an additional column was included in the table for comments. The participants were asked to note the reason they decided to change their assessment.

Tables similar to the sample above were provided for the whole set of questions instead of asking participants to verify only the ones about which the model developer felt suspicious. This is done to minimize any type of influence by the model developer and provide an equal chance to reassess any ratings. However, since there were hundreds of ratings to review, those assessments that deviated more than one rating were highlighted for their convenience.

5.4.2 Results

Tables 5-15 and 5-16 provide an example of confirmation and calibration assessment results. Table 5-15 is the result of the first round assessment and Table 5-16 is the result of the second round assessment.

Table 5-15: A Sample Assessment Data Sheet (after initial interviews)

	Item 51	Item 52	Item 53	Item 54	Item 55
A					
B					
C	-2	2	-2	-2	-2
D					
E	1	1	2	2	1
F	-2	0	0	-1	-1
G	-1	2	0	0	0
H					
I	3	0	0	0	0
J	2	1	2	0	1
K	-2	0	0	-1	-1

Table 5-16: A Sample Assessment Data Sheet (after confirmation interviews)

	Item 51	Item 52	Item 53	Item 54	Item 55
A	-2	0	-1	-1	-2
B					
C	-2	2	-2	-2	-2
D					
E	-1	-1	-2	-2	-1
F	-2	0	0	-1	-1
G	-1	1	0	0	0
H	-1	0	-1	0	-1
I	-3	0	0	0	0
J	-2	1	-2	0	-1
K	-2	0	0	-1	-1

As shown in the Tables 5-15 and 5-16, some ratings were newly assessed (see participant H) and some re-assessed (see those highlighted in Table 5-16). According to the comments collected along with the re-assessed values, some were reassessed because there had been misunderstanding of directions (see participants E and J) and one changed of opinion (se participant E). The second-round assessment therefore validated and calibrated participants' opinions. The possible improvement in the level of agreement is examined and discussed in next section (5.4.1 – 5.4.2).

5.5 Assessment Results

This section presents the results of assessment process. The first two sub-sections discusses about levels of consensus among respondents after first and second round interviews. The process had stopped after second round because the level of consensus had reached desired level. The next section presents the final assessed values.

5.5.1 Measurement of level of consensus

One of the most important issues in deciding upon interaction rating from expert assessments is level of consensus among participants. As mentioned earlier, one of the reasons that second-round (confirmation and calibration) assessments were necessary was improving the level of consensus. Therefore, the measurement of the level of consensus among participants' opinions is discussed extensively in this section.

There are many different methods that are often used to measure level of consensus. The following are brief descriptions on some methods that have been used more often in research similar to this.

Inter-quartile Range (IQR)

Inter-quartile range (IQR) is a measure of the spread of responses and is defined as the difference between the 25th and 75th percentiles. A small IQR means a smaller spread in responses and indicates that consensus has been achieved. As shown in Figure 5-5, more consensus data set (lower graph) has less IQR value.

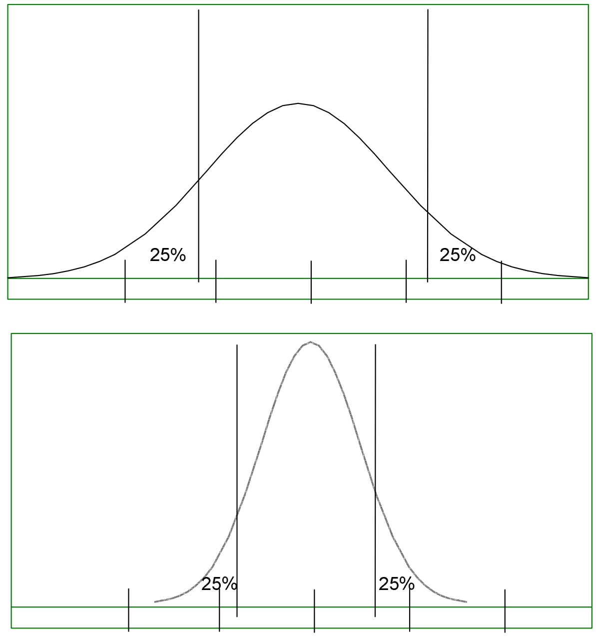

Figure 5-5: Inter-quartile range (IQR) as a measure of the spread of responses

Standard Deviation

The standard deviation is a measure of dispersion that can be applied to the range of opinions. A perfect consensus on an item is indicated when its standard deviation equals zero. By definition, about 68 percent of opinions fall within plus- and minus-one standard deviation, and about 95 percent fall within plus- and minus-two standard deviations (Figure 5-6). There is no threshold standard-deviation values directly indicating level of consensus of the current data. However, various studies, especially those utilizing Delphi method, have asserted that a decreasing standard deviation between rounds indicates an increasing level of agreement (Yeung et al. 2007).

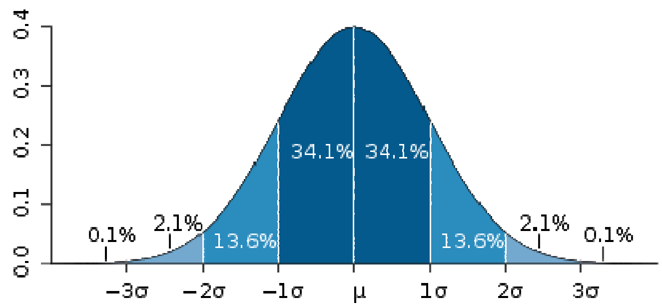

Figure 5-6: A Sample of Standard Deviation

Percent Top Issues

Another measure of agreement that has been used in past studies is the percent of respondents that has rated an item in a top-issue (Brancheau and Wetherbe 1986; Doke and Luke 1987). In Table 5-17, four out of five participants have rated item A as 2. In this case the rating of 2 is the top issue and percentage of this top issue is 80%. For item B, rating 1 and 2 are top-issues and percent top-issue percentage is 40%. This indicates that there is a greater consensus of opinion on item A than on item B.

Table 5-17: An Example of Percent Top Issues

	A	B	C	D	E	Top Issue	Percentage
Item A	2	1	2	2	2	2	80%
Item B	2	1	2	1	3	1 and 2	40%

Kendall's Coefficient of Concordance (W)

Kendall's coefficient of concordance (*W*) is a statistic that measures the agreement among sets of rankings or ratings by two or more judges, and was first introduced by Kendall, Babington-Smith, and Wallis (1939). It is a normalization of the statistics derived from the Friedman test, and can be used for assessing agreement among raters. Kendall's coefficient indicates the current degree of agreement among participants.

Kendall's W ranges from 0 (no agreement) to 1 (complete agreement). The value of this coefficient increases as agreement increases. If the test statistic W is 1, then all the survey respondents have been unanimous, and each respondent has assigned the same order to the list of concerns. If W is 0, then there is no overall trend of agreement among the respondents, and their responses may be regarded as essentially random. Intermediate values of *W* indicate a greater or lesser degree of unanimity among the various responses. Schmidt (1997) proposed a table of interpretation of Kendall's W values (Table 5-18). However, the values in the table should be used only as a guideline and are not intended to show exact threshold number in all situations.

Table 5-18: Interpretation of Kendall's *W* Values (Schmidt, 1997)

W	**Interpretation**
0.1	Very weak agreement
0.3	Weak agreement
0.5	Moderate agreement
0.7	Strong agreement
0.9	Unusually strong agreement

Two cases exist for calculating Kendall's *W*. The first case is when no ties exist. This is classic formula of Kendall's *W*. One typical example of this case is ranking. In a typical ranking system, there are no ties among assessments.

The classic formula of Kendall's coefficient of concordance *W* is (Kendall 1948; Kendall and Smith 1939):

$$W = \frac{S}{\frac{1}{12}K^2(N^3 - N)}$$

S = sum of squares of the deviations from the mean
N = number of items ranked
K = number of experts

Ties in the evaluation method are not considered in this classic formula of Kendall's W. Ties depress the value of W as calculated by the classic formula. However, it is known that if the proportion of ties is small, that effect is negligible, and the classic formula may still be used (Siegel 1956). However, if the proportion is large, a correction factor should be applied to compensate for this effect.

The formula of Kendall's W computation corrected for ties is:

$$W = \frac{S}{\frac{1}{12}K^2(N^3 - N) - K\sum_T T}$$

S = sum of squares of deviations from the mean
N = number of items ranked/rated
K = number of experts
$\sum_T T$ = sum of values of T for all K experts

$$T = \frac{\sum t^3 - t}{12}$$

t = number of observations in a group tied for a given rank/rate

For the assessment in this research, where the values are ratings (i.e., not rankings) and many ties exist, it was necessary to use the modified (i.e., corrected for ties) formula. For the purpose of this study, a computer software (SPSS 14.0 for Windows) was used to compute Kendall's *W* of overall assessment data instead computing them manually using the formula above.

5.5.2 Level of consensus of assessed ratings

The impact rating for each pair of GPM variable were assessed from two rounds of questionnaire and interviews. The level of consensus of the results of first round assessment was relatively low in some areas, so a second round of assessment was necessary to improve it. In the second round of assessment, experts had the opportunity to reconsider their initial assessments and make adjustments.

The consistency of the participants' ratings of both initial assessment and confirmed assessment values were checked by standard deviation and Kendall's coefficient of concordance (*W*).

Tables 5-19 and 5-20 are examples of assessed ratings from the first- and second-round interviews. Table 5-19 shows the results of the first assessment and Table 5-20 the results of second assessment. There were a total of eleven interview participants whose assessed ratings for each variable pair are listed numerically (SIG+ = 3+, etc). The highlighted ratings are those which have been adjusted in the second-round assessment.

Table 5-19: A Sample Table of Assessment Results (after 1st round)

	Item 11	Item 12	Item 13	Item 14	Item 15		Item 21	Item 22	Item 23	Item 24	Item 25
A	3	0	2	2			2	0	2	2	
B	3	3	3	2	2		3	2	2	1	3
C	3	3	2	2	2		3	-2	3	3	3
D	3	2	2	1			2	1	0	1	
E	2	2	2	3	1		3	2	3	1	0
F	3	2	1	3	2		2	2	1	3	0
G	3	-1	2	3	1		3	1	1	3	1
H	3	2	2	2	1		2	2	1	1	2
I	3	2	2	2	1		3	3	2	1	1
J	3	1	2	2	1		3	2	1	1	0
K	2	0	0	2	0		2	0	2	2	0
Mean	2.82	1.45	1.82	2.18	1.22		2.55	1.18	1.64	1.73	1.11
Median	3.00	2.00	2.00	2.00	1.00		3.00	2.00	2.00	1.00	1.00
Standard deviation	0.15	1.56	0.22	0.40	0.24		0.25	1.95	0.89	0.84	1.39

Table 5-20: A Sample Table of Assessment Results (after 2nd round)

	Item 11	Item 12	Item 13	Item 14	Item 15		Item 21	Item 22	Item 23	Item 24	Item 25
A	3	2	2	2	1		2	2	2	2	1
B	3	3	3	2	2		3	2	2	1	3
C	3	3	2	2	2		3	2	3	3	3
D	3	2	2	1			2	1	0	1	
E	2	2	2	3	1		3	2	3	1	0
F	3	2	1	3	2		2	2	1	3	0
G	3	0	2	3	1		3	1	1	3	1
H	3	2	2	2	1		2	2	1	1	2
I	3	2	2	2	1		3	3	2	1	1
J	3	1	2	2	1		3	2	1	1	0
K	2	0	0	2	0		2	0	2	2	0
Mean	2.82	1.73	1.82	2.18	1.20		2.55	1.73	1.64	1.73	1.10
Median	3.00	2.00	2.00	2.00	1.00		3.00	2.00	2.00	1.00	1.00
Standard deviation	0.15	0.67	0.22	0.40	0.23		0.25	0.32	0.89	0.84	1.23

The highlights in Figure 5-19 indicates the items relative high SD (larger than 1) and highlights in Figure 5-20 indicates the items and assessments that had been changed from first round to second round.

Of note in Tables 5-19 and 5-20 is the decrease in standard deviation in some ratings. The standard deviations of items 12 and 22 decreased quite a bit due to adjustments. After the first round of assessment, there were three ratings with standard deviations larger than one. After the second round, only one rating still had standard deviation larger than one. This is an indicator of improvement of overall level of consensus. For the whole set of impact ratings of this model, the number of cases with standard deviation higher than one (SD>1) decreased from 37 to 13.

Another indicator of improvement in level of consensus is Kendall's coefficient of concordance (*W*). Computation using SPSS show an increase in *W* from 0.29 to 0.57. According to Schmidt's table of interpretation (1997), this increase is an improvement from weaker to stronger agreement. Table 5-21 summarizes these indicators for each of the two rounds of assessment.

Table 5-21: Change in Consensus from Initial to Conformation Assessment

	Initial Assessment (1st round)		Confirmation Assessment (2nd round)	
	No. of cases SD>1	Kendall's W	No. of cases SD>1	Kendall's W
Decision to Drivers	6	0.35	2	0.76
External Variables to Drivers and Processes	11	0.13	7	0.39
Cross-impacts of Drivers and Processes	13	0.24	5	0.51
Processes to Outcomes	7	0.22	1	0.48
Total	37	0.29	13	0.57

As shown in Table 5-21, assessment iteration stopped at the second assessment because the level of consensus had reached the satisfactory level. In order to confirm this, three different tests were conducted – Kendall's *W*, sensitive analysis of the assessments with SD>1, and expectation of improvement in further rounds of assessment.

First, Kendall's *W* was computed for the whole set of assessment data. As discussed earlier, the *W* value for the second round was 0.57. According to Schmidt's table of interpretation, this value is close to strong agreement.

Table 5-22: Interpretation and Confidence Level of Kendall's *W*

W	Interpretation	Confidence level
0.1	Very weak agreement	None
0.3	Weak agreement	Low
0.5	Moderate agreement	Fair
0.7	Strong agreement	High
0.9	Unusually strong agreement	Very high

This result shows that there was enough agreement among participant opinions, especially because the assessments were done through questionnaire and interview rather than a workshop. Assessments were done in an individual-interview setting, and there was absolutely no interaction among participants. Therefore, it was difficult to expect a high level of agreement, and the current level was already higher than expected. In a previous study of partnering performance index which is similar to project performance measure of this study, survey was stopped after four rounds once *W* reached 0.3 (Yeung et al. 2007). This indicates that the level of consensus of second-round (which is 0.57) is satisfactory.

The second test measures the sensitivity of the possible improvement from another assessment round. If one or more rounds of interview or discussion are conducted, the level of agreement of may improve (i.e., smaller SD value). However, it is not certain that this improvement in level of agreement actually changes the end result. In other words, the improvement in level of agreement from further rounds may not be enough to change the end result. To find this out, a simple test was conducted.

Table 5-23: Assumed Improvements from further Rounds of Assessment

Item 25	1st round	2nd round	3rd round (Assumption)
A		1	1
B	3	3	2
C	3	3	2
D			
E	0	0	0
F	0	0	0
G	1	1	1
H	2	2	2
I	1	1	1
J	0	0	0
K	0	0	0
Mean	1.11	1.10	0.90
Median	1.00	1.00	1.00
SD	1.39	1.23	0.61

Table 5-23 examines possible changes from another round of assessment to the final result and their impact to average ratings. In the case of item 25, SD after a second round of assessment is 1.23, which may be one indication of low level of agreement. If another round of assessment is conducted, some participants may change their assessment and end up improving the level of consensus for this item. In this case, it is assumed that two of the participants have changed their assessment from 3 + (SIG+) to 2 + (MOD+) improving SD from 1.23 to 0.61. However, this change was not significant to the final result and the average value remained the same (SLI+). Therefore, it can be concluded that a third round was not necessary, at least in terms of the final result. This test was conducted for other 12 cases with SD>1, and it was found that a third round of assessment was significant to the result only in a few cases (3 or 4 cases out of 13 – varies by the assumption of how many assessments would be changed from an additional round).

The final point of argument is that even those final assessment values that may be changed from an additional round do not make any real difference in final simulation results. A few test simulations were run to see how much would be changed. The results show that the difference would be less than one percent (the simulation graphs are not presented here because they are visually indistinctive). Therefore, it is safe to say that possible changes from an additional round are insufficient to make any significant differences in simulation outcomes.

5.5.3 Final Assessment Values

The final values of interaction ratings of each pair of GPM variables are shown in Tables 5-24 and 5-25. In Table 5-24, the final ratings of external variable interaction to drivers and processes are listed. In Table 5-25, cross-impact ratings of drivers and processes are listed. Also, impact ratings of processes on project performance outcomes are listed. These values are entered into the model and the computer software for further model simulation.

Table 5-24: Final Values of Impact Ratings (From External Variables to Drivers and Processes)

		Project size	Specification Type	Project complexity	Delivery Method	Innovation Preference	Need for work	Financial Strength	Experience Level	Surety Risk Attitude	Level of competition
Drivers	Transferred Risk	MOD+	MOD+	MOD+	SLI+	SLI+	MOD+	SLI+	SLI+	NO	MOD+
	Control & Innovation	MOD+	MOD+	MOD-	MOD+	MOD+	SLI+	SLI+	SLI+	NO	SLI+
	Quality/Cost Tradeoff	MOD+	MOD+	SLI+	SLI+	SLI+	SLI+	NO	SLI+	SLI+	SLI+
	QA/QC	SLI+	SLI+	MOD+	SLI+	NO	SLI+	NO	MOD+	NO	NO
	Post Const. Maintenance	NO	SLI+	NO	NO	NO	NO	NO	NO	SLI+	NO
Processes	Procurement	SLI+	SLI+	SLI+	SLI+	SLI+	SLI+	SLI+	NO	NO	MOD+
	Design	MOD+	MOD+	SLI+	MOD+	MOD+	SLI+	SLI+	SLI+	NO	MOD+
	Construction	MOD+	SLI+	SLI+	SLI+	SLI+	SLI+	NO	MOD+	NO	SLI+
	Inspection	SLI+	SLI+	MOD+	MOD+	NO	NO	NO	SLI+	NO	MOD+
	Maintenance	SLI+	NO	NO	SLI+	NO	NO	NO	NO	NO	SLI+

Table 5-25: Final Values of Impact Ratings (Cross-impacts among Drivers and Processes)

		Transferred Risk	Innovation	Quality Improv.	QA / QC Plan	Maintenance	Procurement	Design	Construction	Inspection	Maintenance
Drivers	Transferred Risk		MOD+	SLI+	MOD-	SLI-					
	Control & Innovation	MOD+		SLI+	NO	NO					
	Quality/Cost Tradeoff	MOD+	MOD+		NO	SLI+					
	QA/QC	MOD+	SLI+	MOD+		SLI+					
	Post Const. Maintenance	SLI+	NO	SLI+	SLI+						
Processes	Procurement	NO	SLI+	SLI+	NO	NO					
	Design	MOD+	MOD+	MOD+	NO	NO	MOD+				
	Construction	SIG+	SLI+	MOD+	MOD+	NO	SLI-	MOD+			
	Inspection	MOD+	SLI+	MOD+	MOD+	SLI-	NO	SLI+	SLI+		
	Maintenance	SLI+	SLI+	SLI+	SLI+	MOD+	NO	SLI+	NO	NO	
Outcomes	Construction Cost						MOD+	SIG-	MOD-	SLI-	NO
	Design (DBer) Cost						SLI-	MOD-	NO	NO	NO
	Warranty Bond Cost						NO	NO	NO	NO	NO
	Maintenance Cost						NO	SLI+	MOD+	MOD+	SLI+
	Repair (Agency) Cost						NO	MOD-	MOD-	SIG-	SLI-
	Repair (DBer) Cost						NO	SIG+	MOD+	SIG-	MOD+
	Contractor Margin						MOD-	SLI-	SLI-	SLI-	NO

5.6 Chapter Summary

This chapter presented the plan, process, and result of assessing impact ratings for each pair of variables. The first process of assessment was defining questions to be asked and selecting interviewees with sufficient experience in both general project administration and warranty (Section 5.1). Once, the questionnaire was prepared and interviewees were selected, the ratings were determined by two rounds of practitioner interviews (Section 5.2 and Section 5.3). After second round, the level of consensus among interviewees had reached the satisfying level (moderate to strong agreement), so the results of second round assessment were taken as final. The final values were presented in Section 5.4.

As the next step, the determined impact ratings were used as input data for the model along with project characteristics that had been derived from hypothetical projects. This process and results are presented in the next chapter.

CHAPTER 6: SIMULATION RESULTS

Descriptions of model input data, case projects, simulation processes and a summary of simulation results are presented in this chapter. The developed GPM model was simulated with various input data to find variations in project performance outcomes for different project characteristics and warranty decision options. Along with the impact ratings assessed and presented in the previous chapter, a total of five hypothetical case projects are prepared as input data for model simulation runs. Each case project has unique characteristics such as project size, delivery method, and specification method. For each case project, the project performance outcomes were forecasted by the simulation. Due to the large the amount of required computations, model simulations were run by computer software, GPM 2.0. Theoretical background and the simulation processes are presented in a step by step fashion in the following sections. A relevant sample of the simulation results are presented at the end of the chapter.

6.1 Overview

Figure 6-1 below is an overview of the model simulation process. The simulation process consists of four steps – model input, computation, output, and simulation results.

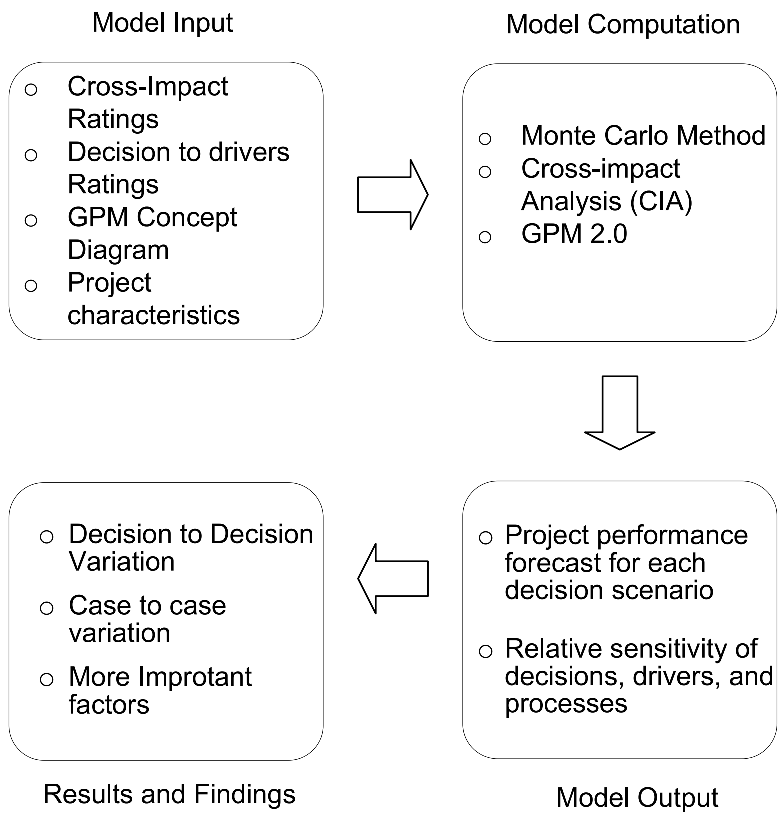

Figure 6-1: Overview of Simulation Process

The first step in model simulation is to decide upon input variables. There are four different types of input variable for this model. Key variables are determined by expert assessment (Chapter 5) and from various project and environmental characteristics. Other minor variables are assumed by the researcher and later tested for their sensitivity on the model. The next step is computation of project performance. The main method used in this simulation run is Monte Carlo method. A computation tool called GPM 2.0 is used for automated cross-impact computations and simulations. For the results of simulations, the model is expected to produce an estimation of project performance for each decision scenario. Also, the model is expected to show the relative sensitivity of each factor. As the last step, the simulation results are summarized into a graph and description.

6.2 Model Inputs

There are four different types of input that are necessary for model simulation:

- Decision options table;
- Cross-impact matrix;
- Project and environmental characteristics; and
- Initial conditions (probabilities and outcome values).

The first two types – decision options table and cross-impact matrix – had been determined by expert assessment (Chapter 5) and they were directly inputted into the model. These data are fixed parameters which mean that, once determined, they remain the same for any project. The latter two types are project-specific. They vary by project given different project characteristics and environments. Detailed descriptions and samples of each of these four input variables are presented in following sub-sections.

6.2.1 Decision Options

The decision options table defines how strategies impact drivers. In a decision options table, the impacts on drivers of each possible scenario are analyzed. A scenario is a specific combination of the states that the different strategic characteristics can adopt. For example, Table 6-1 shows one decision and four possible alternatives and their impact on drivers. For each decision option, a table similar to this was constructed and inserted into the model. Impact on drivers is assessed as one of five ratings – very positive (PP), positive (P), no effect (O), negative (N), and very negative (NN). The ratings in Table 6-1 below are examples and may not match with the assessment results.

Table 6-1: Decision Alternatives and Their Impact on Drivers

	Decision Options				Drivers				
	No Warranty	3 Years	5 Years	10 Years	Amount of Risk	Innovation Chance	Quality improvement	QA/QC	Post-const. Maintenance
Scenarios	√				O	O	O	O	O
		√			P	P	P	P	O
			√		PP	P	P	PP	P
				√	PP	PP	PP	PP	P

6.2.2 Cross-impact Matrix

The next type of input is a cross-impact matrix. This structure stores information that defines how the impacts of strategies are propagated through the model structure. Specifically, it defines how the drivers impact the processes and themselves and how the processes impact the outcomes and themselves. The model uses a modified cross-impact analysis algorithm to propagate changes in probability distribution in a chain of impacts. Figure 6-2 is an example of a cross-impact matrix. Impacts between each pair of drivers, processes, and outcomes were rated as one of seven ratings of SIG+, MOD+, SLI+, NO, SLI-, MOD-, and SIG- (Chapter 2) and decided by practitioner assessment (Chapter 5).

