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# Spatial model for the management of a system of infrastructure facilities

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# SPATIAL MODEL FOR THE MANAGEMENT OF A SYSTEM OF INFRASTRUCTURE FACILITIES

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# Abstract

Infrastructure asset management is an important tool that provides decision makers with optimized plans for the maintenance, repair and rehabilitation of systems of infrastructures facilities. The optimization is performed in terms of a limited budget and a pre-defined duration. The first step of this thesis was to create three optimization models. First, a standard model that fragments the asset into fractions distributed over the possible conditions to which actions are applied until the assets reach the targeted conditions over the plan's horizon and within budget. Second, was a robust model that assessed the worst case scenario by the integration of uncertainty of the deterioration of the asset. Finally, a Hurwics Criterion model that enhanced the previous models by integrating a level of optimisms to reflect realistic scenarios in which the worst case would not necessarily occur. These models were implemented in a linear and nonlinear integer technique. These models assumed that the asset can be segmented, and then grouped by percentage and assigned to a certain condition. However, in the case of continuous stretches of assets such as pavements, it was noted that this technique does not take into account the distances between the segments of the asset from one another, which was the main challenge this thesis focused on. In order to overcome this gap, a Spatial Model was developed, upgrading the available models to account for the distances. All seven models were then applied on a real case study, which is the Ring Road surrounding Greater Cairo. It was found that the linear integer models have an impact on both the duration of the optimization exercise and the goodness of the final results. Moreover, the Robust Model always gave higher expenses as opposed to the others as it customized itself for the worst case scenario. Furthermore, the Hurwics criterion model once assigned an optimism level different than zero allowed the overall expenses to decrease. Finally, the Spatial model was tested. It included a simulation that was set to give the minimum score and in order to verify the model, the mean and maximum simulations were carried out and as expected they gave higher costs. Finally all seven models were validated through 10 experts that have tested the models.

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# I- Introduction

## A. Introduction

A developed country is identified by the level of services provided by the government to the public. These services vary over a large span that includes transportation (ground, air, waterway and mass transit), water and wastewater (water supply, structures, agriculture water distribution), waste management (solid, hazardous and nuclear waste), energy (electrical, gas and petroleum production and distribution as well as nuclear power station), buildings (residential public, sports, theaters, manufacturing and hotels) and finally communication (telecommunications, television, wireless/satellite networks and information networks). The aforementioned infrastructure assets are necessary to ensure that the public receives the basic needs of a quotidian life of a modern world – a hygienic environment, easy commuting, basic education and the required energy sources.

An emerging nation's policies will always be directed toward the construction of these assets to satisfy its citizens. However, in the case of a developed country that reached saturation in the services it offers, it will be quintessential for it to ensure that these assets are maintained and provide the same level of service and function they were built for.

Maintaining an asset can be achieved through various interventions that include routine maintenances, repairs that can be either minor or major and finally through a complete reconstruction of an asset. The challenge that is usually met though by the decision makers responsible for these assets is the setting out of a plan over a specific horizon of time and a limited budget to achieve the aforementioned objective. For this the science of infrastructure asset management has grown. It is a tool through which a decision maker can identify the optimum intervention measures required to maintain a certain set of facilities (infrastructure assets) with a bounding time and budget.

The research carried out and presented in the subsequent sections is an exposé of three different infrastructure asset management models- standard, robust and Hurwics criterion models. These models are taken one step ahead in order to include uncertainties that are dependent on the costs assigned for each intervention. It was also worthy to test the implementation of the optimization process, and for that, linear and nonlinear models were developed and compared. The models developed address pavements however; they can be tailored for any system or group of facilities. They account for uncertainty factors that have an impact on the final results outputted. The thesis ends with a real case study where these models are applied on the Ring Road surrounding Cairo for further analysis of the dynamics of the model and an in depth analysis of the produced results. Following is a summarization of the different sections this report offers.

## B. Objectives

The objectives of this thesis can be summarized as enlisted below.

Objective 1: Develop infrastructure models that account for uncertainties using the standard, Robust and Hurwics Criterion approach implementing them by a linear and nonlinear technique.

Objective 2: Further develop the standard nonlinear model to account for the distances between the pavement segments that will be reconstructed.

Objective 3: Apply all the developed models on a real case study (Ring Road) for an analysis of the models effectiveness.

## C. Methodology

This section presents the strategy adopted to carry out this research work. Figure 1 at the end of this section is a flow chart that illustrates what is described in the following paragraphs.

The first step is to perform a holistic research that tracks the development of infrastructure asset management throughout the years. This step acts as a foundation to this thesis and leads to the identification of the various possible models that can be developed.

The second step would be to extract the obtained information from the literature review identifying the required inputs necessary for models generations. The aforementioned includes the form in which the *data should be collected*. It is a necessary stage that has the objective of creating an inventory where the existing assets are to be determined with all their information (conditions, geographical location, and geometric features) and composing elements. The real data is to be collected at a later stage once a real case study is under study.

Once the asset inventory is determined, a *rating system* is to be identified. In other words, the technique by which anasset will be evaluated is to be identified given that it will be at the basis of the study to come.

Following, the set of possible interventions to maintain, repair or rehabilitate the asset are identified. They are the actions that are to be taken (*condition rating*). A table of definition relating those actions to a numbering system is the objective in this case.

From the available inventory that includes each asset's history, a model is to be built to *predict the behavior of that asset* in the future. TheMarkovian method is used in this case. It is quintessential to note that the same deterioration model will be used from a year to the other, assuming that the deterioration is constant. Additionally, the movement of the asset from a condition to the other depending on the action applied will also be defined by a similar matrix of probabilities.

Once all of the above inputs are provided, the development of the *optimization model* is possible in all of its forms, namely the standard, robust and Hurwicz criterion forms. Moreover, each model will be created in a linear integer and nonlinear integer form.

The Standard model is then taken one step ahead in order to account for the impact the distances between the segments to be reconstructed has on the final outcome. In other words, a customized model that will have the objective of grouping these segments together.

The models are then applied in a real case study, the Ring Road encompassing Greater Cairo. The results of all models are extracted, analyzed and compared. The best alternative is selected, which is the *project selections and plans phase*.

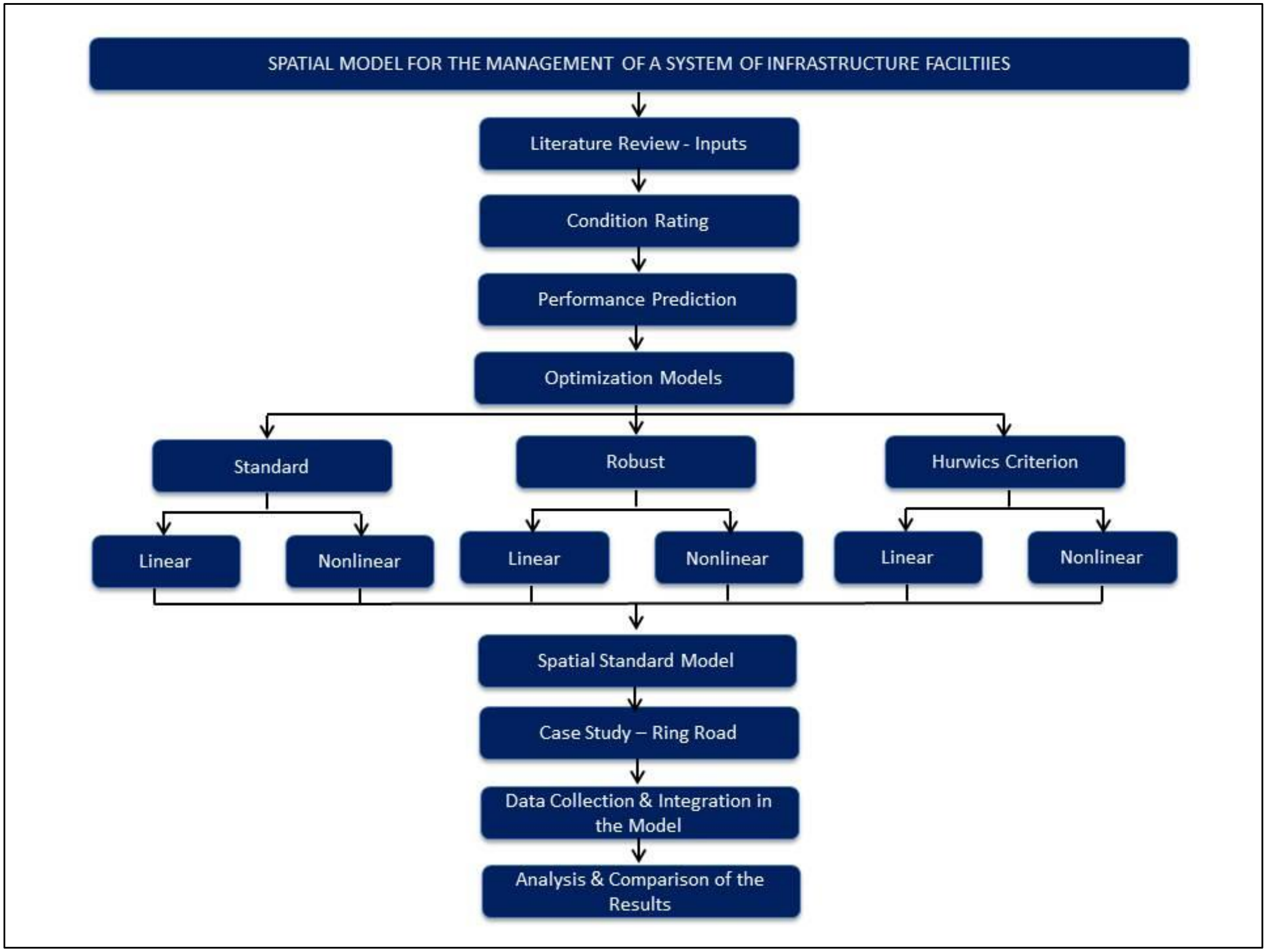



**Figure 1: Methodology Flow Chart**

## D. Thesis Structure

The thesis is divided into eight chapters as described below:

Chapter I – Introduction: This section presents a general introduction of the topic that was studied offering the basic definition of infrastructure asset management over which the rest of the research work was built followed by the objectives this thesis has and ends with the methodology that was followed to tackle the subject.

Chapter II – Literature Review: This section is a summarization of the research efforts that were carried out regarding this topic, highlighting the liaisons and research chains that have been previously done by reputable scholars acting as a foundation to this thesis works and allowing for the identification of the gaps that allows this research work to be an advancement to the previous efforts and allowing it to be a work of added value.

Chapter III – Models Development: This section presents in depth how the different models were initiated. Three out of four modules in each of the models are presented in this section. It acts as a foundation to the subsequent section

Chapter IV – Optimization Models: This section goes step by step to explain the model engines that were develop. It is in this Module that all computations and optimization take place.

Chapter V – Spatial Model: This section presents the advancement this thesis aimed to achieve. In this section are presented all the steps that were followed in order to produce the Spatial Model that accounts for the distances between the pavement segments for them to be factored in the optimization computations.

Chapter VI – Model Validation: This section presents the technique that was used in order to validate all seven models developed.

Chapter VII – Case Study: Ring Road: This section presents an application of the generated models on a real case study which is the Ring Road that surrounds Greater Cairo. The section begins with an overview of the importance of maintaining such an asset then is followed by the application of the models and the analysis and comparison of the different outcomes of the different models.

Chapter VIII – Conclusion & Recommendations: This section ends the thesis concluding the main findings of it as well as offering recommendations to future areas that can be of interests to others.

# II- Literature Review

## A. Introduction

This chapter presents the previous research work that was carried out addressing infrastructure asset management. The chapter begins with general definitions followed by researches that have been performed showing the importance of infrastructure asset management and its benefits. Subsequently, different tools of optimization and different applications of it are presented. Finally, three models that were developed to produce the infrastructure asset management plans are discussed and the gap in the research chain is presented.

## B. Definition and Objectives of Infrastructure Asset Management

Many definitions of Infrastructure asset management exist. The American Association of State Highway and transportation Officials define it as a "*systematic process of operating, maintaining, upgrading and disposing of assets cost effectively*" (AASHTO, 2011). On the other hand, Behairy (2013) defines it as cost-effective resource allocation and programming decisions.

In all cases, infrastructure asset management has mainly three objectives according to the Federal Highway Administration. First, it aims at preserving the assets as well as minimizing their whole life cost. The second objective is to operate the assets in a financially sustainable manner. Finally, infrastructure asset management provides a framework to improve the assets performance on a long term basis (FHA, n.d).

## C. Infrastructure Asset Management Benefits and Effectiveness

The State of Connecticut aiming to enhance its transportation network has encouraged its scholars to carry out researches to identify the benefits that can be generated from transportation asset management. This was done through extensive discussions of a focus group composed of most of the stakeholders that have to do with this sector (transportation department officials, citizens, engineers, etc). It was concluded that transportation asset management is key in the enhancement of this sector in specific on the condition of guaranteeing five essential aspects, namely, clarity of the overall vision and final objectives that are aimed that should be determined and extracted from the end users, a communication scheme that is unambiguous among all the responsible for the execution of a certain plan, a champion that can be identified as the decision maker that will study and implement the asset management plans developed, consistency in the application of policies, plans and projects to gain the public trust and finally comprehensiveness to ensure that all asset are accounted for and that the enhancement of the service in general is tangible to all the public (Lownes, Zofka and Pantelias, 2010).

Another study was performed for the water structures and networks given their importance that can be described in terms of distributing properly potable water to the public, preventing floods, generating electricity and ensuring a hygienic environment. This was done by studying four water utilities by implementing AWARE-P technique. The latter can described as a program that is customized for such structures and incorporates certain risks inputted by the owner of such facilities. It was concluded that by the implementation of asset management, it is possible to develop a plan that would be successful in maintaining the water structures in good serviceable conditions. Through the results obtained, it was concluded also that the revision and modification of the initial objectives can lead to better results (Cardoso, et al, 2012).

Moreover, a study has been carried out in order to examine the effectiveness of the application of infrastructure asset management. The methodology followed was to conduct a series of interviews with professionals that belong to different levels in the hierarchy of the provincial public agency in the Netherlands (road inspectors, technical managers and policy makers) along with the use of the "*policy documents, maintenance contracts, inspection reports and planning documents*" available. It was found that the effectiveness of infrastructure asset management is dependent upon the clear definition of the strategic, infrastructure and stakeholder's objectives and their proper formulation into multiple projects that take into account a set of factors that are related to specific interests (costs, safety, etc.) which all lead to the possible implementation of an operational plan that would maximize benefits with the use of the minimum resources (Schraven, Hartmann, & Dewulf, 2011).

## D. Infrastructure Asset Management Procedures

Based on the above definitions and outcomes of infrastructure asset management, it can be looked upon as an optimization exercise that in order to produce it requires some steps to be followed (Lemer, APWA International Public Works Congress, n.d.). It starts with the collection of data of the set of facilities that will be under study. The accuracy by which this step is carried out is directly reflected in the goodness of the final results (Migliaccia, 2014). Then, a condition rating system is to be determined. In other words, a tool through which the condition of a certain asset can be described based on a predefined scale as well as the possible interventions or actions that could be taken to move the asset from one condition to the other. The subsequent step is to identify the pattern by which the assets are predicted to deteriorate. The latter can span over four categories, namely, a mechanistic tool - which is used for mechanical components such as joints or any other elements that have an engineering life that is linear; second, is the regression analysis approach, which consists of the creation of an equation that can predict the behavior of an element in the future based on the available history and a striking pattern that the asset follows to deteriorate; third, is the Markovian method, which is used when there is no historical data of the elements composing an asset; however, the deterioration of the elements in the future can be predicted using a matrix of probabilities dependent on the element's current state, this matrix is raised to the power of "n" years to predict its rating condition at year "n" (Yang, 2011); and finally, the fuzzification method that is used for the elements that do not have a historical data and whose behavior cannot be predicted based on a current state, it is based on giving ranges for the condition rating of the element from which a deterioration graphical representation can be developed (Lau and Dwight, 2011). The following step would be to run the optimization model including all the parameters of the problem. Infrastructure asset management ends with the project selection and plans, which is the translation of the model outputs into real projects that should then be implemented and monitored.

## E. Modes of Failure of Pavement

Asphalt pavement is a visco-elastic material, in other words, asphalt behave differently under different temperatures and different loading. Asphalt may experience the three main modes of failure according to the environmental conditions and traffic volumes and types (Abdel Raouf, 2010).First isfatigue failure that can happen to paved asphalt. It happens due to excessive cycles of loading and unloading. Over the serviceability years of the structure and to those cycles, the strength of the materials is reduced, producing the alligator skin look alike cracks shown in Figure 2 (Castell, et al, 2000).

**Figure 2: Fatigue mode of failure**

Second, is low temperature cracking. In freezing conditions, it can be expected that asphalt may experience low temperature cracking that is transversal as shown in Figure 3 (Rajbongshi and Das, 2009).

**Figure 3: Low temperature cracking mode of failure**

This kind of cracking is always perpendicular to the longitudinal direction of the road. To make sure the asphalt available will not experience such failure, it is necessary to assess its performance and determine the lowest temperature at which it will be able to resist such failure.

Finally, rutting failure that occurs due to heavy loads on the road and due to high temperatures of the environment where the road is located. The rutting mode of failure looks as follows in Figure 4 (Ramsamooj, et al, 1998).

**Figure 4: Rutting mode of failure**

**F. Optimization Techniques**

Focusing on the optimization exercise itself, there exist two main broad categories through which such a problem can be solved: a mathematical solution (a solution that provides the ultimate optimum, however a method that is not practical to use in complex problems) and a Heuristic solution (one that uses evolutionary algorithms and reaches the near optimum solution, however a method that is practical to use in complex problems). The latter includes sub-categories such as genetic algorithms, memetic algorithms, particle swan, ant colony and shuffled frog leaping methods. All the aforementioned differ from one another based on the way the marriage between each population and another happens for the production of a new generation of solutions. However, they all have in common the following: an objective function that is to be optimized either by minimizing it, maximizing it or setting it to reach a specific value, the determination of the variables that should be shuffled to reach a solution, and finally a set of constraints that should be respected (El Beltagy, et al, 2005).

Moreover, there exist four sub-categories that fall under each one of the abovementioned optimization techniques, which are: linear, non linear, linear integer and nonlinear integer. The difference between the basic form and the integer one is the set of decisions variables. The standard form can take any value in the time that the integer one can only take the form of a rounded number (1,2,3,..,n). The other distinction is whether it is linear or nonlinear. The latter is usually defined by a set of constraints such as the “IF” function of Excel, whereas the former is a pure multiplication of matrices to one another. Linear programming has proven to be a better technique of optimization reaching a better solution in less time than the other technique (Luenberger, 2005).

## G. Challenges of Infrastructure Asset Management

It was noted though that the models of infrastructure asset management developed on any of the levels (operation, project or strategic), encountered challenges. A study was conducted with the objective of determining an optimal maintenance, repair and rehabilitation plan to a set of facilities. It was performed by the creation of an optimization model for the water industry in the United Kingdom that was analyzed in depth. It was concluded that there exist three main challenges; namely, the definition of the assets (the segmentation of an asset into its main constituents), the lack of historical data and the management of the existing uncertainties. It is important to note that these three challenges have prevented advancements of this science. All research work objectives since the introduction of this science have been to find supporting tools to overcome these challenges(Zhang & Wang, 2013).

Focusing on the last challenge- uncertainties, Madanat (1991) identified three categories of uncertainties that affect the goodness of the results obtained from infrastructure asset management and its relevant developed optimization model. The first category includes all external factors –exogenous, such as the surrounding environment impacts and the level at which an asset is used. The second set of factors is endogenous such as the design or the materials that compose the asset that will eventually lead it to behave differently one from the other when exposed to the same environment. Finally, there is the category of factors that includes statistical errors due to information that is missing.

## H. Infrastructure Asset Management Models

In order to be able to address those challenges, the progression of the research work of Madanat (1991), BenAkvial (1993), Durango (2002) and Kuhun (2006), was followed. The emphasis of the research work performed with the collaboration of several reputable scholars throughout the years has been concerned with pavement. In their early research work, BenAkiva1, Humplick and Ramaswamy (1993), it was concluded that the segmentation of this type of facility is done by unit length as there is only one element composing the asset – asphalt pavement. Moreover, the asset- in this case the multiple segments of pavement, were dealt with in terms of fractions that have a total that adds up to 1. It was quintessential then to find an appropriate scale by which the state of the pavement can be described, in other words, the previously mentioned condition rating system. Based on the nature of the asset, its conditions can range over eight predefined states that start from 1, representing a brand new pavement, to 8, representing an unusable stretch of pavement. Moreover, the set of interventions possible to maintain the asset or move it from one state to the other were identified as seven actions. Respectively from 1 to 7 the set of actions are to do nothing, do a routine maintenance, do a 1 inch overlay, do a 2 inch overlay, do a 4 inch overlay, do a 6 inch overlay and reconstruct the pavement stretch. The model runs by making the actions the variable parameters that will be given for each set of fractions at a certain condition at a specific year until the near optimum solution is reached. This work reached an infrastructure asset management plan that addressed the challenge of the segmentation of the asset.