Table 6-2: Impact Ratings from External Variables to Drivers and Processes

		Transferred Risk	Innovation	Quality Improv.	QA / QC Plan	Maintenance	Procurement	Design	Construction	Inspection	Maintenance
Drivers	Transferred Risk		MOD+	SLI-	MOD-	SLI-					
	Control & Innovation	MOD+		SLI+	NO	NO					
	Quality/Cost Tradeoff	MOD+	MOD+		NO	SLI+					
	QA/QC	MOD+	SLI+	MOD+		SLI+					
	Post-const. Maint.	SLI+	NO	SLI+	SLI+						
Processes	Procurement	SLI+	SLI+	SLI+	NO	NO					
	Design	MOD+	MOD+	MOD+	NO	NO	MOD+				
	Construction	SIG+	SLI+	MOD+	MOD+	NO	SLI+	MOD+			
	Inspection	MOD+	SLI+	MOD+	MOD+	SLI-	NO	SLI+	SLI+		
	Maintenance	SLI+	SLI+	SLI+	SLI+	MOD+	NO	SLI+	NO	NO	

6.2.3 Project Characteristics

The next type of input variable is project characteristics. In this model, most of project characteristics are categorized as external variables that are defined to influencing drivers and processes. Similar to cross-impact matrix, external variable impact on drivers and processes are assessed as one of seven ratings – SIG+, MOD+, SLI+, NO, SLI-, MOD-, and SIG-. The performances of various case projects with different project characteristics were simulated. Details of these case projects are presented in later sub-sections (6.2.3.1 to 6.2.3.5).

Five case projects were used in the model simulation. These five cases are unique and have varying project characteristics such as size, complexity, delivery type, and specification type. Each of these case projects was inputted into the developed model, and the performance results were simulated. The combination of unique project characteristics corresponding to simulation results is expected to yield various findings such as project character impact on warranty decision, sensitivity of drivers and expected performance.

All of the cases have been abstracted from actual projects. The characteristics have been changed slightly (or significantly in two cases) to yield projects that represent the actual project, but also test the model in its extremes. Two hypothetical cases are designed to hold characteristics that are expected to yield a best outcome when extreme warranty conditions are given. One is a higher-end scenario (preferable for longer warranty) and the other a lower-end scenario (preferable for short or no warranty decision). The other three cases are realistic cases which closely follow the actual projects. These five hypothetical cases are selected to represent various project characteristics that are expected to influence warranty decision and project performance.

A summarized description, project scope table and simple section drawing of all five cases are presented in the following sub-sections. The five case projects are labeled as Case A, Case B, Case C, Case D and Case E for convenience of recognition. Case E is created to hold all parameters that are preferable to warranty. Case A is the other extreme that is unfavorable to warranty.

It may be questionable whether the five case projects are good representation of all kinds of paving projects. These five case projects may not represents all project types that exist; however, they certainly represents some of the more common types, and the results of this study provide insights as to how some key project characteristics (i.e. size, complexity, delivery types) influence warranty, which in turn affects project performance outcome. As it is shown project descriptions below, case projects were designed to have unique characteristics which are anticipated to influence for significant changes to warranty effects on project outcome.

6.2.3.1 *Case A – Paving over two existing lanes.*

This is a hypothetical project that is consists of characteristics that are supposed to have negative impacts on the performance of a project with warranty. This project is assumed to be performed on a rural road where traffic volume is relatively low and the current condition of existing pavement is decent enough that overlaying new pavement without milling of existing pavement is possible. This method can lower initial cost of construction but increases risk of future defect significantly. It is used sometimes for driveways and parking lots but rarely in road construction where consequence of failure is significant.

Figure 6-2 describes some characteristics of this project.

Name	Pave-over 4 lanes
Award Date (Duration)	01/01/2009 (6 months)
Facility Type	2 lane rural arterial
Existing Condition	10" Asphalt (HBP)
Lane & Length	4 lanes 5 miles
Pavement tonnage	43000
Scope	3" paving, adhesive
Complexity	High
Specification	Prescriptive
Delivery	Design-bid-build
Innovation Chance	Low
Competition (Bid Number)	Low (2 bidders)
Bidder Qualification	Low
Estimate (Low bid)	4.4 Million $
$/ton & $/lane mile	$102/ton, $220000/lane-mile

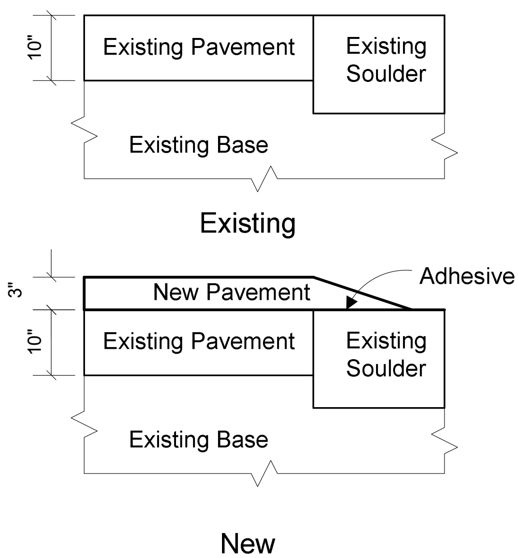

Figure 6-2: Overview of Case Project A

6.2.3.2 Case B – Overlaying four existing lanes

The project was based on a major interstate highway located in a suburban area approximately ten miles outside a mid-size city. It is expected to have significant commuting traffic during early morning and late afternoon. The scope of the project is overlaying (milling and overlaying new) of all four existing lanes of the road. Milling and new layer thickness is relatively light in order to minimize cost of construction materials. Key project characteristics and graphically depicted the project scope are summarized in Figure 6-3.

Name	Overlaying 4 lanes
Award Date (Duration)	02/14/2000 (9 months)
Facility Type	4 lane highway
Existing Condition	10" Asphalt (HBP)
Lane & Length	4 lanes 5.33 miles
Pavement tonnage	71900 ($40/ton)
Scope	¾" milling, 4" paving
Complexity	Low
Specification	Prescriptive
Delivery	Design-bid-build
Innovation Chance	Low
Competition (Bid Number)	Medium (3 bidders)
Bidder Qualification	Medium
Estimate (Low bid)	5.67 (4.77) Million $
$/ton & $/lane mile	$79/ton, $266000/lane-mile

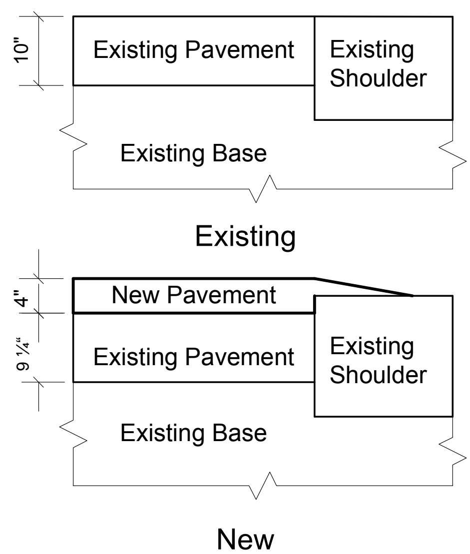

Figure 6-3: Overview of Case Project B

6.2.3.3 Case C – Two New Eastbound Lanes

The project was based on a state highway in a rural area. Although it is not near a major city, medium traffic is expected. Traffic control is not a major issue in this project as existing lanes will stay open while additional lanes are being constructed. The project scope is to build two eastbound lanes which are separated from two existing westbound lanes. Since there is no connection to existing lanes, this project holds characteristics of new-road construction despite being an expansion project. There are more chance for contractor design input and innovation. Though it is a design-bid-build project, many specifications are written-performance based. Key project characteristics are summarized in Figure 6-4.

Name	New Eastbound 2 lanes
Award Date (Duration)	08/12/2004 (13 months)
Facility Type	4 lane principal arterial
Existing Condition	Existing westbound
Lane & Length	2 lanes 5.3 miles
Pavement tonnage	72000 ($19/ton)
Scope	6" base, 8" paving
Complexity	Medium
Specification	Performance
Delivery	Design-bid-build
Innovation Chance	Medium
Competition (Bid Number)	Medium (3 bidders)
Bidder Qualification	Medium
Estimate (Low bid)	5.82 (5.18) Million $
$/ton & $/lane mile	$80.8/ton, $549000/lane-mile

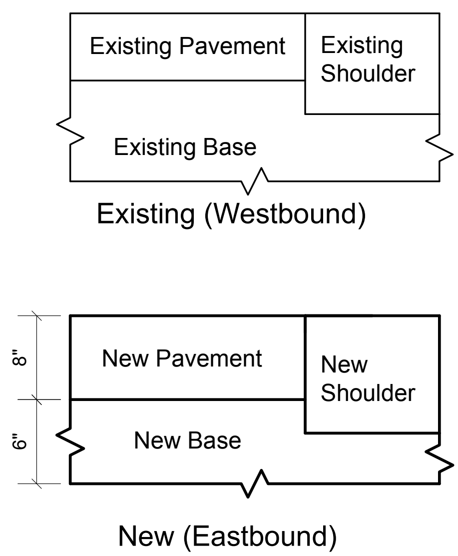

Figure 6-4: Overview of Case Project C

6.2.3.4 Case D – Adding two lanes to existing two lanes (DBB)

This project was based on a typical design-bid-build expansion project in that design and construction method are provided to the contractor. Due to the connection between existing and new pavement, project complexity is relatively high, and the engineer's estimate is significantly higher than in projects of other similar size. Traffic control is a major problem in this project as at least one lane should remain open for traffic at all the times and two lanes during heavy traffic hours. The scope of this project includes milling of existing pavement, removal of existing shoulder, and installation of an adhesive joint system between new and existing pavement, new base, new pavement and new shoulder. Due to water penetration at the connection, oil coat and permeable base material are required. Key project characteristics are summarized in Figure 6-5.

Name	Expend 2 lanes
Award Date (Duration)	01/16/2000 (11 months +)
Facility Type	Expending to 4 lane highway
Existing Condition	6¾" Asphalt (HBP)
Lane & Length	2 lanes 7.3 miles
Pavement tonnage	60332 ($39.9/ton)
Scope	Connection and 6 ¾" paving
Complexity	High
Specification	Prescriptive
Delivery	Design-bid-build
Innovation Chance	Medium
Competition (Bid Number)	High (5 bidders)
Bidder Qualification	Medium
Estimate (Low bid)	13.85 (12.58) Million $
$/ton & $/lane mile	$229/ton, $948000/lane-mile

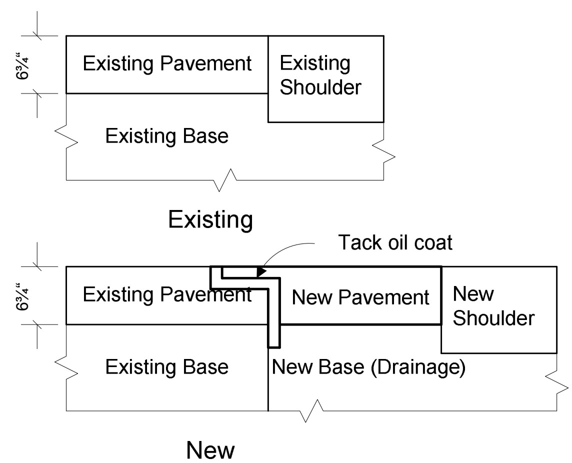

Figure 6-5: Overview of Case Project D

6.2.3.5 Case E – Adding two lanes to existing two lanes (DB)

This is another hypothetical project which holds all characteristics favorable to warranty. This is very similar to case D in terms of project scope and size, though quite different in terms of delivery and specification methods. This is a typical design-build project with performance-based specification. In other words, the chances of contractor input and innovation are much greater. As it is shown in Figure 6-6, the contractor has come up with a new method of bonding existing to new pavement. This design requires more paving material but eliminates the joint between existing and new pavement which will minimized water penetration, separation and joint cracking. Also, the new design provides a new surface on existing pavement increasing the overall quality of all four lanes. Key project characteristics are summarized in Figure 6-6.

Name	Add 2 lanes
Award Date (Duration)	01/01/2009 (12 months)
Facility Type	2 lane to 4 lane highway
Existing Condition	8" Asphalt (HBP)
Lane & Length	2 lanes 7 miles (+2 lanes)
Pavement tonnage	90000
Scope	Add 2 lanes any method
Complexity	Low
Specification	Performance
Delivery	Design-build
Innovation Chance	High
Competition (Bid Number)	High (5 bidders)
Bidder Qualification	High
Estimate (Low bid)	15.5 Million $
$/ton & $/lane mile	$172/ton, $11070000/lane-mile

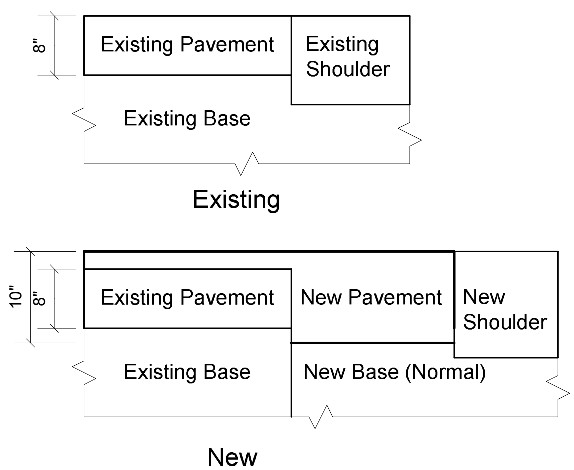

Figure 6-6: Overview of Case Project E

6.2.3.6 Summary of project characteristics

The main purpose of using five different cases for model simulation is to study the effects of various project characteristics on project performance and warranty decision. Because most project characteristics are inputted into the model as discrete values (i.e. small, medium and large size), it is necessary to examine each case and categorize it for each characteristic – project size, complexity, procurement type, etc.

Table 6-3 is a summary of project information for five case projects.

Table 6-3: Project Information for Five Case Projects

	Engineer's Estimate ($)	Paving Material (ton)	Lane Mile (Miles)	$ / ton	$ / Mile
Case A	4,400,000	43,000	20.0	102.0	220,000
Case B	5,700,000	71,900	21.3	78.8	266,000
Case C	5,800,000	72,000	10.6	80.8	549,000
Case D	13,800,000	60,300	14.6	229.0	948,000
Case E	15,500,000	90,000	14.0	172.0	1,107,000

The first project characteristic that needs to be inputted is project size. For the purpose of this simulation, it is assumed that the project size can be decided by the estimated cost value. There is no clear threshold cost value that defines project size, but among only five selected cases, it is clear that case projects A is relatively small, and cases D and E are relatively large in terms of dollar amount (first column of Table 6-3). Therefore, projects A was categorized as small, and D and E as large size, and B and C as medium size project.

The next project characteristic is complexity. Unlike project size, it is not clear which project are more or less complex than others. There is no clear indicator of project complexity in the given project information. For a clear indication of project complexity, the cost of each project was normalized by lane-mile. The results of this analysis are shown in the Tables 6-7. Table 6-7 shows the differences among case projects in terms of price per lane-mile.

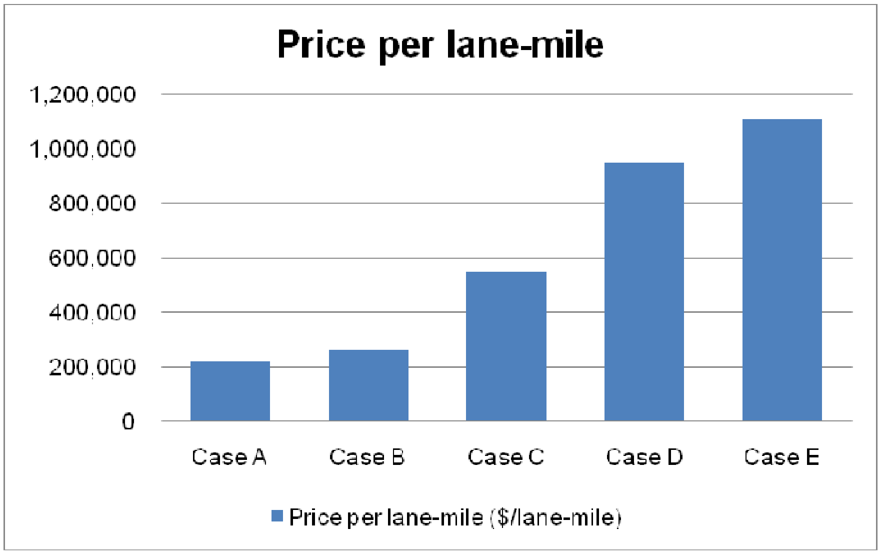

Figure 6-7: Price per lane-mile for Case A through E

In general, a more complex project is more likely cost more per lane-mile of road. For example, an expansion project tend to cost more than a new project despite the fact that they have same lane-mile because more tasks (such as connection to existing lanes and traffic control during construction) are involved in an expansion project. With more tasks and other risk factors, the project tends to be more complex than others. Therefore, it is a logical assumption that projects with higher cost per lane-mile are more complex. From this assumption and a normalized project-cost graph, the case projects can be categorized by their level of complexity.

In the cost per lane-mile graph, it appears that cases A and B are relatively low-cost and D and E relatively high cost per lane-mile. Case C is in the middle in terms of cost per lane-mile. In the cost per unit of paving material graph, cases A, B and C are relatively low-cost while D and E cost significantly more. Considering both relative cost graph, it can be concluded that cases A and B can be categorized as low-complexity projects. Likewise, case C can be categorized as medium-complexity, and cases D and E as high-complexity.

Categorization of specification type and procurement type is simple as they are clearly defined in the project description. By project definition, case A, B and D have prescriptive specification while cases C and E have performance specification. Also, case E is the only project which is delivered by DB method.

The owner's preference in innovation is not clearly defined in the project descriptions, but it can easily be determined from other characteristics such as specification type and delivery type. It is reasonable to assume that projects which are delivered by design-build with performance-based specifications are more likely to have more room for innovative ideas. Also, it would be a reasonable assumption that new construction, in comparison to overlaying, would accommodate more innovation. From these assumptions, projects were categorized to low, medium and high owner preference for innovation.

Figure 6-8, summarizes some of the key project characteristics of five simulation case projects. These characteristics were directly inputted into the model.

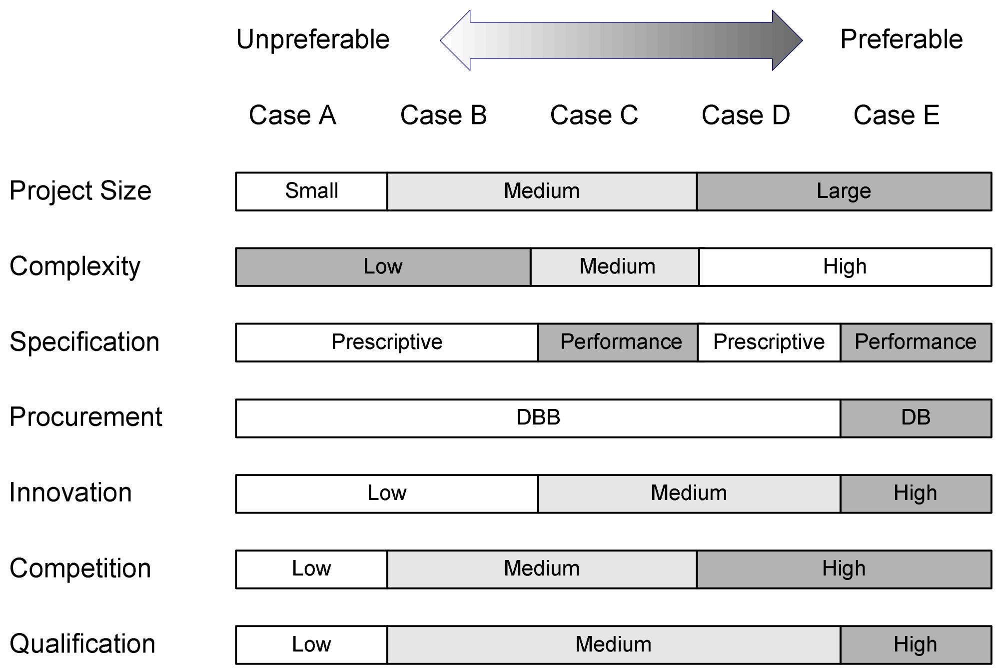

Figure 6-8: A spectrum of Project Characteristics (Case A through E)

6.2.4 Initial Conditions

The last type of input parameter is the initial conditions. The initial conditions include the initial probability of occurrence and resulting consequence of each outcome event before the interaction among variables, including decisions, is applied. In this model, it is estimated from project performance before warranty decision is made and applied. Before simulation, the model user must input these initial probabilities and expected values for each event. Among the GPM elements, external conditions and performance outcomes require these user inputs. However, in this specific model for the five case studies, all external conditions are assumed to be fixed inputs. Therefore, the only variable in this model which requires initial condition input is performance outcome. Table 6-4 is an example of an initial-condition chart. The users are asked to input expected values for each probable, best, and worst scenario and the model recognizes them as a beta-probabilistic distribution function.

Table 6-4: An Example of Initial-Condition Table

		Scenarios		
		Best	Probable	Worst
Outcomes	Construction cost	$200,000	$ 250,000	$300,000
	Warranty Bond cost	$15,000	$20,000	$30,000
	Agent maintenance cost	$ 0	$ 30,000	$40,000
	Agent future repair cost	$ 50,000	$ 100,000	$250,000

When inputting expected or estimated values for each scenario in this specific model, the user must discount future value into present value. Despite the fact that all the performance outcomes are measured in terms of life-cycle cost items with different times of payment, there is no built-in function in the model that adjusts these costs into the same time scale (i.e. discounting future costs into present costs). Therefore, the user must adjust some costs manually prior to inputting them into the model. Some commonly used methods of life-cycle analysis are explained in Chapter 2.

6.3 Computing Tool and Simulation Parameters

Once all the necessary model inputs are decided and inserted into the model, it is ready for simulation and estimation of project performance for each decision scenario, considering the unique project and environmental characteristics. In this section, the computer tool that was used for model simulation and some of the simulation parameters is described. Although all the simulations were run automatically using the GPM software, a sample calculation is presented in Appendix 3 to explain the computing process.

6.3.1 Computing Tool

All of the simulation and computations for this study were done with GPM 2.0 (General Performance Model Software Version 2.0), a computer implementation of the modeling concepts, developed by Alarcon and Bastias (Alarcon and Bastias 1998). This software was developed specifically to simulate GPM models and includes a highly interactive interface to support the modeling process. This computer system provides a graphical interface to help the users in building a conceptual model of the decision problem, the firm and its environment. The model is a simplified structure of the variables and interactions that influence the decisions, including internal as well as external variables, which represent the external environment of the project. The system provides analysis capabilities such as: sensitivity analysis, to identify the most important variables in the decision problem; prediction of selected outcomes for a given strategy; scenario analysis, to test strategies under different external conditions; comparative analysis of the effects of alternative firm strategies on individual or combined performance measures: and others.

The system has been implemented in a PC microcomputer platform for Windows 95 & Windows NT, using the development environment Microsoft Visual and programming language C ++ (Alarcon and Bastias 1998).

6.3.2 Simulation Parameters

For simulation runs, some parameters (i.e. number of simulation runs) must be specified by the user. The following are short descriptions of these parameters used for the model simulation.

First, the initial probability of performance of drivers and processes are assumed as in the Table 6-5. These are used as default values and applied to all drivers and processes which were not specifically defined. For this specific model, these values were applied to all drivers and processes.

Table 6-5: Default Initial Probabilities for Variables

Performance Level	Initial Probability
Very high	0.1
High	0.2
Medium	0.4
Low	0.2
Very low	0.1

Second, the initial values of project performance outcomes are assumed as a beta distribution curve. The beta distribution is a type of continuous probability distribution defined on the interval 0 to 1 and specified by two positive parameters, typically denoted by α and β. In this model, estimated maximum and minimum values are used as these two positive parameters.

Thirdly, for each combination of decision options, the project performance outcomes were estimated from ten thousand simulation runs. The performance of each performance factor in the model was randomly selected according to its initial or posterior probability, and the result of each run was cumulative for ten thousand simulation runs. Their average value was provided to the user as model output.

6.4 Outputs and Results

From simulation runs, the model is expected to produce three types of outputs. One is a project performance estimate for each decision scenario. The second output is difference in warranty influence on project performance for varying project characteristics.

The third output is relative sensitivity of various performance outcome factors – decisions, drivers and processes. By comparing project performance estimates for each decision scenarios, the model provides valuable information about to the relative variation between the decision scenarios in terms of performance outcomes. From this information, decision makers can understand how decisions propagate their impact throughout various project factors and change project outcomes. Also, comparisons of outcomes for the various case projects provide valuable information about case-to-case variation. This information demonstrates how differences in project characteristics result in difference in warranty impact on project outcomes. Finally, sensitivity analysis outputs can be used to distinguish more important from less important factors among many variables in the model.

Key results of simulation runs are presented in the next three sub-sections – variation among decision alternatives, variation among case projects and sensitivity of variables.

6.4.1 Variation among Decision Alternatives

The model's main purpose was to predict the project performance of various warranty decision scenarios. The simulation outputs were organized and graphed to show various project outcome estimates for each warranty decision scenario. Life cycle costs (LCCs) are used as representative measures of project performance for outcomes including construction cost, maintenance cost, and repair cost.

Table 6-6 is a sample of the simulation results for Case B.

Table 6-6: A Sample of Forecasted LCCs for Various Decision Alternatives

Case B		Construction (M$)	Design (M$)	Bond (M$)	Maintenance (M$)	Contractor's Repair (M$)	Agency's Repair (M$)	Contractor margin (%)
Warranty Period	0 years	5.324	0.279	0.101	0.149	0.145	0.780	1.143
	3 years	5.505	0.321	0.100	0.100	0.305	0.500	2.236
	5 years	5.587	0.341	0.100	0.077	0.379	0.371	2.735
	10 years	5.711	0.374	0.099	0.044	0.491	0.185	3.557
Required Performance Level	Max.	5.799	0.016	0.105	0.024	0.470	0.089	0.801
	Average	5.571	0.015	0.105	0.042	0.333	0.294	0.271
	Min.	5.501	0.015	0.105	0.050	0.269	0.394	0.029
Limited Liability	Yes	5.503	0.015	0.105	0.051	0.264	0.398	0.172
	No	5.531	0.015	0.105	0.042	0.333	0.324	0.271
Maintenance Requirement	Yes	5.578	0.016	0.105	0.029	0.233	0.138	1.559
	No	5.445	0.014	0.105	0.067	0.142	0.390	0.274

Case B			Total Contractor's Expense (M$)	Expected Bid price (M$)	Total repair cost (M$)	Total Life Cycle Cost (M$)		
Warranty Period	0 years		5.850	5.916	0.925	6.845		
	3 years		6.232	6.371	0.804	6.971		
	5 years		6.407	6.582	0.750	7.030		
	10 years		6.675	6.913	0.676	7.141		
Required Performance Level	Max.		6.390	6.441	0.089	6.554		
	Average		6.025	6.041	0.294	6.377		
	Min.		5.889	5.891	0.394	6.336		
Limited Liability	Yes		5.886	5.897	0.662	6.346		
	No		5.985	6.001	0.657	6.367		
Maintenance Requirement	Yes		5.932	6.025	0.371	6.192		
	No		5.706	5.722	0.532	6.179		

Various LCCs costs in Table 6-6 are estimated from model simulation for each different warranty decision option. From these model outputs, warranty effects on various cost items can be examined. For example, according to the simulation results, it seems that warranty period tends to increase initial construction cost and decrease agency's future repair cost. For convenience in data analysis, key simulation results are graphed and displayed.

Figure 6-9 and 6-10 present the estimated agency costs for varying warranty periods. Figure 6-9 is for hypothetical project Case A, which is the extreme case and holds all the characteristics unfavorable for a warranty. No warranty or a short-term warranty is assumed to be the preferable choice. Figure 6-10 is for Case E, which is at the extreme at the other end of the variable-case spectrum and holds all the characteristics that are favorable for long-term warranty.

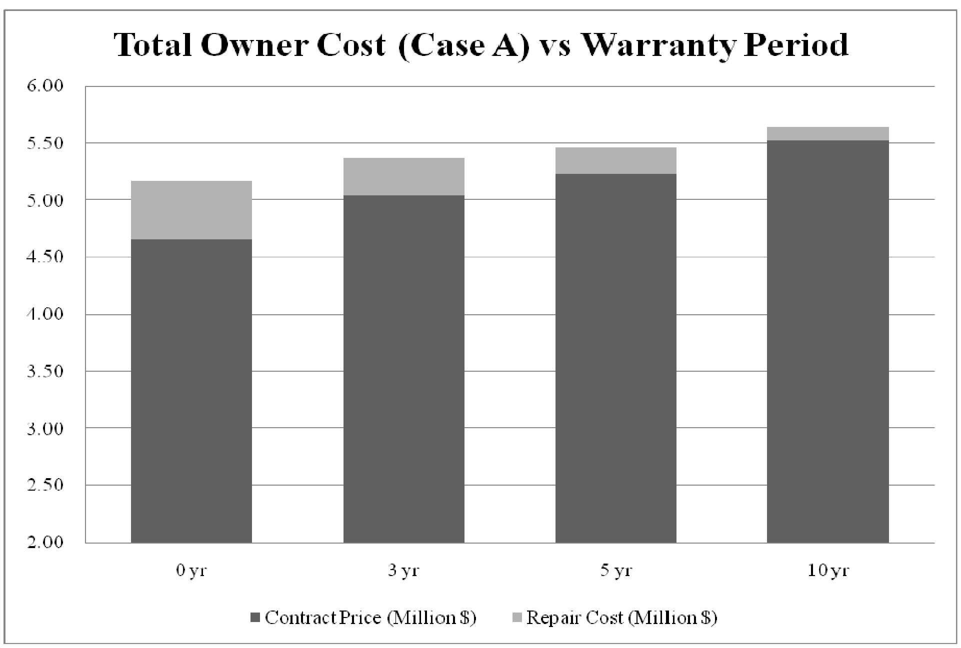

Figure 6-9: Estimated Agency Costs for Varying Warranty Periods (Case A)

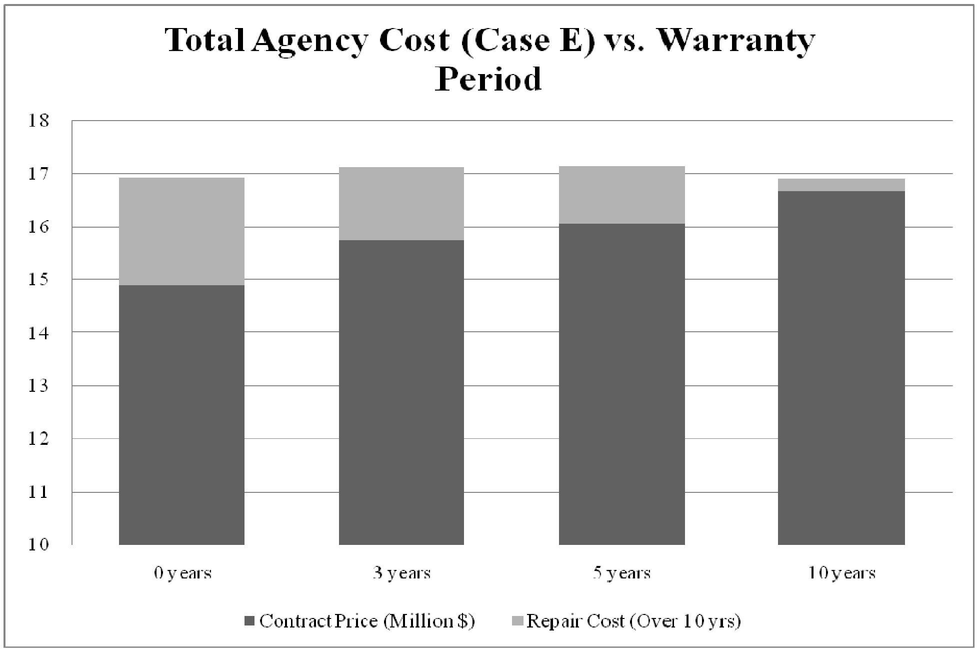

Figure 6-10: Estimated Agency Costs for Varying Warranty Periods (Case E)

The two Figures show estimates for each warranty period of zero to ten years. The first estimate is the expected contract price (same as bid price in Table 6-6). The contract price represents the agency's initial cost to build or rehabilitate the facility, and is computed from simulation results for construction cost, design cost, bond cost, and contractor margin. In addition, the agency's expected repair cost for the next ten years is estimated and graphed. Finally, the sum of these two costs – initial and future agency cost – makes up an LCC of the facility for over ten years of the analysis period.

As shown in Figures 6-9 and 6-10, contract price tends to increase as warranty period gets longer. Contrarily the agency's expected repair cost tends to be less for the project with longer warranty, as anticipated. These tendencies are the same for both cases, A and E. Since cases A and E represent the extreme ends of the project-to-project variation spectrum, it would be safe to assume that these tendencies will also be applicable for other case projects, B, C and D.

The other point of interest in the result is the total LCC variation for different warranty periods. From the simulation results, it appears that total LCC for case A continues to increases as the warranty gets longer. This could mean that if a project that is similar to case A, a longer warranty is not a good decision option. However, it is different for case E. In case E, the total agency cost increases from no warranty to three-year warranty, but decreases when the warranty gets longer than five years and savings in future repair cost begin to overtake initial cost increases. As a result, the expected overall agency cost is less with a ten-year warranty than with three- and five-year warranties.

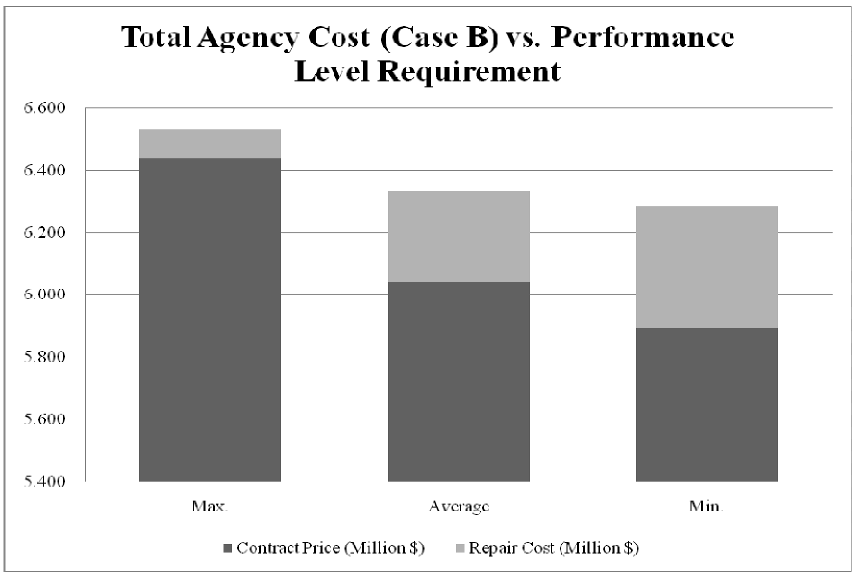

Figure 6-11: Estimated Agency Costs for Varying Performance Requirement Level (Case B)

Figure 6-11 shows the project outcome estimates for various warranty options. The variation in expected costs is due to the level of performance requirement. Like the warranty period variation graph, the graph shows expected contract price and repair cost for differently from the decision alternatives. This time, the aspects of the warranty that varies is the performance level requirement. Warranty specifications include threshold value of performance level requirement that the agency expects the contractor to maintain throughout the warranty period. The higher the performance threshold value is the greater the responsibility and risk for maintaining high quality.

Similar to the results of agency cost versus warranty periods, a higher contract price is expected when a higher level of performance is required. Also, agency's expected repair cost is less when a high level of performance is required during warranty period. One distinctive finding in Figure 6-11 is that the cost increase is quite significant when maximum performance is required, while cost increase is relatively small when average and minimum level requirements are applied. This may lead to a finding that excessive performance requirements can be overwhelming to the contractor and result in significant price increase.

Figures 6-12 and 6-13 compares estimated contractor margins for different warranty periods. The contractor margin is also referred to as markup and is the difference between the cost of a good or service and its selling price. A markup is added to the total cost incurred by the producer of a good or service in order to create profit. In construction, a certain percentage of pure construction cost (i.e., materials, labor cost) is added to the bid price as contractor profit and also as compensation for unexpected additional expenses. Due to the nature of a competitive bidding environment, the markup value is affected by many factors such as number of bidders, market situation, company situation, and certainty in base cost estimation (Chua and Li 2000; Skitmore et al. 2007). In the perspective of markup value or amount of contractor margin, a warranty is considered to be a risk factor. Therefore, longer warranty tends to increase markup value.

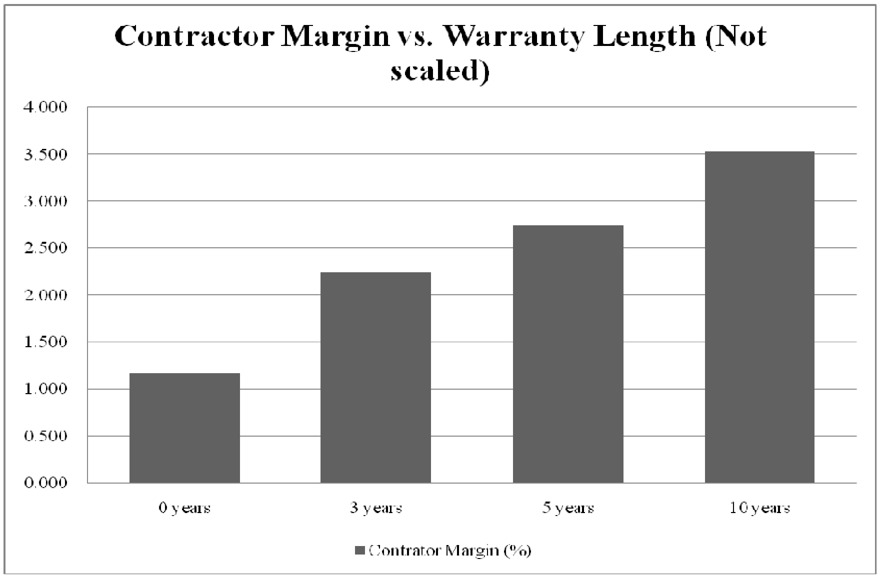

Figure 6-12: Estimated Contractor Margin for Varying Warranty Periods (Case B)

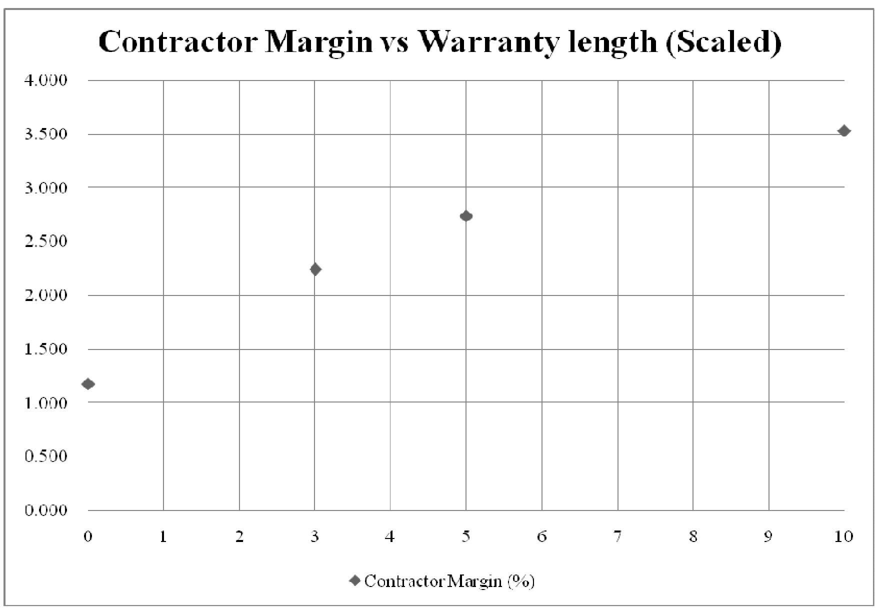

Figure 6-13: Estimated Contractor Margin for Varying Warranty Periods (Case B – In Scale)

Figure 6-12 displays changes in amount of contractor margin or markup value variation due to warranty. As shown in the graph on the left, markup value tends to increase as the warranty period gets longer. This is a reasonable result, as contractor's risk increases as warranty burden on the contractor gets heavier for longer warranty.

Another point of interest is the rate of increase in markup. The rate of increase in markup percentage is not quite linear. This becomes clear when the markup percentage is graphed with warranty length in scale. According to the simulation results, markup rate increases linearly from no warranty to five-year warranty. However, the rate of increase slows down somewhat after the five-year. This result is interesting and will be discussed further in findings in the concluding chapter.

A number of other graphs were constructed based on the simulation results of other warranty decisions (i.e., limited liability, bond requirement and maintenance requirement). However, there were no significant findings from the simulation results. According to the relative sensitivity of decisions (6.4.3), warranty period and level of performance requirement were, by far, the two decisions of highest significance to the outcomes; therefore, the other graphs are omitted from this discussion.

6.4.2 Variation among Cases

The project outcome can vary with the influence of not only different decision options, but also with project characteristics. In order to examine the impacts these project characteristics on project outcomes, outcomes were estimated by simulating five different case projects with varying characteristics, as described in earlier section (6.2.3).

Among many simulation results, increase in contract price and decrease in expected repair cost due to inclusion of a ten-year warranty were graphed to demonstrate different degrees of warranty impact in different projects.

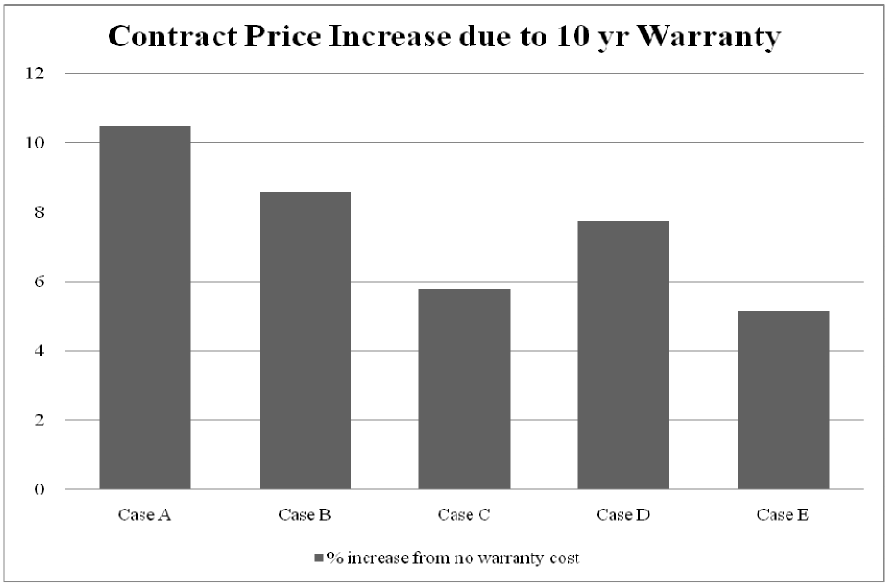

Figure 6-14: Estimated Contract Price Increase (%) for Various Cases

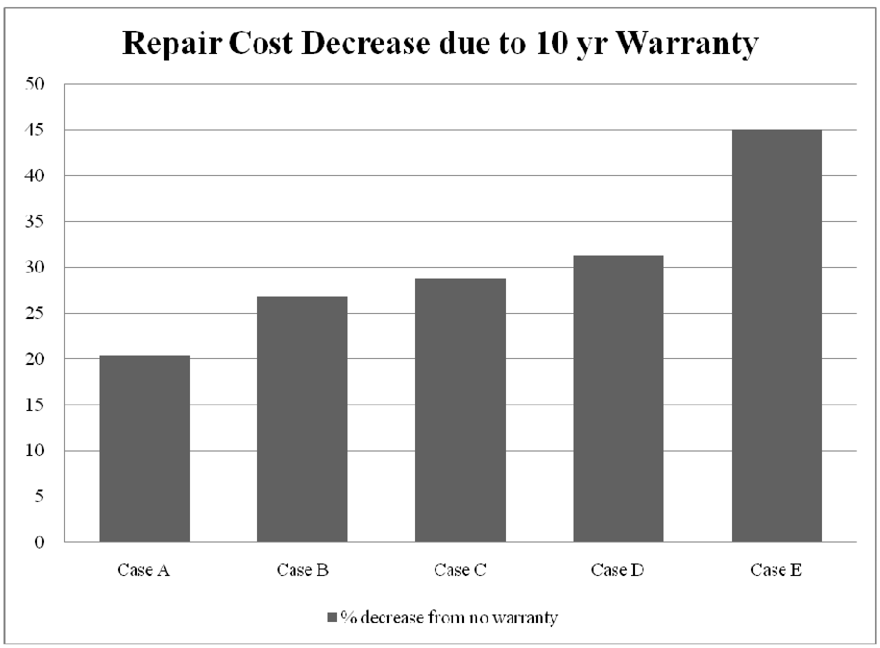

Figure 6-15: Estimated Repair Cost Decrease (%) for Various Cases

Figure 6-14 shows the percentage price increase from the project without warranty to the same project with a ten-year warranty. As discussed earlier, the introduction of a warranty to a project tends to increase contract price due to additional risk and improvement of initial quality as an effort to minimize repair needed during warranty period. This is more so in cases in long-term warranty such as ten-year warranty, which is the case here. However, the amounts of increase can be different for projects with different characteristics. The graph displays this difference by comparing percent increase in contract price for various case projects. Percent increase is relatively high in case A and low in case E. For B, C and D, percent increases gradually decrease from A to E in general. One interesting result is that the increase is significantly less in cases C and E. It is clearly shown in case C, as it is even lower than in case D. This may be due to the fact that case C is a new road construction, and there was relatively more contractor control in both design and construction method. With more control, the contractor may have less pressure from warranty requirement. More discussion about this finding will be presented in the conclusion.

Figure 6-15 is similar to Figure 6-14, except that the percent decrease in future repair cost is presented. It is expected that inclusion of warranty motivates the contractor to pay more attention to future performance of the product, and can result in lowering future repair cost. Just as in the case of contract price increase, the significance of warranty effect on repair cost saving can also be different from project-to-project. According to the simulation results, the percent saving from no warranty to a long-term warranty gradually increases from case A to E. One interesting point is that saving in case E is a bit more significant than in the others. This may due to the fact that case E is the only case project with design-build delivery method in which the contractor has more control over the design and chance for innovation.

6.4.3 Sensitivity of Variables

The last set of simulation results relates to the sensitivity of overall outcome (LCC in this model) to the variables. Sensitivity analysis is performed to check how sensitive the outcome is to changes of one variable in the model. If the outcome is found to be more sensitive to a certain variable than others, this indicates that the variable is significant and influential to the outcome and it must be considered more carefully (Clemen 1996). Hence, sensitivity analysis can determine which variables are more important to the variation in the outcome.

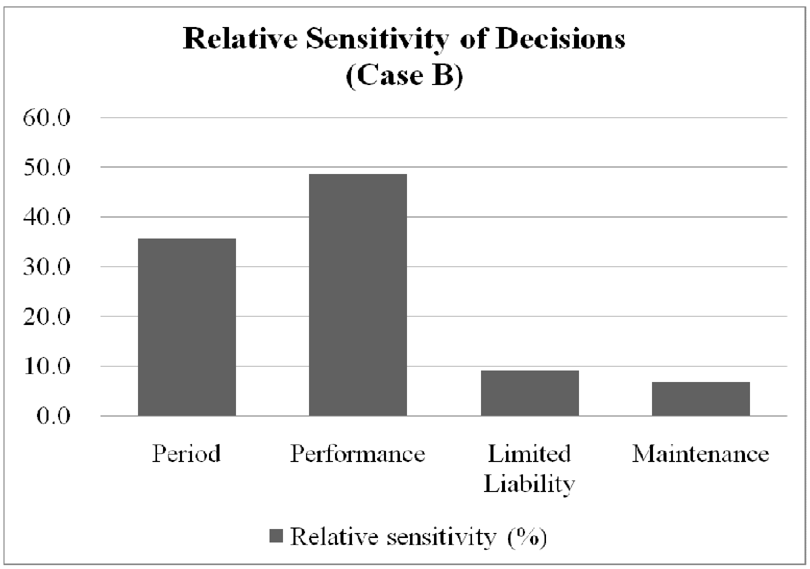

Figure 6-16: Relative Sensitivity of LCC to Various Decision Alternatives

Figure 6-16 above displays the relative sensitivity of decisions in this model. Four different decisions are shown in the graph. The warranty bond decision was excluded from this analysis because its impact was insignificant. Somewhat as expected, the warranty period and required performance levels were two significant decisions that influenced project outcome. Two other decisions – limited liability and maintenance –

were found to be less sensitive to the outcome. Of the two major decisions – warranty period and performance level – performance level turned out to be more sensitive, but the difference was not great enough to be distinctive.