The optimum solution in this case is translated in terms of the lowest possible summation of the agency costs and users costs. The former can be described as the money that will be paid by the government in order to carry out the actions recommended by the model, whereas, the latter is defined as "*the estimated daily cost to the traveling public resulting* *from the construction work being performed. That cost primarily refers to lost time caused by any number of conditions*" (Daniels, et al, 1999)

Durango and Madanat(2002) collaborated and took the previous research work one step further by integrating the uncertainty factors previously discussed that have an impact on the optimization model results. The uncertainties related to statistical errors were the objective of this study. To tackle this problem robust optimization was used, which is a tool that takes into account that the probabilities assigned for the asset to move from one condition to the other might not necessarily be representative of the real deterioration process of the asset. The aforementioned is due to the fact that these probabilities are originally based on experts' opinions then tuned furthermore with every newset of data that is collected of completed infrastructure asset plans. Given the previous mentioned case, the deterioration model valueswere modified from fixed to variable parameters that are allowed to vary up to an extremity that is set by the user that describes the level of uncertainty of the deterioration model that can range from 0, that represents complete certainty, to 1, that represents complete uncertainty. Based on this study and in comparison to the previous one, it was concluded that an uncertainty of at least 0.6 exits in the deterioration models. It is quintessential to note though that this model maximizes the results to reach the uncertainty level selected by the user, which can be translated into accounting for the worst case scenario where it is expected that the described uncertainties have a holistic impact on the results.

The last statement not being necessarily true and may lead to an unjustified overall expensive plan, Kuhun and Madanat (2006) worked together in order to develop a model that would account for the endogenous and exogenous uncertainties. The objective of this research study was to offer the users with a tool that balances the effects of such uncertainties; in other terms, that even if they do exist, it is expected that they will not entirely act against the assets making their deterioration reach the extreme –worst case scenario, level. This tool is labeled the Hurwicz criterion. Given that the studies are linked to one another, the previous model was used and advanced furthermore. The philosophy adopted in this case is to allow the user to enter a level of optimisms that ranges from 0, representing the most pessimistic level, to 1, representing the most optimistic level. The philosophy adopted in reaching the optimum cost is computing the costs incurred in the best and worst case scenarios and by summing the outcome of both multiplied by the weight of optimism and pessimism respectively. This study results showed that taking into account the uncertainties of the data as well as allowing the user to select the level of impact of the endogenous and exogenous factors provides eventually the most realistic management plans that automatically becomes a the most economical solution.

## I. Gap in the Chain of Research

From the previously discussed models it was noted that all of the infrastructure asset management models developed for pavement, none take into account the proximity of the stretches of pavement that will be maintained, repaired or rehabilitated. In other words, dealing with the segments as percentages regardless of their positioning and ignoring the costs incurred due to the mobilization of the equipment and site personnel presented itself as motive for this thesis.

# III- Models Development

## A. Introduction

The models created are composed of four modules each. The objective of this chapter is to present the first three modules that are common between all of them. The chapter begins with the objective that acts as a foundation to all the models and guides their development followed by the explanation of the first three modules.

## B. Models Objectives

The objective is to build an optimization model for pavements in order to identify the optimum maintenance, repairs and rehabilitations (MR&R) measures to take to ensure the set of assets are in serviceable conditions to cater to the public with a limiting funding budget and minimizing the user costs that are incurred.

## C. Module 1 -- Asset inventory

The asset inventory module includes three major information: the segment number that starts from 1 to n, the condition of the asset at year 0 that ranges from 1 to 8 and finally the total number of assets under study. Figure 5 is a snapshot of this module. This module is to be completed by the user. It is expected that an inspection team will routinely visits the assets and perform an investigation to extract this information that is then filled in this table.

| Segment ID | Current Condition |
|---|---|
| 1 | 4 |
| 2 | 4 |
| 3 | 4 |
| 4 | 4 |
| 5 | 4 |
| 6 | 4 |
| 7 | 4 |
| 8 | 4 |
| 9 | 4 |
| 10 | 4 |
| 11 | 6 |
| 12 | 6 |
| 13 | 5 |
| 14 | 5 |
| 15 | 5 |
| 16 | 5 |

| | |
|---|---|
| Total Number of sections | 401 |

**Figure 5: Module 1 – Asset Inventory**

## D. Module 2 - Condition Rating, Definitions and Costs

The second module includes two main categories of information. First are a set of definitions, namely, the condition rating system and the set of actions and their equivalent coding. The system upon which the pavement is evaluated is presented in Table 1. It can be summarized as a description of the pavement conditions from a scale of 1 to 8, with 1 illustrating a brand new stretch of pavement and 8 an unusable one. Accompanied to the aforementioned table is the set of actions that are possible to maintain, repair and rehabilitate the assets which span from doing nothing, to a series of overlaying layers of pavement until complete reconstruction of the asset (Table 2). This conditional rating system was adopted in previous researches (Kuhun and Madanat, 2006).

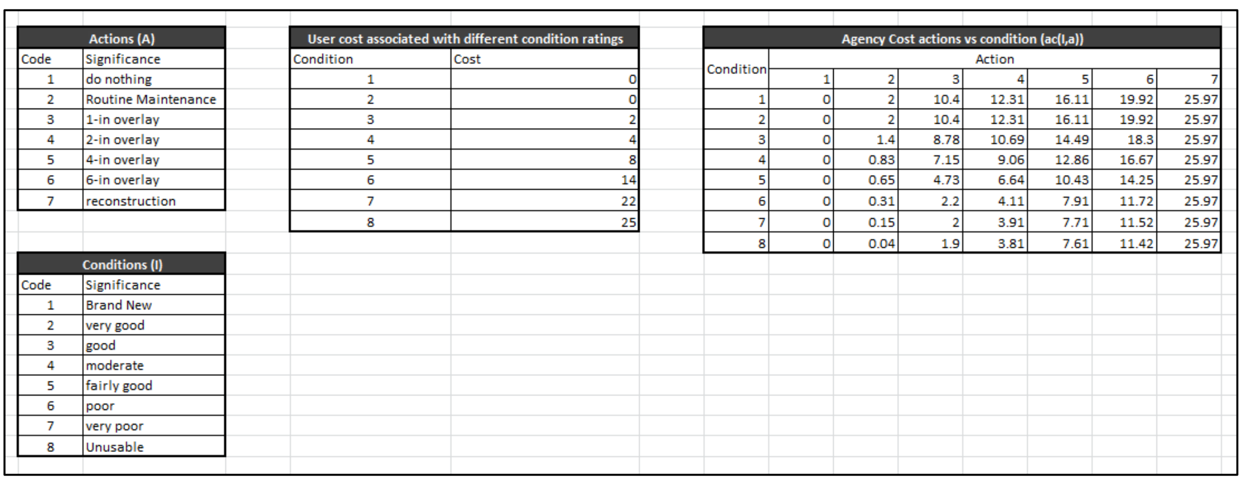
**Table 1: Condition Rating System**

| Conditions (I) | |
|---|---|
| **Code** | **Significance** |
| **1** | Brand New |
| **2** | Very Good |
| **3** | Good |
| **4** | Moderate |
| **5** | Fairly Good |
| **6** | Poor |
| **7** | Very Poor |
| **8** | Unusable |

**Table 2: MR&R Actions**

| Actions (A) | |
|---|---|
| **Code** | Significance |
| **1** | Do Nothing |
| **2** | Routine Maintenance |
| **3** | 1-in Overlay |
| **4** | 2-in Overlay |
| **5** | 4-in Overlay |
| **6** | 6-in Overlay |
| **7** | Reconstruction |

Second, are matrices that cover the financial information. The first matrix includes the user costs incurred due to the asset condition and serviceability. The figures presented are only dependent upon the condition of the asset. Then is a matrix that includes the cost incurred to carry out a certain action given the asset condition. It is important to note that this category varies from case study to the other. Figure 6 is a snapshot of this module for better illustration.



| Actions (A) | |
|---|---|
| Code | Significance |
| 1 | do nothing |
| 2 | Routine Maintenance |
| 3 | 1-in overlay |
| 4 | 2-in overlay |
| 5 | 4-in overlay |
| 6 | 6-in overlay |
| 7 | reconstruction |

| Conditions (I) | |
|---|---|
| Code | Significance |
| 1 | Brand New |
| 2 | very good |
| 3 | good |
| 4 | moderate |
| 5 | fairly good |
| 6 | poor |
| 7 | very poor |
| 8 | Unusable |

| User cost associated with different condition ratings | |
|---|---|
| Condition | Cost |
| 1 | 0 |
| 2 | 0 |
| 3 | 2 |
| 4 | 4 |
| 5 | 8 |
| 6 | 14 |
| 7 | 22 |
| 8 | 25 |

| Agency Cost actions vs condition (ac(I,a)) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Condition | Action | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 0 | 2 | 10.4 | 12.31 | 16.11 | 19.92 | 25.97 |
| 2 | 0 | 2 | 10.4 | 12.31 | 16.11 | 19.92 | 25.97 |
| 3 | 0 | 1.4 | 8.78 | 10.69 | 14.49 | 18.3 | 25.97 |
| 4 | 0 | 0.83 | 7.15 | 9.06 | 12.86 | 16.67 | 25.97 |
| 5 | 0 | 0.65 | 4.73 | 6.64 | 10.43 | 14.25 | 25.97 |
| 6 | 0 | 0.31 | 2.2 | 4.11 | 7.91 | 11.72 | 25.97 |
| 7 | 0 | 0.15 | 2 | 3.91 | 7.71 | 11.52 | 25.97 |
| 8 | 0 | 0.04 | 1.9 | 3.81 | 7.61 | 11.42 | 25.97 |

**Figure 6: Module 2 – Condition Rating, Definitions and Costs**

## E. Module 3 – Deterioration Model

In this step the probabilities are assigned for the asset to move from a condition to the other. This movement is dependent on the action taken. The first matrix, which is equivalent to performing no interventions, is set in a way that the asset can either remain in its condition or with a defined probability downgrade to the following condition. This matrix is used either as a decision for a given year or as a transition from a year to the other. On the other hand, the matrix of action 2, which is the equivalent of a routine maintenance, allows the probabilities of the asset to stay in the same condition to be higher. A graphical representation of the aforementioned along the years is provided in Figure 7. Moreover, all the repairs intervention (actions 3, 4, 5 and 6) either maintain the asset in its same conditions, upgrade it to the preceding level or with much lower probabilities downgrades it to the subsequent condition (in the case the intervention is not sufficient). The way this probability is distributed is provided in Table 3 as an example for action 4. The values presented are dummy in this case as they change from case study to the other. Finally, the matrix of probabilities of action 7, which is equivalent to reconstructing the asset, moves the asset from any condition to condition 1- brand new. What is common between all these different forms of deterioration is the fact that the expected condition of an asset in the future is dependent on its current state, which is the definition of a Markovian deterioration model. Figure 8 is a snapshot of the interface of Module 3.

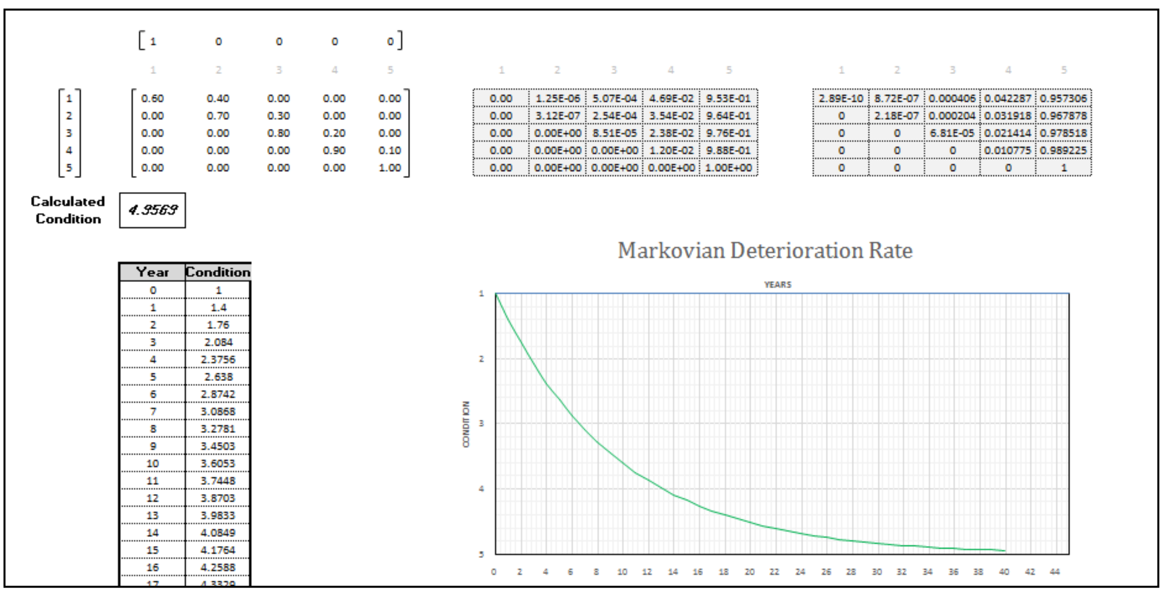



**Figure 7: Example of a Markovian Deterioration Model**

**Table 3: Markovian Deterioration Model for a Given Action**

| Action 4 = 2-in overlay | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 1 = do nothing | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.7 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 2 = Routine Maintenance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 3 = 1-in overlay | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.8 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 4 = 2-in overlay | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 5 = 4-in overlay | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 6 = 6-in overlay | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 7 = reconstruction | | | | | | | |
|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 4 | 5 | 6 | 7 | 8 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 8: Module 3 – Deterioration Model**

# IV- Optimization Models

## A. Introduction

The objective of this Chapter is to present Module 4 of each of the models developed. This module is entitled Model Engine. The computations that lead to the final results and optimum solutions take place in this module as well as the iterations of the variable parameters and the insertion of the constraints. Each of the aforementioned is unique to every model. This section ends with an overview of the implementation of these models in a linear format.

## B. Standard Optimization Model

The first step to do in order to be able to develop a model is to express its objective function and constraints into a set of equations. For the standard model, this set of equation was directly extracted from previous research work and can be listed as follows (Madanat, et al, 1993)

Objective function:

$\min_f \sum_{t=0}^{T} \alpha^t \left[\sum_{i\in I} \sum_{a\in A} t_c(i,a) f_t(i,a) N\right]$

- Constraints

(1) $\sum_{a\in A} f_0(i,a) = init_i, \qquad \forall i \in I$

(2) $f_t(i,a) \geq 0, \qquad \forall i \in I, a \in A, t \in \{0,1,\dots.T\}$

(3) $f_t(i,a) = 0, \qquad \forall i \in X, a \in A, t \in \{0,1,\dots.T\}$

(4) $\sum_{i\in I} \sum_{a\in A} f_{t-1}(i,a) p(j|i,a) = \sum_{a\in A} f_t(j,a), \qquad \forall j \in I, t \in \{1,2,\dots.T\}$

(5) $\sum_{i\in I} \sum_{a\in A} ac(i,a) f_t(i,a) N \leq b(t) \qquad \forall t \in \{0,1,\dots.T\}$

The parameters and variables used in the above equations can be summarized as *p(j|i,a)* being the probability of an asset to move from a condition (*I*) to the other at a certain year

(*T*)to the subsequent one given the application of a certain action *A*, *ac(i,a)* representing the repair costs that will be incurred given the application of a certain action, *tc(i,a)* representing both the repair costs incurred and the user cost due to the application of a certain action in a certain condition, *b(t)* representing the total budget available, $\alpha$ being a factor that brings the monetary value of different years to the present worth, $init_i$ representing the initial conditions of all the facilities, *X* being arbitrary conditions that are set by the user depending on the decision makers objectives to limit the model not to allow for certain states and finally $f_t(i,a)$ representing the fraction of facilities that will move to a certain state at a given year due to the application of a certain action. The model runs by making the actions the variable parameters that will be given for each set of fractions at a certain condition at a specific year until the near optimum solution is reached.

Figure 9 is a snapshot of this module that shows all the elements that it includes that is described hereafter.

The model engine is divided into three main parts. First is a table that is divided into five years, that exhibits the horizon of applicability of this model. The table is divided into ten columns (numbered as shown in Figure 5), the below list is an in depth explanation of the aforementioned.

- Column 1 gives the years (T) that are under study, in this case 5 years. This column is constant at all times.
- Column 2 provides all the possible conditions (I) an asset can be assigned to, they range as previously discussed from 1 to 8. This column is constant at all times.
- Column 3 presents the fractions of facilities ($f_t(i,a)$) that belong to a certain condition at a given year. In the first year the fractions are obtained from the asset inventory by a simple equation: $\frac{Number\ of\ Assets\ at\ condition\ I\ at\ Year\ 0}{Total\ Number\ of\ Assets}$. In the successive years- 2, 3, 4 and 5, the fractions account for both the impact of the actions taken at the preceding year (either by deteriorating more, being maintained or upgrading to a better condition) and the effect of a year passing since the implementation of that action (which follows the deterioration model of

action 1- doing nothing, that leads the asset to either maintain its condition or downgrade to the subsequent one).

| Year | Condition | Fraction 1 | Fraction 1 Check | Action | Fraction 2 | Fraction 2 check | User Cost | Agency cost | Total Costs |
|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 1 | 1 | 0.000 | 1 | - | 0.000 | 1 | 0 | 0 | 0 |
| | 2 | 0.000 | | - | 0.000 | | 0 | 0 | 0 |
| | 3 | 0.000 | | - | 0.000 | | 0 | 0 | 0 |
| | 4 | 0.025 | | 1 | 0.015 | | 42000 | 0 | 42000 |
| | 5 | 0.945 | | 1 | 0.483 | | 3183600 | 0 | 3183600 |
| | 6 | 0.030 | | 1 | 0.485 | | 176400 | 0 | 176400 |
| | 7 | 0.000 | | - | 0.018 | | 0 | 0 | 0 |
| | 8 | 0.000 | | - | 0.000 | | 0 | 0 | 0 |
| 2 | 1 | 0.000 | 1 | - | 0.309 | 1 | 0 | 0 | 0 |
| | 2 | 0.000 | | - | 0.000 | | 0 | 0 | 0 |
| | 3 | 0.000 | | - | 0.004 | | 0 | 0 | 0 |
| | 4 | 0.009 | | 4 | 0.004 | | 15120 | 50198 | 65318 |
| | 5 | 0.247 | | 1 | 0.125 | | 832860 | 0 | 832860 |
| | 6 | 0.435 | | 1 | 0.298 | | 2564709 | 0 | 2564709 |
| | 7 | 0.296 | | 7 | 0.261 | | 2742894 | 6475723 | 9218617 |
| | 8 | 0.013 | | 7 | 0.000 | | 132300 | 274866 | 407166 |
| 3 | 1 | 0.278 | 1 | 1 | 0.690 | 1 | 0 | 0 | 0 |
| | 2 | 0.031 | | 2 | 0.057 | | 0 | 3899 | 3899 |
| | 3 | 0.003 | | 3 | 0.006 | | 2646 | 5821 | 8467 |
| | 4 | 0.004 | | 4 | 0.002 | | 5897 | 19577 | 25474 |
| | 5 | 0.064 | | 1 | 0.032 | | 214565 | 0 | 214565 |
| | 6 | 0.181 | | 1 | 0.104 | | 1068877 | 0 | 1068877 |
| | 7 | 0.257 | | 7 | 0.109 | | 2379817 | 5618533 | 7998350 |
| | 8 | 0.183 | | 7 | 0.000 | | 1923532 | 3996330 | 5919861 |
| 4 | 1 | 0.621 | 1 | 1 | 0.730 | 1 | 0 | 0 | 0 |
| | 2 | 0.115 | | 2 | 0.173 | | 0 | 14485 | 14485 |
| | 3 | 0.016 | | 3 | 0.019 | | 13215 | 29072 | 42287 |
| | 4 | 0.003 | | 5 | 0.011 | | 4812 | 25094 | 29906 |
| | 5 | 0.017 | | 5 | 0.007 | | 56541 | 181780 | 238322 |
| | 6 | 0.058 | | 1 | 0.025 | | 341022 | 0 | 341022 |
| | 7 | 0.095 | | 7 | 0.035 | | 882475 | 2083443 | 2965918 |
| | 8 | 0.076 | | 7 | 0.000 | | 801658 | 1665524 | 2467181 |
| 5 | 1 | 0.657 | 1 | 1 | 0.641 | 1 | 0 | 0 | 0 |
| | 2 | 0.212 | | 2 | 0.256 | | 0 | 26716 | 26716 |
| | 3 | 0.048 | | 1 | 0.055 | | 40291 | 0 | 40291 |
| | 4 | 0.013 | | 2 | 0.026 | | 21054 | 6842 | 27896 |
| | 5 | 0.008 | | 4 | 0.014 | | 27137 | 61465 | 88602 |
| | 6 | 0.013 | | 6 | 0.006 | | 79153 | 206929 | 286082 |
| | 7 | 0.025 | | 7 | 0.001 | | 234404 | 553407 | 787811 |
| | 8 | 0.024 | | 7 | 0.000 | | 255767 | 531381 | 787148 |

| Budget |
|---|
| 25,000,000 |

| Agency Cost |
|---|
| 21,831,088 |

| Total Cost |
|---|
| 39,873,834 |

- Minimize the total cost.
- Initial conditions are known.
- All fractions should be positive
- The folowing fractions should equal to zero:
(1) condition 8 year 2,
(2)condition 8 year 3,
(3)condition 8 year 4,
(4)conditions 8 year 5.
- At year 5, condition 1 should have at least 0.5 of the segments
- Action 7 can only be used in conditions 7 and 8
- The sum of all fractions after optimization each year should equal 1.
- The total agency cost should range between the budget and 80% of it

**Figure 9: Module 4 – Model Engine**

- Column 4 sums all the fractions distributed over the different conditions at each year. The sum should always add up to 1 in order to ensure that it accounts for all the assets in the study. Both columns 3 and 4 for the first year addresses the first constraint, namely, (1) $\sum_{a \in A} f_0(i,a) = init_i, \ \forall i \in I$, which depicts that all the conditions of the asset at the first year are known.
- Column 5 is the set of variable parameters, namely, the actions (A) that can range from 1 to 7 as previously described. The model will try different populations of actions until the most optimum is reached based on a set of constraints that are explained further below.

- Column 6 redistributes the fraction on the different conditions depending on the action taken at a given year based on the deterioration models previously explained.
- Column 7 is provided only to check that the addition of all the fractions of column 6 add to 1, in other words all the facilities are accounted for. Column 4 and 7 together address constraint(4) $\sum_{i\in I}\sum_{a\in A} f_{t-1}(i,a)p(j|i,a) = \sum_{a\in A} f_t(j,a), \forall j \in I, t \in \{1,2, \dots . T\}$, which ensures that all the assets are accounted for and take part in the optimization process after being multiplied by probabilities in the deterioration model- module 3.
- Column 8 calculates the user cost based on the matrix given in Figure 3. What happens is that the model looks for the condition at which it stands and multiplies the relevant user costs to the fraction of facilities in this condition as well as the total number of facilities N to obtain the representative figure in a certain currency per unit length.
- Column 9 computes the agency cost based on the matrix given in Figure 3. What the model does is that it looks for both the condition at which it stands as well as the action that has been found as an optimum one (for each single row) and looks for the equivalent repair costs in the matrix in module 2 that it multiplies to the fraction of assets and the total number of assets to obtain the representative figure in a certain currency per unit length ($ac(i,a)f_t(i,a)N$).
- Column 10 is an addition of column 8 and 9 to obtain the total incurred costs ($t_c(i,a)f_t(i,a)N$).

The model engine –i.e. the table previously described, should meet the requirements stated in the equations provided in the beginning of this section. Therefore, the two other parts of this module are provided. Part two includes the total budget available (*b(t)*) that can be modified by the user according to the case under study as well as the total user and agency costs that will be incurred that needs to minimized (objective function: $\min_f \sum_{t=0}^{T} \alpha^t \left[\sum_{i\in I}\sum_{a\in A} t_c(i,a)f_t(i,a)N\right]$) and the total agency cost that should be equivalent to the budget. Equation (5) requires the total agency cost to be smaller than the budget, however in real life, agencies will always try to spend the available funds they receive in order to ensure a continuous flow of funds in the subsequent years and therefore, in this model this equation has been modified to: (5) $(b(t)x\,0.85) \leq \sum_{i \in I} \sum_{a \in A} ac(i,a) f_t(i,a) N \leq b(t) \quad \forall t \in \{0,1,\ldots.T\}$. Therefore, the total agency cost can't exceed the budget and cannot be smaller than 85% of it.

Finally the third part enlists all the constraints and objective function of the model. Most of them were addressed in the previous description but two- constraint 3 and 4. These constraints appear in the optimization tool used such as EVOLVER, where all the fractions are not allowed to take negative value ((2) $f_t(i,a) \geq 0,\ \forall i \in I, a \in A, t \in \{0,1,\ldots.T\}$) and a set of arbitrary conditions that are not allowed to occur have been set ((3) $f_t(i,a) = 0, \forall i \in X, a \in A, t \in \{0,1,\ldots.T\}$). Those conditions can be enlisted as below:

- The following fractions should equal to zero in order to ensure that at the end of the five years horizon none of the assets will be unusable:
    - Condition 8 at year 2,
    - Conditions 8 at year 3,
    - Conditions 8 at year 4,
    - Conditions 8 at year 5.
- Action 7 can only be used in conditions 7 and 8
- At least half of the segments should have a condition of 1 at year 5.

## C. Robust Optimization Model

The development of this model was basically the advancement of the standard one. Everything is identical but some changes in module 3 and 4 that translate the new set of constraints and variable parameters extracted from previous research work of Durango and Madanat (2002). The philosophy is that the probabilities assigned in the deterioration model are not necessarily correct and can be modified up to a certain bound selected by the users, the uncertainty level. In this case the parameter *p(j|i,a)* was modified from a fixed to a variable one that is allowed to vary up to an extremity that is set by the user that describes the level of uncertainty of the deterioration model that can range from 0, that represents complete certainty, to 1, that represents complete uncertainty. This new parameter is labeled δ. The initial probabilities assigned for the deterioration of the asset from which the $p(j|i,a)$ are going to be compared were labeled $q(j|i,a)$. The same model that was used in the previous model was applicable in this case but with a different objective function and three newly added constraints as shown in the below equations directly extracted from this study.

- Objective function:

$\min_f [\max_p \sum_{t=0}^{T} \alpha^t \ [\sum_{i \in I} \sum_{a \in A} t_c(i,a) f_t(i,a) N]$

- Constraints

(1) $\sum_{a \in A} f_0(i,a) = init_i, \qquad \forall i \in I$

(2) $f_t(i,a) \geq 0, \qquad \forall i \in I, a \in A, t \ \in \{0,1, \dots .T\}$

(3) $f_t(i,a) = \ 0, \qquad \forall i \in X, a \in A, t \ \in \{0,1, \dots .T\}$

(4) $\sum_{i \in I} \sum_{a \in A} f_{t-1}(i,a) p(j|i,a) = \ \sum_{a \in A} f_t(j,a), \qquad \forall j \in I, t \ \in \{1,2, \dots .T\}$

(5) $\sum_{i \in I} \sum_{a \in A} ac(i,a) f_t(i,a) N \leq \ b(t) \qquad \forall t \ \in \{0,1, \dots .T\}$

(6) $p(j|i,a) \geq 0, \qquad \forall i \in I, a \in A, j \in I$

(7) $\sum_{j \in I} p(j|i,a) = 1, \qquad \forall i \ \in I, a \in A$

(8) $|p(j|i,a) - q(j|i,a)| \leq \delta, \qquad \forall i \in I, a \in A, j \in I$

This was translated by changing module 3 as shown in Figure 10.

The initial assumptions of the deterioration of asphalt were maintained in a table that is constant at all times of the process of the optimization, which is the first table that is equivalent to the parameter $q(j|i,a)$. Then a second table was developed that represents the parameter $p(j|i,a)$, which in this case is a variable parameter. During optimization, the values of this second table are the one used in module 4- model engine, to compute the fractions at each year and condition. These parameters can vary from $q(j|i,a)$ by a certain percentage entered by the user depending on his level of confidence of the deterioration model. It can range between 0 and 1. In order to ensure that this arbitrary limit is respected, the third table was provided, which computes the absolute difference of $p(j|i,a)$and $q(j|i,a)$. The first constraint entered in the optimization tool is that the probabilities in the second table cannot take a negative value, respecting equation(6) ($p(j|i,a) \geq 0, \forall i \in I, a \in A, j \in I$). Second, the probabilities in each row should have a total value of 1, respecting equation (7) ($\sum_{j \in I} p(j|i,a) = 1, \ \forall i \ \in I, a \in A$). Finally, the third table is constrained to have values that do not exceed the uncertainty level entered by the user in order to respect equation (8) ($|p(j|i,a) - q(j|i,a)| \leq \delta, \forall i \in I, a \in A, j \in I$).

Once those constraints are expressed in module 3, the optimization model can be run. In this case, the actions (A) of module 4 and the probabilities of module 3 will vary until the optimal solution is reached which is expressed by the objective function $\min_f[\max_p \sum_{t=0}^{T} \alpha^t \ [\sum_{i \in I} \sum_{a \in A} t_c(i,a) f_t(i,a) N]$. What happens in this case is that due to the constraints entered for module 3, the probabilities $p(j|i,a)$will change to reach that set uncertainty level. The MAXMIN objective function is translated in the model by minimizing the computation of the sums of the costs and maximizing the final output.

| UNCETAINITY LEVEL |
|---|
| 0.3 |

INITIAL ASUMMED DETERIORATION

| | Action 1 | | | | | | | | Action 2 | | | | | | | | Action 3 | | | | | | | | Action 4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| onditic | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.8 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.2 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

VARIABLE PARAMATERS

| | Action 1 | | | | | | | | Action 2 | | | | | | | | Action 3 | | | | | | | | Action 4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| onditic | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.8 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.2 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

Difference

ABSOLUTE DIFFERENCE

| | Action 1 | | | | | | | | Action 2 | | | | | | | | Action 3 | | | | | | | | Action 4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| onditic | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 10: Module 3 of the Robust Model**

**D. Hurwicz Criterion Model**

Once again, this model is the advancement of the preceding one. Everything is identical but some changes in modules 3 and 4 as well. The philosophy adopted in this case is to allow the user to enter a level of optimisms labeled β that ranges from 0, representing the most pessimistic level, to 1, representing the most optimistic level. In order to develop a workable model given the new objectives, a set of new parameters was introduced, namely, $p_b(j|i,a)$ and $p_w(j|i,a)$ that respectively represent the best and worst deterioration possible for a specific asset. Moreover, new parameters were introduced which are the fractions of the assets at each of these conditions- best and worst, respectively, $f_b(i,a)$ and $f_w(i,a)$. The philosophy adopted in reaching the optimum cost is by summing the effects of the worst and best conditions depending on the selected level of optimism. The following objective function and constraints are directly extracted from previous research work and illustrates the aforementioned description (Kuhun and Madanat, 2006)

- Objective function:

$$\text{Max}_{pw}\text{min}_{pb}\text{min}_f \sum_{i\in I}\sum_{a\in A} t_c(i,a)f_0(i,a)N + \alpha[\beta t_c(i,a)f_{1b}(i,a)N + (1-\beta)t_c(i,a)f_{1w}(i,a)N]$$

- Constraints

(1) $\sum_{a\in A} f_0(i,a) = init_i, \quad \forall i \in I$

(2) $f_t(i,a) \geq 0, \quad \forall i \in I, a \in A, t \in \{0,1,\dots.T\}$

(3) $f_t(i,a) = 0, \quad \forall i \in X, a \in A, t \in \{0,1,\dots.T\}$

(4.1) $\sum_{i\in I}\sum_{a\in A} f_0(i,a)p_b(j|i,a) = \sum_{a\in A} f_{1b}(j,a), \quad \forall j \in I$

(4.2) $\sum_{i\in I}\sum_{a\in A} f_0(i,a)p_w(j|i,a) = \sum_{a\in A} f_{1w}(j,a), \quad \forall j \in I$

(6.1) $p_b(j|i,a) \geq 0, \quad \forall i \in I, a \in A, j \in I$

(6.2) $p_w(j|i,a) \geq 0, \quad \forall i \in I, a \in A, j \in I$

(7.1) $\sum_{j\in I} p_b(j|i,a) = 1, \quad \forall i \in I, a \in A$

(7.2) $\sum_{j\in I} p_w(j|i,a) = 1, \quad \forall i \in I, a \in A$

(8.1) $|p_b(j|i,a) - q(j|i,a)| \leq \delta, \qquad \forall i \in I, a \in A, j \in I$

(8.2) $|p_w(j|i,a) - q(j|i,a)| \leq \delta, \qquad \forall i \in I, a \in A, j \in I$

In the model engine, a new set of columns was inserted and they are presented in the snapshot of the module hereunder in figure 11.

| Year | Condition | Fraction 1 | Fraction 1 Check | Action | Fraction 2 (worst) | Fraction 2 worst check | Fraction 1 (Best) | Fraction 1 Best Check | Fraction 2 (Best) | Fraction 2 best check | User Cost | Agency cost | Total Costs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (11) | (12) | (13) | (14) | (8) | (9) | (10) |
| 1 | 1 | 0 | 1 | 4 | 0.000000 | 1 | 0.000 | 1.00 | 0.000 | 1.00 | 0 | 0 | 0 |
| | 2 | 0 | | 3 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 3 | 0 | | 3 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 4 | 0.024937656 | | 2 | 0.017456 | | 0.025 | | 0.017 | | 168000 | 27300 | 195300 |
| | 5 | 0.945137157 | | 1 | 0.480050 | | 0.945 | | 0.480 | | 12734400 | 0 | 12734400 |
| | 6 | 0.029925187 | | 1 | 0.484539 | | 0.030 | | 0.485 | | 705600 | 0 | 705600 |
| | 7 | 0 | | 3 | 0.017955 | | 0.000 | | 0.018 | | 0 | 0 | 0 |
| | 8 | 0 | | 3 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| 2 | 1 | 0 | 1 | 1 | 0.308678 | 1 | 0.000 | 1.000 | 0.309 | 1.00 | 0 | 0 | 0 |
| | 2 | 0 | | 2 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 3 | 0 | | 1 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 4 | 0.010473815 | | 1 | 0.105087 | | 0.010 | | 0.105 | | 70560 | 0 | 70560 |
| | 5 | 0.247007481 | | 4 | 0.214461 | | 0.247 | | 0.214 | | 3328080 | 3769050.6 | 7097130.6 |
| | 6 | 0.433840399 | | 3 | 0.328389 | | 0.434 | | 0.328 | | 10229436 | 6415317.7 | 16644754 |
| | 7 | 0.296109726 | | 7 | 0.043384 | | 0.296 | | 0.043 | | 10971576 | 12951447 | 23923023 |
| | 8 | 0.012568579 | | 7 | 0.000000 | | 0.013 | | 0.000 | | 529200 | 549732.96 | 1078933 |
| 3 | 1 | 0.277810474 | 1 | 1 | 0.250029 | 1 | 0.278 | 1.000 | 0.250 | 1.00 | 0 | 0 | 0 |
| | 2 | 0.03086783 | | 1 | 0.052475 | | 0.031 | | 0.052 | | 0 | 0 | 0 |
| | 3 | 0 | | 1 | 0.031395 | | 0.000 | | 0.031 | | 0 | 0 | 0 |
| | 4 | 0.063052369 | | 3 | 0.091232 | | 0.063 | | 0.091 | | 424771.2 | 502291.94 | 927063.14 |
| | 5 | 0.149265586 | | 4 | 0.080938 | | 0.149 | | 0.081 | | 2011144.8 | 2277621.5 | 4288766.3 |
| | 6 | 0.238586284 | | 1 | 0.110361 | | 0.239 | | 0.110 | | 5625578.28 | 0 | 5625578.3 |
| | 7 | 0.210048628 | | 1 | 0.206166 | | 0.210 | | 0.206 | | 7782805.8 | 0 | 7782805.8 |
| | 8 | 0.030368828 | | 1 | 0.177403 | | 0.030 | | 0.177 | | 1278679.5 | 0 | 1278679.5 |
| 4 | 1 | 0.225026484 | 1 | 1 | 0.652310 | 1 | 0.225 | 1.000 | 0.652 | 1.00 | 0 | 0 | 0 |
| | 2 | 0.066983192 | | 1 | 0.076089 | | 0.067 | | 0.076 | | 0 | 0 | 0 |
| | 3 | 0.032471222 | | 1 | 0.061790 | | 0.032 | | 0.062 | | 109376.064 | 0 | 109376.06 |
| | 4 | 0.064157805 | | 3 | 0.072605 | | 0.064 | | 0.073 | | 432218.304 | 511098.14 | 943316.45 |
| | 5 | 0.076961983 | | 4 | 0.070281 | | 0.077 | | 0.070 | | 1036954.97 | 1174351.5 | 2211306.5 |
| | 6 | 0.084613444 | | 4 | 0.058464 | | 0.085 | | 0.058 | | 1995083.47 | 1523388.7 | 3518472.2 |
| | 7 | 0.128066551 | | 7 | 0.008461 | | 0.128 | | 0.008 | | 4745173.08 | 5601461.1 | 10346634 |
| | 8 | 0.321719319 | | 7 | 0.000000 | | 0.322 | | 0.000 | | 13545991.9 | 14071576 | 27617568 |
| 5 | 1 | 0.587078735 | 1 | 1 | 0.528371 | 1 | 0.587 | 1.000 | 0.528 | 1.00 | 0 | 0 | 0 |
| | 2 | 0.126102332 | | 1 | 0.159590 | | 0.126 | | 0.160 | | 0 | 0 | 0 |
| | 3 | 0.058470572 | | 1 | 0.090990 | | 0.058 | | 0.091 | | 196952.273 | 0 | 196952.27 |
| | 4 | 0.062099922 | | 3 | 0.074264 | | 0.062 | | 0.074 | | 418354.756 | 494704.5 | 913059.25 |
| | 5 | 0.064182427 | | 4 | 0.038301 | | 0.064 | | 0.038 | | 864768.354 | 979350.16 | 1844118.5 |
| | 6 | 0.058526108 | | 1 | 0.029829 | | 0.059 | | 0.030 | | 1379975.4 | 0 | 1379975.4 |
| | 7 | 0.037616962 | | 1 | 0.046401 | | 0.038 | | 0.046 | | 1393798.73 | 0 | 1393798.7 |
| | 8 | 0.005922941 | | 1 | 0.032255 | | 0.006 | | 0.032 | | 249385.434 | 0 | 249385.43 |

**Figure 11: Module 4 of the Hurwicz Criterion Model**

The four newly added columns can be described as enlisted below.

- Column 11computes the fractions of assets from year to year before the implementation of an action following the "best" deterioration model, which is in this case the initial set of transition probabilities that were added in module 3 for the model engine to read from it.
- Column 12 is to check that the addition of these fractions each year gives a total of 1 to ensure all the segments were accounted for.

- Column 13 computes the fractions of assets at a certain condition when a certain action is implemented using the "best" deterioration model.
- Column 14 is the summation of the fractions of column 13 each year to make sure they add up to 1 and that all assets are accounted for.

Columns 12 and 14 allow for the integration of constraints (4.1) and (4.2) respectively, $\sum_{i\in I}\sum_{a\in A} f_0(i,a)p_b(j|i,a) = \sum_{a\in A} f_{1b}(j,a),\ \forall j \in I$ and $\sum_{i\in I}\sum_{a\in A} f_0(i,a)p_w(j|i,a) = \sum_{a\in A} f_{1w}(j,a),\ \forall j \in I.$

In module 3, the transition probabilities were constraint in Evolver to account for equation (6.1) $p_b(j|i,a) \geq 0,\ \forall i \in I, a \in A, j \in I$, (6.2) $p_w(j|i,a) \geq 0,\ \forall i \in I, a \in A, j \in I$, (7.1) $\sum_{j\in I} p_b(j|i,a) = 1, \forall i \in I, a \in A$ and (7.2) $\sum_{j\in I} p_w(j|i,a) = 1, \quad \forall i \in I, a \in A.$ All of the aforementioned ensures that the probabilities always have positive values and that that the distribution of probabilities of each condition over the others adds up to 1- otherwise, the deterioration model will not be correct and not all possibilities of the movement of an asset from a condition to the other will be accounted for.

The last constraint that was integrated in the model is to forbid the probability matrices to deviate for more than the entered uncertainty level (which is similar to what was performed in the Robust optimization model). For the worst case, equation (8.2) $|p_w(j|i,a) - q(j|i,a)| \leq \delta,\ \forall i \in I, a \in A, j \in I$ was followed as for the best conditions, equation (8.1) $|p_b(j|i,a) - q(j|i,a)| \leq \delta,\ \forall i \in I, a \in A, j \in I$ was followed. It is known that the latter will always be equal to zero given the made assumption that the best conditions are the same as the initial deterioration model.