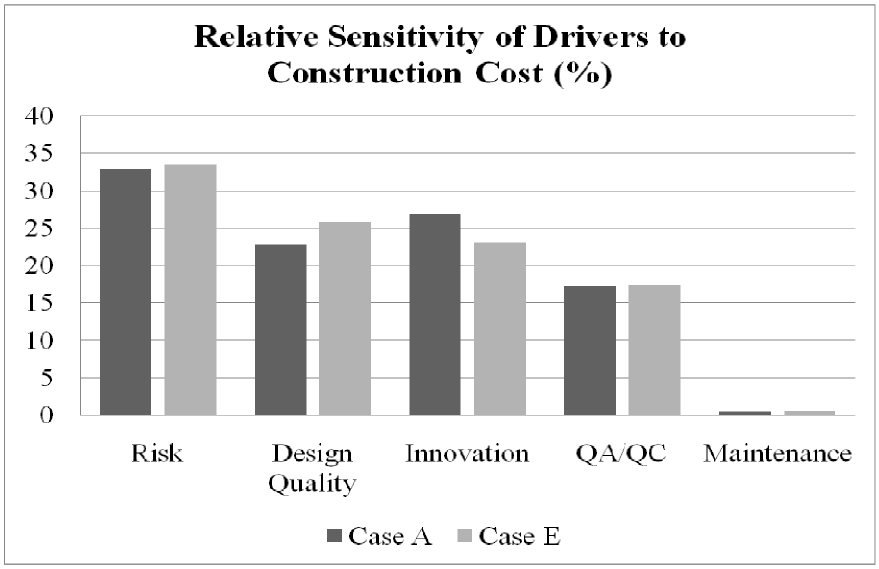

Figure 6-17: Relative Sensitivity of Construction Cost to Various Drivers

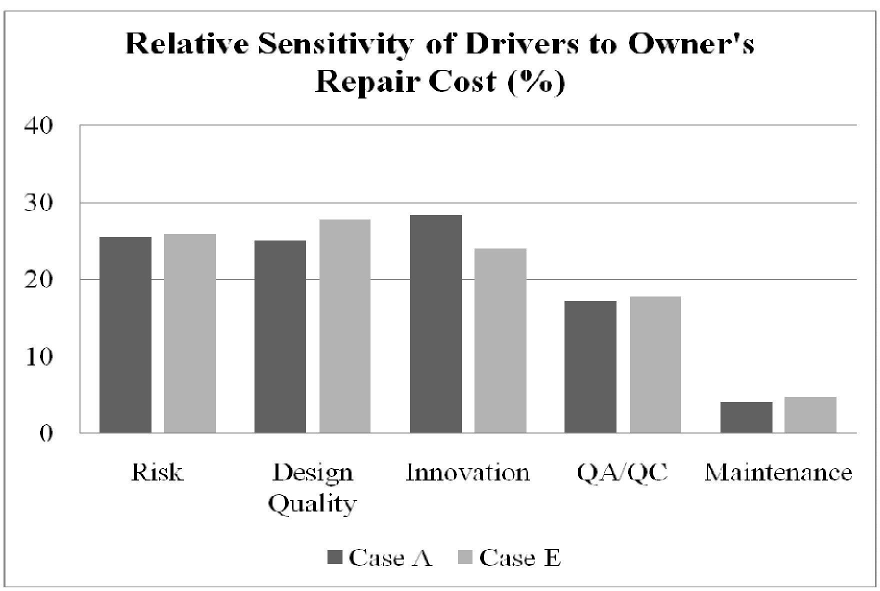

Figure 6-18: Relative Sensitivity of Repair Cost (Owner's) to Various Drivers

Figure 6-17 displays the relative sensitivity of construction cost to drivers and

Figure 6-18 displays the relative sensitivity of owner's repair cost to drivers. The "effort on post-construction maintenance" driver was found to be insignificant to both construction and repair cost. Other four drivers of risk, design quality, innovation and QA/QC were found to be more significant. Although there were no considerable differences among these four drivers, 'amount of risk' was somewhat more sensitive to construction cost, and 'innovation chance' was more sensitive to future repair cost.

6.5 Chapter Summary

This chapter presented process and results of simulation. First, descriptions on various input data for the model were presented. Two sources for input data are the results from the assessment (Chapter 5) and project characteristics. In order to run simulations, five hypothetical cases with various project characteristics were adapted and their characteristics were modified and categorized to be used as input data. Second, with all the input data prepared, simulations were conducted and outputs were collected for further analysis. Finally, the output data were analyzed and several graphs and charts were constructed. Descriptions and discussions on these results were also included in this chapter.

Further analysis and discussion on the results are presented in Conclusion (Chapter 8)

CHAPTER 7: VALIDATION

In previous chapters, the process of developing a warranty decision model (Ch. 4), assessment process of measuring interactions among variables (Ch. 5), and key results of model simulations were presented (Ch. 6). In this chapter, the validity of the developed model is tested through the requisite model validation process proposed by Phillips (Phillips 1984). Through this validation process, it will be demonstrated and proved that this newly developed model is a reasonable representation of the actual system; it simulates system behavior with enough reliability; and it produces results that satisfy research objectives.

In the first two sections (7.1 & 7.2), fundamental principles of qualitative model validation concepts and methods are discussed. The next sections (8.3, 8.4, & 8.5) include descriptions of the framework, plan, process, and the results of the model validation. In the final sections (7.6 & 7.7), each of the suggestions from practitioners is examined for possible modifications to the current model and prospects for future research.

7.1 Model Validation Principles

In this research, a model is developed to predict project performance outcomes for various warranty decision alternatives and project characteristics. In order to implement this model for any usage (i.e., decision support, information, simulation and prediction), it is necessary to validate the model first. In this section, some principals of model validation in general are discussed.

A model is a simplified and abstracted representation of a complex reality (Apostel

1961). As it is defined above, since a model is designed to represent some aspects of a real system not the whole system, it is not expected to reflect the actual system completely with perfect accuracy. Instead, if the model is accurate enough to serve the right purpose, the model can be considered valid. This principal of model validation is also shown in Macal's definition of validation as it is defined as the process of proving that the developed model is a reasonable representation of the real system, addresses the right problem, and satisfies intended requirements (Macal 2005).

In preparation for building a validation framework for this model, fundamental principles of model validation are examined and presented in this section. The discussion is presented in terms of three separate subjects. The first subject is the examination of external or environmental factors to be considered in validating a model. The second sub-section is a discussion of the model evaluation objects. The third is an examination of key approaches/methods of model validation.

7.1.1 Consideration Factors

In the previous definition of model validation, the word "reasonable" is imprecise and needs to be defined. Then, how to define reasonableness in a model? It can be defined in various different aspects such as (Macal 2005; Sargent 1998; Schlesinger 1979):

- Development objectives;
- Desired functions;
- Questions that need to be answered;
- Appropriate level of detail; and
- Required level of accuracy.

The first aspect is the purpose and objectives of the model. Models are developed to fulfill many different needs such as prediction, estimation, simulation and demonstration. A model which is designed for the purpose of demonstration can be quite different from one developed for prediction. Accuracy in a demonstration model may not be as important as it is in a prediction model. The focus in developing a demonstration model is more likely on effectiveness in communication, so the developer would emphasize appropriate visualization of the model and straightforwardness in presentation. As noted above, the different objectives of the models result in different forms, methods, and outcomes. Therefore, these differences in objectives and purposes must be considered in validating a model (Sargent 1998).

Second, models with different expected functions and application (Schlesinger 1979) must be validated accordingly. Despite sharing the same objectives, one model's expected functions may be different from another's. For example, despite having the same objective of supporting decision makers, one decision model may be focused on the function of providing information to the decision maker while the other is designed to suggest the best decision alternative. In validating these models, completeness of information is more important for the former model and accuracy for the latter.

The purposes of developing a model are to find an answer to a question. Depending on what the question is, a model is designed to represent different parts of the system at different level of detail. The same model can be valid for one question but not for another. Therefore, in validating a model, it is important to consider what question the model is intended to answer.

By its nature, a model is more abstract than the system it represents. Not only it is impossible to model the whole system, but also unnecessary and uneconomical. In addition, the inclusion of unnecessary data sometimes results in misleading and/or dilutes important findings. With given objectives and questions that need to be answered, the model developer should eliminate unnecessary detail and focus on the elements within the system which are most important. Therefore, when validating a model, one should consider whether the model excludes unnecessary details or parts and includes all important parts that are necessary to answer the questions and fulfill the objectives.

Finally, in any model, some degree of inaccuracy is unavoidable and even necessary. Sometimes, the abstraction process introduces inaccuracy, and this is somewhat expected and even intended (Sargent 1998; Shannon 1975). In order to improve accuracy, the model should be less abstract and reflect more of the actual system, but the model would be uneconomical. Therefore, when validating a model, the level of necessary and intended accuracy in output must be considers. This concept is called operational validity and it is often applied to complex computerized models.

7.1.2 Evaluation Objects

Although they vary from one model to another, for most models, there are four separate objects which should be analyzed during model validation (Carson 2002; Hillston 2003; Macal 2005; Sargent 1998):

- Assumptions and limitations;
- Model mechanism;
- Input parameters and values; and
- Output values and findings.

Figure 7-1 graphically shows evaluation objects within a model application process. The two boxes in the middle of the figure represent the abstract nature of a model. The outer box represents the actual system and the inner box the model. The ellipses on the left and right sides of the figure represent input and output of the model.

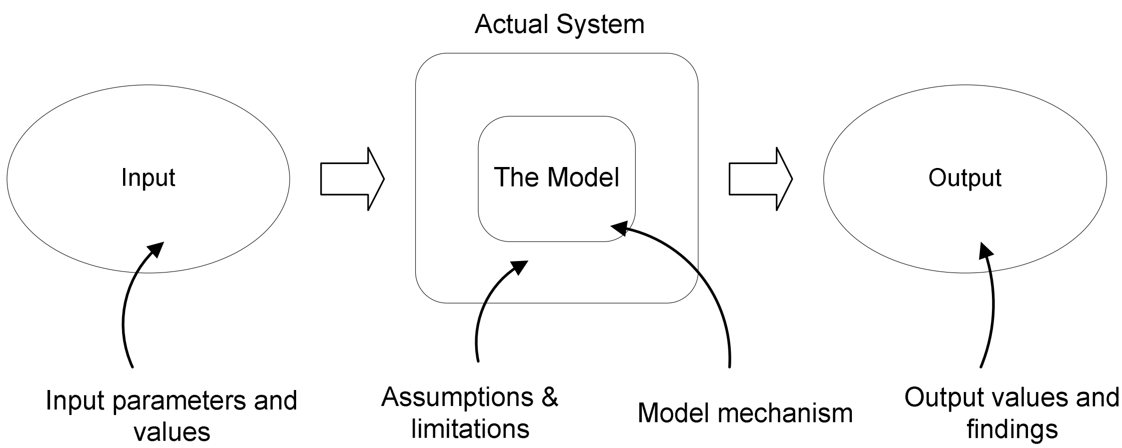

Figure 7-1: Validation Objects in a Typical Model

No model is complete as the real system. Therefore every model has its limitations and often built around assumptions. Some models are applicable only to a specific environment, time, project and people. In validating a model, these limitations should be evaluated as to their influences upon the fulfillment of the model's objectives, intended function, etc.

The second model object that needs to be evaluated is validity of modeling method and technique. The mechanism of a model should have a sound theoretical and logical basis. Therefore, each model system and process should be analyzed to determine whether it is logically consistent and valid.

Most models include multiple inputs, and in the validation process, validity of these must be examined. This is particularly important because inaccuracy in input parameters and values will lead to inaccurate output regardless of the completeness of the model itself.

Finally, the output of the model needs to be evaluated. This is somewhat obvious as model output is often tied to the main objectives of model development. It is usual that model output is evaluated first in the initial validation phase. If the model outputs are too far from the realistic, it means either model mechanism or model input is not valid. Then, the model developer may move on the evaluation of other part of the model such as mechanism, and input. In this way, one can validate the model more efficiently.

In practice it may be difficult to achieve validation in every aspect of the model, especially if the system being modeled is not yet well-known; if accuracy of input parameter values is not known; and if there is no actual outcome value to be compared to model output. In such cases, only selected aspects (i.e., output only, mechanism only) are evaluated. This may affect the reliability of the validation, but it is often unavoidable.

7.1.3 Approaches

This section presents some of validation methods. Although there are thousands of different methods, broadly speaking, there are four basic approaches to model validation, and any combination of which may be applied as appropriate to the different aspects of a particular model. These approaches are (Hillston 2003; Sargent 1998):

- Theoretical;
- Comparison to real system or other models;
- Data-based empirical; and
- People-based empirical.

In a theoretical approach each phase of a model mechanism must be evaluated through known and proven theories which have sound theoretical bases. If the model mechanism is perfectly validated by this approach, there is no need for validating the output as long as that input parameter values are correct. This approach is most reliable validation method. However, it is simply not feasible for many models, especially in the social sciences, in which interactions among people are often studied and are much more difficult to validate theoretically.

The second approach is comparing the model of interest directly to real system or similar models. If sufficient amount of real system data are available, the model can be compared to the real-system to validate the model. In case such data are not available, the model can be compared to other models with similar purpose and function. This approach is often used when a new and improved model is introduced and compared to existing models. This approach is usually used in evaluation of the model output. Assuming that input values are the same, the output value of the newly developed model should be close enough to the output value of other models that have previously been proven to work. This approach is clear and straightforward. However, in order to use this approach, there should be a least one other model that has sufficient similarity to the one that is being validated. The model mechanism does not have to be matched, but input and output parameters should be the same or at least reasonably close.

The third approach is the data-based empirical method. In this approach, the model is validated based upon actual evidence as opposed to theory. Some facts are not possible to prove theoretically, but can be proven by means of direct observation and experiment. The model can be validated in comparison to actual data. This method is used widely in any field of study, but in order to use this approach, sufficient amounts of reliable data are a must.

The fourth approach is the people-based empirical method. When not enough physical data are available, people who have sufficient experience are consulted in order to validate a model. The intuition of the people who have observed an actual system many times on different occasions can be quite reliable in model validation. This approach can be used in any perspective of model validation. The people with sufficient model building experience can be consulted to validate the model mechanism. Similarly, such people can be employed to validate the output of the model in comparison to their experience with real systems. Some drawbacks of this approach are difficulty of measuring expertise level, bias and inconsistency. In order to minimize these drawbacks, interviewing and surveying mechanisms such as the Delphi method have been developed.

7.2 Definition and Validation of a Requisite Model

For the purpose of validating the specific model developed in this research, requisite model validation method is used as described by Phillips (Phillips 1982; 1984). Requisite model validation is a people-based empirical approach that is often used in decision models in the social sciences. Definition and validation process of a requisite model shares some similarity with those of generic model (7.1), but it is distinctive in some aspects. Details on these differences are discussed in following sub-sections.

7.2.1 Requisite Model Overview

The fundamental basis and also distinguishable characteristics of requisite model are that it is developed and also validated in comparison to socially accepted knowledge pools rather than actual systems. As proposed by Phillips, requisite model is defined as a "simplified representation of social understanding whose form and content are sufficient to solve a particular problem" (Phillips 1984). This definition is similar to the definition of any general model. The only significant difference is that the model does not directly represent any real system; but instead a social understanding of a real system. Figure 7-2, displays this difference.

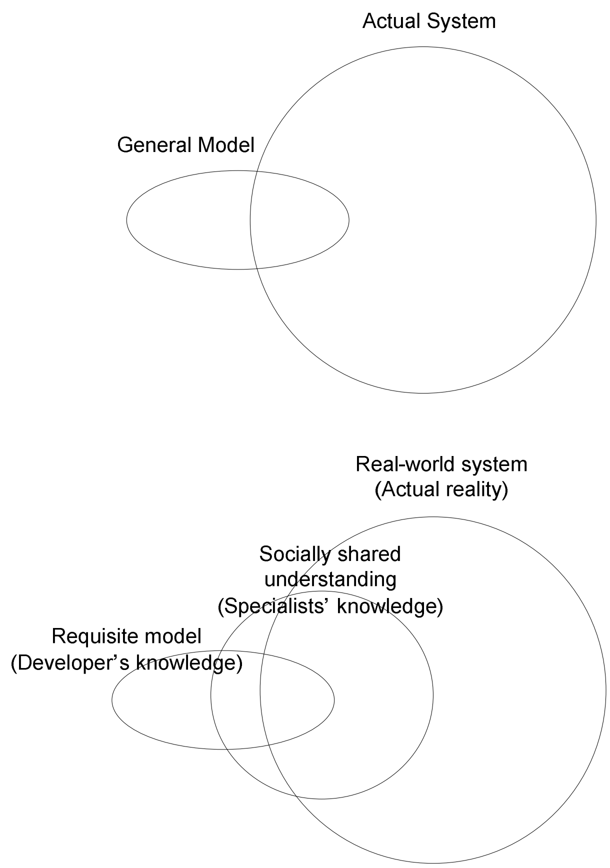

Figure 7-2: General and Requisite Model (adapted from Phillips 1984)

In his theory, Phillips insists that there are limits to what people (specialists, consultants) know about an actual system, and a model can only be developed within those limits. In other words, what is known to people is limited to some portion of an actual system, and a requisite model is one representation of that specific portion of a real system.

This difference (between a requisite model and a general model) in model definition causes some differences in its validation approach. In order to validate a general model which is defined as representative of a real system, the model has to be compared to the mechanism, constitution, and results of the actual system. This direct-comparison requirement can be problematic when not much about the actual system is known. In a requisite model, the model is validated through comparison with social understanding of the system instead of the actual system. This concept not only makes the validation easier, but also more logically sensible especially in the social sciences.

In his studies, Phillips proposes guidelines for validating a requisite model. In this research, the newly developed model is validated through this process.

7.2.2 Validation Checkpoints

To be a valid requisite model, the model should be checked for various requirements. The following is a list of validation checkpoints proposed by Phillips (Phillips 1984).

7. Model form is sufficient
8. Model content is sufficient
9. Enough interaction between specialists & model developer
    A. Specialist input to the form
    B. Specialist input to the content
10. No new intuition emerges about the problem
    A. The model is totally exhaustive of social understanding of the problem

11. Social knowledge that is not included in the model

    A. Insignificant

    B. Too complex to be modeled

12. Defined limitation

    A. Conditional to problem, problem owner, time, environment

Corresponding to these six checkpoints, the developed warranty model is evaluated for its validity. A brief description for each checkpoint is presented below.

The first requirement to become a requisite model is that the model should have proper form (i.e. method, structure) for the model objective. The developed model was produced by means of general performance modeling technique which consists of a unique organization method and utilizes cross-impact analysis computation mechanism. Also, the model utilizes Monte Carlo simulation to predict project performance in decision strategies and alternatives. Finally, the model's input and output are expressed in terms of various life-cycle-cost elements. Therefore, in all, five different modeling techniques are used in the model, and each needs to be validated.

The second check point of the model validation is sufficiency of model elements. In this step, all the elements of model should be evaluated by specialists who have enough expertise in the subject. In the developed model, five different types of variables need to be reviewed – warranty decision alternatives, drivers, processes, outcomes, and external factors.

The third check point is interaction between model developer and specialists. In order to be a valid requisite model, there should be enough interaction between the one who develops the model and the expert group, so that the model can become a reasonable representation of the social understanding of the question. Through these interactions, the model's developer is supposed to get enough feedback and apply it to both model form and model contents.

The fourth requirement is no new intuition from specialists. This checkpoint is closely relevant to the third checkpoint. When there has been enough interaction and feedback, there should not be any more new intuition. In order to fulfill this requirement, the model should be totally exhaustive of social understanding of the question.

The next checkpoint concerns any other social knowledge that is not included in the model. As it shows in Figure 7-3, the model covers only some portion of social understanding of the question (the model is not totally exhaustive). The area beyond the model scope represents information known to specialists but not included in the model. In order to validate a requisite model, the model developer should prove that such information is either less important than that being considered or impossible to include in the model.

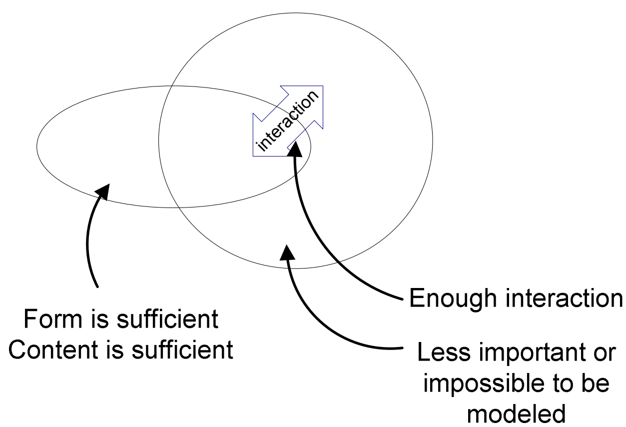

Figure 7-3: Requisite Model Checkpoints

The last checkpoint is clearly defined limitations. For many reasons such as abstract nature and incomplete information, all models have limitations. Although it is impossible to eliminate these limitations, it is necessary to examine each of these limitations to produce a valid requisite model.

7.2.3 Understanding Limitations of Requisite Model Approach

The optimal method for validating an analytical model would be a combination of qualitative and quantitative methods. However, “Requisite model validation method”, which is a qualitative validation method, was solely applied to validate this model. Therefore, with the current validation method, the validity of this model has the limitations of any qualitative validation method. Some of the limitations of qualitative validation methods are presented below.

- Validation participants’ understanding in both actual system and model system is critical. Therefore, the actual validity of the model depends on the qualifications of participants and their responses.
- Without quantitative validation of the model, the model can be considered only a heuristic model. Therefore, the validity of the model may change as circumstances change (i.e., more experience is gained over time).

Despite the limitations of a qualitative validation approach, the requisite model validation method was selected for this model mainly due to the lack of actual data to which quantitative validation methods could be applied.

7.3 Validation Plan

This section includes descriptions of validation methods and plans that were used in this research. Similar to the assessment process (Chapter 5), the principal method was a series of structured interviews. A total of nine interviews were conducted with people with sufficient experience and expertise in warranty applications. An overview of the method, plan, and a summary of interview results are presented below.

7.3.1 Method

In a structured interview, a set of questions (a questionnaire) is prepared and provided to the participants to ensure that each interviewee is presented with exactly the same questions in the same order. The purpose of using this method is to standardize the interviews and hold the questions consistent across all respondents. This mechanism increases the reliability and credibility of the answers and constancy in interviews ensures that comparisons between subgroups can be made. Within a structured interview, the choice of answers to the questions is often close-ended for the purpose of consistency, but some open-ended questions can also be included. Sometimes, open-ended discussion leads to new findings.

Structured interview is a both quantitative and qualitative research method commonly used in research. As a quantitative method, structured interviews can be used as a means of collecting data. They cal also can be used qualitatively to analyze and compare participant responses. In this research, the responses collected from structured interviews are used more qualitatively and are analyzed in order to further improve and validate the model.

In this research, structured interviews were conducted with a set of pre-determined questions and additional open discussions. The objectives of these structured interviews were to:

- Further enhance the interactions between the model and the socially accepted knowledge pool
- Improve the model by modifying
- Collect ideas for future research
- Validate the developed model

By conducting interviews with industry practitioners, the model developer is likely to learn some more about their knowledge of the topic. Some of this knowledge may either be applied to improvement of current model or kept for future research. Finally, from analysis of the interview results, the model can be validated. If there is enough interaction between the model and the socially understood knowledge, and no more new intuition emerges, the model is defined to be a valid requisite model.

7.3.2 Interviewees

For the purpose of this validation process, ten interviews were planned with people with enough experience and expertise in warranted construction projects.

The first goal in selecting participants is to select only those with enough expertise. Because of it is difficult to define reasonable expertise and check each and every possible participants, the model developer started contacting participants in previous warranty research projects. One of these previous projects was the pavement warranty symposium which was held in Grand Rapids, MI, in 2003 (Ferragut 2003). Also the attendees of a workshop for NCHRP 10-68 – Guidelines for pavement warranties – were invited to participate.

The second goal in participant selection was diversity of participants. With proper diversity, the participants could be divided into various sub-groups, and the results of interviews could be categorized by these sub-groups and compared. The differences among these sub-groups may provide additional information and findings. In this research, two different sub-group categories were used. One is the groups of assessment participants and additional participants:

- Assessment interview participants
- New participants

The answers of those who participated in the earlier assessment interviews were expected to be different from those of the new participants. Therefore, about half of the interviewees were selected from the earlier assessment interview participants, while the others had not been involved in this research before. One drawback of interviewing some of the participants was the possible influence of bias on the model's validity as they 1) had been previously informed and seen the model and 2) participated in its development to a certain degree. Despite the possible bias problem, the researcher decided to include previous assessment participants in model validation, because 1) there were a limited number of practitioners, and 2) previous participants were more interested in the results. In order to minimize any possible bias that previous participants might have, the researcher mentioned the possibility of bias and asked them to be cautious. Also, the researcher checked the end results for significant differences between the two groups (previous participants and new participants).

The second grouping basis is participants' profession type. There were three profession types:

- Consultants

- Government Agencies
- Contractors

The interview participants were selected from three different professional groups – consultants, agencies, and contractors. Each of these professional groups represents a different knowledge pool. The consultants are likely to possess more knowledge of research and are proficient at judging modeling technique and other academic aspects of the problem. Both the owners and contractors may approach the problem in more practical perspective. However, the opinions of these two groups can be different even on the same problem. Hence, it is important to interview people of all these profession groups and acquire variety of information and different opinions.

7.3.3 Questionnaire Contents

This section presents the contents of the questionnaire that was provided to the interview participants prior to the interview and also used as the basis of the interview process. The questionnaire consists of two sections of model demonstration and a set of questions. In model demonstration section, an overview of the research, the model, and some simulation results are presented to help the participants understand the objectives and process of the research and the role of the model. Base on this information, in comparison to their own experience, the participants are asked to provide their opinions about the warranty problem itself, the appropriateness of the model, the reasonableness of the results, and possible improvement for both the current model and future research.

7.3.3.1 Research and Model Demonstration

In order to understand the research and determine appropriateness of the model, some key research components were presented to the participants. The research overview includes the research question, a list of objectives, an overview of model mechanism and base theories, case projects for simulation, and research assumptions and limitations.

Research Question

How do warranty decisions (e.g., warranty period, liability limitations) and other project characteristics impact the performance of highway pavement projects?

Research Objectives

- Identify attributes of warranty decisions and performance outcomes.
- Develop a decision model that simulates warranty impacts on project performance.
- Examine impacts of warranty decisions on project performance by model simulations.

Modeling Method

There are four theories the model is based:

- Cross-impact Analysis (CIA)
- General Performance Modeling (GPM)
- Monte Carlo Simulation
- Life Cycle Cost Analysis

Figure 7-4 is a portion of the model and shows one of the project outcomes – repair cost (none to ten year life cycle cost), one decision, one driver, and one process. The input variables for the repair cost are shown in Table 7-1.

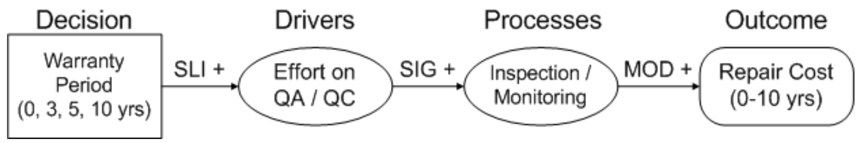

Figure 7-4: A Demonstration of Impact Ratings among Variables

Table 7-1: A Demonstration of Changes from Initial to Posterior Probabilities

Outcome	Initial probability	Posterior Probability	Value
Good	0.2	**0.3**	$50,000
Normal	0.5	**0.6**	$70,000
Bad	0.3	**0.1**	$100,000

For this example, three possible outcomes – good, normal and bad are assumed. For each event, an initial probability and resulting value is estimated. At this point, warranty factor is not considered when deciding initial probabilities and resulting values. When resulting values are assigned, in this case repair cost, they should be input as present value with appropriate discount rate (life cycle cost analysis).