Finally to run the model, the following objective function was used.

$$\text{Max}_{pw}\text{min}_{pb}\text{min}_{f}\sum_{i\in I}\sum_{a\in A} t_c(i,a)f_0(i,a)N + \alpha[\beta t_c(i,a)f_b(i,a)N + (1-\beta)t_c(i,a)f_w(i,a)N]$$

What happens in this case is that due to the constraints entered for module 3, the probabilities $p_w(j|i,a)$ will change to reach that set uncertainty level. The MAXMINMIN objective function is translated in the model by minimizing the computation of the sums of the costs and maximizing the final output. However, in this case the sum of the costs is not straight forward as it combines the multiplication of the total cost incurred, if the best deterioration model is used, to the $\beta$ factor, which represents the optimism level as described previously and the multiplication of the cost incurred in the case the worst deterioration model is used to the remaining portion of the total optimism level- 1. This equation ensures that both impacts of the best and worst conditions are accounted for.

## E. Linear and Non Linear Implementation

For the first three models – standard, robust and Hurwics criterion, three other relevant models were developed; however, these models are linear. The difference between both the linear and non-linear models is in the expression of the calculations to be performed. In the non-linear models, functions such as “IF, COUNTIF, etc” are usually used, which are functions that add constraints to the calculation that should take place. As extracted from the literature review, the aforementioned technique supposedly prologues the optimization time. On the other hand, the linear model is mainly the multiplication and addition of the matrices to one another. Therefore, based on the aforementioned, the linear models were developed in order to test whether it has an impact on the results and optimization time or not.

The first step was to change the interface of the data inventory module as the condition of each segment had to be translated into two matrices. The first one being all the possible conditions for an asset to be in and the second matrix is a set of 0 and 1. Figure 12 hereunder is a snapshot of the aforementioned.

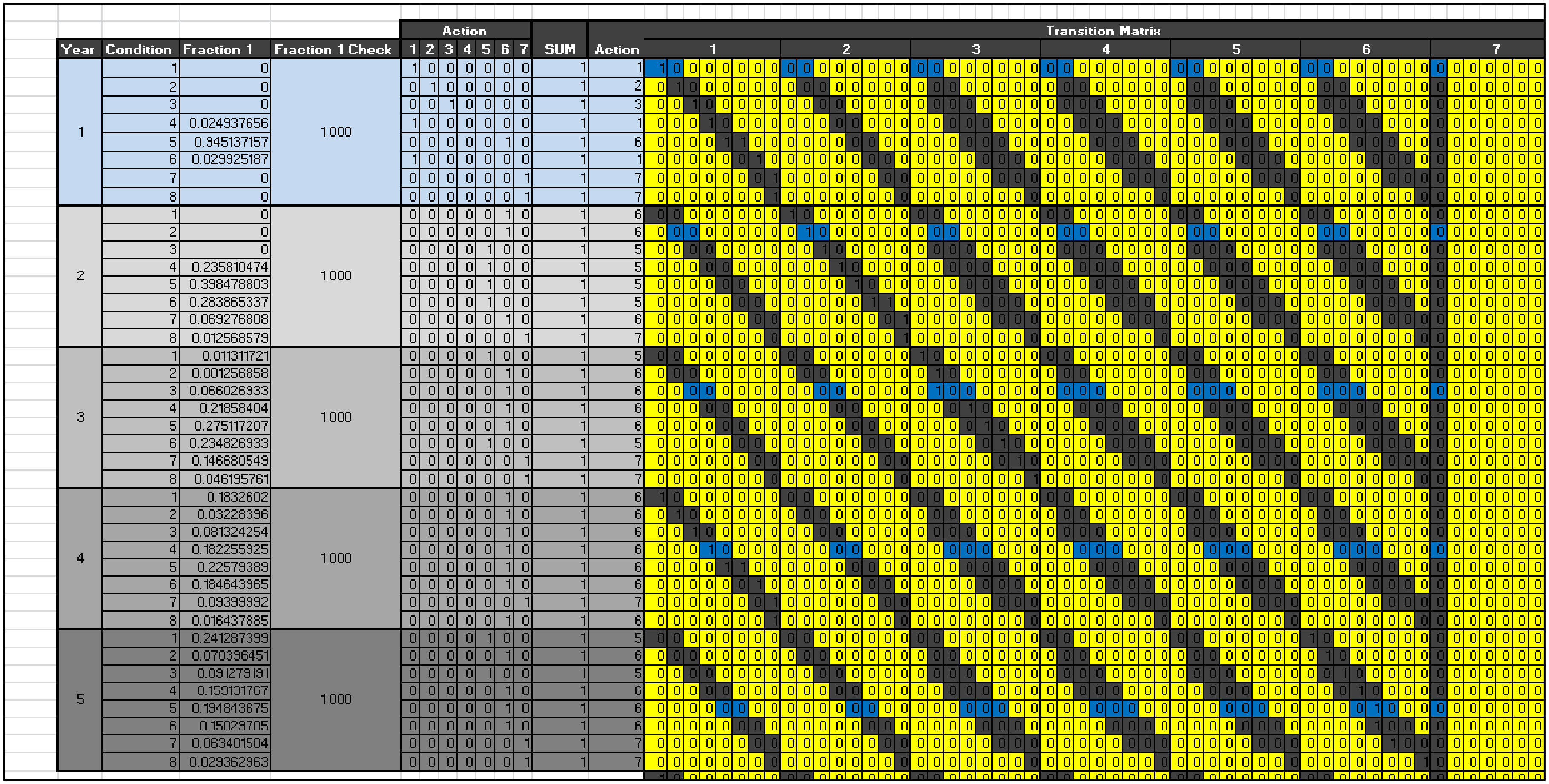
| Segment ID | Cond. 1 | Cond. 2 | Cond. 3 | Cond. 4 | Cond. 5 | Cond. 6 | Cond. 7 | Cond. 8 |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |

| | |
|---|---|
| Total Number of sections | 401 |

**Figure 12: Module 1 of the Standard Linear Model**

This allows for the summation of the number of segments at a certain condition and the total number of segments without the use of equations such as “COUNT” and “COUNTIF”

As for module 4, the following snapshot shows the configuration in which it was modeled for an initial illustration that is followed by its description (Figure 13).



| Year | Condition | Fraction 1 | Fraction 1 Check | Action 1 | 2 | 3 | 4 | 5 | 6 | 7 | SUM | Action |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 1.000 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| | 2 | 0 | | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| | 3 | 0 | | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 3 |
| | 4 | 0.024937656 | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| | 5 | 0.945137157 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 6 | 0.029925187 | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| | 7 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 |
| | 8 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 |
| 2 | 1 | 0 | 1.000 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 2 | 0 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 3 | 0 | | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| | 4 | 0.235810474 | | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| | 5 | 0.398478803 | | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| | 6 | 0.283865337 | | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| | 7 | 0.069276808 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 8 | 0.012568579 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 |
| 3 | 1 | 0.011311721 | 1.000 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| | 2 | 0.001256858 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 3 | 0.066026933 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 4 | 0.21858404 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 5 | 0.275117207 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 6 | 0.234826933 | | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| | 7 | 0.146680549 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 |
| | 8 | 0.046195761 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 |
| 4 | 1 | 0.1832602 | 1.000 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 2 | 0.03228396 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 3 | 0.081324254 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 4 | 0.182255925 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 5 | 0.22579389 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 6 | 0.184643965 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 7 | 0.09399992 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 |
| | 8 | 0.016437885 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| 5 | 1 | 0.241287399 | 1.000 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| | 2 | 0.070396451 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 3 | 0.091279191 | | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| | 4 | 0.159131767 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 5 | 0.194843675 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 6 | 0.15029705 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 6 |
| | 7 | 0.063401504 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 |
| | 8 | 0.029362963 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 |

**Figure 13: Module 4 of the Standard Linear Model**

As depicted from Figure 13, the actions now cannot vary from 1 to 7 as was previously done in the precedent models; however, matrices were created for the set of variables to be either 0 or 1. The multiplication of the aforementioned matrix to the matrix of possible actions gives the action number. The former matrix is also used to be multiplied by the deterioration models in module 3, which eventually gives the right hand side of Figure 13 –which is explained into details later on, which is a customized deterioration model for a certain condition at a given year, all the matrices of actions that have not been selected give zeros, while the deterioration matrix of the selected action shows the probabilities to be used. The latter is then fed into the subsequent columns to give the fractions distributions over the conditions after the performance of the action. In this case the addition of all possible fraction movements was added to one another noting that each time only the relevant deterioration model was going to have an impact as the others would give a value of zero. Moreover, the action matrix (made of 0 and 1) was multiplied to the agency costs (by feeding each condition with it applicable matrix of costs) then multiplied to the fraction of assets and total number of assets to give the final cost.

Module 3 had to be modified then in order to suit this new model engine. It was necessary to give the complete set of deterioration models of all the seven actions to each condition at each year. This is due to the fact that each set of transition probabilities was equipped was a matrix that reads the action selected in the model engine, multiplies it to the complete set of deterioration models and produces the right hand side of figure 13 as previously stated. A snapshot of module 3 is shown in Figure 14 for better illustration.

The abovementioned concept and modifications were adopted and implemented in the generation of the Robust and Hurwics Criterion models.

**CONDITION 1 - Year 1**

| | Action 1 | | | | | | | | Action 2 | | | | | | | | Action 3 | | | | | | | | Action 4 | | | | | | | | Action 5 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 |
| 1 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 |
| 2 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.8 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

**CONDITION 2 - Year 1**

| | Action 1 | | | | | | | | Action 2 | | | | | | | | Action 3 | | | | | | | | Action 4 | | | | | | | | Action 5 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 |
| 1 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 |
| 2 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.8 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

**CONDITION 3 - Year 1**

| | Action 1 | | | | | | | | Action 2 | | | | | | | | Action 3 | | | | | | | | Action 4 | | | | | | | | Action 5 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 |
| 1 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0.95 |
| 2 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.8 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

**Figure 14: Module 3 of the Standard Linear Model**

# V- Spatial Model

## A. Introduction

The previous models consider the asset as a pool of segments from which portions are selected and treated randomly. However, the aforementioned is not necessarily the most practical solution given the nature of the asset under study, which is a continuous strip of pavement. The repair and re-construction cost of a continuous stretch is directly proportional to the distances that separate each segment from the other as they include the mobilization of equipment, personnel and caravans. Therefore, it was quintessential to take the model one step further to account for these distances. Figure 15 is an illustration of the concept adopted.

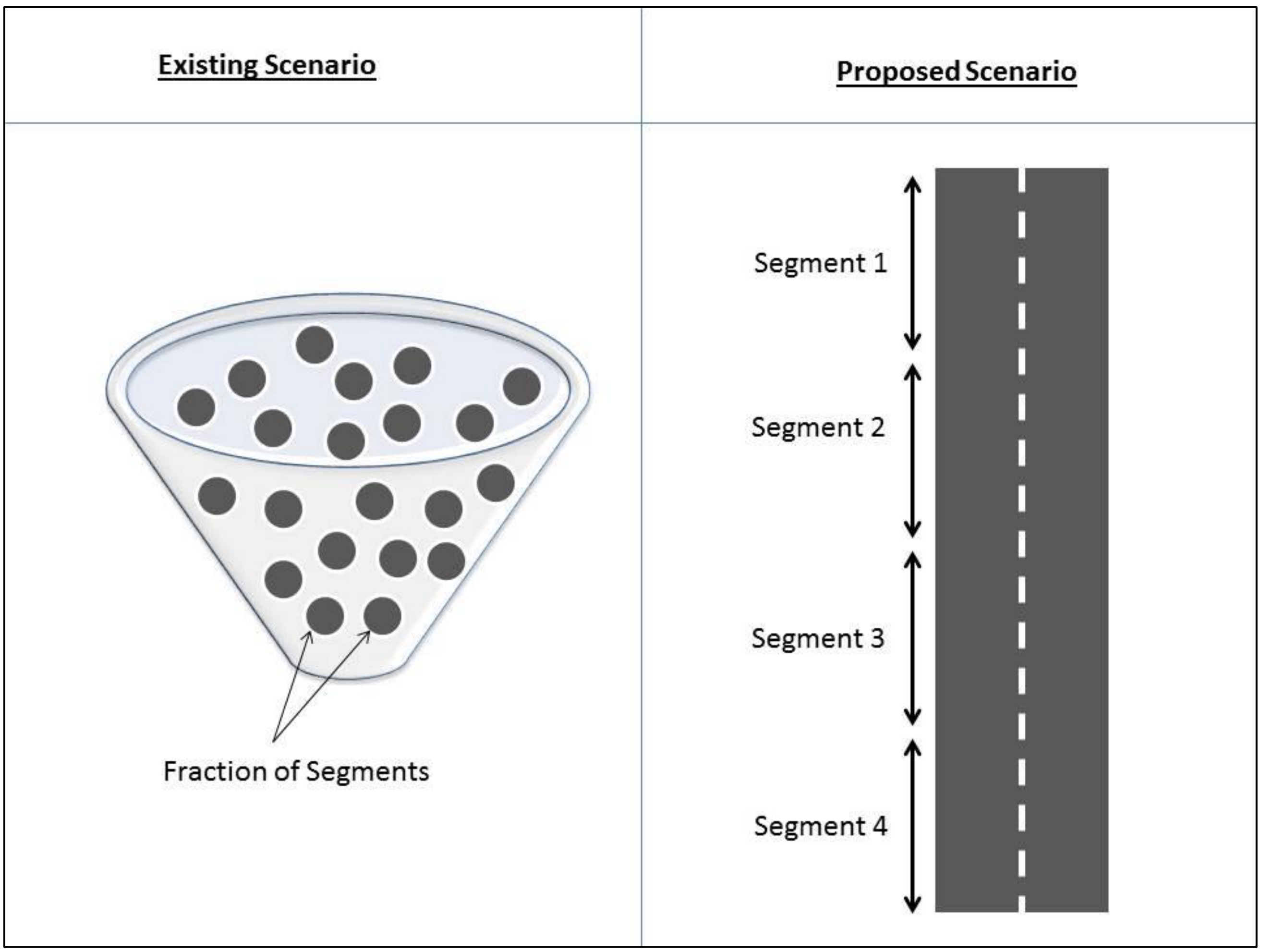



**Figure 15: Existing Vs. Proposed Scenarios**

## B. Model Development

The aforementioned was translated in the model by a complete change of the Model Engine Module. It is quintessential to note that this was only performed for the standard model and that the impact of the distances was only accounted for whenever action 7, re-construction, was used. This is due to the fact that the latter is associated with higher expenses than the other actions.

In order to be able to model an idea, it is to be expressed first as a set of equations as was previously derived from the literature review for the creation of the first three models. The following includes the new parameters used, the complete set of constraints of the model and finally the objective function.

- New model parameters

(a) S represents one segment of the pavement stretch under study (1,2,3,…,s)

(b) R represents a matrix that computes the absolute difference from segment to the other.

(c) L represents the length of each segment.

(d) Q represents a triangular matrix of 0 and 1.

(e) $D = \sum L \times R \times Q \times A_{7matrix} \times transpose\ A_{7matrix}$

(f) *Rand* which represents a random number that ranges from 0 to 1.

- Objective function:

$\min_D \min_S \sum_{t=0}^{T} \alpha^t \left[\sum_{i\in I} \sum_{a\in A} t_c(i,a)D\right]$

- Constraints

(1) $\sum_{a\in A} S_0(i,a) = init_i, \qquad \forall i \in I$

(2) $S_0(i,a) > 0, \qquad \forall i \in I,\ a \in A,\ t \in \{0,1,\dots.T\}$

(3) $S_t(i,a) = 0, \qquad \forall i \in 8,\ a \in A,\ t \in \{2,3,4,5\}$

(4) $\sum_{i \in I} \sum_{a \in A} S_{t-1}(i,a) p(j|i,a) = \sum_{a \in A} S_t(j,a), \qquad \forall j \in I,\ t \in \{1,2, \dots . T\}$

(5) $b(t)x0.85 \leq \sum_{i \in I} \sum_{a \in A} ac(i,a) \leq b(t) \qquad \forall s \in \{1,2, \dots, S\}\ \forall t \in \{0,1, \dots . T\}$

(6)$\sum_{j \in I} Rand = 1, \qquad \forall i \in I,\ a \in A, j \in I$

Equation (1) ensures that the initial conditions of all assets are known before carrying out any optimization. Equation (2) ensures that the condition of the segment and the applied actions do not take any negative values and that they only range within the possible set of conditions and actions- 1 to 8 for the former and 1 to 7 for the latter. Equation (3) represents the conditions that are unacceptable; namely,starting year 2, all assets must have a higher condition than 8. Equation (4) ensures that all the assets are included in the optimization from year to year. Equation (5) mandates that the summation of all the agency costs throughout the planned horizon ranges between 85% and 100% of the allocated budget.

At the difference of the previous models, the movement of a segment from a condition to the other is not straight forward. This is due to the fact that in the first version of the model, the segments were grouped into percentages that could be multiplied by probabilities and distributed over different conditions after the implementation of an action and from year to year. However, in this case, each segment must be assigned to a specific condition. For that the new *Rand* variable was introduced. What happens is that not only an optimization is performed but also a simulation is carried out. The model is set in a way that the probabilities of an asset remaining in a certain condition, upgrading or downgrading to another conditions is dependent on the random variable that is generated at each simulation. The important thing to note is that these random variables are ranges that impose the selection of a certain condition to a certain asset and therefore for each condition depending on the relevant action deterioration model, this range should not exceed a total of 1- Equation (6).

The integration of the distance from segment to segment that is assigned an action 7 is explained hereunder in Figure 16with a sample of ten segments only. The equation that is explained is (e) $D = \sum L \times R \times Q \times A_{matrix} \times transpose\ A_{matrix}$.

What happens is that the absolute difference between each segment and the other is computed first, then multiplied to a constant that represents the segment length in order to make the penalty of segments being far away from one another higher at a later stage. All the aforementioned is multiplied to two matrices that represents at which segment the action 7 was used (by a 1 and 0). These two matrices are the transposes of one another. Finally, all the above is multiplied by a triangular matrix of 0 and 1's as it eliminates the duplication of the effect of the distance. The outcome of the aforementioned is a matrix that includes a set of zeros (either for those segments to which action 7 was not applied or for the half of the matrix that was multiplied by 0 by the triangular matrix) and other values that represent the distance impact. These numbers are summed.

This new factor computed as previously described (D) is multiplied to the summation of the total costs. The objective function aims at minimizing the product, therefore minimize each term separately. This ensures both the minimal overall costs and the assemblage of the segments to which action 7 is applied

The first two modules were maintained as the asset inventory and the set of definitions are always independent from the modifications or upgrades performed to the other modules 3 and 4. For module 3, only Random variable generating cells were inserted and a summation column to each row to maintain the previously discussed constraint was added. As for module 4, it was completely modified to match the previously discussed and illustrated theory. Figure 17 is a snapshot of the aforementioned. Finally, given that the model engine became filled with matrices and is not user friendly, a "Summary" module was added which reads from the model engine and only reflects the year, condition, action and condition after the performance of an action. This module is customized in a way that every time action 7 is used, the cells change their colors to red for a better visualization of the outcome (Figure 18).

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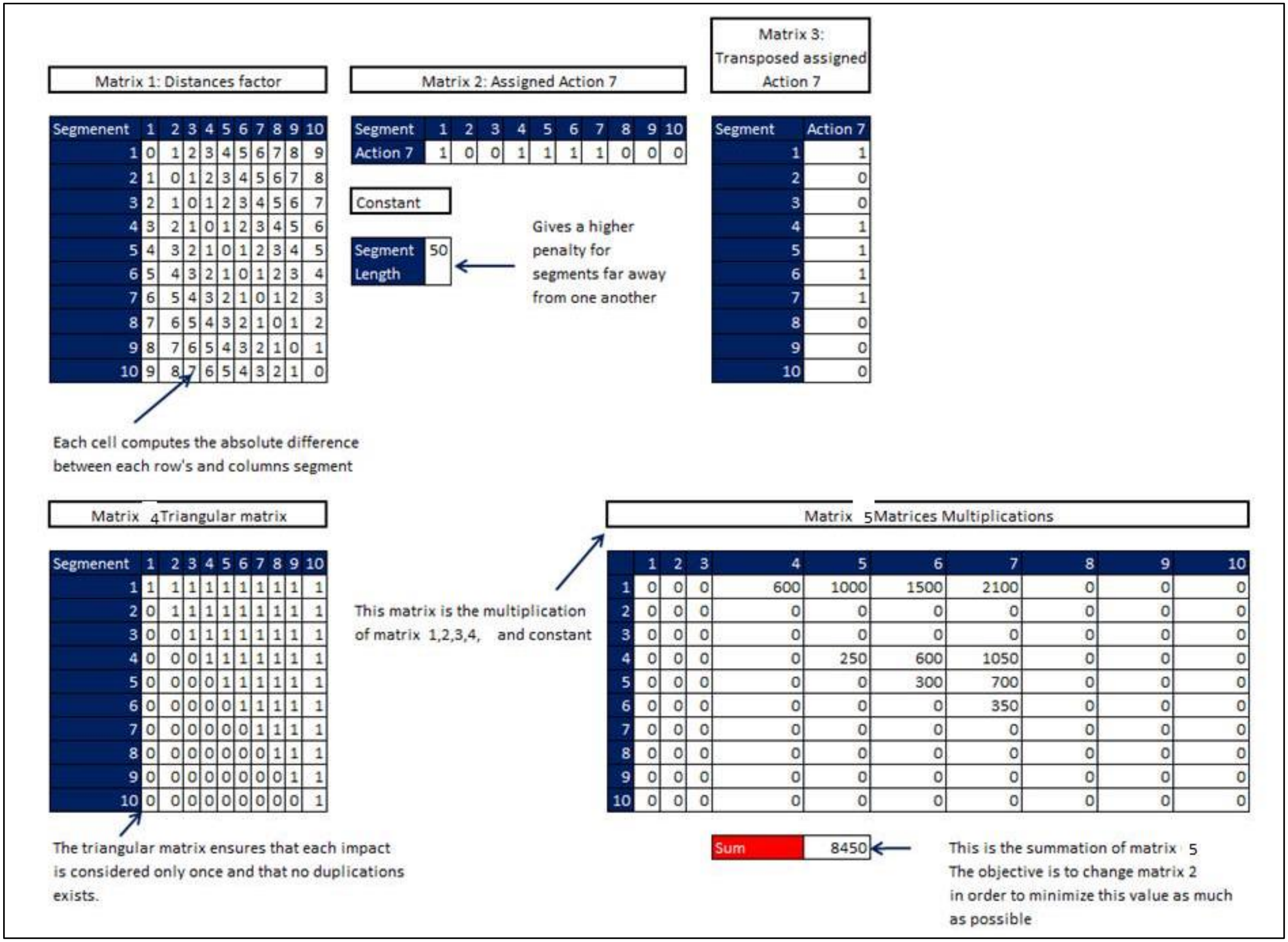



**Figure 16: Distance Impact Calculation (D)**

YEAR 1

| Segment | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Condition** | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 4 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Actions | | | | | | | | | | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 4 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 5 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 7 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | |
| Sum of Act. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| Action | 7 | 7 | 7 | 5 | 4 | 3 | 4 | 5 | 6 | 5 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 1 | 1 | |
| User cost | 16800 | 16800 | 16800 | 16800 | 16800 | 16800 | 16800 | 16800 | 16800 | 16800 | 58800 | 58800 | 33600 | 33600 | 33600 | 33600 | 33600 | 33600 | 33600 | 33600 | 3360 |
| Agency Cost | 109074 | 109074 | 109074 | 43806 | 27888 | 19866 | 27888 | 43806 | 59850 | 43806 | 109074 | 109074 | 109074 | 109074 | 109074 | 109074 | 109074 | 109074 | 0 | 0 | |
| Total Cost | 125874 | 125874 | 125874 | 60606 | 44688 | 36666 | 44688 | 60606 | 76650 | 60606 | 167874 | 167874 | 142674 | 142674 | 142674 | 142674 | 142674 | 142674 | 33600 | 33600 | 3360 |
| Distance Impact | | Segment length | | | | 50 | | | | | Total distance impact | | | | 7,419,500.00 | | | | | | |
| 1 | 0 | 100 | 300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5500 | 6600 | 7800 | 9100 | 10500 | 12000 | 13600 | 15300 | 0 | 0 | |
| 1 | 0 | 0 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4950 | 6000 | 7150 | 8400 | 9750 | 11200 | 12750 | 14400 | 0 | 0 | |
| HIDDEN 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4400 | 5400 | 6500 | 7700 | 9000 | 10400 | 11900 | 13500 | 0 | 0 | |
| CELLS 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| **Condition after action** | 1 | 1 | 1 | 4 | 7 | 7 | 7 | 4 | 7 | 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | |
| 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 3 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 4 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| SUM | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | |

**Figure 17: Module 4 of the Stochastic Spatial Model**

| Budget |
|---|
| 45,000,000 |

| Agency Cost |
|---|
| 8164086 |

| Total Cost |
|---|
| 30541686 |

| Sum of Distance Impact |
|---|
| 37,097,500 |

| Distance x Total Cost |
|---|
| 1,133,020,196,385,000 |

| | SEGMENT NUMBER | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR 1 | CONDITION BEFORE ACTION | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 |
| | ACTION | 2 | 2 | 2 | 5 | 4 | 3 | 4 | 5 | 6 | 5 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 5 | 4 | 3 | 4 | 5 | 6 | 5 | 5 | 5 | 3 |
| | CONDITION AFTER ACTION | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 4 | 3 | 7 | 3 | 7 | 1 | 1 | 2 | 4 |
| YEAR 2 | CONDITION BEFORE ACTION | 1 | 1 | 1 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 3 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 |
| | ACTION | 1 | 1 | 1 | 5 | 4 | 3 | 4 | 5 | 6 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 5 | 4 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| | CONDITION AFTER ACTION | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 3 | 7 | 3 | 7 | 3 | 7 | 1 | 1 | 2 | 4 |
| YEAR 3 | CONDITION BEFORE ACTION | 2 | 2 | 1 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 |
| | ACTION | 7 | 7 | 7 | 7 | 7 | 7 | 4 | 5 | 6 | 5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 4 | 3 | 4 | 5 | 6 | 5 | 1 | 1 | 1 |
| | CONDITION AFTER ACTION | 1 | 1 | 1 | 5 | 9 | 4 | 9 | 5 | 5 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 7 | 3 | 7 | 4 | 7 | 4 | 1 | 1 | 1 |
| YEAR 4 | CONDITION BEFORE ACTION | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 |
| | ACTION | 7 | 7 | 7 | 5 | 4 | 3 | 4 | 5 | 6 | 5 | 7 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 5 | 6 | 5 | 7 | 7 | 7 |
| | CONDITION AFTER ACTION | 1 | 1 | 1 | 4 | 2 | 1 | 2 | 4 | 7 | 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 3 | 7 | 1 | 7 | 2 | 1 | 1 | 1 |
| YEAR 5 | CONDITION BEFORE ACTION | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 5 |
| | ACTION | 7 | 7 | 7 | 5 | 4 | 3 | 4 | 5 | 6 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 4 | 3 | 4 | 5 | 6 | 5 | 7 | 7 | 7 |
| | CONDITION AFTER ACTION | 1 | 1 | 1 | 7 | 7 | 7 | 7 | 7 | 4 | 7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 7 | 3 | 7 | 2 | 7 | 3 | 1 | 1 | 1 |

**Figure 18: Module 5 of the Stochastic Spatial Model**

# VI- Model Validation

## A. Introduction

The objective of this chapter is to illustrate the method used in order to validate the models that were developed at earlier stages. The benefit of this step is to ensure that the models are workable and of added value to the users.

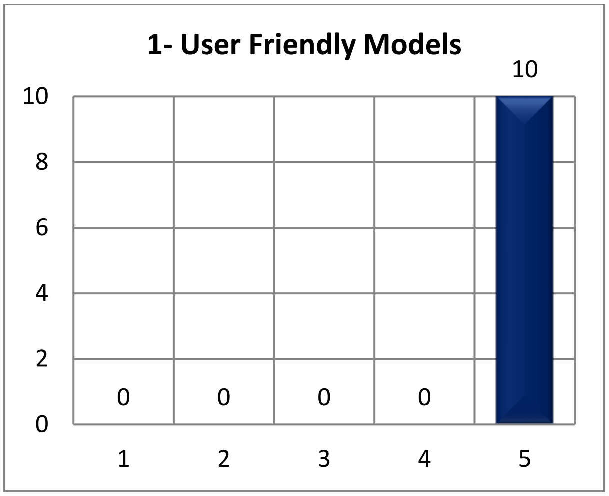
## B. Validation Technique

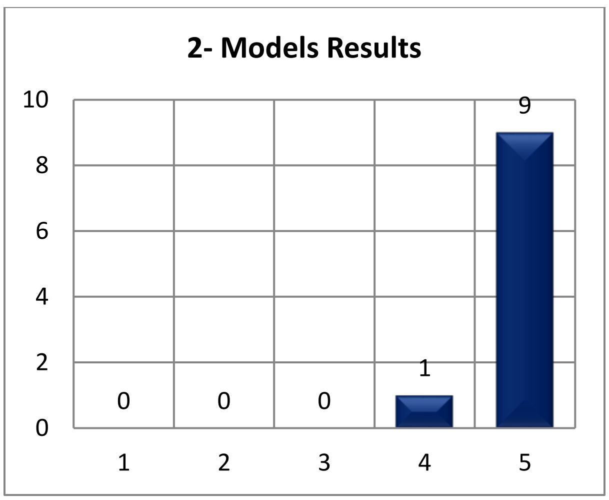
In this case the validation was carried out by giving the models to experts in the field in order to test them. The models were accompanied with seven questions to which the users had to give a mark (the scale used in this case ranged from 1 to 10, with 1 being poor and 10 excellent). Ten experts were given the models and they work in different disciplines – transportation, environmental and structural. The questions asked can be enlisted as enlisted hereafter.

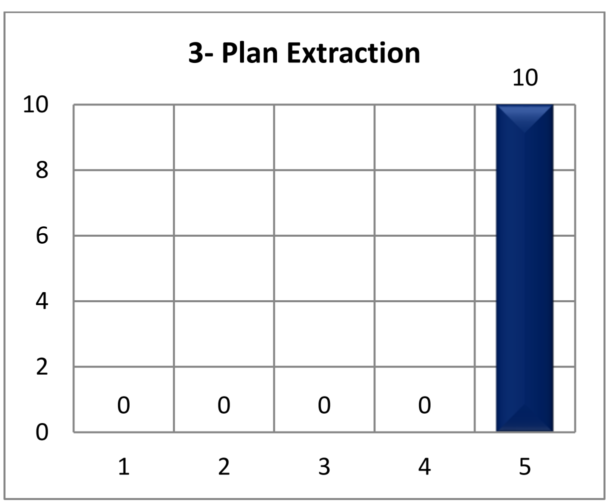
1. Are the models user-friendly?
2. Do the models output logic results / comparable results to previous asset management plans?
3. Is the setting out of a management plan easy to determine from the results of the models?
4. How beneficial are the three basic models for your discipline?
5. How beneficial is the spatial model for your discipline?
6. Rate the applicability of the models on the different assets in Egypt.
7. Rate your level of recommendation for the acquisition of these models at your work place.

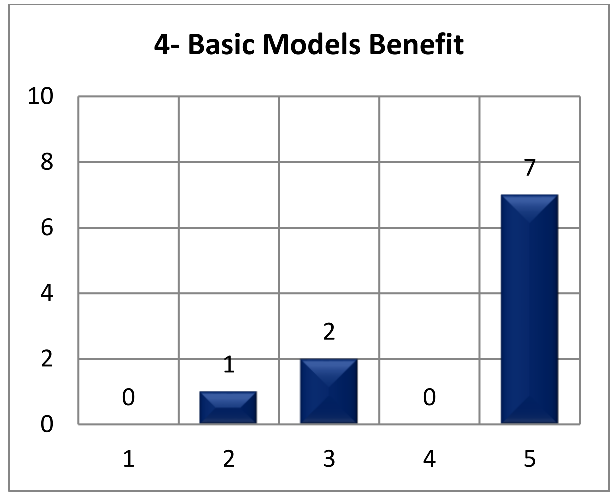
## C. Validation Results

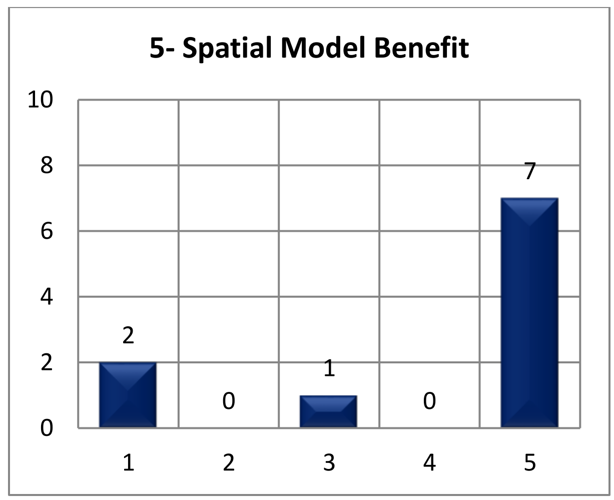
This section presents a summary of the responses of the questionnaires. The results are given in bar charts format followed by an analysis of the results.

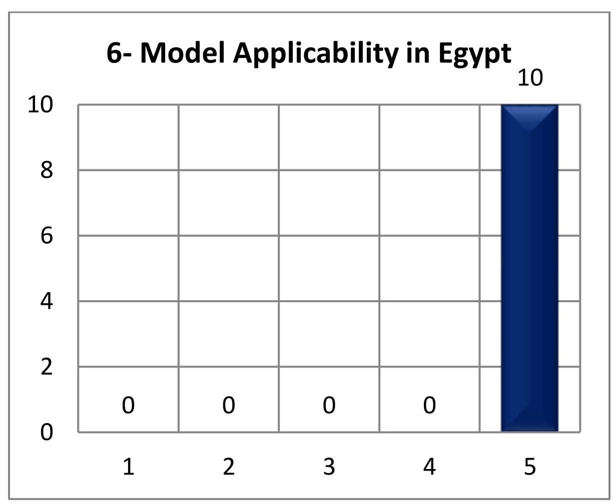

1- User Friendly Models
10
8
6
4
2
0
0 0 0 0 10
1 2 3 4 5

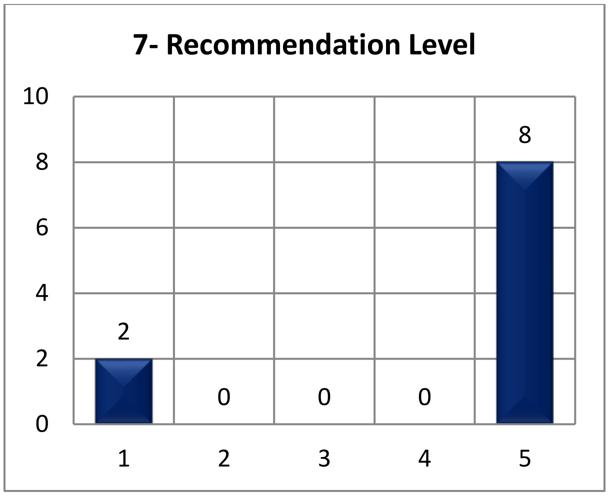

2- Models Results
10
8
6
4
2
0
0 0 0 1 9
1 2 3 4 5


3- Plan Extraction
10
8
6
4
2
0
0 0 0 0 10
1 2 3 4 5


4- Basic Models Benefit
10
8
6
4
2
0
0 1 2 0 7
1 2 3 4 5


5- Spatial Model Benefit
10
8
6
4
2
0
2 0 1 0 7
1 2 3 4 5


6- Model Applicability in Egypt
10
8
6
4
2
0
0 0 0 0 10
1 2 3 4 5




Some conclusions can be drawn from the above results and they can be enlisted as follows:

- The models are easy to interact with. It was stated by the experts that it was easy to find their way around the models as the they are made of very limited modules that are straight forward.
- The models results were comparable to previous work that was carried out and the results were logical in their opinion.
- All the experts believe that the extraction of a plan to be implemented was straight forward from the configuration of the model and the way the model engine ends up exhibiting its results.
- The basic model was less beneficial for the structural engineers and an environmental engineer concerned with barrages. This is due to the fact that the segmentation of the asset was not applicable to structures and therefore they were more concerned with the breakdown of the asset, The latter is also applicable for the spatial model.
- In the opinion of the experts, the models are applicable in Egypt for assets such as highways and pipelines.
- Finally the two structural engineers were not interested in all models at the difference with transportation and environmental engineers that gave an excellent rating to the acquisition of such models at their own working places.

# VII- Case study: Ring Road

## A. Introduction

Cairo roads are highly congested which leads to many negative impacts. First are travel delays impacts that were described in the World Bank Annual Report. They were quantified based on counts that comprised automatic traffic counts on links for a period of 3-7 days and classified turning movement counts (manual) at junctions during peak periods of a normal weekday. It was concluded that the average car speed ranged between 15 to 40 Km/hr in the time the roads were designed to have a serviceable speed of 60 to 80 Km/hr, and, therefore, "*when making a trip during peak hours, one should expect at least double the normal travel time*"(Nakat & Herrera, 2010). Second, are the economic impacts that were provided by Japan International Corporation Agency (JICA) in 2008.The study factored the waste of fuel, health impacts that are caused due to the environment pollution generated, accidents (rates of 4,000 injured and 1,000 deaths are expected yearly) and the wasted productivity due to prolonged waits in traffic congestions. It was concluded that the economy of the country loses around 50 billion Egyptian Pounds yearly (Matsuoka, 2008).

The previously described status quo was to be tackled from an analytical perspective in order to identify the root causes of the problem at hand. This was carried out using a time series study along with the examination of the graphical results developed in the previous two studies. It was found that three factors lead to congestion, accidents and an economy at trough. These factors comprise a socio-economic factor (poverty and lack of education), a political will factor (lack of enforcement of the law and the absence of a holistic vision) and an abused infrastructure that cannot cater to the public anymore (CAPMAS, 2011).

From a socio-economic perspective, Egypt lives with a high percentage of its population that is not educated properly, which eventually leads to drivers who do not have the basic knowledge of the rules to be followed whilst on the road. Also, the status quo of the country forces many to buy cars that are in bad conditions that usually break down and block traffic lanes. Cheap old cars have a wide market and are traded daily amongst the majority of the population. People find in the purchase of an old car a cheap means of commuting since petrol is subsidized by the government. Therefore, only a relatively high –yet affordable– initial cost is necessary and running costs are disregarded.

The aforementioned is a natural outcome of the lack of the Egyptian government's vision that does not provide a concrete public transport system that can be depended upon illustrated in a metro network that reaches all corners of Cairo or a bus system that is in good condition to suit users of different social classes. Moreover, the government fails to reinforce the existing laws to teach those unaware of identifying wrong behavior that negatively impact the traffic and, unfortunately, leads to people injured or dead.

The final category that plays a role in this daily struggle is the conditions of the road network of Cairo. Being an old city, Cairo's infrastructure has surpassed its engineering life; in other words, it does not offer the function it was built for anymore. The two major types of structure failure observable in Cairo streets are pavement fatigue and rutting.

The latter –an abused infrastructure, is due to the fact that Cairo is an old city and its infrastructure was established several decades ago; hence, the fact that the repair efforts are minor and are not performed under a clear holistic plan make the road conditions worse every year and, therefore, require more funding to be rehabilitated due to the immense yearly backlogs.

From the previous findings (catastrophic economic losses and poorly functioning road networks), it can be concluded that it is imperative to develop a plan that would comprise the maintenance, repair and reconstruction of the roads within a limited budget; in other words, the implementation of infrastructure asset management.

In order to address this specific issue, a stretch of the Ring Road that encompasses both Cairo and Giza was studied. The Ring Road is as shown in the figure hereunder from an aerial view (Figure 19).