The next step is inserting warranty decision into the picture. The hypothesis is that warranty decisions have a certain impact on the project outcome and change initial probability to posterior probability (Cross-impact analysis). Figure 7-5 shows change in probability distribution curve before and after warranty factor is considered. As the figure shows, expected repair cost is decreased with the introduction of warranty.

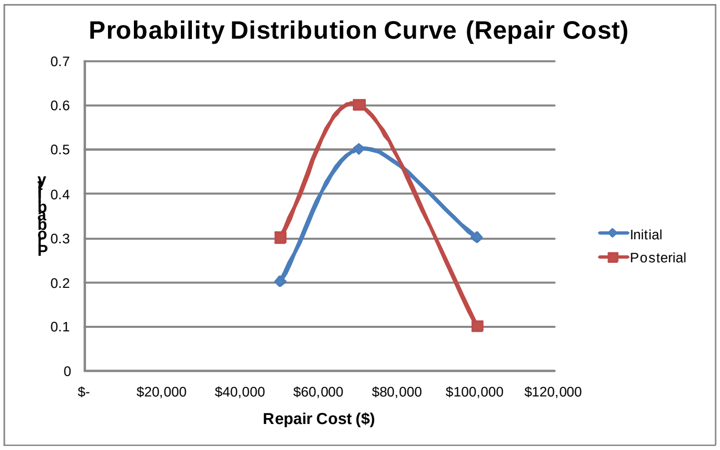

Figure 7-5: A Sample Probability Distribution Curve (Demonstrates Changes from Initial to Posterior)

Impact Rating Assessment Results

Instead of assuming that the decision has direct impact on project performance, it is assumed that a decision influences drivers, and drivers impact one or more construction processes. The magnitude (significant, moderate, or slight) and direction (positive or negative) of these influences were assessed by practitioners with sufficient experience (general performance modeling).

Input Data (5 cases)

Once the impact ratings among variables are decided, the model is complete and ready to simulate project performance with given project characteristics and warranty decision options.

For sample simulation runs, five hypothetical projects were used. The characteristics of these five case projects are summarized in Figure 7-6. For more detailed descriptions of these cases, see Chapter 6.

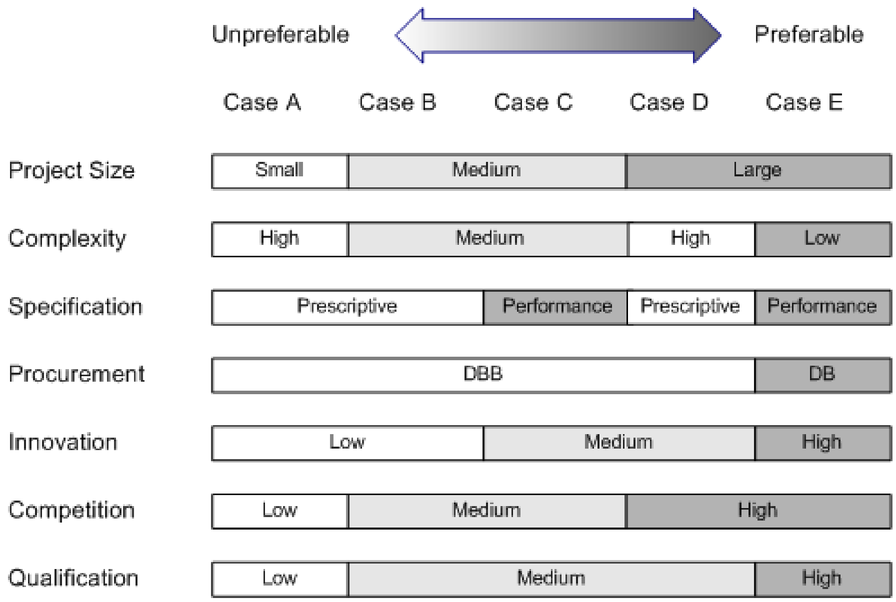

Figure 7-6: A Spectrum of Project Characteristics (Case A through E)

Research Assumptions

In this research and the model, the following are assumed. For projects with characteristics that deviate from these assumptions, the model may not work properly.

- The project performance outcomes are measured in life-cycle-cost (LCC).
- The timing of warranty decision is somewhere between pre-qualification and final bid.
- The model is optimized for highway asphalt pavement projects (twenty year design life).

7.3.3.2 Question Set A

Question objectives:

- Determine appropriateness GPM and other methods to warranty decision problems
- Validates sufficiency of model form (1)

Sample Question

- GPM is a modeling technique that is used to predict performance of a project for various alternative decision scenarios. In GPM, the users are to set the expected performance level and initial probability. Then the decisions, external variables and other model components impact and change initial probabilities to new probabilities. With the use of Monte Carlo simulation software, this process is repeated enough times to find an estimation on the project performance for each decision scenario. Is GPM method appropriate for warranty decision?

7.3.3.3 Question Set B

Question objectives:

- Examine comprehensiveness of decision types, drivers, processes, and performance measures
- Receive recommendations for other factors that are not considered in the model
- Validate sufficiency of model content (2) and check for new intuition (4)

Sample Question

- In my warranty decision model, five drivers are used:
  - Amount of additional risk transferred due to warranty
  - Contractor’s attitude toward design quality improvement
  - …

  Do you think all of my drivers are appropriate for the model?

If there is any other driver you can think of, please recommend it.

7.3.3.4 Question Set C

Question Objectives

- Presents simulation cases and results
  - Results of various warranty decisions and project characteristics
  - Results of various cases
- Check reasonableness and usefulness of the results
- Interact with specialists (3) and check for unexplored specialist knowledge (5)

Sample Question

The figure shows cost increase due to long-term warranty for five case projects

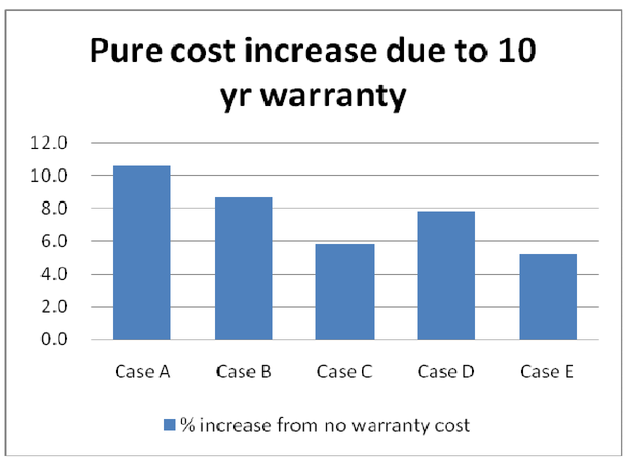

Figure 7-7: Percent Cost Increase Due to a 10-year Warranty

- Is the information useful to you?
- What other information would you like?

7.3.3.5 Question Set D

Question objective:

- Examine model limitations
  - Research scope
  - Shortcomings
  - For other decision timing, project type, warranty environment, etc.
- Defines limitation of the model in terms of time, environment, user, and problem type (6)

Sample Question

- Although all the cases I have used for simulation are asphalt paving projects, the model can be for other project types. What model elements should be changed if the model is to be applied to concrete pavement project?

7.4 Validation Results

7.4.1 Interview Participants

A total of nine participants were interviewed. Four of nine were participants in assessment interviews and the other five were new. Among nine participants, three were consultants; four were government agencies; and other two were contractors.

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Table 7-2 lists validation interview participants along with their experience type and level and the sub-groups to which they belong.

Table 7-2: Qualification of Validation Interview Participants

Participant	Construction Experience	Warranty Experience	Assessment Interview	Profession
A	5+ yrs in DOT	10+ warranted projects	Yes	Agency
B	20 yrs in DOT	Numerous warranted projects	Yes	Agency
C	Many yrs in DOT and academia	Warranted projects and research	No	Consultant
D	10+ yrs in construction business	As a company owner, involved in 5+ warranted projects	Yes	Contractor
E	10+ yrs in DOT	Have written a few reports on warranty	Yes	Agency
F	15+ yrs as consultant and researcher	A few comprehensive researches on warranty	No	Consultant
G	Many years in DOT and became a consultant after retirement	Many projects with or without warranty	No	Consultant
H	10+ yrs in a pavement construction company	Did construction for some warranted projects	No	Contractor
I	20+ yrs in DOT	Number of warranted projects and reports	No	Agency

7.4.2 Findings from Practitioner Interviews

From the notes taken from interviews, a summary of opinions collected from interviews with practitioners is constructed and presented in Appendix 5. In the summary, no distinction is made either between previous and new participants or among professions.

There was no significant difference between previous and new participants other than that it was easier for previous participants to understand the model. However, there were some differences among the different professions. In particular, two contractors provided some different and interesting opinions about various aspects of the model and simulation results. Further discussion on these differences is presented in concluding chapter along with other findings.

7.5 Validity of the Model

A list of validation checkpoint for a requisite model appears at the beginning of this chapter (7.2.2). In order for a model to be a valid requisite model, all of the checkpoints must be examined and sufficiently fulfilled. In this section, each of these checkpoints and corresponding interview results is analyzed to test the validity of the model.

7.5.1 Sufficiency of the Model Form

The basis of this warranty model is GPM and CIA. Among various probabilistic approaches, GPM and CIA emphasize the interactions among variables. In addition, life-cycle cost analysis and Monte Carlo simulation method were used. These probabilistic analysis methods were used in an attempt to predict project performance for each decision alternative. Interviewees were asked to validate appropriateness of the model to the research question and suggest possible improvements.

Most of the interview participants were satisfied with the appropriateness of GPM method for a warranty decision model. According to the participants, there is no single analytical decision model that is commonly used. Currently, most warranty decisions are made through discussion or checklist-based guidelines. According to interview results, most participants agreed that GPM method is a new and reasonable approach to warranty decision. However, there were a few differing opinions.

One participant pointed out that accuracy in output of this GPM decision model relied too much on the accuracy of the input variables. However, this problem of inaccuracy of input value is common for all models and should not be a factor in determining the validity of a model. A guideline for preparing input variables could be added to the model in order to help the model users, those, at this point, it is out of the scope of this research.

Another participant pointed out that for most projects, the engineers' estimate is provided as a single number rather than a probabilistic distribution of possibilities. Therefore some input variables (i.e. initial probability) are not available to the decision maker. However, the participant also pointed out that there is a movement toward changing engineer's estimates from single numbers to probabilistic possibilities, so this problem will be resolved eventually.

7.5.2 Sufficiency of Model Contents

In the developed model, many variables are included in four categories – decision, driver, process, outcome and external variables. For this checkpoint, various questions are asked to distinguish factors that are unnecessary for this model or that need to be added to it.

There was an opinion that some of decisions (i.e., inclusion of bond, post-construction maintenance, limited liability) are not completely an agency's decisions. Bond requirement and limited liability are either required or prohibited by government regulation and are not decided on a project-to-project basis. In the case of post-construction maintenance, most agencies see it unnecessary for relatively short warranties (less than five years.) for any type of project. Therefore it is a decision that is applicable only for a long-term warranty. These opinions are reasonable, but the model developer does not feel the need for excluding these factors, because they are still possible decision options, even if no one chooses to use them. Other than these, the participants were satisfied with the decision options included in the model.

One other possible warranty decision option suggested by interview participants is limited responsibility to traffic load. Due to uncertainty in traffic load prediction and excessive traffic load being one of most critical factor to long-term performance of pavement, without load limitation in warranty clause, the contractor has to take additional risk. Therefore, a few states include a clause that specifies warranty expiration base on the traffic load in addition to time (period). This is similar to warranty clause of automobile industry in which the warranty responsibility is limited by mileage and time (this is referred as a two-dimensional warranty). This could be a solution of minimizing warranty cost, however, in order to use this “limited traffic load” option, the contracting agency must keep track of number and type of traffic and it requires additional resources. Hence, this method is only being used in a few agencies only. However, this could be an additional warranty decision option and could be included in the model.

In terms of drivers, a few participants suggested including “level of competition”. “Level of competition” corresponds well to the definition of driver as it is influenced by warranty decision and could influence the performance of various construction processes. The model developer agrees that “level of competition” is an important factor very well suited as an additional driver to the model. However, the current model is still a valid requisite model because it already includes “level of competition” as an external factor. According to one of model assumptions, decision timing is somewhere between pre-qualification and bid. If decision timing follows pre-qualification, it can be assumed that the number of bidders is already decided and known to the agency. Therefore it is more reasonable to include it as an external factor rather than as a driver. If the model is expanded to cover a wider range of decision timing, the factor “level of competition” could be included as a driver.

One other opinion on drivers is to separate construction method quality and design quality. One of the participants insisted that even with the same design, a construction method can be different, and this difference can cause some change in project performance. Again, this is a reasonable opinion. In the current model, quality improvement is included as a driver, but there is no distinction between design and construction method quality. In the original model development phase, construction method was considered as a possible driver, but later was combined with design quality and became a single quality-improvement driver. The main reason for this decision was to minimize the number of drivers and other factors due to the difficulty of assessing too many variable pairs. This limitation was unavoidable due to research resource limitations.

One last key opinion on the model content has to do with measuring project performance with various life cycle costs. Most participants agreed that this is the most reasonable method for this model and topic. However, there were some comments on this matter.

The first comment suggests the inclusion of user cost in addition to current agency cost items. There were mixed opinions on this matter. Some practitioners felt that the public owner should be concerned about user cost, and the model should include it as additional cost items. However, some others insisted that, in practice, most agencies do not consider user cost, and the model is complete as it is.

One other opinion on project performance measurement raised the idea of including convenience and safety measures such as ride quality and skid distance. However, even those who voiced this opinion agreed that it would be out of scope of this research because it would involve a whole new area of study.

7.5.3 Enough Interaction between Specialists & Model Developer

There were enough interactions with industry specialists, and some of whose opinions were contributed to the model's improvement. In this research, there were three different interaction opportunities.

First, prior to model development, in addition to literature review, the model developer visited three states and conducted in-person interviews with agencies of departments of transportation to learn about their methods of warranty decision and general policy on warranty. From these interviews, the model developer was able to collect various decision attributes and key warranty factors that may influence project performance. This information is applied to the model in its development stage (Chapter 4).

The second interaction was made possible through a total of twelve assessment interviews (Chapter 5 and Appendix 1). In addition to collection of assessment data, some general discussions of the topic were conducted, and information collected from these discussions was considered and used for further refinement of the model.

More interactions between specialists and the developer were achieved through validation interviews (Chapter 8 and Appendix 4). A total of nine practitioners with sufficient warranty experience were interviewed to provide comments on every aspect of the model including model form, model contents, simulation cases, results, and findings.

7.5.4 No new intuition emerges about the Problem

The model should be totally exhaustive of social understanding of the problem to be a valid requisite model. In order to check if there has been enough interaction, all ideas have been collected, and in the absence of any new ideas, a table is constructed. Table 7-3 below summarizes some of the key ideas the interview participants who raised them. In the table, participants are listed in the order in which their interviews were conducted.

Table 7-3: Some of Comments from Interview Participants

	Inaccuracy in input data results in inaccurate output	Probabilistic Engineer's Estimate not available	Restrictions in agency decision (regulation, Funding, etc)	Level of competition as a possible driver	Separation of design quality and construction method quality	Inclusion of user cost	User convenience and safety	Resource limitation (Mega-project)	Longer LCC period for longer warranty
A	√			√					
B		√	√			√	√		
C				√		√			
D					√		√	√	
E			√			√			√
F		√	√	√					
G	√		√	√					
H				√				√	
I	√	√	√		√		√		√

As the table shows, most items were brought up by multiple participants. In other words, there were repetitions of ideas among practitioners. As interviews were conducted one by one, new ideas were exhausted. After five interviews, no new intuition emerged from later interviews (no new ideas from participant F). With the assumption that the answers of interview participants were a reliable representation of social understanding, it can be concluded that all relevant ideas were brought up and the model has become totally exhaustive of social understanding.

7.5.5 Social knowledge of those not included in the model

A requisite model is defined as a reasonable representation of social understanding of the problem. In other words, a model is not expected or practically impossible to reflect all aspects of the problem; however, it should include a reasonable fraction of social understanding of the problem, and should cover all of the views that are more important. Therefore, to validate a requisite model, the developer should prove that the ideas that are not included in the model are either insignificant or practically impossible to model.

In this section, three key intuitions, which were brought up in validation interviews, are examined to find out if it is reasonable to exclude them from the model.

The first intuition which was brought up by multiple interview participants is restrictions in agency decisions. No matter what the simulation results show, some agencies simply do not have any choice in some decisions. Sometimes government regulation does not allow an agency to choose. Warranty bond is one example. Most states required all their warranted projects to be bonded. Similarly, limitation of government agency's staff or of construction funding restricts the agency from selecting some decision options. There is no doubt that these limitations in decision alternatives are important in real-world application. However, these limitations are not considered in the model. Omission of these decision limitations can be justifiable for the two reasons below.

- Setting limitations is not feasible in GPM system.
- Limitations in decision alternatives can be manually applied.

A GPM system is designed to simulate project performance for all combinations of decision options. Unless the whole model is rebuilt, there is no simple way to apply decision restrictions to the model. However, the user can simply ignore those decision alternatives which are possible for them to choose (due to any restrictions). The user can always select the next best alternative.

The second idea that was brought up is about adding performance measures other than agency costs. Other than agency costs which is the sole measurement of project performance in the current model, three different performance factors: (the participants suggested.)

- Convenience
- Safety
- User cost

It is simply not possible to include user convenience and safety measures at this point because there is no reliable measuring and testing method commonly used and proven to work. As more research is conducted on these topics, they may become available. One possible modification to the current model would be the inclusion of user-cost items. Although there would be some difficulty, it is still feasible. However, there are different opinions among government agencies about considering user cost in warranty decision. Some agencies are willing to consider user costs, but others think that would be too much for them to consider. Therefore, it is concluded that inclusion of user cost is not quite a socially agreed upon item for the model.

The last key idea is separating warranty risk to controllable and uncontrollable by the prime contractor. Some contractors feel that some risks are not supposed to transfer to them as the corresponding work is done mostly by sub-contractors, or outcome depends heavily on supply price. However, the model developer feels that the difference between the contractor taking the risk and a sub-contractor taking the risk would be insignificant in either an agency's or decision maker's perspective. Therefore, this opinion is not applied to the model.

Like the three examples above, all the suggestions collected from interviews were examined. However, no significant changes were made to the current model.

7.5.6 Limitations of the model

All models have limitations. Some models are designed to work only for certain situations, times and environments. Likewise, the warranty model has limitations, some of which have already been identified and defined by the developer. However, there could be additional limitations. Therefore, interview participants were asked to suggest any unforeseen limitations. Some of the key limitations of the model that were discovered are listed below.

- The model works only on asphalt pavement, small to mid-size projects
  - Needs some modification for concrete pavement

    - Won't work for other types of construction (bridge, ITS)
    - Additional factors to be considered in Mega Projects
- The model works only for specific decision timing
    - The model works for earlier decision with some modifications
    - Situation will be totally different for post construction warranty
- As time passes, the model will need to be modified
    - Different environments (especially bond issues)
    - Changes in project financing mechanism (privatization, etc)

Considering these limitations, the model can be considered a valid requisite model as long as it is applied to warranty decisions in small to mid-sized asphalt pavement construction projects; decisions are made during the project scoping phase; and industry environment does not change significantly.

7.6 Chapter Summary

This chapter discussed the method and procedure of model validation. The chapter was begun with descriptions on general model and model validation methods and moved onto the discussion about requisite model and its validation process. Requisite models are unique and distinctive from other general models in perspective that they represent social understanding of the problem or common knowledge pool among practitioners (specialists) rather than the real system. This difference makes their validation process differ from that of general models also.

Based on six checkpoints of requisite model validation process, a questionnaire was constructed and interview participants were selected. The constructed questionnaire includes a brief demonstration of the research process, the mechanism of the model, input data (case projects), model outputs, and simulation results. Based on the information provided in the questionnaire, the participants were asked to answer various questions concerning model method, contents, and reasonableness of the simulation results.

Once the validation interviews were conducted and the opinions from nine participants were collected. From the analysis of interviewees' opinions, it was determined that the model is a valid requisite model.

CHAPTER 8: CONCLUSION

This chapter summarizes the research process including the model development, assessment, simulation and model validation. It consists of five sections. The first summarizes the entire research process from research question to simulation results. Next, a summary of findings from both model simulation and interviews are presented. The third section discusses the contributions of this study to both academia and industry. In the fourth section, limitations of this research and the developed model are discussed. Also presented in this section is a discussion of some assumptions which had to run the model. Following up on the discussion of limitations of this research and the developed model, the last section presents some possible improvements to the current model, areas for expansion of the research, and some new ideas for future research either in direct relation to this research or in a new approach.

8.1 Summary of the Research Process

8.1.1 Research Question and Objectives

Given the background and scope of this research the following question was developed to guide this research.

How do warranty characteristics and project characteristics impact the performance of highway pavement projects?

To answer this question, the research has the following objectives:

- Examine various internal and external factors and determine the important factors in making warranty decisions.
- Develop a decision model that simulates warranty impacts on project performance indicators.
- Run simulations of projects with varying scopes and processes in order to examine impacts of warranty characteristics (e.g., decision variables of warranty period, limited liability characteristics, etc.) and project characteristics on project performance.

8.1.2 Methodology

To answer the questions listed above, the research was conducted in three steps. First, a warranty decision model was constructed. Second, using the developed model, performance of various case projects were simulated for each decision scenario. Finally, simulation results were analyzed to yield findings such as optimal warranty scenario for each case project, relative sensitivity of warranty attributes, etc.

The primary decision modeling method used in this study is general performance modeling (GPM). GPM introduces a unique model structuring mechanism designed to fit specifically well to decision models that simulate project performance outcomes for various decision alternatives. In terms of decision analysis and probability computation, the GPM utilizes a cross-impact analysis (CIA) method.

In terms of research process, this research was conducted consisting following five steps. Corresponding chapter is noted for each step.

1. Model organization and content decision (Chapter 4)
2. Assessment of impact ratings among variables (Chapter 5)
3. Simulation of cases with various project characteristics (Chapter 6)
4. Analysis of simulation results (Chapter 6)
5. Validation of model form, contents, simulation results and findings (Chapter 7)

8.1.3 Validity of the Model and Reliability of the Simulation Results

As described in detail in Chapter 7, the developed model was validated through a requisite model validation process, a qualitative validation method. Unlike quantitative validation methods where a model is validated in comparison to actual data or theoretically approved analysis, the requisite model validation method is limited in that it can validate the model only within the social understanding of the problem (i.e., what participants have experienced and understand). Therefore, the model and simulation results are validated only within social understanding (practitioners' knowledge) and for the actual system, which is different from or outside of their social understanding.

8.2 Findings

Some of the results of this research and findings from the analysis of these results are presented in this section. The presentation of research findings in this section is organized in a subject-by-subject fashion.

There were basically two sources for these findings – model simulation and practitioner interviews. Prior to drawing any conclusion from simulation results, the appropriateness of the model was successfully validated through a requisite-model validation process. In the process of model validation (i.e., practitioner interviews) some findings were determined and are presented below. Also, some findings were extracted from previous interviews – initial survey of current warranty practices and assessment questionnaire and interviews. Once the model was validated, more findings were extracted from the results of model-simulation runs. The model was simulated to estimate the difference in project performance for varying warranty-decision options and project characteristics. Some findings from model simulation runs are also presented in this section (see Chapter 6 for more examples of simulation runs).

Key processes for collecting and analyzing data to extract these findings were described in previous chapters (see Chapter 6 for model simulation and Chapters 5 and 7 for practitioner interviews); therefore, in this section the findings are presented without further description of processes, sources, or analysis methods.

8.2.1 Purpose and effectiveness of warranty

The model simulation and interview results have revealed that risk transfer is the widely accepted purpose of warranty implementation throughout the country. It was also discovered that warranties can have a positive effect on project performance if there is a sufficient term, appropriate delivery method, and appropriate specification mechanism. Additionally, research findings indicate that another effect of warranties is providing flexibility in utilization of agency's human and financial resources. More detailed discussions on these findings follows below.

According to practitioner-interview results, all practitioners agreed that warranty is an effective contracting method for both purposes. However, there were mixed opinions on the significance of these two objectives of warranty implementation. It was found that those practitioners with more experience in short-term and material and workmanship warranties believe that risk transfer is the main purpose of warranty. Those practitioners consider the improvement in initial quality and long-term performance as possible, but not certain, benefits of warranty but not the main reason for using warranty. In other words, they do not expect that the use of warranties would make too much difference in terms of long-term quality. However, practitioners with experience in long-term and performance warranty or warranty research, tend to believe that the use of warranties does make significant difference in terms of quality. Also the interviewed contractors stated that they tend to put more effort into selection of construction methods, materials, and project monitoring when they are not certain about required building project that require long-term performance warranties.

This divided opinion as to the effect of warranty on contractor motivation and quality improvement was due to by the type and length of warranty with which the practitioners had experienced and which had been available to them. The practitioners with long-term and performance warranty experience tended to emphasize the quality-improvement effect of warranty rather than the purpose to transfer risk.

The variation of warranty effects on long-term performance was also shown in the simulation results. According to the simulation results, warranties tend to increase contract price and decrease repair cost. Since reduction in future repair cost is directly relevant to a facility's improved long-term performance, it can be concluded that the use of a warranty has some positive effect on long-term performance. Also, the simulation results showed that as the warranty lasts longer, the magnitude of these effects becomes more significant. In other words, the effect of a warranty on long-term performance is more apparent when the warranty period is longer.

The simulations with project characteristic variation (cases A through E) showed that project delivery and specification method also influence the effects of warranties on project performance. The simulation results showed that effect of a warranty is more distinctly apparent when a project is delivered through design-build and performance specifications.

These results match the interview results and explain why the practitioner with long-term warranty experience emphasizes quality improvement effect of warranty. From these findings, it can be conclude that a warranty of sufficient term with proper delivery and specification mechanism has positive effects on long-term project performance.

The availability of agency resources is another reason for implementing warranties discovered through this research. There are two types of agency resources – human resources, and construction and maintenance funds. One purpose of implementing warranties is to minimize the need for owner's design review, inspection and monitoring of construction process. Theoretically, with sufficient warranty requirements (i.e., period, level of performance, etc.), the owner does not have to monitor every processes. Therefore, the agency can save significant cost and minimize responsibility of hiring and maintaining a workforce to monitor the construction process. Also, with adjustable warranty options, the owner can have flexibility in balancing between initial construction cost and future maintenance cost. In most agencies, there are separate funds for construction and maintenance, and, depending on availability of these funds, an agency may choose to apply a stricter warranty to pay more in front for construction and save on future maintenance cost or vice versa. The interview results showed that availability of construction and maintenance funds is one basis for warranty decisions.

From the discussions above, three major purposes of warranty usage were found.

- Transferring initial-defect risk is the most commonly accepted purpose of warranty.
- Enhancement of initial quality and long-term performance is another purpose of warranty. Maximum effects on long-term project performance can be achieved only with sufficient term with proper delivery and specification mechanisms.
- Warranties also provide flexibility in funding allocation and staff utilization

8.2.2 Cost and benefit of warranty

The use of warranties brings many benefits to a contracting agency, such as insurance against early defects and motivation of the contractor for better long-term performance. Most of these benefits are closely related to the owner's purposes in warranty implementation that were previously discussed.

In exchange for these benefits, higher contract prices are expected, and the simulation results have demonstrated that a project with a longer warranty period and higher performance level requirements tends to increase the initial contract price. Then a question can be asked as to how exactly these warranty factors increase the contract price.

According to the results from both model simulation and practitioner interviews, design-quality improvement and warranty risk are the two main causes of increase in contract price. The first factor that contributes to cost increase was found to be design-quality improvement, which means that, due to the inclusion of a warranty, the contractor tends to pay more attention to improving initial and long-term quality. They may choose to use different design, materials, and methods which are likely to be more expensive. Therefore, these improvements end up increasing initial costs. This trend was shown in the simulation results as the cost of design and construction costs increased as the warranty period extends and higher performance levels are required. The question is that if this increase in initial costs worthwhile. According to the sensitivity analysis, design improvement was found to be equally significant to both increase in construction cost and decrease in expected repair cost (Figure 8-1 and Figure 8-2). In other words, although the owners may be forced to pay more upfront, there is a good chance that they will end up saving repair cost. Therefore, additional cost in exchange for quality improvement could be more of a benefit than a loss to the owner.

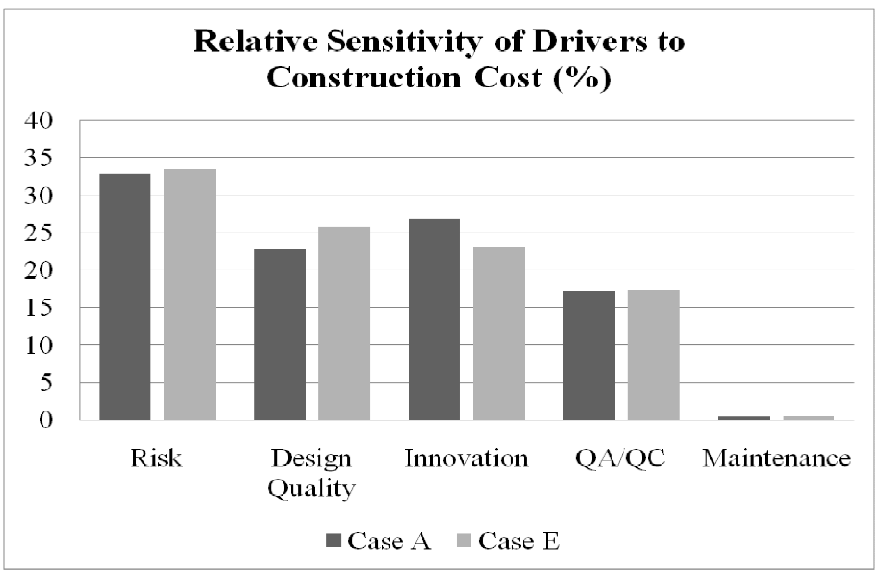

Figure 8-1: Relative Sensitivity of Construction Cost to Various Drivers

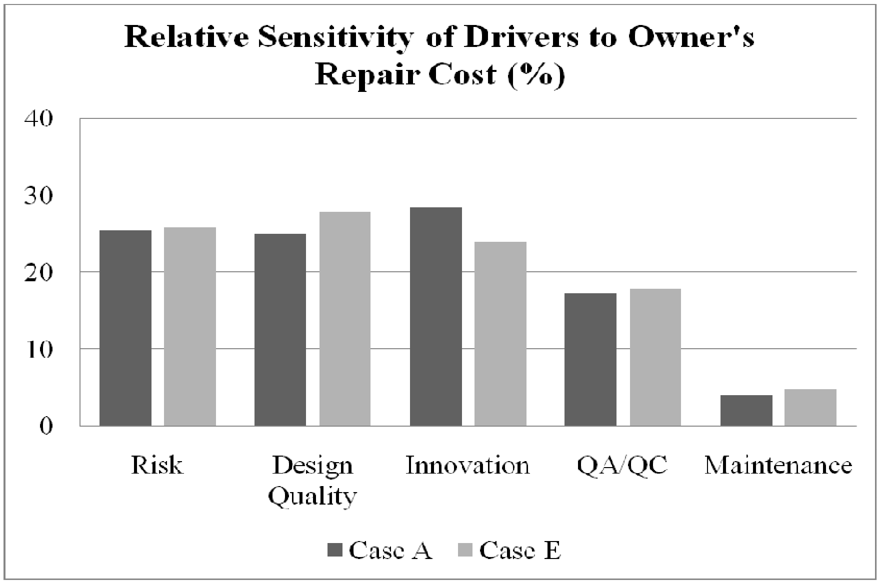

Figure 8-2: Relative Sensitivity of Repair Cost (Owner's) to Various Drivers

Second, the burden of excessive risk to contractor due to warranty was determined to be the other most important cause of price increase. Again the question is whether this additional cost due to warranty risk is worthwhile. The sensitivity analysis results showed that the increase in warranty risk was found to be, by far, the most significant factor in construction cost increase, but only the second important factor to decrease in future repair cost next to design quality (Figures 8-1 and 8-2). This difference indicates that warranty risk increases initial price but may not decrease future repair cost as much. Therefore, transferring risk more likely causes more cost increase but bring less benefit, and the owner may want to be careful not to transfer excessive risk.

Since transferring excessive risk was found to be a problematic, it should be clearly defined what is excessive and what is not. It is difficult to determine what are necessary and what are excessive because the distinction heavily relies on owner's preference, which varies by agencies, projects and environment. Furthermore, this research is not designed for answering such a question. However, there were a few findings that may provide some hints to answering these questions.

First, the graph of total agency cost vs. performance level requirement (8-3) shows that there is significant increase from the medium-performance level to high (Maximum) performance level.

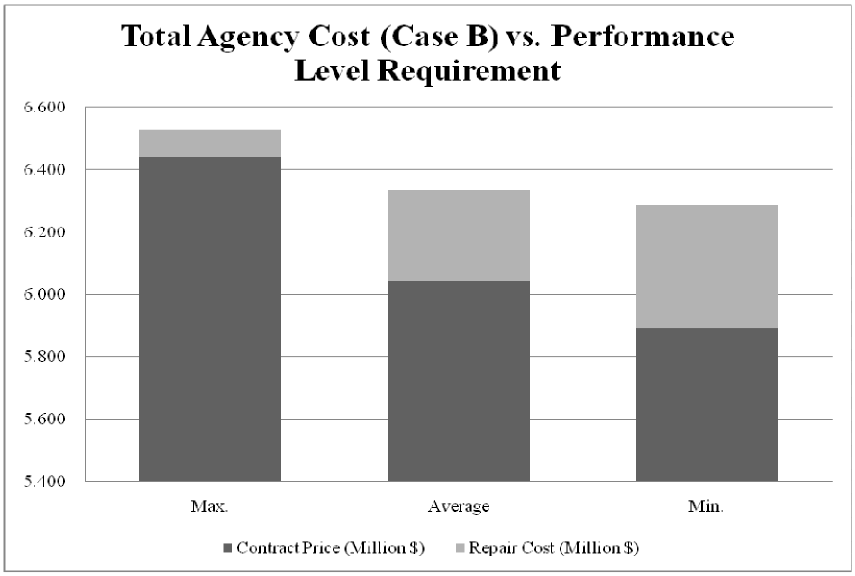

Figure 8-3: Estimated Agency Costs for Varying Performance Requirement Level (Case B)

Obviously maintaining the high performance level until the end of a warranty period (especially for long-term) would be difficult and presents significant risk to the contractor. As a result of burden of responsibility and risk, the contract price increased too much and benefit (decrease in future repair cost) could not catch up to it. This results demonstrate what could happen if the performance level for a warranty is set too high. Therefore, the owner should take into consideration the length of the warranty and expected decline in performance level when deciding performance-level requirements to be applied throughout the warranty period.

Second, a reliable indicator of pure risk premium would be a contractors' markup percentage (if it could be known by the agency). Although there are many other factors affecting contractor markup decisions, additional risk due to warranty is one important factor. From the simulation results for estimated contractor markup percentage (Figure 6-12), another hint for defining excessive risk can be acquired. One interesting finding from the markup variation for the varying warranty period is that the rate of increase in markup percentage per warranty period. The simulation results showed that the rate of increase slows down after a five-year warranty. This fact may lead to a conclusion that effectiveness of short-term warranty is not significant enough to effect any real change in terms of long-term performance, but the owner still pays a premium for risk despite the fact that actual risk is low. Therefore, in order to minimize risk cost and maximize warranty benefit, the owner may need to choose either a long enough warranty or no warranty at all.

The third finding is the relevance of warranty risk to contractor control.

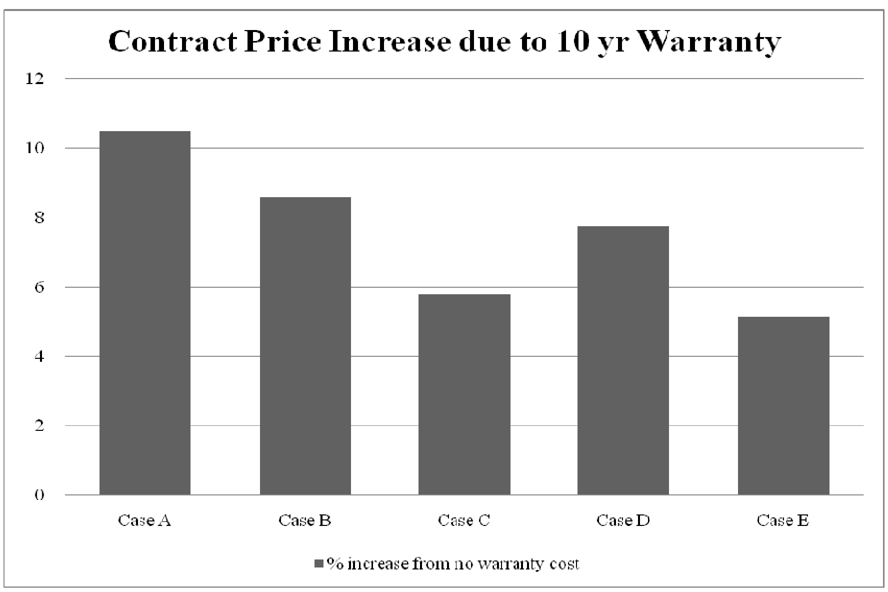

Figure 8-4: Estimated Contract Price Increase (%) for Various Cases

According to percent increase in contract price in various simulation cases (Figure 8.4), the increase in contract price due to warranty was less in cases C and E. The difference between these cases and others was the amount of contractor control. Case C was a new road construction in which the contractor or designer had greater flexibility in both design and construction. Also, since it is new construction in Case C, there is no pre-existing condition they had to deal with. Case E was a design-build project, and there was an assumption that the contractor had come up with an alternative design. In both cases, depending on the project environment, it is reasonable to conclude that the contractor had greater control over the project, and that the pressure of risk transfer was less. A similar assessment was offered by some of the practitioners during interviews. Both of the contractors who participated in the validation interviews insisted that warranty could be overwhelming to the contractor when they don't have sufficient control. One case they pointed out is when there is existing condition which is either bad or unpredictable. They commented that the agency should not require warranty for such projects because most contractors would either not bid or increase the bid price to compensate for the risk. Therefore, when making a warranty decision, the owner must check if the contractor has enough control to determine the outcome to avoid paying extra for the risk. In some cases, the contracting agency may be able to alleviate the problem of uncontrollable risk by providing more room for contractor input and control. Some possible methods would be design-build project delivery, performance-based specifications, or a post-construction maintenance contract. For other cases, it may be wise to require a warranty with shorter period and/or lower level of performance requirement or no warranty at all.

The findings from the discussions above are:

- Excessive risk transfer is the most significant cause of price increase;

- Improvement in quality may contribute the increase in contract price, but it also contributes on saving in future repair cost;
- High level of performance requirements tend to increase the price significantly; and
- Contractors are most sensitive to the risks they don't have control. Therefore, in order to avoid paying too much risk premium. The agency must:
    - Provide sufficient contractor control (by design-build delivery, performance criteria, etc); and
    - Consider not to use warranty for the projects with too much uncertainty.

8.3 Contributions

This research was initiated from the idea that current warranty decision methods and models were deficient in some aspects. It intended to provide an improved model and new findings from simulation results.

This research has made the following three principal contributions:

- Added formalism to the decision process to minimize the influence of personal opinion and bias;
- Through the use of the GPM process, this study deviated from purely quantitative analysis and has incorporated broader perspective to the decision
- Examined warranty influence propagating through contractor motivation factors (drivers), performance of each construction process (processes), and

outcomes.

- In this research, a different assessment method (guided interviews) was used instead of that utilized in previous GPM models (workshop).

First, this research provided a requisite warranty decision model that was developed and validated on the basis of commonly shared social understanding. Over thirty interviews with warranty practitioners (e.g., representatives of contracting agencies, contractors, and consultants), have provided input on the purpose of warranty, decision process, and impacts on project performance. Based on the acquired knowledge, a decision model was developed and refined. Then, the developed model was validated for its form, content and comprehensiveness.

Second, through the use of the GPM process, this research applied a probabilistic forecasting mechanism to examine warranty impacts on project performance. Also, the model has incorporated broader perspectives to the decision. Table 8-1 summarizes topical areas and research methods of previous studies and this research.

Table 8-1: Objectives and Methods of Previous Warranty Research

		Won (2010)	Bayraktar et al. (2006)	Damnjanovic et al. (2005)	Oh et al. (2005)	Bayraktar et al. (2004)	Cui et al. (2004)	Thompson et al. (2002)
Research Objective	State of Practice					√		√
	Warranty Bond	√	√					
	Warranty Cost & Value				√		√	
	Warranty Period Decision	√		√				

	Post-construction Maintenance	√						
	Variable project characteristics	√						
Research Method	Cost Optimization & Reliability			√	√			
	Survey & Interview	√	√			√		√
	Real Option						√	
	Game Theory							
	Probabilistic forecasting	√						

In terms of research methods, studies to date of warranties in construction have been limited to survey and interview methods with the exception of only a few (Cui et al. 2004; Damnjanovic and Zhang 2005; Oh et al. 2005). In their study, Cui et al. had utilized real option theory in attempt to determine the value of including warranty option. Damnjanovic and Zhang have found optimum warranty period for given projects using analytical approaches. Oh et al. have compared various cost items such as agency and user cost between the projects with warranty and without warranty (controlled projects). Although those previous studies may provide some information, none of these studies produced a decision model that is designed to help the contracting agencies make formal warranty decisions.

This study was first to develop a probability-based decision model which is design to investigate warranty impact on project performance by forecasting probable performance for various decision alternatives and external conditions. In terms of the topical area, this research is first to consider performance of post-construction processes such as preventive maintenance. Also, in addition to the impact of the warranty decision, impacts of various project characteristics on project performance outcomes were also examined. Some of project characteristics that were examined are design-build delivery method, performance-based specification, project size, complexity, etc. This study also introduces factors beyond the project parameters such as market and contractor characteristics.

Third, the model employed an indirect influence approach which is designed to minimize effects of personal bias and opinions in assessing decision impacts to project outcome. Although the ultimate objective is to measure impact of warranty decision to project performance outcome, in GPM, any direct impact from decision to outcome are prohibited. Instead, by definition, decisions can only impacts drivers; drivers impact processes; and processes impact outcomes. Therefore, decisions can only impact project outcomes indirectly. In this system, warranty impact propagates through various model components before it reaches the outcome. This mechanism allows for unbiased assessments of impact ratings among variables.

Finally, a new assessment mechanism, guided interviews instead of workshop, was introduced among GPM models. Although the interview method has some limitations, this study has shown that interview can be used as an alternative to workshop when workshop is not an available option.

8.4 Assumptions and Limitations

The assumptions made for the model and limitations of the model are discussed in this section. These limitations were unavoidable because of: 1) representative nature of a model; 2) the shortcomings of applied methods; and 3) the research scope. Although these assumptions and limitations were unavoidable, they were all examined and clearly defined in this section. Some limitations will be discussed further as prospects for future research, while others will be ignored because they are either insignificant or impossible to cover.

8.4.1 Performance measures

Project performance outcomes were measured in terms of life-cycle-cost (LCC), and other performance features which are not measureable by LCC were ignored. This is one limitation of this research and the developed model. The following are discussions of other quality and cost measures which might have been included but were omitted.

Various studies have determined the possible measures for project performance. The most fundamental measures used in most previous studies are project cost and duration (Barraza et al. 2004; Chan et al. 2001; Gransberg et al. 1999; McKim et al. 2000; Thomas et al. 2004). In most cases, cost and duration performance were measured in terms of percent increase or decrease from original estimate or schedule. In addition to time and cost, other measurements such as quality, conformance to owner's requirements (McKim et al. 2000), claims and disputes (Gransberg et al. 1999), number and cost of change orders (Gransberg et al. 1999; Thompson et al. 2002) were used to determine project success. Also, in some in-depth studies of success measurements, some new measurements such as communication, relationship, equal opportunity, and maintainability were introduced (Grififith et al. 1999; Hinze et al. 1995).

Among these various measurements found in literature review and discussions with practitioners, warranty impacts on construction duration and user costs are discussed in this study. Other measurements such as non-functional features such as aesthetic quality, safety issues and serviceability were not discussed.

As has been pointed out in other studies of project performance, project duration (sometimes called schedule performance) is an important measure of project success and owner satisfaction. However, it was decided at the model development stage to omit schedule performance from the model, because the practitioners who were interviewed agreed that inclusion of warranty does not impact project duration in most cases. If necessary, schedule performance could be included in future refinements to the model using a time-to-cost conversion formula introduced by previous studies (Gransberg et al. 1999; McKim et al. 2000).

One other performance measure closely related to warranties is user cost, which is often included in other life-cycle cost analysis (LCCA). According to practitioner interviews, some agencies consider user cost or user satisfaction when they make warranty decisions. Therefore it may be reasonable to include user cost in the developed model. If user cost had been included, the project performance forecast would have been preferable for longer warranty and stricter performance requirements as benefit of warranty is amplified. However, the question is to what extent user cost should be considered and how exactly it should be measured. Due to its ambiguous nature, it was decided to omit user cost from this model, but more discussion of it will follow in the future-research section.

8.4.2 Decision timing

For the developed model, the timing of warranty decision was assumed to be somewhere between pre-qualification and final bid. Therefore, it was assumed that all project characteristics (i.e., scope, pre-existing condition) were known and other decisions (i.e., delivery method, specification method) had already been decided before the warranty decision. Also, since the decision is made after pre-qualification, it was also assumed that the agency knew how many contractors were going to bid for the project and who they were. The purpose of this assumption was to make the decision and the model as simple as possible. Also, this assumption was made in order to investigate the difference in performance forecast for various project characteristics. However, if the decision is to be made at a different time, the model may need some modifications.

In case the decision is to be made at some earlier time, which is the case for most real warranty decisions, some factors must become random variables instead of fixed values. For example, if the decision is to be made before pre-qualification, the number of bidders would not be known to the decision maker, and should be inputted to the model as a probabilistic random variable. However, necessary modifications can be made relatively easily since the model is designed to support probabilistic values for all the input variables.

A problem arises when the warranty decision is made after procurement or even after project completion. This sort of case is rare, but there have been a number of projects in which the owner either had the option to exercise a warranty requirement or decided to get one through negotiation. Although, most of interviewed practitioners agreed that it is not a good idea to make warranty decisions after construction, there have been cases and most likely there will be more. This model cannot forecast performance if warranty is decided after construction either through option or negotiation unless a major modification or rebuilding is made.

8.4.3 Project type

Although the model was designed to be generic and applicable to warranty decisions in any type of project, it was optimized for highway asphalt pavement projects. It was found during simulation process and validation interview that this model must be modified if it is to be applied to different project types.

This model would not work properly for concrete pavement because of the unique characteristics of the two different materials. One necessary modification is the length of LCC. The model is designed to forecast performance in terms of ten-year LCC, which was validated as appropriate for asphalt pavement. However, since concrete pavement has much longer expected service life, LCC over longer time (preferably half of service life) is necessary. Another unique characteristic that must be considered and applied to the model is the abrupt failure tendency of concrete pavement. In the case of asphalt, the rate of failure increases relatively linearly, therefore long-term performance is somewhat predictable a few years after the completion of the project. However, in the case of concrete pavement, it is much more difficult to predict long-term performance. Therefore, some practitioners have insisted that short-term warranty for concrete pavement is meaningless. Therefore, in order for the model to be applicable to concrete pavement, some components must be replaced and impact ratings reassessed.

The model is even less applicable to other project types such as bridges, tunnels and intelligent traffic system (ITS). In cases of bridges and tunnels, the expected service life is far too long for this model to be applied. Components with relatively short lives such as bridge painting and decks and tunnel lighting are being warranteed and the model could be applied with some modification.

Without modification and recalibration, practically, the use of current model is limited to asphalt pavement only.

8.5 Future Research

This section discusses some prospective topics for future research, some of which were implied by the limitations and shortcoming of this research and others suggested by practitioners.

Table 8-2 summarizes future research topics along with shortcomings of current and descriptions for future research.

Table 8-2: Future Research Topics

Research Topic	Shortcomings of Current research	Description of future research
Improvement in the level of detail	The number of model components such as drivers and processes was limited due to difficulty of assessment.	Further breakdown of current model components is desired. The problem of difficulty of assessment can be resolved through a workshop instead of individual interviews
Guideline for input data preparation	Despite the fact that the accuracy of the forecast depend heavily on the accuracy of input data, most data for current model must be inputted in a probabilistic form. However, contracting agencies do not usually make probabilistic estimations.	A guideline for probabilistic input data preparation is needed for practical usage of the developed model. Since some state governments are in process of implementing probabilistic estimation, sufficient resources could be available.
Post-construction warranty decision through option or negotiation	The use of the developed model is limited to specific timing. Although it can be easily modified for earlier timing, it requires new form and contents for post-construction decision.	Post-construction warranty decision involves negotiation process unless an option is previously specified. A new research approach is required as it is more of negotiation than a decision.
Change in warranty environment	As time passes, it is expected that warranty environment will be changed. Depending on how much the change will be, a major modification to the model may be required.	According to practitioners' assessments, three probable changes will affect warranty usage: - Agency's staffing and funding mechanism - More public-private-partnership projects - Change in bond price depending on market condition and stability of contractors
Quantitative and hybrid model	Quantitative approach was an option for this research. However, appropriate data were not available.	When sufficient warranty data are accumulated from more frequent use of warranty, the same research question may be answered with quantitative analysis methods such as cost-benefit, and LCC. It would be interesting if the results from two different methods are compared. A hybrid model of two or more different methods can be developed.
Warranty bond cost	Because the influencing or influenced factors for bond decision were completely different from the factors in other decisions, the impact of warranty bond decision did not propagate through the developed model as expected.	Additional set of factors required for model to catch the impact of bond decision. The set of factors should include market condition and contractor's financial strength as drivers rather than external factors.
Appropriate level of performance requirements	Despite the importance, performance requirements during warranty were simplified as three levels of high, medium and low.	Appropriate level of performance requirement must be determined from considerations on warranty period and other requirements. Variation in requirements (different requirements each year after construction) may be an option.

8.5.1 Level of detail

In this research, the number of model components such as drivers and processes was limited due to difficulty of assessment. Because the impact ratings were assessed from individual interviews, multiple rounds of interviews were necessary to reach satisfactory level of consensus among respondents. Therefore, each interview had to be relatively short, and the model developer had to cut down the number of required assessments by limiting the number of drivers, processes and outcomes. Improvement on this limitation could improve the model's level of accuracy and confidence.