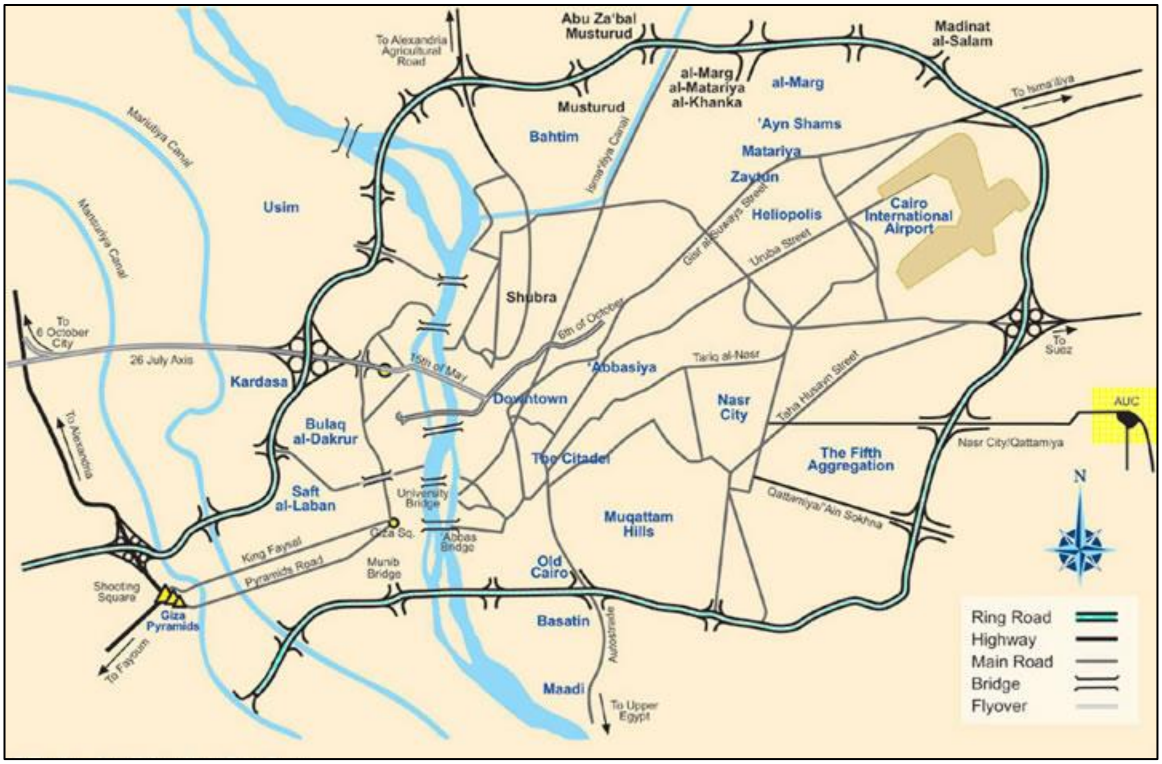



**Figure 19: Ring Road Key Plan**

The objective of this section is to apply the previously developed infrastructure asset management models that accounts for the different types of uncertainty and the location of its segments to this asset.

**B.Module 1 - Asset Inventory**

The data inventory of the asset under study is presented below. They include the road's name and route and the data of traffic, geometry and structure.

The Ring Road encompasses both Cairo and Giza.

The traffic data collected from multiple traffic counts are 150,000 vehicles/day. It is important to note that the road is furnished with New Jersey barriers; however, the overall safety rating of the road is very low (illustrated in an elevated rate of accidents) and the joints of the overpass crossing roads are in poor condition due to the lack of routine maintenance.

The geometric data collected is the cross section of the Ring Road that can be described as an eight-lane divided road with a median that is 7 meters wide (each direction is 20 meters wide) and the overall length of the Ring Road that is 100 Kilometers.

The structure of the Ring Road can be divided into two main categories. First, there are the at grade sections that are composed of an asphalt concrete structure. Second, there are the crossing roads (overpasses) that are all reinforced concrete bridges.

The models created being concerned with the pavement structure; an at-grade section of 20 kilometers was extracted and studied. This stretch starts at the Alexandria exit and continues toward Al Salam tunnel. It is divided in 400 segments of 50 meters each. (GARBLT, 2014). Figure 20 hereafter summarizes the data extracted in a graphical presentation.

It is important to mention that Hassan Allam Company carried out this study through various site visits and many assets inspection. Moreover, the condition rating system used while collecting the data was different than the scale of 1 to 8 discussed all along the thesis so far. It was based on a scale of 1 to 100 with the latter representing brand new conditions and the former unusable conditions. In order to translate the condition from a rating system to the other, the below matrix was utilized (Table 4).

**Table 4: Condition Rating Converter**

| Condition | Equivalent |
|---|---|
| 1 | 90-100 |
| 2 | 80-90 |
| 3 | 70-80 |
| 4 | 60-70 |
| 5 | 40-60 |
| 6 | 30-40- |
| 7 | 10-20 |
| 8 | 0-10 |

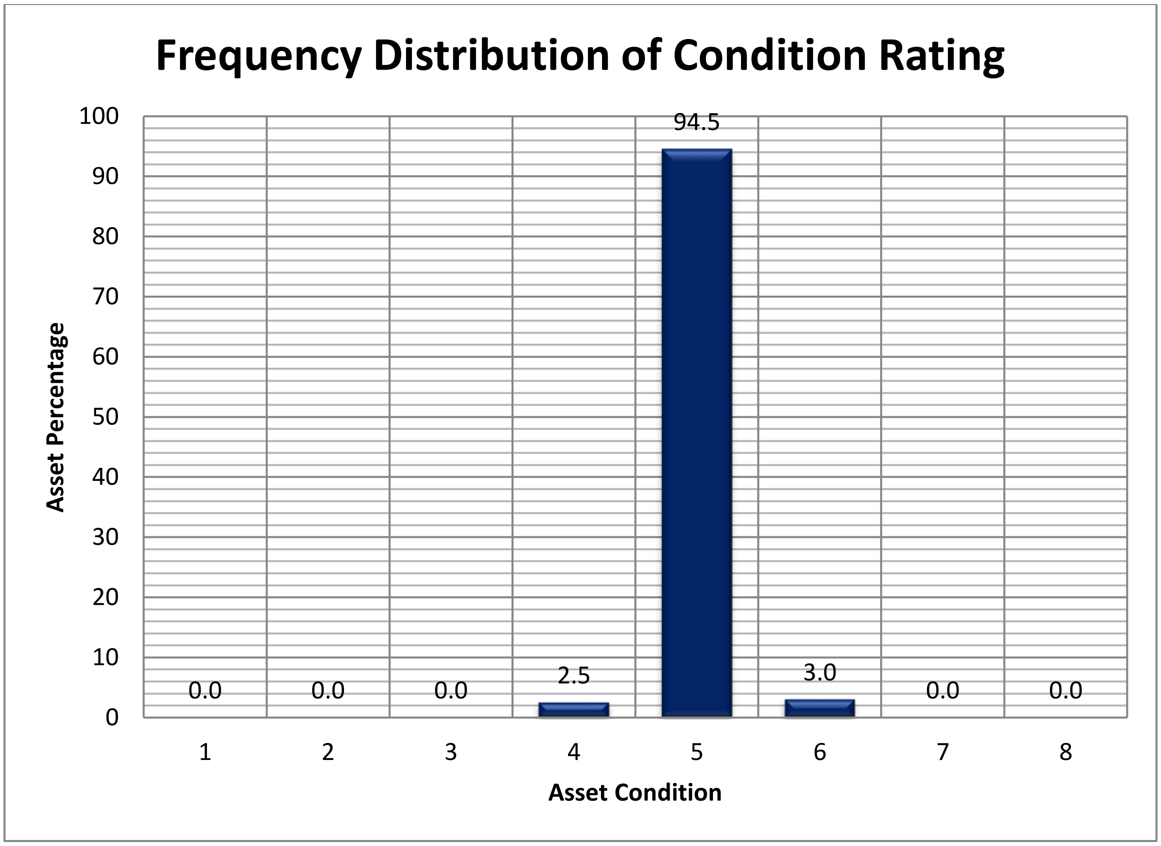



**Figure 20: Frequency Distribution of Condition Rating**

**C. Module 2 – Condition rating and Costs**

The set of definitions is the same as the one provided in the previous section, however the user cost and agency costs per segment length are specific to this case. They were obtained from transportation expert Ahmed Hazem (2014) through an interview, respectively in Tables 5 and 6. The fact that one expert's opinon only is taken into account is a limitation in this cases.

**Table 5: User Costs Associated with Different Conditions Ratings**

| User cost associated with different condition ratings | |
|---|---|
| Condition | Cost (EGP/segment/year) |
| 1 | - |
| 2 | - |
| 3 | 2,100 |
| 4 | 4,200 |
| 5 | 8,400 |
| 6 | 14,700 |
| 7 | 23,100 |
| 8 | 26,250 |

**Table 6: Agency Costs Depending on the Condition and Action**

| Agency Cost actions vs condition (ac(I,a)) – (EGP/segment) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Condition | Action | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 0 | 84 | 3,990 | 8,001 | 15,981 | 23,982 | 54,537 |
| 2 | 0 | 315 | 4,200 | 8,211 | 16,191 | 24,192 | 54,537 |
| 3 | 0 | 651 | 4,620 | 8,631 | 16,611 | 24,612 | 54,537 |
| 4 | 0 | 1,365 | 9,933 | 13,944 | 21,903 | 29,925 | 54,537 |
| 5 | 0 | 1,743 | 15,015 | 19,026 | 27,006 | 35,007 | 54,537 |
| 6 | 0 | 2,940 | 18,438 | 22,449 | 30,429 | 38,430 | 54,537 |
| 7 | 0 | 4,200 | 21,840 | 25,851 | 33,831 | 41,832 | 54,537 |
| 8 | 0 | 5,000 | 23,500 | 27,500 | 35,000 | 43,000 | 54,537 |

## D. Module 3 – Deterioration Model

A Markovian deterioration model is used. Figure 21 hereafter is a graphical representation of the later. It is important to note that for both actions 1 and 2, the trend of the curve is the usual Markovian one. It increases a lot during the first years of the asset and then slowly reaches the worst conditions. As for actions 3, 4, 5 and 6, given that they have the objective of upgrading the asset, their trends are different. The asset still deteriorates with the years, however this deterioration happens slowly and the worst condition is avoided. The severity of deterioration is dependent upon the intervention intensity. Final Action 7 has a straight line that remains at condition 1 given it means complete reconstruction and the asset is always brand new in this case. For the tabulated data refer to Appendix A that was obtained from the interview carried out wit transporation expert Ahmad Sherine (2014). The use of one expert’s opinion for the extraction of this data is a limitation in this case.

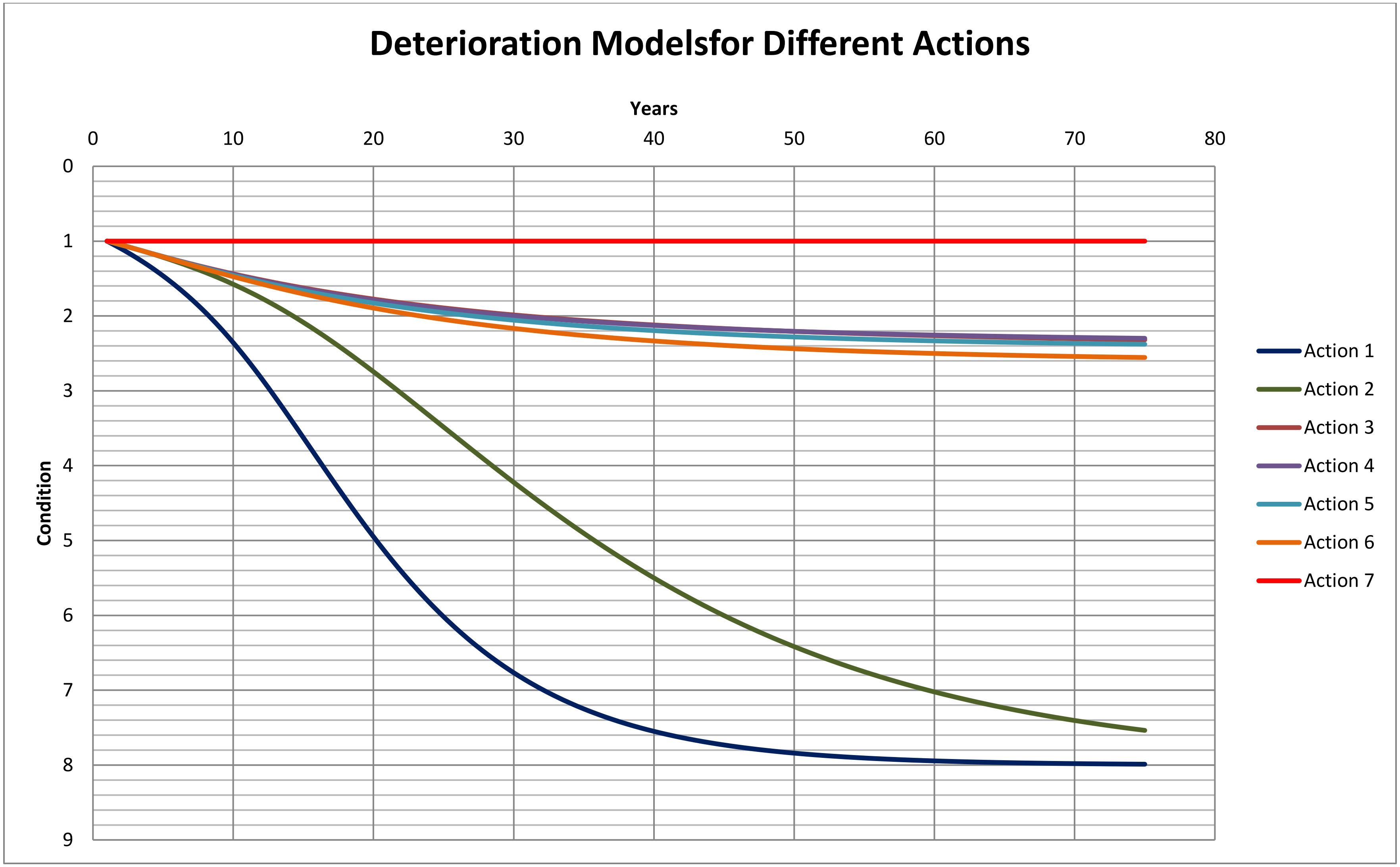



**Figure 21: Deterioration Model for Different Actions**

## E. Module 4 – Model Engine: Results and Discussion

This section presents the results obtained after running the optimization models, in other words, it reflects the finding of module 4- the model engine. The outcome is a 5 year plan with the necessary action to take for the different segments of the stretch under study. Table 7 groups the results of the nonlinear models and table 8 groups the results of the linear ones.

It is quintessential to note that for the robust models an uncertainty level of 0.3 was taken into account. As for the Hurwics criterion model an uncertainty level of 0.3 and an optimism level of 0.5 were considered.

Additionally, the models were set to alternate populations of a size of 500 and to stop once the results do not vary more than 2%.

Moreover, a total budget of 25,000,000 Egyptian Pound was allocated for all the models.

For the complete model engine outcomes of each model, refer to, refer to appendix B.

**Tables 7: Nonlinear MR&R 5 Years Plan**

| | | NONLINEAR MODELS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | STANDARD | | | ROBUST | | | HURWICS CRITERION | | | |
| Year | Condition | Fraction 1 | Action | Fraction 2 | Fraction 1 | Action | Fraction 2 | Fraction 1 | Action | Fraction 2 (Worst) | Fraction 2 (Best) |
| 1 | 1 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 |
| | 2 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 |
| | 3 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 |
| | 4 | 0.025 | 1 | 0.015 | 0.025 | 1 | 0.017 | 0.025 | 1 | 0.013 | 0.015 |
| | 5 | 0.945 | 1 | 0.483 | 0.945 | 2 | 0.368 | 0.945 | 1 | 0.348 | 0.498 |
| | 6 | 0.030 | 1 | 0.485 | 0.030 | 3 | 0.615 | 0.030 | 6 | 0.632 | 0.485 |
| | 7 | 0.000 | - | 0.018 | 0.000 | - | 0.000 | 0.000 | - | 0.003 | 0.003 |
| | 8 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 |
| 2 | 1 | 0.000 | - | 0.309 | 0.000 | - | 0.160 | 0.000 | - | 0.635 | 0.635 |
| | 2 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 |
| | 3 | 0.000 | - | 0.004 | 0.000 | - | 0.009 | 0.000 | - | 0.000 | 0.000 |
| | 4 | 0.009 | 4 | 0.004 | 0.011 | 4 | 0.142 | 0.007 | 1 | 0.003 | 0.004 |
| | 5 | 0.247 | 1 | 0.125 | 0.341 | 3 | 0.134 | 0.125 | 2 | 0.153 | 0.146 |
| | 6 | 0.435 | 1 | 0.298 | 0.488 | 2 | 0.311 | 0.228 | 4 | 0.195 | 0.186 |
| | 7 | 0.296 | 7 | 0.261 | 0.160 | 7 | 0.244 | 0.635 | 7 | 0.006 | 0.023 |
| | 8 | 0.013 | 7 | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 |
| 3 | 1 | 0.278 | 1 | 0.690 | 0.160 | 1 | 0.485 | 0.635 | 1 | 0.635 | 0.572 |
| | 2 | 0.031 | 2 | 0.057 | 0.000 | - | 0.001 | 0.000 | - | 0.000 | 0.064 |
| | 3 | 0.003 | 3 | 0.006 | 0.009 | 1 | 0.103 | 0.000 | - | 0.000 | 0.000 |
| | 4 | 0.004 | 4 | 0.002 | 0.094 | 5 | 0.100 | 0.002 | 1 | 0.024 | 0.022 |

| | | NONLINEAR MODELS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | STANDARD | | | ROBUST | | | HURWICS CRITERION | | | |
| Year | Condition | Fraction 1 | Action | Fraction 2 | Fraction 1 | Action | Fraction 2 | Fraction 1 | Action | Fraction 2 (Worst) | Fraction 2 (Best) |
| | 5 | 0.064 | 1 | 0.032 | 0.172 | 6 | 0.032 | 0.054 | 6 | 0.026 | 0.028 |
| | 6 | 0.181 | 1 | 0.104 | 0.242 | 1 | 0.219 | 0.100 | 1 | 0.005 | 0.045 |
| | 7 | 0.257 | 7 | 0.109 | 0.325 | 7 | 0.063 | 0.201 | 1 | 0.301 | 0.120 |
| | 8 | 0.183 | 7 | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.141 |
| 4 | 1 | 0.621 | 1 | 0.730 | 0.484 | 1 | 0.603 | 0.635 | 1 | 0.942 | 0.878 |
| | 2 | 0.115 | 2 | 0.173 | 0.002 | 1 | 0.003 | 0.000 | - | 0.000 | 0.064 |
| | 3 | 0.016 | 3 | 0.019 | 0.103 | 4 | 0.102 | 0.000 | - | 0.006 | 0.006 |
| | 4 | 0.003 | 5 | 0.011 | 0.067 | 6 | 0.066 | 0.012 | 4 | 0.002 | 0.005 |
| | 5 | 0.017 | 5 | 0.007 | 0.064 | 1 | 0.059 | 0.020 | 1 | 0.011 | 0.011 |
| | 6 | 0.058 | 1 | 0.025 | 0.165 | 1 | 0.128 | 0.017 | 1 | 0.013 | 0.017 |
| | 7 | 0.095 | 7 | 0.035 | 0.120 | 7 | 0.043 | 0.307 | 7 | 0.017 | 0.010 |
| | 8 | 0.076 | 7 | 0.000 | 0.000 | 2 | 0.000 | 0.000 | - | 0.000 | 0.000 |
| 5 | 1 | 0.657 | 1 | 0.641 | 0.602 | 1 | 0.601 | 0.942 | 1 | 0.942 | 0.848 |
| | 2 | 0.212 | 2 | 0.256 | 0.004 | 2 | 0.033 | 0.000 | - | 0.000 | 0.094 |
| | 3 | 0.048 | 1 | 0.055 | 0.102 | 6 | 0.093 | 0.004 | 1 | 0.002 | 0.003 |
| | 4 | 0.013 | 2 | 0.026 | 0.044 | 3 | 0.022 | 0.003 | 1 | 0.003 | 0.003 |
| | 5 | 0.008 | 4 | 0.014 | 0.077 | 1 | 0.073 | 0.005 | 1 | 0.003 | 0.004 |
| | 6 | 0.013 | 6 | 0.006 | 0.100 | 1 | 0.081 | 0.007 | 1 | 0.003 | 0.005 |
| | 7 | 0.025 | 7 | 0.001 | 0.076 | 1 | 0.102 | 0.031 | 1 | 0.038 | 0.014 |
| | 8 | 0.024 | 7 | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.021 |