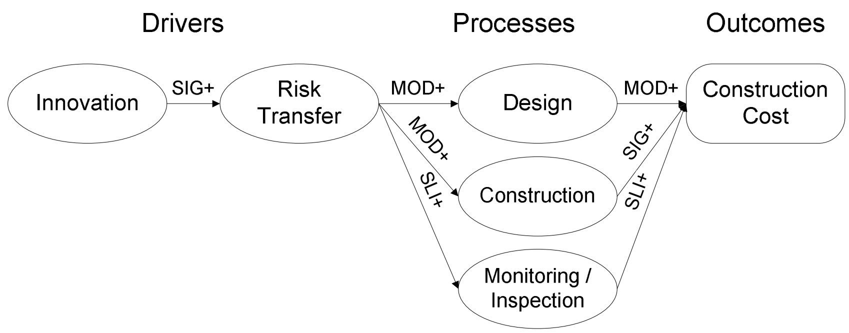

Figure 8-5: Level of Detail in Current Model

Figure 8-5 displays a portion of the current model which shows impact relationship between two drivers and how this impact propagates through the process and to the outcome. As shown in the figure, the driver "innovation" has a single impact rating to another driver "risk".

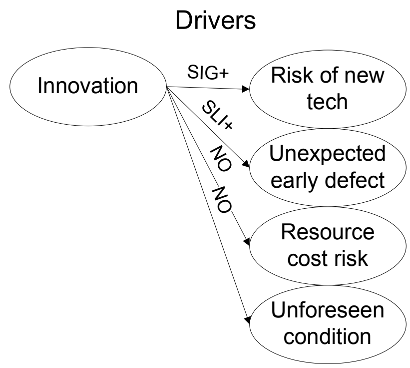

Figure 8-6: Level of Detail in Future Research

Figure 8-6 shows the same portion of the model, but this time the driver "risk" is broken down further into four different risk factors. As shown in the figure, the driver "innovation" now has four different impact ratings for four risk factors. With a higher level of detail, accuracy and confidence levels in the model may improve. Also, more information can be acquired from the model and simulation runs.

The only problem with breaking down the model components further is the increased number of assessments required, which was overwhelming in the current research environment, but is a prospect for further research.

8.5.2 Quantitative and hybrid model

At the research development phase, some quantitative methods were considered. However, those were not selected mainly because of the lack of appropriate data. In order to answer the research question and fulfill the objectives, the researcher needs complete data sets (present and future cost data for ten year LCCA) for five projects with desired characteristics such as similar size projects with different delivery method, specification method, etc. Since, sufficient data was not available, GPM method was selected instead.

As a greater number and variety of projects have been contracted with warranty and historical data have been accumulated for projects which have been built with warranty, sufficient data will soon be available. Then, with sufficient historical data, a quantitative model can be developed. The model can be an inclusive LCCA, cost-benefit analysis with quantified performance measures, or any other methods.

The flowcharts in Figure 8-7 display an actual algorithm of a current GPM model and the flowchart in Figure 8-8 display a probable quantitative (LCC) model to be used in further research. The objective of both models is to examine changes in warranty cost for various decision alternatives (warranty periods in) this specific case.

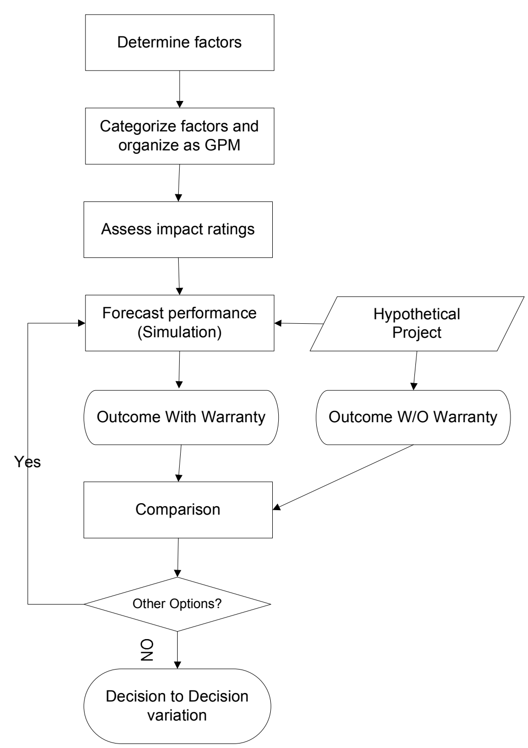

Figure 8-7: Algorithm of a current GPM model

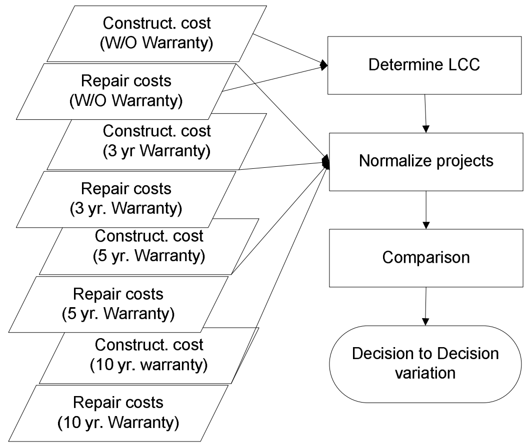

Figure 8-8: Algorithm of a Future LCCA Model

The input data for GPM models are impact ratings and project characteristics from a hypothetical project. For LCCA models, there is only one type of data, which is actual cost data. Figure 8-8 shows that eight sets of data are required (initial cost and future repair cost data for each warranty period options). This is a much greater amount of data compared to GPM models, which require only one set. However, the process for LCCA models is simpler than for GPM models as it takes only three steps – determining LCC, normalization, and comparison. Another advantage of an LCCA model is that it utilizes actual data and there is no process that requires people-based assessment. Therefore, the results can be free of any type of bias, miscommunication, or mistake. Also, since it is built on the basis of real data, it should be more reliable as long as the analysis is done correctly.

As shown in Figure 8-7 and 8-8, each method – GPM and LCCA – has its own strengths and weaknesses. One way to build a complete model is to combine two methods into one model so that they complement each other. There could be various forms of such a hybrid model. The same GPM model structure can be retained, and only actual project data can be used instead of hypothetical project data. The real data can be used to validate and calibrate the GPM model components and impact ratings. On the other hand, a GPM model may be used as a supplement to a LCCA model as a method of normalizing data from projects of different characteristics.

8.5.3 Warranty bond cost

The warranty bond decision was one of five decision alternatives that were included in the model. However, a few problems were found during the model analysis and validation process. One is that most of practitioners suggested that it is more of a given condition rather than a decision alternative. For most of contracting agencies, a warranty bond is not a decision which is determined on a project-to-project basis. It is more of a regulation which is required for all the projects with warranty. Therefore, some practitioners suggested considering it as an external condition.

Another problem involves inappropriate model contents for the warranty bond decision. Figure 8-9 shows a portion of developed GPM model and it demonstrates this problem. As shown in the figure, the warranty bond decision impacts one of drivers, but the impact does not reach to the outcomes because none of processes impact the bond cost outcome. Therefore, no matter what impact the warranty decision has on driver, the warranty bond decision has no impact to bond cost outcome.

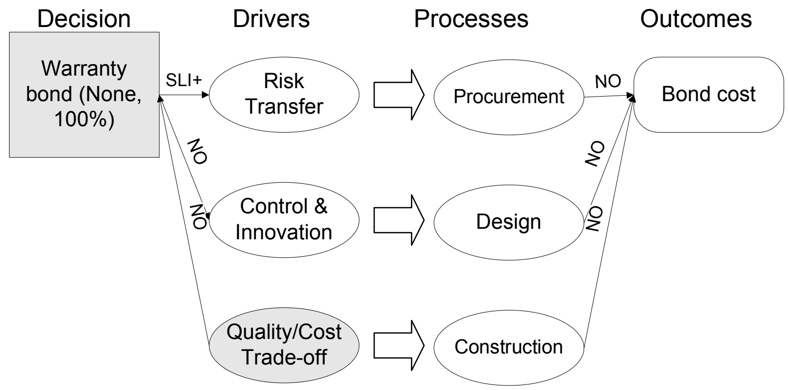

Figure 8-9: Problem of Bond Decision

The simulation results also demonstrate this problem as the bond cost remains same for all warranty decision alternatives (Table 6-6). This problem arises because none of processes are closely relevant to bond cost. In order to correct this problem, a different set of processes must be applied to the model, but it was not feasible to do so by the time this problem was discovered. This problem could be resolved in future research.

8.6 Chapter Summary

This concluding chapter consists of summary of research processes, key findings, research contribution, shortcoming and limitations, and prospects of future research. Brief descriptions of each research process – model development, assessment, simulation results, and model validation – were presented. The main focus of these descriptions was to inform the readers of the objectives of each process and what the key results were. The discussion continues with key findings. Some of representative contributions from the research process and findings were discussed. Finally, the shortcomings of the model and the research procedure were discussed and possibilities for future research were presented.

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APPENDICES

Appendix 1: Initial Assessment Questionnaire Packet

General Information

This questionnaire is a part of a study which aims to develop a warranty decision model for design-build road pavement projects. In spite of recent growth of design-build and warranty usage in highway projects, there has not been enough research on warranty impact on lifetime performance of the product. The uniqueness of the design-build process has not been considered in any previous research. In order to compensate for such deficiency, a new warranty decision model is being developed. Once developed, it will be used to simulate performance outcomes of projects involving various conditions, characteristics, and decisions. The simulation results will provide valuable information such as critical warranty decision criteria and project characteristics and their impact on lifetime performance. The process and end result of this model development and simulation should be helpful to future decision makers.

The model includes a number of variables that impact one another as well as outcomes. For the development of a complete model, these inter-relationships must be considered. In this questionnaire, participants are asked to make judgments regarding the direction and strength of relationships among variables. The strength of relationships determined from this questionnaire will be used as important data in prioritization of critical warranty decision attributes and their influence on overall project performance.

In this questionnaire, there are eight assessment tables that need to be answered by the participants. The expected time requirement to complete this questionnaire is about one hour (40 minutes for assessment and 20 minutes for general comments). This is guided questionnaire, which means the researcher will be available either in person or through phone call for any necessary assistance such as clarification on definitions and assessment procedure.

This questionnaire is consisted of three sections. First in Participant Information, participants are asked to state their information regarding their past experience that is relevant to warranty and other innovative contracting method such as design-build. This information will be used to justify that resulting assessments are done by qualified experts who has enough experty on the topic. The second section is guideline to the assessment. The guideline briefly describes assessment procedure and method. It also includes a list of definition. Finally, assessment section includes eight tables the participants are to fill out.

Participant Information

Name:

Phone:

E-mail:

Address:

Job title and description:

Organization:

Experience in Construction (in years, previous job description, etc):

Experience with warranty (in number of projects, publications, etc):

Experience with other innovative contracting methods (design-build, A+B, lane rental, etc):

Project Information

Project Name:

Project Size (in Million dollars, lengths, lanes, etc):

Project type (Mark all that is relevant):

New Expansion Rehabilitation Demolition
Road (Highway) Building
Pavement Bridge ITS Tunnel
Other features:

Delivery type:

Design-bid-build
Design-build
Design-build-operate-maintenance
Design-build-operate-maintenance-Finance
Other:

Procurement type:

Low bid

Muli-parameter bid
A+B(time) A+B+Q(Quality) Lane rental Others
Best-value
Low bid (meets technical criteria)
Adjusted bid
Adjusted technical point
Weighted criteria
Fixed price design competition

Contract type (Payment method)

Lump-sum Unit price Cost+Fee Guaranteed Max.

Warranty

Performance or Material & workmanship

Duration:

Bond coverage & amount:

Maximum liability clause?:

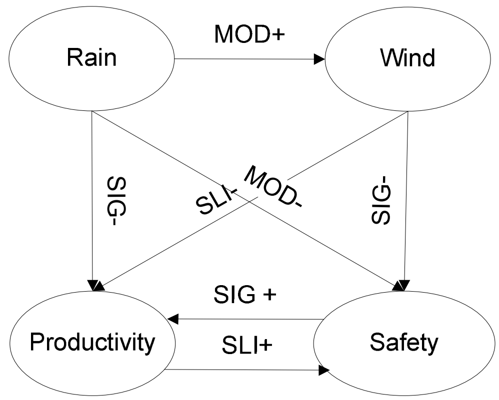
Maximum load clause?:

Required maintenance during warranty period?

Others?

Assessment Guideline

The idea is that if one variable is to occur, other variables will be impacted by this result in certain directions and at certain strengths. For example, there are four variables shown in the figure below (rain, wind, safety, productivity), and some variables influence others. Weather conditions (i.e. rain and wind) influence productivity and safety of construction.



The impact can be in either a positive or negative direction. In other words, event "Rain" may increase (+) or decrease (-) expected performance level of "Safety" and "Productivity". In the example above, rain influences both "Safety" and "Productivity" negatively. Also, impact rating can be of one of three magnitudes (Significant, Moderate and Slight). "Rain" influences "Productivity" significantly and "Safety" moderately. Combining direction and magnitude of influence, the relationships among variables can be assessed as any of seven ratings SIG +, MOD +, SLI +, NO, SLI-, MOD-, SIG- as listed in the table below. Participants are to assess each relationship by assigning one of the seven ratings.

Symbol	Meaning
SIG +	Significant impact in the same direction
MOD +	Moderate impact in the same direction
SLI +	Slight impact in the same direction
NO	No impact
SLI –	Slight impact in the opposite direction
MOD –	Moderate impact in the opposite direction
SIG –	Significant impact in the opposite direction

Finally, some variables have cross-impact characteristic. In other words, some variables may influence each other. "Productivity" influences "Safety" and "Safety" influences "Productivity, but direction and magnitude are not same. In the example, "Productivity" impacts "Safety" slightly positive while "Safety" impacts "Productivity" significantly negatively.

In this questionnaire, the participants are asked to fill out impact-rating tables aim the example below. The tables contain same information as the influence drawing above, but it is more compact and convenient in terms of assessment purpose. Therefore, tables are used in this questionnaire instead of influence diagrams.

The table includes four variables and twelve required assessments. The participants assess the direction and strength of each of twelve relationships and note them using symbols defined earlier. Each space is designated for the impact rating from column item to row item. For example, the highlighted rating (MOD+) is impact rate from “Rain” to “Wind”.

		Rain	Wind	Safety	Productivity
Condition	Rain	X	NO	NO	NO
	Wind	MOD+	X	NO	NO
Outcome	Safety	MOD-	SIG-	X	SLI+
	Productivity	SIG -	SLI-	SIG+	X

Drivers

Drivers	Risk Transfer	This is a measure of amount of risk transferred to the design-builder from the owner due to the use of a warranty contract. Examples include cost to repair post-construction defects, rework, etc. *Positive – More risk* *Negative – Less risk*
	Control and Innovation	This is measure of level of contractor control and chance of innovation. Control and chance of innovation can be applied to both design and construction. *Positive – More control and chance of innovation* *Negative – Less control and chance of innovation*
	Quality/Cost Tradeoff Decision	This refers to the likelihood of the design-builder selecting higher quality design (or construction method) over the design that yields lower cost due to the use of a warranty contract. *Positive – More likely to choose higher quality over lower cost* *Negative – Less likely to choose higher quality over lower cost*
	QA/QC Plan and Execution	This measures design-builder's involvement and level of effort in planning and performing QA/QC during construction. This measure includes various efforts such as developing more rigorous QA/QC plans assigning more and more qualified personnel for QA/QC monitoring. *Positive – More effort in QA/QC* *Negative – Less effort in QA/QC*
	Post Construction Maintenance	This measures design-builder's motivation or desire for planning and performing post construction maintenance to maintain high quality level during warranty period. *Positive – More effort in post construction maintenance* *Negative – Less effort in post construction maintenance*

Processes

Processes	Procurement	This measures likely performance of procurement phase. Performance in procurement includes chance of getting quality proposal, minimizing time delay and fair competition. This is a measure for performance of both parties - the owner and the design-builder. *Positive – Higher chance of good performance in procurement* *Negative – Lower chance of good performance in procurement*
	Design	This is performance measure of design phase. This phase includes only the final design phase that is performed by the design-builder. Preliminary design in the programming phase is not included in this measurement. *Positive – Higher performance in design* *Negative – Lower performance in design*
	Construction	This measures performance of construction process. *Positive – Higher performance in construction* *Negative – Lower performance in construction*
	Inspection	This measures level of quality and effectiveness of design-builder's self-inspection. A higher rating means that it is less likely to have defects at project completion and during and after the warranty period. *Positive – Higher performance in inspection* *Negative – Lower performance in inspection*
	Maintenance	This measures the performance of post construction maintenance. Maintenance performance does not affect quality at project completion. *Positive – Higher performance in post construction maintenance* *Negative – Lower performance in post construction maintenance*

Outcomes

Outcomes	Construction Cost	This is the cost of construction which includes material, labor and staff cost. Performance of some of processes such as higher design quality, more inspection staffs may impact this cost positively and negatively. *Positive – Higher Cost* *Negative – Lower Cost*
	Design (DBer) Cost	This is cost for hiring or utilizing design staff. This cost does not include cost for initial design (pre-procurement). *Positive – Higher Cost* *Negative – Lower Cost*
	Warranty Bond Cost	This is cost of buying the required warranty bond. Bond requirements such as amount and period are decided by the owner and surety company sets appropriate price depending on bond requirements and each design-builder's credibility. *Positive – Higher Cost* *Negative – Lower Cost*
	Maintenance Cost	This is cost of performing preventative and routine maintenance. This cost does not include cost that is used to repair defects. *Positive – Higher Cost* *Negative – Lower Cost*
	Repair (Agency) Cost	This is cost paid by the agency to repair defects that are discovered after the warranty expiration and before to the end of products' design life. *Positive – Higher Cost* *Negative – Lower Cost*
	Repair (DBer) Cost	This is cost paid by the design-builder to repair defects during warranty period. *Positive – Higher Cost* *Negative – Lower Cost*
	Contractor Margin	This is a service fee that the design-builder adds to the estimated pure cost as their profit. Often this is measured as percentage to the estimated construction and design cost. Amount of contractor margin heavily depends on level of competition, company situation, level of risk, etc. *Positive – Higher Margin* *Negative – Lower Margin*

Decision Variables

Decision	Warranty Period	This measures length of warranty period. A higher value corresponds to a longer the warranty. *Positive – Longer warranty period* *Negative – Shorter warranty period*
	Performance level	This measures required level of performance at project completion and during warranty period. Example indicators include rutting, cracking, friction, etc. *Positive – Stricter performance criteria* *Negative – Looser performance criteria*
	Preventive maintenance	This is requirement for preventive and routine maintenance the design-builder is required to perform during warranty period. This is the owner's option. *Positive – Require frequent preventive maintenance during warranty* *Negative – Does not require preventive maintenance*
	Warranty Bond	The owner may choose the option of requiring the proposers to purchase warranty bond from surety and submit in order to ensure the design-builder to perform repair task as specified in the warranty. *Positive – Require warranty bond* *Negative – Does not require warranty bond*
	Limited liability	The owner may choose to limit design-builder's liability on post construction repair cost. With a limit, the owner retains some risk and avoids paying an excessive risk premium. *Positive – Sets limit on maximum liability* *Negative – No limit in liability*

Project Characteristics

Project	Project Size	This is size of project in terms of dollar amount. *Positive – Larger project* *Negative – Smaller project*
	Specification Type	This defines the degree to which the owner utilizes performance specifications for the design of pavement in the contract. A low value corresponds to reliance on prescriptive specifications and a high value corresponds to a high degree of performance specifications. *Positive – Performance based specification (no method specified)* *Negative – Method based specification (prescriptive)*
	Project Complexity	This condition defines project complexity. This includes project environment, existence of traffic during construction, right of way acquisition, etc. *Positive – More complexity* *Negative – Less complexity*
	Procurement method	This defines the importance of technical proposal (i.e. design, QA/QC plan, and qualification) in comparison to price proposal. In case of low-bid fixed design method, technical proposal is less important compare to best-value method with a large technical proposal weighting as compared to price. *Positive – Best-value including technical score* *Negative – Low-bid, no technical score*
	Load uncertainty	This defines uncertainly of traffic load after construction. Load includes both number of traffic and type of traffic (fraction of heavy vehicle). With more uncertainty, the risk of having warranty will increase. *Positive – High uncertainty in future traffic load* *Negative – Low uncertainty in future traffic load*

Owner, Proposer, Surety, Market Characteristics

Owner	Owner preference to innovation	This defines level of owner's preference to innovative and new design and construction method. More preference to innovation often leads to proposers' motivation of new ideas. *Positive – Prefers new and innovative design and method* *Negative – Conservative to conventional design and method*
Proposer	Need for work	This measures if the proposers are in need for work. This impacts how badly the proposers need to win this specific project. *Positive – Need for work to keep their office running* *Negative – No need for immediate work*
	Other objectives (future work)	This measures if the proposers have other objectives other than making profit out of this specific project. Other objective often includes improving relationship with the owner, enlarging chance of winning in future project, etc. *Positive – Proposers have objective other than making profit* *Negative – Proposers' sole objective is making profit*
	Financial Strength	This measures financial strength of participation proposers. *Positive – Proposers are generally financially stable* *Negative – Proposers are not financially sound*
	Level of past experience	This measures amount and performance level of participating proposers in similar past projects. *Positive – Proposers are generally have high level of past experience* *Negative – Proposers does not have past experience*
Market	Level of competition	This is measurement of competitiveness in bidding. Level of competition is often influenced by number of bidder, difficult market condition, etc. *Positive – Highly competitive bidding* *Negative – No competition*
	Resource cost escalation	This measures risk of facing higher pure construction cost due to inflation of resource cost. Resource includes material and labor. *Positive – More chance of unexpected cost escalation* *Negative – Less chance of cost escalation*
Surety	Bond availability	This measures surety companies readiness of issuing warranty bond. In other words, for the type of warranty requirements they are not used to issuing bond for, the price is likely be higher than necessary. *Positive – Surety company willing to issue bond* *Negative – Surety company is reluctant to issue bond*
	Risk attitude	This measures surety companies attitude toward issuing risky bonds. This also measures surety companies' attitude toward future risk and warranty. *Positive – Surety company is willing to take risk in warranty bond* *Negative – Surety company is not willing to take chance*

		Decision Variables				
		Warranty Period	Performance level	Preventive maintenance	Warranty Bond	Limited liability
Drivers	Risk Transferred					
	Control & Innovation					
	Quality/Cost Tradeoff					
	Importance of QA/QC					
	Post-Const. Maintenance					

		Project Characteristics				
		Project Size	Specification Type	Project Complexity	Load uncertainty	Procurement Method
Drivers	Risk Transfer					
	Control & Innovation					
	Quality/Cost Tradeoff					
	Importance of QA/QC					
	Post-Const. Maintenance					

		Owner & Proposer Characteristics				
		Preference to Innovation	Need for Work	Other Objectives	Financial Strength	Level of Past experience
Drivers	Risk Transfer					
	Control & Innovation					
	Quality/Cost Tradeoff					
	Importance of QA/QC					
	Post-Const. Maintenance					

		Market Characteristics				
		Level of Competition	Resource Cost Escalation			
Drivers	Risk Transfer					
	Control & Innovation					
	Quality/Cost Tradeoff					
	Importance of QA/QC					
	Post-Const. Maintenance					

		Owner	**Project**	**Surety Characteristics**	
		Preference to Innovation	Uncertainty in Traffic load	Bond Availability	Risk Attitude on Warranty
Outcomes	Construction				
	Design				
	Warranty Bond				
	Maintenance				
	Repair (Agency)				
	Repair (DBer)				
	Contractor Margin				

		Market Characteristics				
		Level of Competition	Resource Cost Escalation			
Outcomes	Construction					
	Design					
	Warranty Bond					
	Maintenance					
	Repair (Agency)					
	Repair (DBer)					
	Contractor Margin					

		Proposer Characteristics				
		Workload/ Need for work	Other Objectives	Financial Strength	Past Experience	
Outcomes	Construction					
	Design					
	Warranty Bond					
	Maintenance					
	Repair (Agency)					
	Repair (DBer)					
	Contractor Margin					

		Transferred Risk	Control & Innovation	Quality/Cost Trade-off	QA / QC Plan	Maintenance	Procurement	Design	Construction	Inspection	Maintenance
Drivers	Amount of Transferred Risk	X					X	X	X	X	X
	Control & Innovation		X				X	X	X	X	X
	Quality/Cost Tradeoff			X			X	X	X	X	X
	QA/QC Plan and Execution				X		X	X	X	X	X
	Post Const. Maintenance					X	X	X	X	X	X
Processes	Procurement						X	X	X	X	X
	Design							X	X	X	X
	Construction								X	X	X
	Inspection									X	X
	Maintenance										X
Outcomes	Construction Cost	X	X	X	X	X					
	Design (DBer) Cost	X	X	X	X	X					
	Warranty Bond Cost	X	X	X	X	X					
	Maintenance Cost	X	X	X	X	X					
	Repair (Agency) Cost	X	X	X	X	X					
	Repair (DBer) Cost	X	X	X	X	X					
	Contractor Margin	X	X	X	X	X					

Appendix 2: Confirmation Assessment Questionnaire Packet

General Information

This questionnaire is a part of second interview to gather your assessments on warranty impacts on various project performance indicators. As it is explained in the first interview, these assessments will be used as part of the data for a warranty decision model. Also, it will be compared to your 1st assessment for the purpose of verification.

The analysis results on first interview indicated that there are significant deviations among your opinions in some of the assessments. These variations are rather expected since experience based opinions can be quite different one from another. However, I fears that some of your assessments were simple mistakes rather than different opinion. As a matter of fact, data analysis has revealed that some outlying assessments could have been errors. In order to clarify your assessments are mistake fee, I have decided to conduct second interview.