**Tables 8: Linear MR&R 5 Years Plan**

| | | LINEAR MODELS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | STANDARD | | | ROBUST | | | HURWICS CRITERION | | | |
| Year | Condition | Fraction 1 | Action | Fraction 2 | Fraction 1 | Action | Fraction 2 | Fraction 1 | Action | Fraction 2 (Worst) | Fraction 2 (Best) |
| 1 | 1 | 0.000 | - | 1.000 | 0.000 | - | 0.945 | 0.000 | - | 0.945 | 0.945 |
| | 2 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 |
| | 3 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.003 | 0.003 |
| | 4 | 0.025 | 7 | 0.000 | 0.025 | 1 | 0.011 | 0.025 | 5 | 0.012 | 0.012 |
| | 5 | 0.945 | 7 | 0.000 | 0.945 | 7 | 0.014 | 0.945 | 7 | 0.018 | 0.018 |
| | 6 | 0.030 | 7 | 0.000 | 0.030 | 1 | 0.016 | 0.030 | 5 | 0.021 | 0.021 |
| | 7 | 0.000 | - | 0.000 | 0.000 | - | 0.014 | 0.000 | - | 0.000 | 0.000 |
| | 8 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.000 |
| 2 | 1 | 0.900 | 2 | 0.855 | 0.879 | 1 | 0.858 | 0.898 | 1 | 0.853 | 0.853 |
| | 2 | 0.100 | 2 | 0.135 | 0.066 | 2 | 0.114 | 0.047 | 3 | 0.074 | 0.074 |
| | 3 | 0.000 | - | 0.010 | 0.000 | - | 0.013 | 0.003 | 5 | 0.021 | 0.021 |
| | 4 | 0.000 | - | 0.000 | 0.005 | 1 | 0.004 | 0.007 | 5 | 0.008 | 0.008 |
| | 5 | 0.000 | - | 0.000 | 0.010 | 3 | 0.008 | 0.011 | 5 | 0.012 | 0.012 |
| | 6 | 0.000 | - | 0.000 | 0.019 | 7 | 0.003 | 0.016 | 5 | 0.026 | 0.026 |
| | 7 | 0.000 | - | 0.000 | 0.010 | 7 | 0.000 | 0.017 | 6 | 0.003 | 0.003 |
| | 8 | 0.000 | - | 0.000 | 0.011 | 7 | 0.000 | 0.000 | - | 0.003 | 0.003 |
| 3 | 1 | 0.770 | 2 | 0.731 | 0.798 | 1 | 0.743 | 0.811 | 2 | 0.755 | 0.755 |
| | 2 | 0.194 | 2 | 0.223 | 0.145 | 2 | 0.172 | 0.108 | 3 | 0.165 | 0.165 |
| | 3 | 0.034 | 5 | 0.041 | 0.040 | 1 | 0.061 | 0.027 | 6 | 0.055 | 0.055 |
| | 4 | 0.003 | 4 | 0.005 | 0.004 | 6 | 0.013 | 0.006 | 7 | 0.008 | 0.008 |

| | | LINEAR MODELS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | STANDARD | | | ROBUST | | | HURWICS CRITERION | | | |
| Year | Condition | Fraction 1 | Action | Fraction 2 | Fraction 1 | Action | Fraction 2 | Fraction 1 | Action | Fraction 2 (Worst) | Fraction 2 (Best) |
| | 5 | 0.000 | - | 0.000 | 0.004 | 6 | 0.003 | 0.007 | 6 | 0.006 | 0.006 |
| | 6 | 0.000 | - | 0.000 | 0.007 | 1 | 0.005 | 0.013 | 5 | 0.010 | 0.010 |
| | 7 | 0.000 | - | 0.000 | 0.001 | 7 | 0.003 | 0.023 | 7 | 0.000 | 0.000 |
| | 8 | 0.000 | - | 0.000 | 0.000 | - | 0.000 | 0.005 | 7 | 0.000 | 0.000 |
| 4 | 1 | 0.658 | 2 | 0.625 | 0.691 | 1 | 0.643 | 0.717 | 2 | 0.653 | 0.653 |
| | 2 | 0.251 | 3 | 0.274 | 0.179 | 1 | 0.197 | 0.185 | 2 | 0.238 | 0.238 |
| | 3 | 0.073 | 6 | 0.084 | 0.093 | 5 | 0.122 | 0.068 | 3 | 0.085 | 0.085 |
| | 4 | 0.015 | 4 | 0.014 | 0.018 | 6 | 0.019 | 0.010 | 2 | 0.016 | 0.016 |
| | 5 | 0.002 | 5 | 0.002 | 0.008 | 6 | 0.008 | 0.005 | 7 | 0.004 | 0.004 |
| | 6 | 0.000 | - | 0.000 | 0.005 | 3 | 0.006 | 0.006 | 6 | 0.003 | 0.003 |
| | 7 | 0.000 | - | 0.000 | 0.003 | 4 | 0.002 | 0.009 | 7 | 0.001 | 0.001 |
| | 8 | 0.000 | - | 0.000 | 0.003 | 6 | 0.003 | 0.000 | - | 0.000 | 0.000 |
| 5 | 1 | 0.563 | 1 | 0.515 | 0.598 | 1 | 0.564 | 0.620 | 2 | 0.558 | 0.558 |
| | 2 | 0.282 | 1 | 0.338 | 0.191 | 2 | 0.219 | 0.244 | 3 | 0.233 | 0.233 |
| | 3 | 0.114 | 3 | 0.102 | 0.148 | 5 | 0.159 | 0.103 | 4 | 0.172 | 0.172 |
| | 4 | 0.034 | 2 | 0.035 | 0.034 | 6 | 0.034 | 0.018 | 2 | 0.028 | 0.028 |
| | 5 | 0.007 | 7 | 0.010 | 0.013 | 6 | 0.016 | 0.008 | 6 | 0.007 | 0.007 |
| | 6 | 0.001 | 7 | 0.000 | 0.009 | 6 | 0.006 | 0.004 | 7 | 0.002 | 0.002 |
| | 7 | 0.000 | - | 0.000 | 0.003 | 7 | 0.001 | 0.003 | 7 | 0.000 | 0.000 |
| | 8 | 0.000 | - | 0.000 | 0.005 | 7 | 0.000 | 0.000 | - | 0.000 | 0.000 |

In order to be able to understand the 5 year plan that each model resulted in, it is easier to monitor the behavior of both the user cost and the total cost of the 5 years. This is due to the fact that the former is dependent only on the conditions of the segments and the latter reflects the actions taken according to the segments conditions. Figure 22 addresses the user costs of the 6 models.

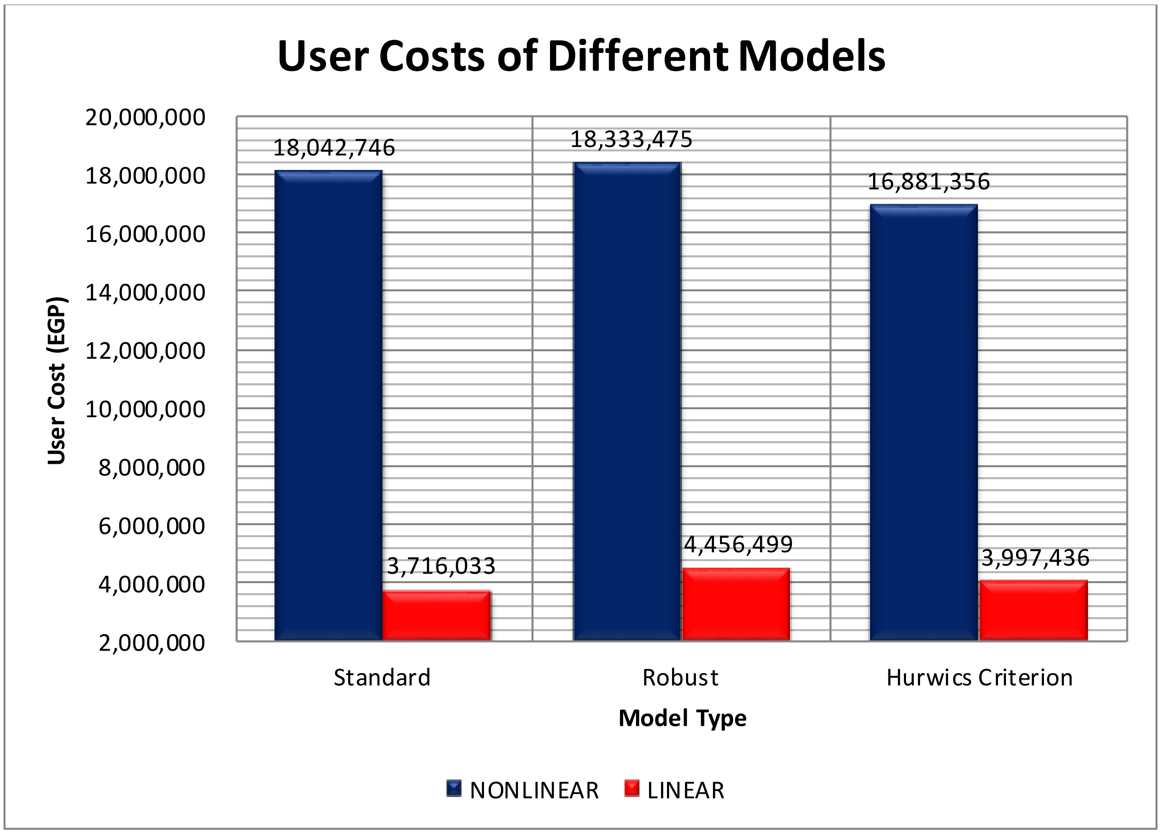



**Figure 22: Final user cost for the different models**

From Figure 22, it can be depicted that the user cost of the standard model has a value that is always smaller than the Robust model. The aforementioned happens due to the fact that the Robust model considers the worst case scenario, in other words that the surrounding environment will lead to a more sever deterioration of the asset, hence an elevated user cost in general. Comparing both the Robust and Hurwics criterion, it is clear that the latter has always a smaller total user cost, which is expected given that by entering a certain optimism level, it translates into balancing the effect of the surrounding environment and therefore, the assets do not necessarily deteriorate following the worst case condition, on the contrary it is tuned in order to consider nature as neither an opponent nor an ally.

Figure 23 hereafter is similar to Figure 22 but for the total cost that reflects the set of actions taken according to the segments conditions.

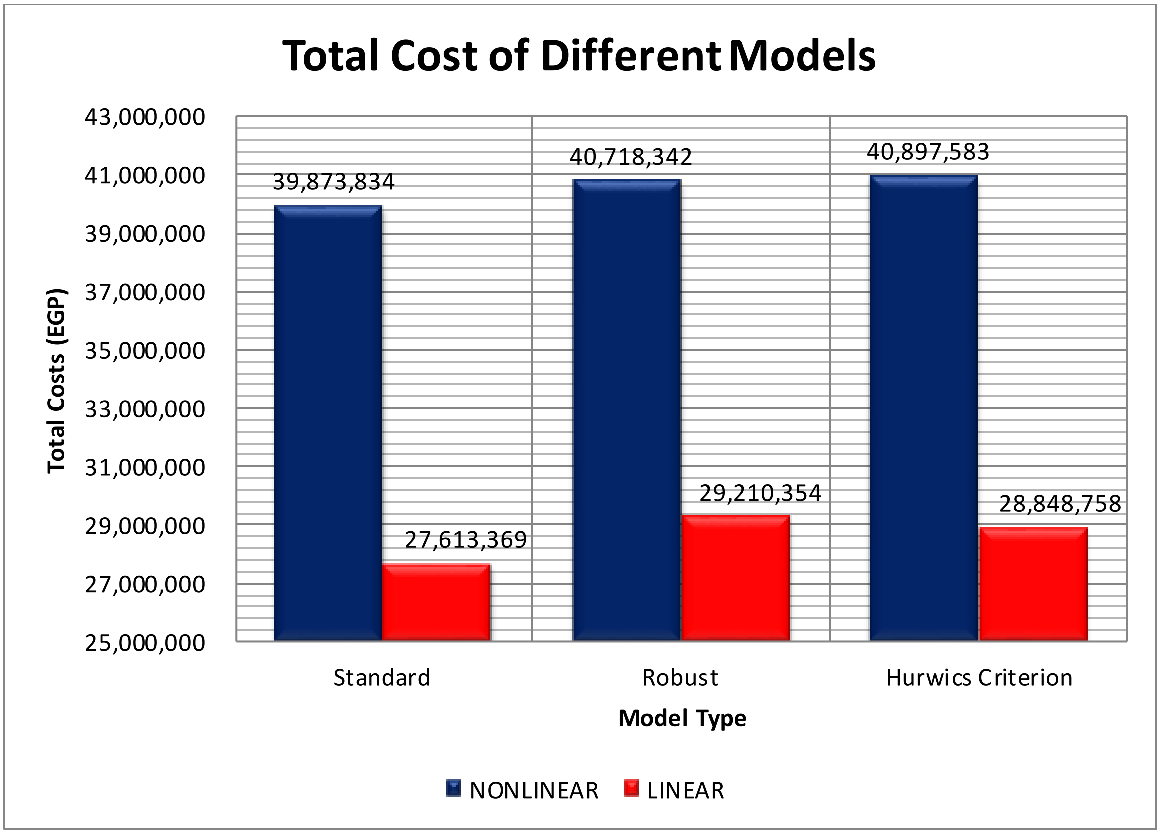



**Figure 23: Final total cost for the different models**

The standard model always gives a smaller total cost than the two other models. This can be translated that it combines both less severe actions and better conditions in general, which is in line with both the results shown in Figure 22 and the actions in Tables 7 and 8. An important observation though is that the Robust and Hurwics criterion models have almost the same total cost.

Now that each model was compared to the other, the set of linear models are compared to the nonlinear ones. The below graphical representation compares the optimization duration of all the models (Figure 24).

It can be concluded that the optimization duration increases with the complexity of the problem in all cases. Moreover, the linear models run faster than the linear ones, which confirm the hypothesis made in the literature review.

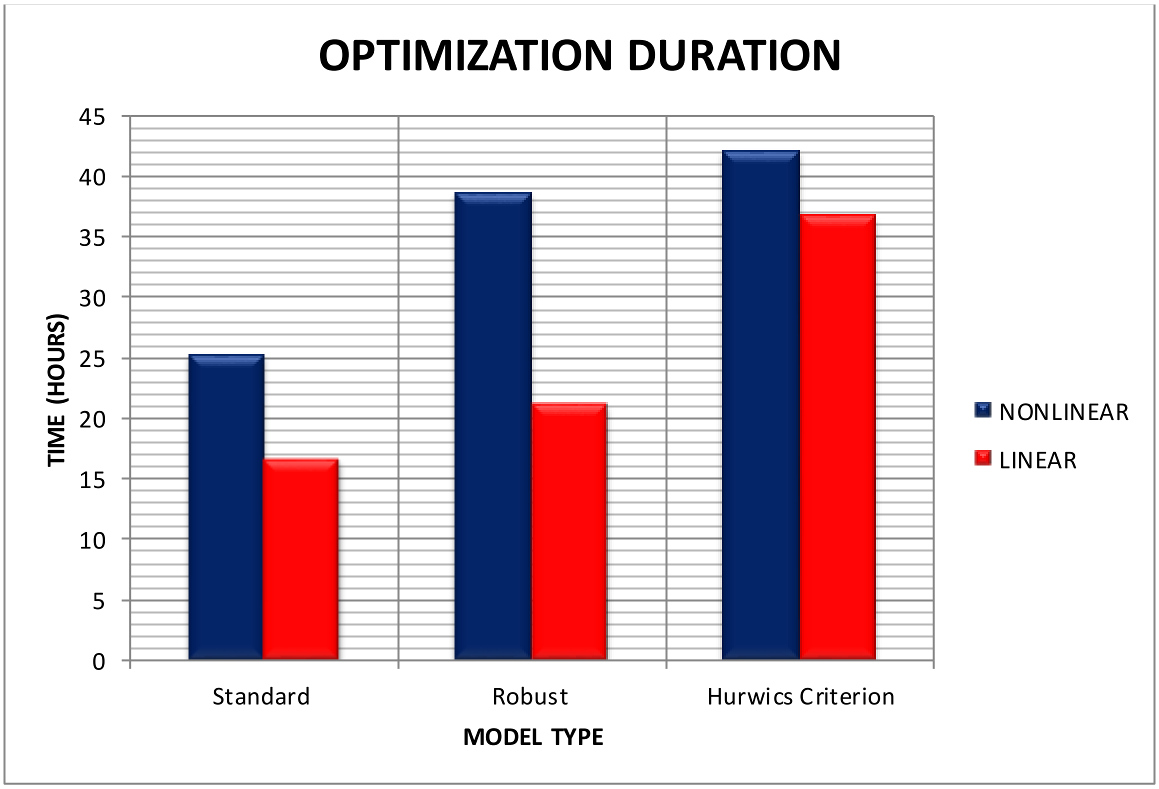



**Figure 24: Optimization duration of the different models**

It is necessary to note that the technique used for optimization highly affects the final results as well not only the duration of the exercise. This is apparent from Figures 22 and 23 that always show that the linear model gives less expensive solutions. This is due to the fact that the linear models have the tendency to allocate most of the budget during the first years by reconstructing most of the poorly rated pavement segments and leave minorities to the subsequent years, which is the opposite of what the nonlinear models do which is distribute the allocated budget over the 5 years and deal with the backlogs yearly.

In order to better visualize the aforementioned, Figures 25 to 30 were prepared, which are graphical representations of the distribution of the fractions of the assets over the different conditions during the 5 years for both the Linear and Nonlinear Models.