The expected time requirement to complete this questionnaire is about 20 to 30 minutes. Considering that this is your second time and are somewhat familiar with the process, it should take less time than it did in your first time.

The questionnaire consists three sections. First in participant and project information section, participants are asked to state your information regarding past experience that is relevant to warranty. This is similar to what you filled out in your first interview, but some has been changed and I hope you fill that out one more time. I have provided four blank pages for your past project or research. If you have less than four past projects, feel free to skip the pages. The second section is assessments. Similar to the first questionnaire, there are a set of assessment tables (27 in total) that need to be answered by the participants. The assessment table includes a column of your previous assessment from 1st interview, the average value of 1st interviews (of all participants), your new assessment (if different from your 1st assessment), and your comments. In order to save your time, I have highlighted the ones that your assessments are far off from others. However, these highlights are just for your reference and you may change any of assessments. The last section is a guideline to the assessment and a list of definitions. This guideline is same as your first questionnaire. This section is included just in case you need it.

I have sent you both a word (.doc) file and a acrobat (.pdf) file. If you choose to fill out a word file, please save and attach it to your e-mail back to me. If you choose to fill out the pdf file, please click on the button below. It will send me your data by e-mail automatically.

Participant Information

Name:

Job title and description:

Organization:

Experience in Construction (in years, previous job description, etc):

Experience with warranty (in number of projects, publications, etc):

Project Information

Name and describe some of your past projects with warranty

Project Name:

Project Size (in Million dollars, lengths, lanes, etc):

Project type (Road, building, pavement, tunnel, etc):

Delivery type (Design-bid-build, design-build, CM at risk, etc)

Warranty type (Performance, material and workmanship)

Other special features concerning warranty (bond amount, limited liability, etc)

		Project size impact on drivers			
		1st Assessment	Average	2nd Assessment	Comments
Drivers	Risk Transferred				
	Control & Innovation				
	Quality/Cost Tradeoff				
	Importance of QA/QC				
	Post-Const. Maintenance				

		Specification type impact on drivers			
		1st Assessment	Average	2nd Assessment	Comments
Drivers	Risk Transferred				
	Control & Innovation				
	Quality/Cost Tradeoff				
	Importance of QA/QC				
	Post-Const. Maintenance				

		Project complexity impact on drivers			
		1st Assessment	Average	2nd Assessment	Comments
Drivers	Risk Transferred				
	Control & Innovation				
	Quality/Cost Tradeoff				
	Importance of QA/QC				
	Post-Const. Maintenance				

Appendix 3: Model Validation Questionnaire Packet

Participant Information

Name:

Job title and description:

Organization:

Experience in Construction (in years, previous job description, etc):

Experience with warranty (in number of projects, publications, etc):

Previous Project or Research Information

Project Name:

Project Size (in Million dollars, lengths, lanes, etc):

Project type (Road, building, pavement, tunnel, etc):

Delivery type (Design-bid-build, design-build, CM at risk, etc)

Warranty type (Performance, material and workmanship)

Other special features concerning warranty (bond amount, limited liability, etc)

Overview of the research and the model

Research Question
How do warranty decisions (e.g., warranty period, liability limitations) and other project characteristics impact the performance of highway pavement projects?

Research Objectives

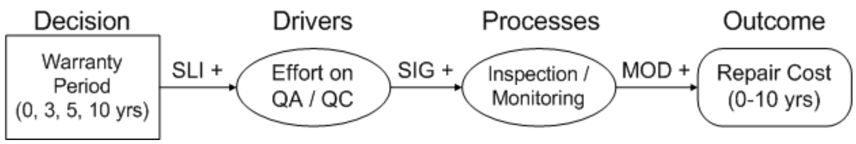
- Identify attributes of warranty decisions and performance outcomes
- Develop a decision model that simulates warranty impacts on project performance.
- Examine impacts of warranty decisions on project performance by model simulations.

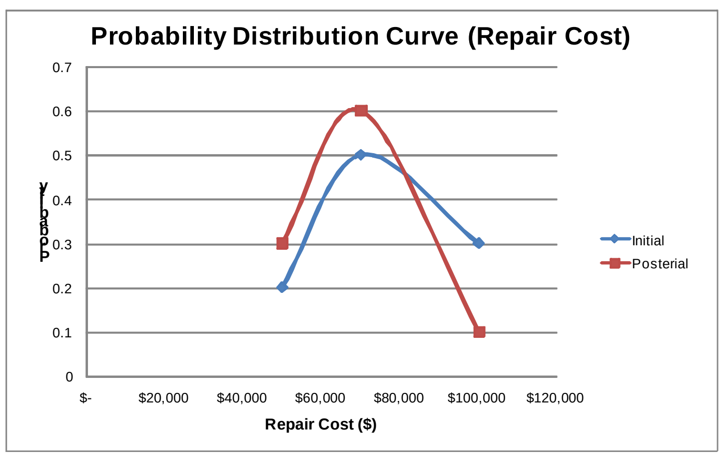
Modeling Method

There are four theories the model is based on.   They are:

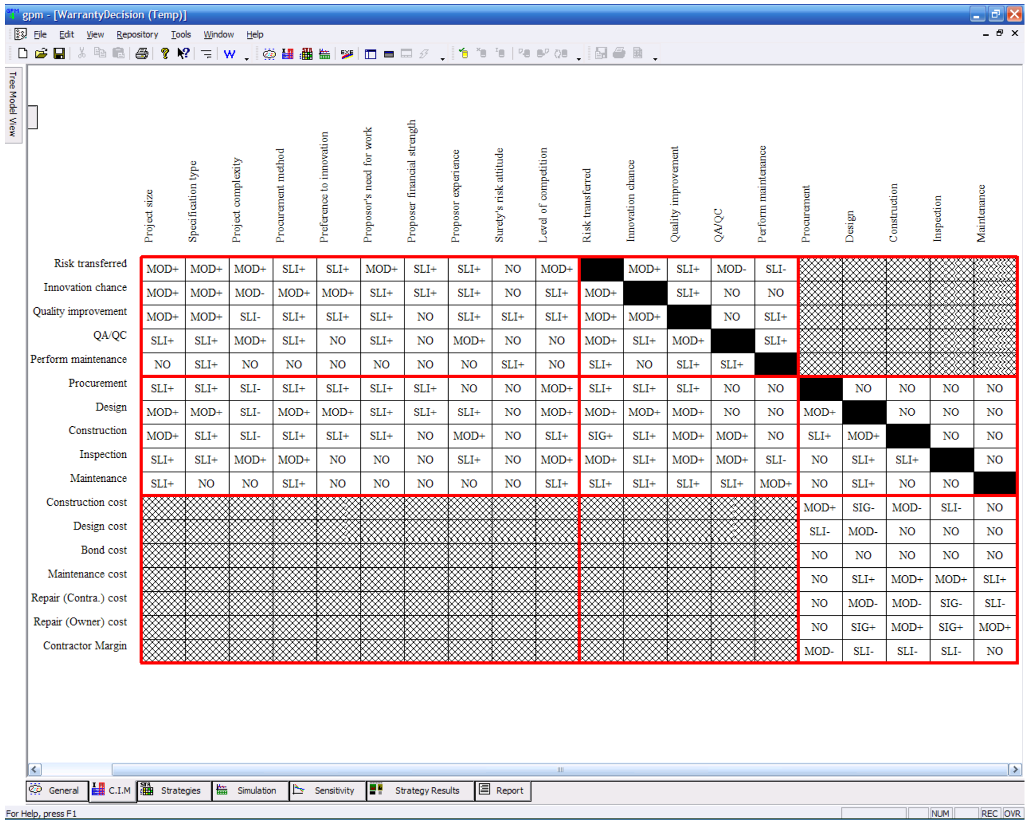
- Cross-impact Analysis (CIA)
- General Performance Modeling (GPM)
- Monte Carlo Simulation
- Life Cycle Cost Analysis

Outcome	Initial probability	Posterior Probability	Value
Good	0.2	**0.3**	$50,000
Normal	0.5	**0.6**	$70,000
Bad	0.3	**0.1**	$100,000



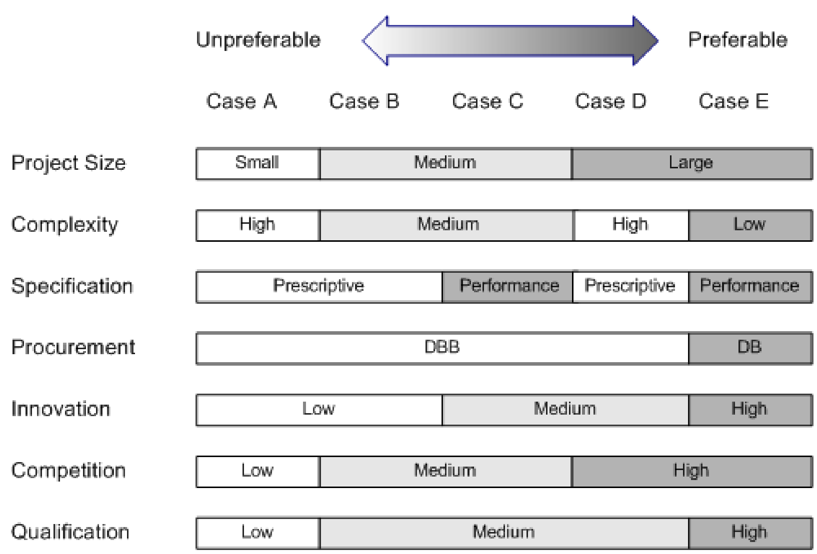


Impact Rating Assessment Results



	Project size	Specification type	Project complexity	Procurement method	Preference to innovation	Proposor's need for work	Proposer financial strength	Proposor experience	Surety's risk attitude	Level of competition	Risk transferred	Innovation chance	Quality improvement	QA/QC	Perform maintenance	Procurement	Design	Construction	Inspection	Maintenance
Risk transferred	MOD+	MOD+	MOD+	SLI+	SLI+	MOD+	SLI+	SLI+	NO	MOD+		MOD+	SLI+	MOD-	SLI-					
Innovation chance	MOD+	MOD+	MOD-	MOD+	MOD+	SLI+	SLI+	SLI+	NO	SLI+	MOD+		SLI+	NO	NO					
Quality improvement	MOD+	MOD+	SLI-	SLI+	SLI+	SLI+	NO	SLI+	SLI+	SLI+	MOD+	MOD+		NO	SLI+					
QA/QC	SLI+	SLI+	MOD+	SLI+	NO	SLI+	NO	MOD+	NO	NO	MOD+	SLI+	MOD+		SLI+					
Perform maintenance	NO	SLI+	NO	NO	NO	NO	NO	NO	SLI+	NO	SLI+	NO	SLI+	SLI+						
Procurement	SLI+	SLI+	SLI-	SLI+	SLI+	SLI+	SLI+	NO	NO	MOD+	SLI+	SLI+	SLI+	NO	NO		NO	NO	NO	NO
Design	MOD+	MOD+	SLI-	MOD+	MOD+	SLI+	SLI+	SLI+	NO	MOD+	MOD+	MOD+	MOD+	NO	NO	MOD+		NO	NO	NO
Construction	MOD+	SLI+	SLI-	SLI+	SLI+	SLI+	NO	MOD+	NO	SLI+	SIG+	SLI+	MOD+	MOD+	NO	SLI+	MOD+		NO	NO
Inspection	SLI+	SLI+	MOD+	MOD+	NO	NO	NO	SLI+	NO	MOD+	MOD+	SLI+	MOD+	MOD+	SLI-	NO	SLI+	SLI+		NO
Maintenance	SLI+	NO	NO	SLI+	NO	NO	NO	NO	NO	SLI+	SLI+	SLI+	SLI+	SLI+	MOD+	NO	SLI+	NO	NO	
Construction cost																MOD+	SIG-	MOD-	SLI-	NO
Design cost																SLI-	MOD-	NO	NO	NO
Bond cost																NO	NO	NO	NO	NO
Maintenance cost																NO	SLI+	MOD+	MOD+	SLI+
Repair (Contra.) cost																NO	MOD-	MOD-	SIG-	SLI-
Repair (Owner) cost																NO	SIG+	MOD+	SIG+	MOD+
Contractor Margin																MOD-	SLI-	SLI-	SLI-	NO

Input Data (5 cases)



Research Assumptions

- The project performance outcomes are measured in life-cycle-cost (LCC).
- The timing of warranty decision is sometime between pre-qualification and final bid.
- The model is optimized for highway asphalt pavement projects (20 yr design life).

A set of questions

The basis of this warranty model is GPM and CIA. These probabilistic analysis methods attempt to predict project performance. Among various probabilistic approaches, GPM and CIA emphasize the interactions among variables.

Question 1-1
This model is design to help warranty decision makers by providing a prediction of project performance for various decision alternatives. In this model, warranty performance is measured through life-cycle costs. Other than project performance as measure through life-cycle costs, what other factors do decision makers consider in making warranty decisions?

Question 1-2:
Have you used or seen any other warranty decision model? If so, what methods are they based on?
The model considers five warranty decision alternatives. They are:

- Warranty period
- Performance level requirement to be maintained during warranty
- Preventive maintenance requirement
- Warranty bond requirement
- Limited liability clause

Question 2-1:
Do you think that any of these five decision alternatives are unnecessary? Are there any decision alternatives missing?

Question 2-2:
Do you think that any of these decisions are prohibited for public procurement or constrained due to limited funding?

Drivers are variables that are influenced by the decision alternatives. These drivers then influence performance of some processes. The model includes five drivers.

- Amount of risk transferred due to warranty
- Chance and motivation for innovation
- Improvement in design and material quality
- Emphasis on QA/QC
- Post-construction maintenance during warranty

Question 2-3:
Do you think that any of these five decision drivers are insignificant and could be excluded from the model?

Question 2-4:
Are there any drivers missing?

In this model, performance is measured through various life-cycle costs (LCC). The LCC is calculated through the following performance measures.

- Design, Construction, warranty bond cost
- Contractor's expected repair cost during warranty period
- Bid margin (Risk premium)
- Owner's maintenance and repair cost

Question 2-5:
What are the advantages and disadvantages of measuring project performance through LCC for a warranty decision model? What other performance measures can you think of that is not listed above?

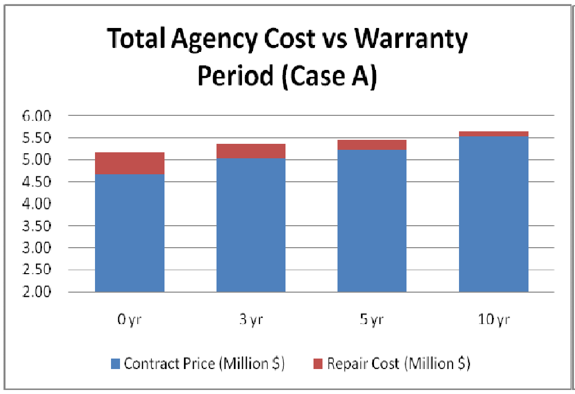
Question 2-6:
The model is design to simulate 0 to 10 years of LCC. What variable influence the period of analysis? What would make it go beyond the period of analysis?

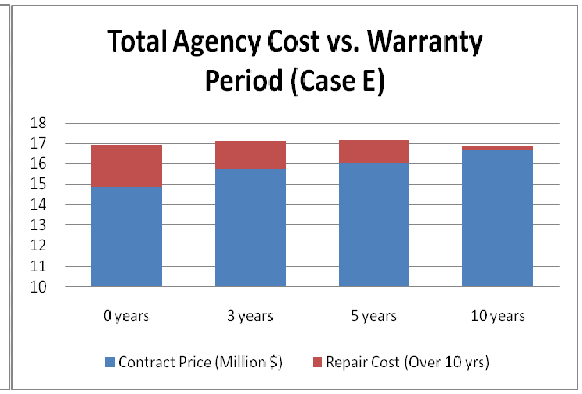
To test the model, five project cases with various project characteristics were developed and tested.

Question 3-1:
Do these five cases represent the range of projects to which warranties can be applied?

Question 3-3:
Please review the results in Figure below. How could you apply this information in making warranty decisions?

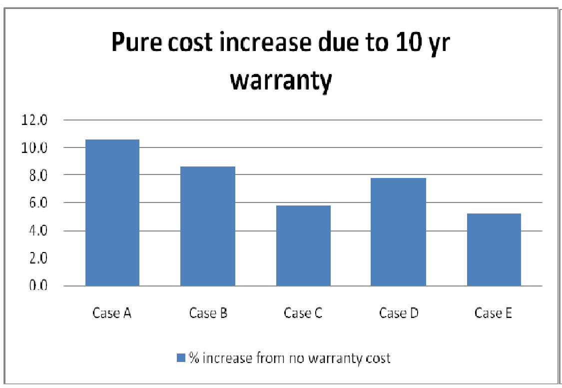
Question 3-4:
What questions or concerns do you have after reviewing these results?

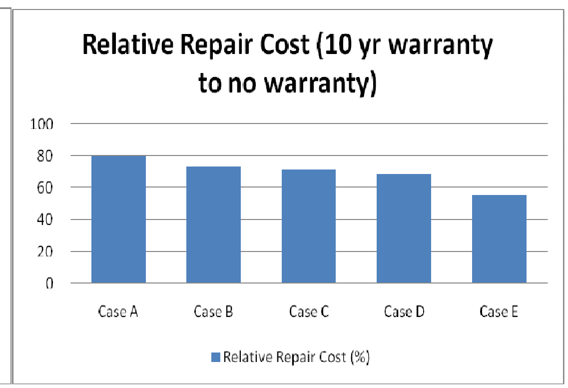




Question 3-5:
Please review the results in figures below. How could you apply this information in making warranty decisions?

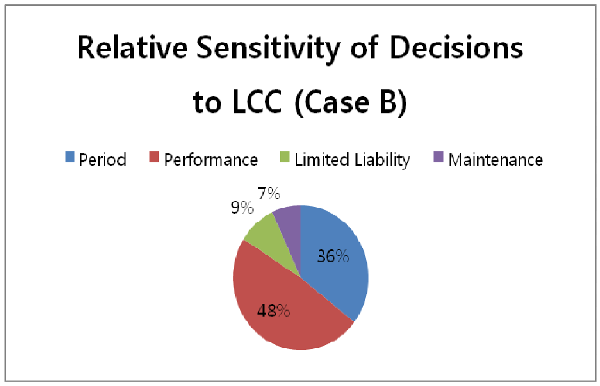
Question 3-6:
What questions or concerns do you have after reviewing these results?





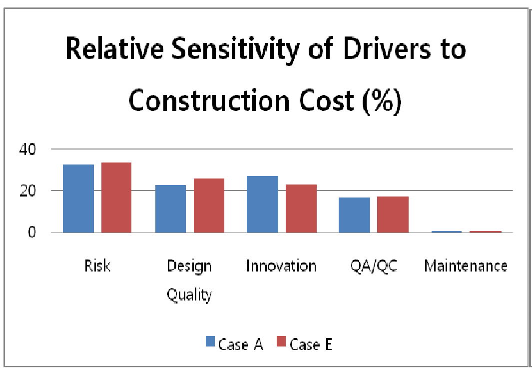
Question 3-7:
Please review the results in figures below. How could you apply this information in making warranty decisions?

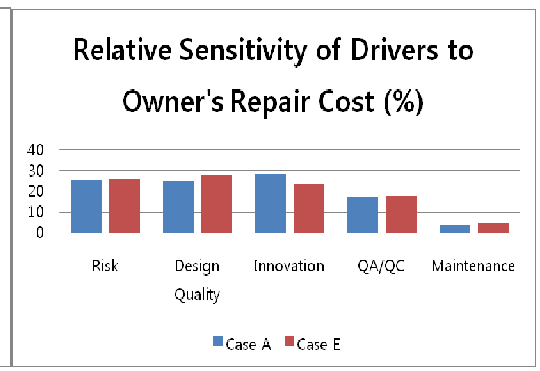
Question 3-8:
What questions or concerns do you have after reviewing these results?



Question 3-7:
Please review the results in figures below. How could you apply this information in making warranty decisions?

Question 3-8:
What questions or concerns do you have after reviewing these results?





The model is developed and tested mainly for small to medium sized asphalt paving projects.

Question 4-1:
Could the model be adapted to concrete pavement? If yes, what other factors should be included?

Question 4-2:
Could the model be adapted to other project types such as bridge, tunnel, ITS, etc? If yes, what other factors should be included?

Question 4-3:
What other factors must be considered if the model is to be applied to mega-projects?

Question 4-4:
What is usual and proper warranty decision timing?

Question 4-5:
What should be changed if the warranty decision is made earlier – in conceptual design, scoping, final design, etc.? What factors should be included or excluded in the model in case decision is made at earlier time?

Question 4-6:
What should be changed if the warranty is decided after bid opening and during contract negotiation? Is there a case warranty is decided after the construction completion (warranty option)? What factors should be included or excluded in the model in case decision is made at later time?

The model is built on the basis of today's current situation.

Question 4-7:
What aspects of this warranty model should be change over time as warranty use becomes more frequent and industry perception is changed?

Question 4-8:
What impact ratings need to be reassessed when warranty situation is different from now?

Appendix 4: Validation Interview Results

The following is a summary of opinions collected from interviews with practitioners who has enough experience with warranty in various construction projects or has warranty research experience. The interview participants belong to one of three different profession groups of government agency, consultant, and contractor. However, in this summary, no distinction is made among professions. Also, some practitioners had participated to the impact rating assessment interviews and some did not. This difference was not significantly distinguishable; therefore no distinction was made for this summary either.

Question Set 1: Model Method

Probabilistic Decision Model / GPM / CIA

- Engineer’s estimate is usually not probabilistic
- Need for accuracy in input data

Measuring project performance as LCC

- LCC is definitely a reasonable method of measuring project performance
- Other than LCC
- User cost (in addition to agency cost) is a factor
- Serviceability performance
- User comfort – Smoothness
- Safety - Friction

Other warranty decision model, method, etc

- No model but guideline is available (Wisconsin, Colorado)
- Discussion (No formal system)

Basis of warranty decision

- Owner’s intention to transfer catastrophic failure risk (Risk transfer)
- Most of projects have similar type of warranty (Regulation)
- Project type and characteristics (design-build – performance warranty)
- Experience with warranty
- Historic database (warranty cost)
- Funding availability
- Limitation in initial cost

- Construction vs. maintenance budget
- Existing condition (Contractor won’t bid for poor condition with warranty)
- Limitation in owner’s staff

Question Set 2: Model Contents

Decisions

- Warranty bond amount (other than Yes / no, 10%, 50%, 100% of contract price)
- Difference bond type (A performance bond with special provision)
- Performance warranty / Material & Workmanship warranty
- Allowing sub-contractor bond (sub-contractor actually do the work)
- Usually post-construction maintenance is not a decision option (not necessary for short term standard warranty)

Drivers

- ‘Level of competition’ should be considered somewhere in the model as warranty limits many contractors bidding the project
- Difficult to acquire bond
- Limited historic data – contractor is not sure about the long-term performance and no way to assess risk
- Selection of construction method and process should be a separate drivers
- Contractor’s control on design, construction method should be included
- Existing condition is a big factor in pavement overlaying projects. It should be included somewhere in the model.

Outcomes

Other performance measures

- Risk assessment for every aspects – labor, material, existing condition
- Serviceability
- User comfort (smoothness, signs, etc)
- Safety (Skid distance, road design, signs, etc)
- Agency considers user costs also

Life cycle analysis over ten years (20 yr design life)

- Proper for asphalt pavement (Colorado contractor)
- LCC should be conducted for the whole 20 year life (Colorado DOT)
- 10 year is enough for 3-5 year warranty
- 20 years LCC for long term warranty – 10+ years

- LCC should be over 20 yrs (Wisconsin DOT)

Question Set 3: Simulation Results

Simulation Cases (5 cases)

- Reasonable
- Additional case to case comparisons
- Performance vs. M&W warranty
- New base vs. Existing base
- Thin overlay vs. thick overlay
- Various existing conditions

Simulation results graphs

- Case E seems a bit dramatic (in saving of repair cost)
- Cost increase due to warranty should be more (10% in simulation, 30% in real)
- Sometimes total agency cost is not so important (Construction money vs. maintenance money)
- Less risk for new construction (more control, no pre-existing condition)

Sensitivity Analysis

- Sensitivity of decisions and drivers are reasonable
- Sensitivity of innovation is reasonable also (Wisconsin DOT, Colorado DOT, Michigan DOT, Contractors)

Question Set 4: Model limitations

Other type of construction (concrete pavement, bridge, etc)

- Longer LCC for concrete pavement
- More flexibility in scheduling (concrete) => less risk
- Fewer concrete pavement company => lower competition
- Longer LCC for bridge (Generally)
- Bridge deck is similar to pavement
- Other project types are totally different from pavement => model should be changed

Mega Projects

- Public relationship
- Multiple material supplier => different price, different characteristics, more risk

- Difficult to supply enough equipment and labor => schedule risk

Different Decision Timing

Usual decision timing

- Proper and usual decision timing is after ‘geotech report’ and before ‘concept design’
- Usual decision timing is during project scoping
- Usual decision timing is ‘before advertise’

Warranty decision after construction

- Warranty options is researched but has not been used (consultants, DOTs)
- Warranty can be added after construction through negotiation (without option)
- Warranty can be an option to dispute (project acceptance) resolution
- It is not recommended to add warranty after construction (difficulty of negotiation, price increase, no warranty impact on process)

Possible changes over time (warranty usage become common)

- Bond issue (some think it will get better, some think it won’t)
- Contractor will have more data to assess risk (Better or worse)
- Improvement in performance measurements, testing methods
- Changes in project financing method (PPP, etc) will change warranty also.