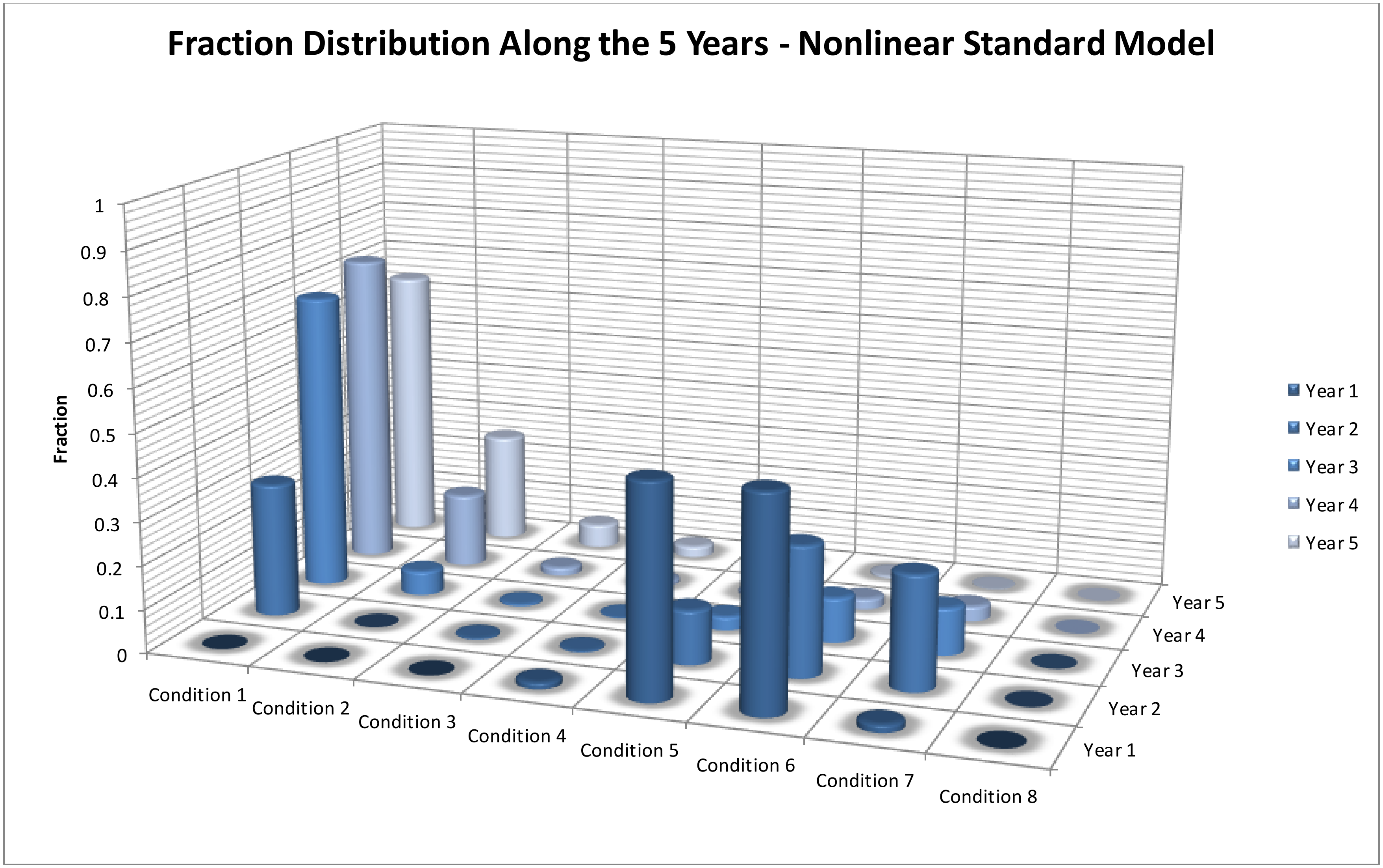



**Figure 25: Fraction Distribution Along 5 Years – Nonlinear Standard Model**

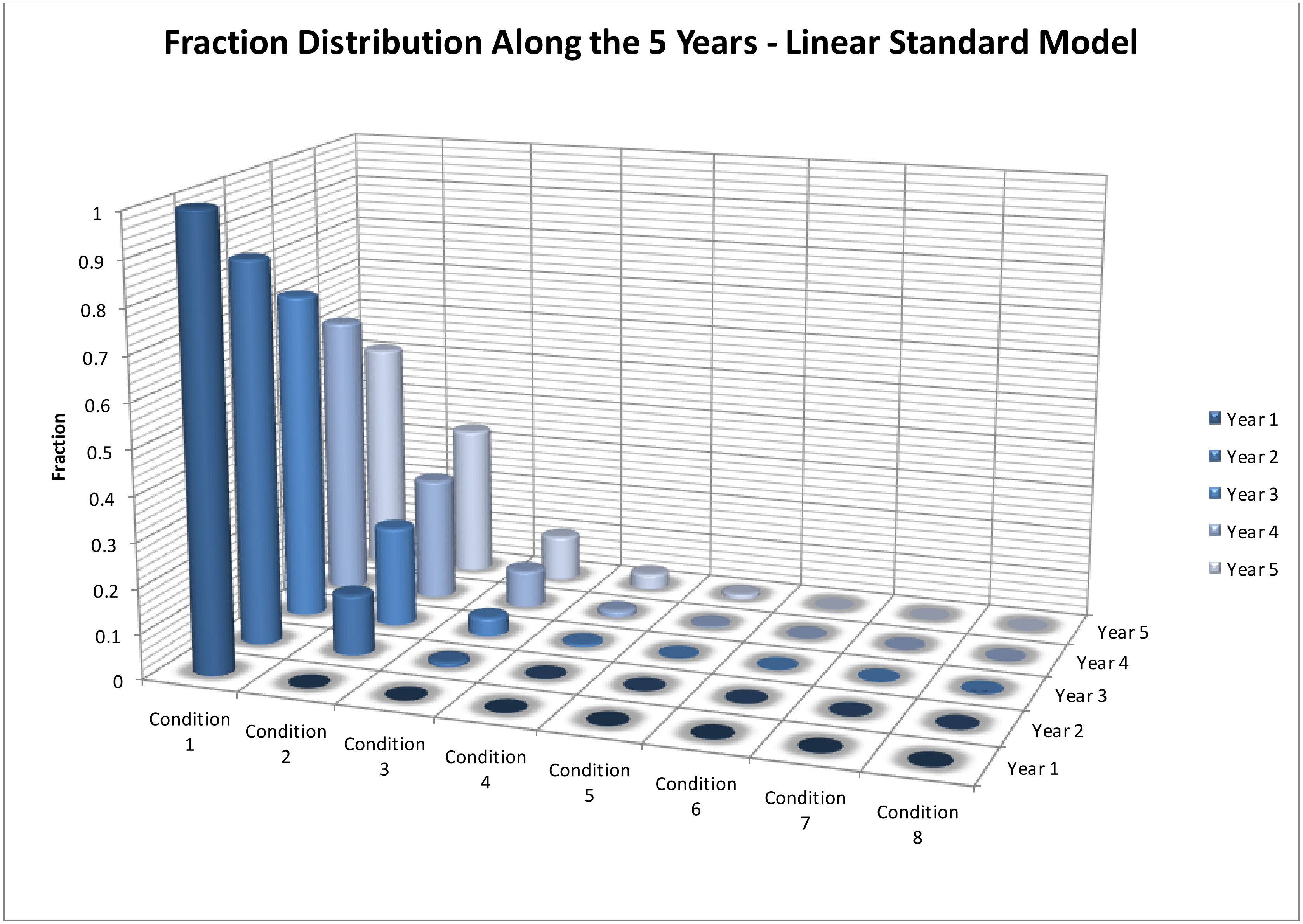



**Figure 26: Fraction Distribution Along 5 Years – Linear Standard Model**

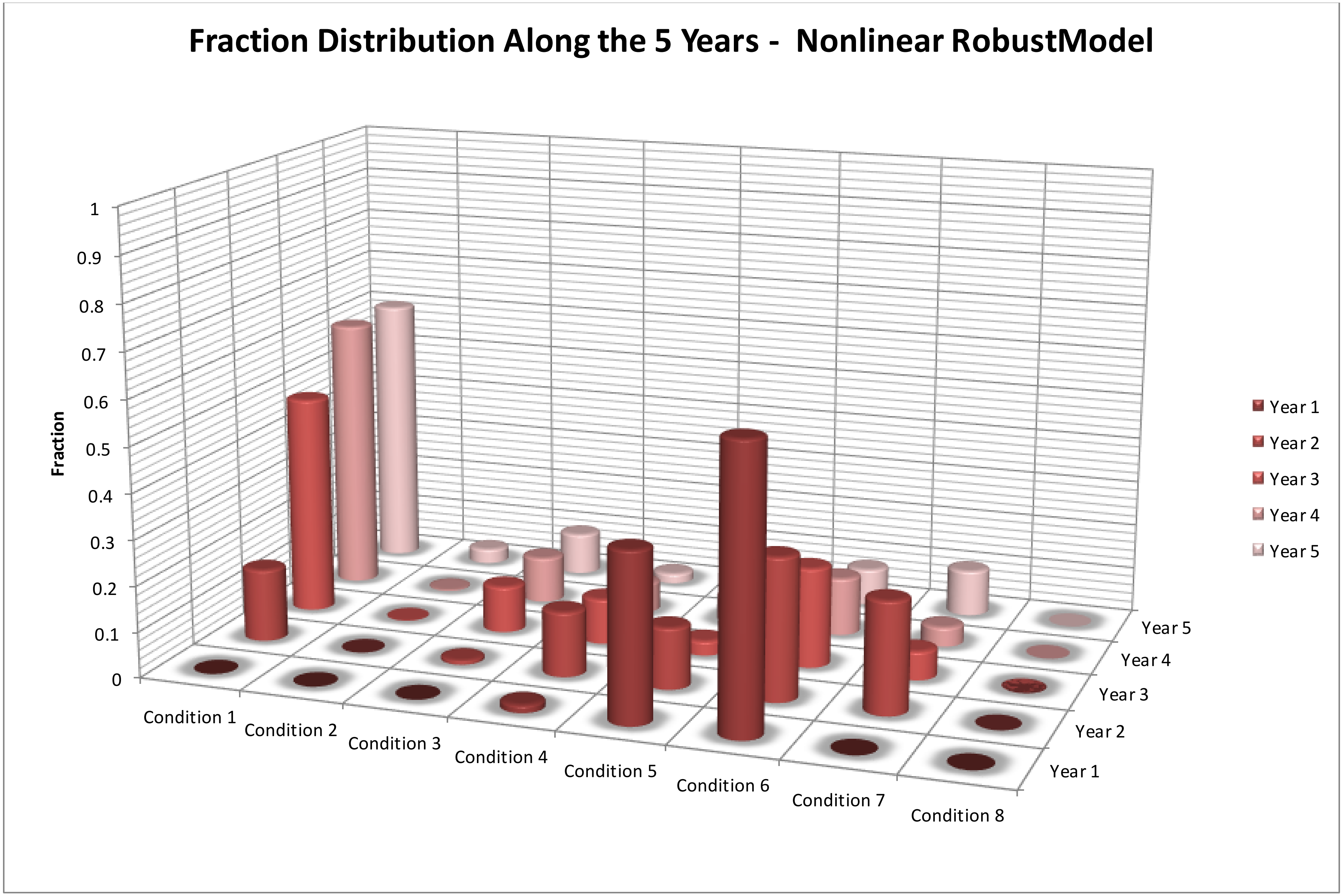



**Figure 27: Fraction Distribution Along 5 Years – Nonlinear Robust Model**

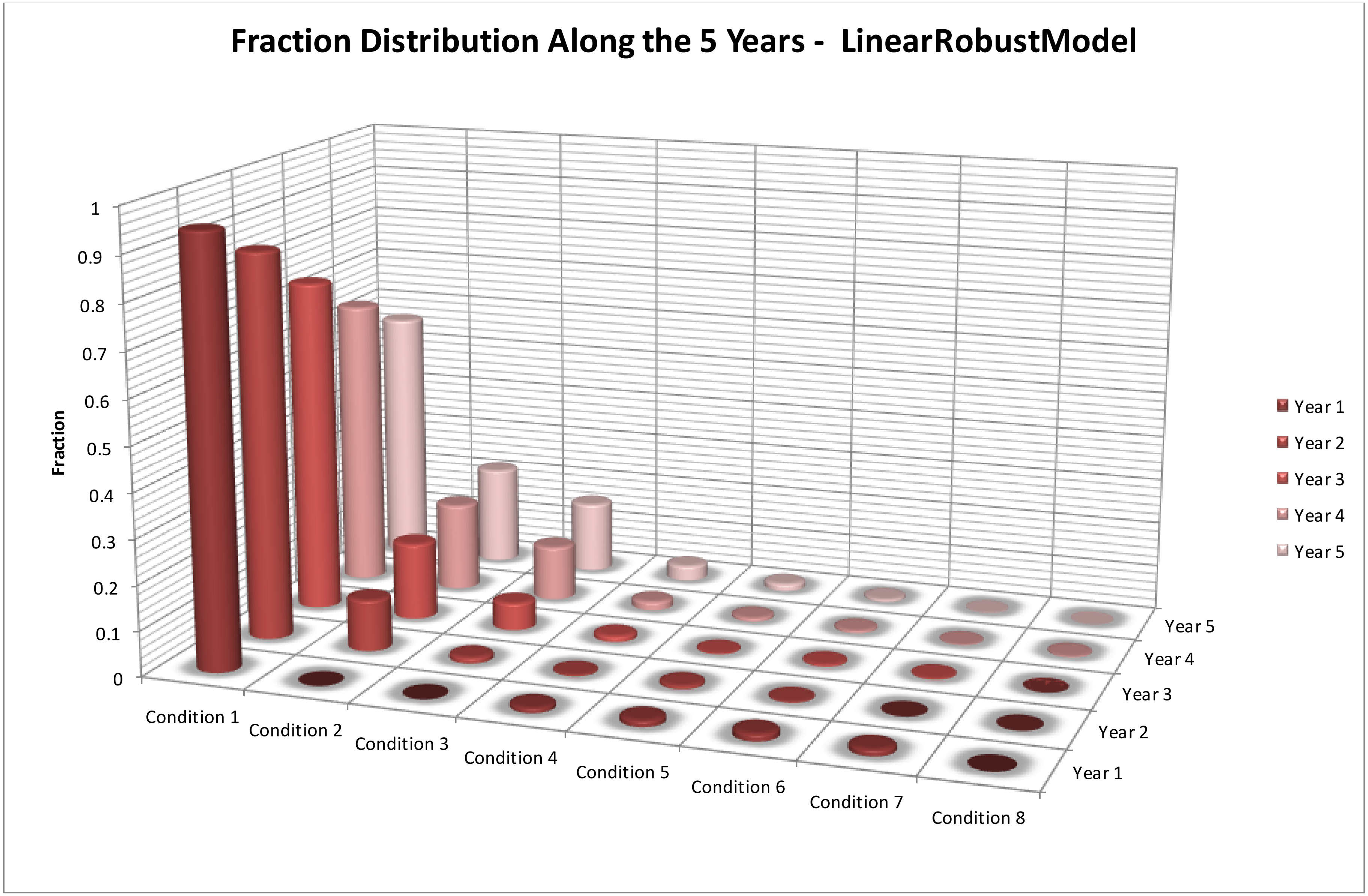



**Figure 28: Fraction Distribution Along 5 Years – Linear Robust Model**

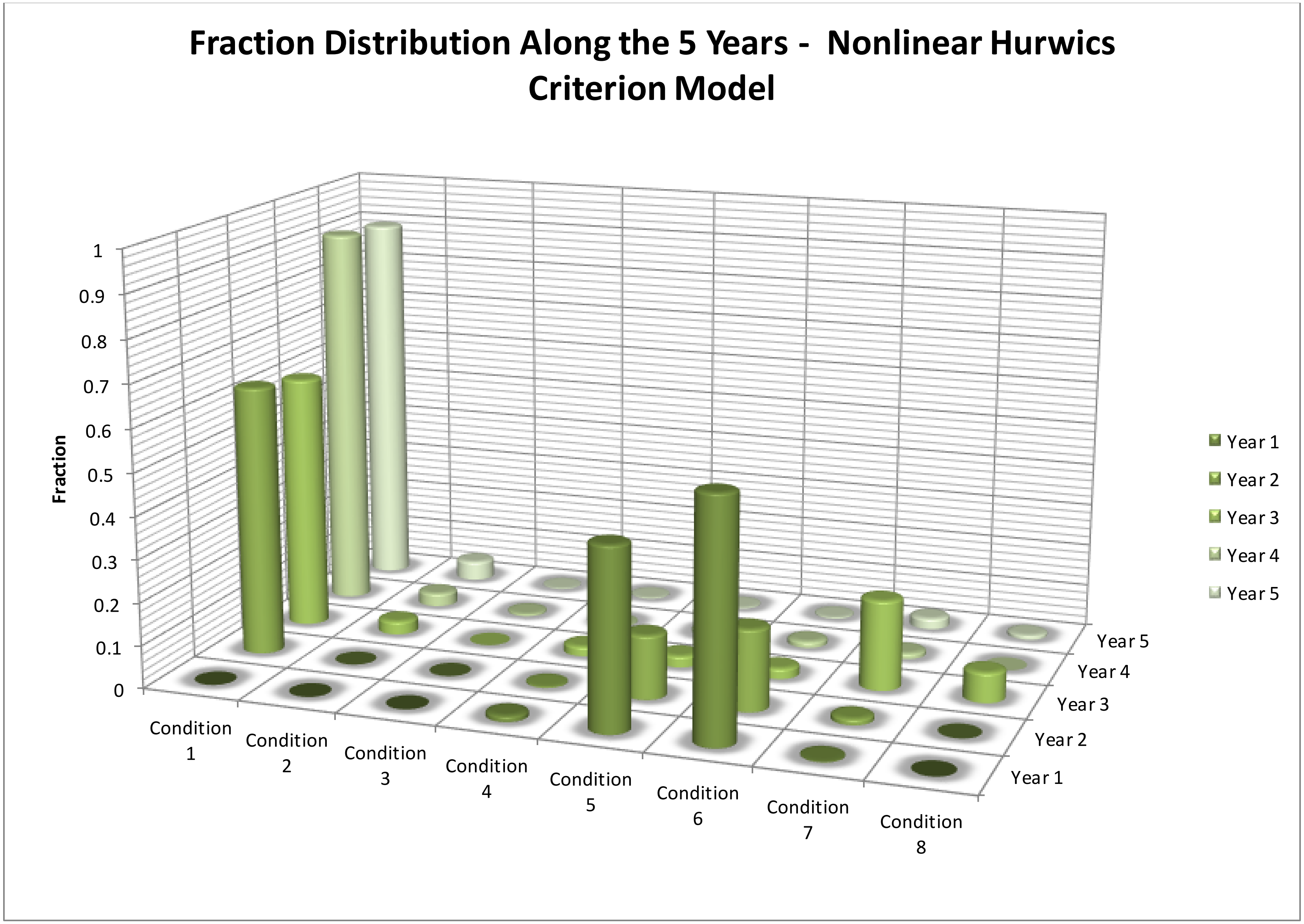



**Figure 29: Fraction Distribution Along 5 Years – Nonlinear Hurwics Criterion Model**

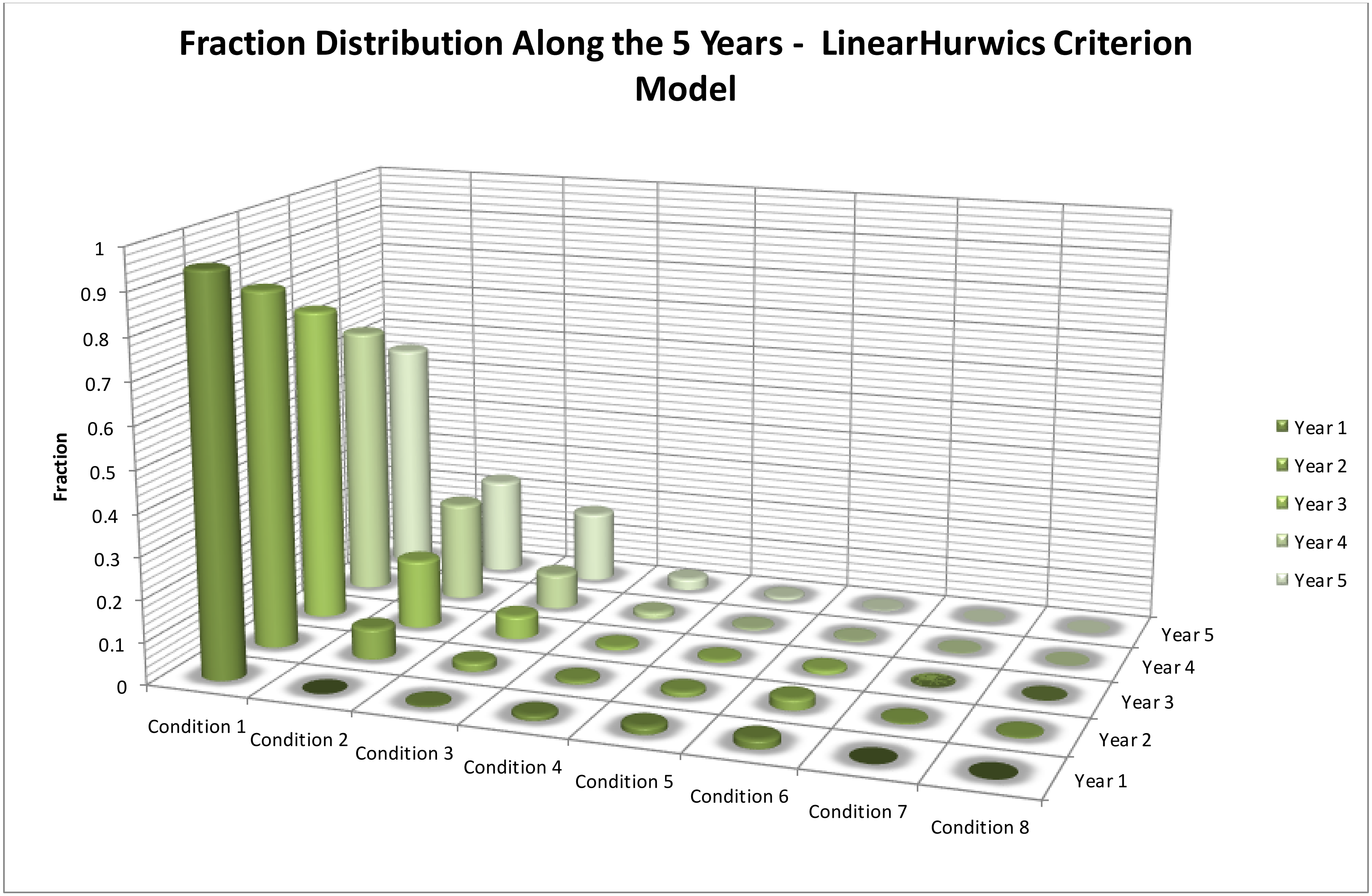



**Figure 30: Fraction Distribution Along 5 Years – Linear Hurwics Criterion Model**

## F. Spatial Model Results and Discussion

The final results to be discussed are the ones of the spatial model. This model was solved using the OptiRisk tool which not only allows for the introduction of an objective function and a set of constraints but runs in parallel a simulation to change the *Rand* variable. As for the population size and optimization stopping conditions, they are exactly the same as the 6 previous models.

It is important to note that only 150 segments were studied in this case as opposed to the 400 of the previous models and therefore the allocated budget in this case was 10,000,000 Egyptians pounds only.

What happens in this case is that the model will eventually look for the minimum value possible in terms of costs, however that minimum value has a minimum, a maximum and a mean depending on the deterioration model selected for each asset and therefore depending on the simulation. The below figure (31) is an illustration of the aforementioned.

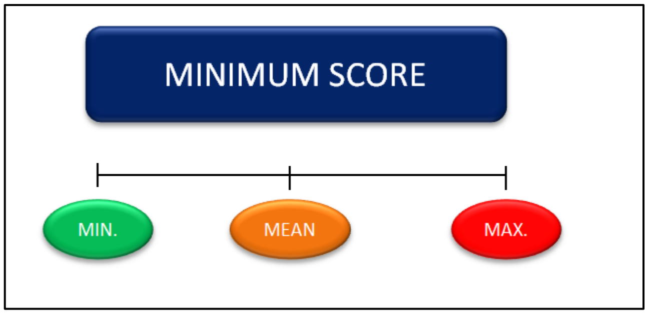
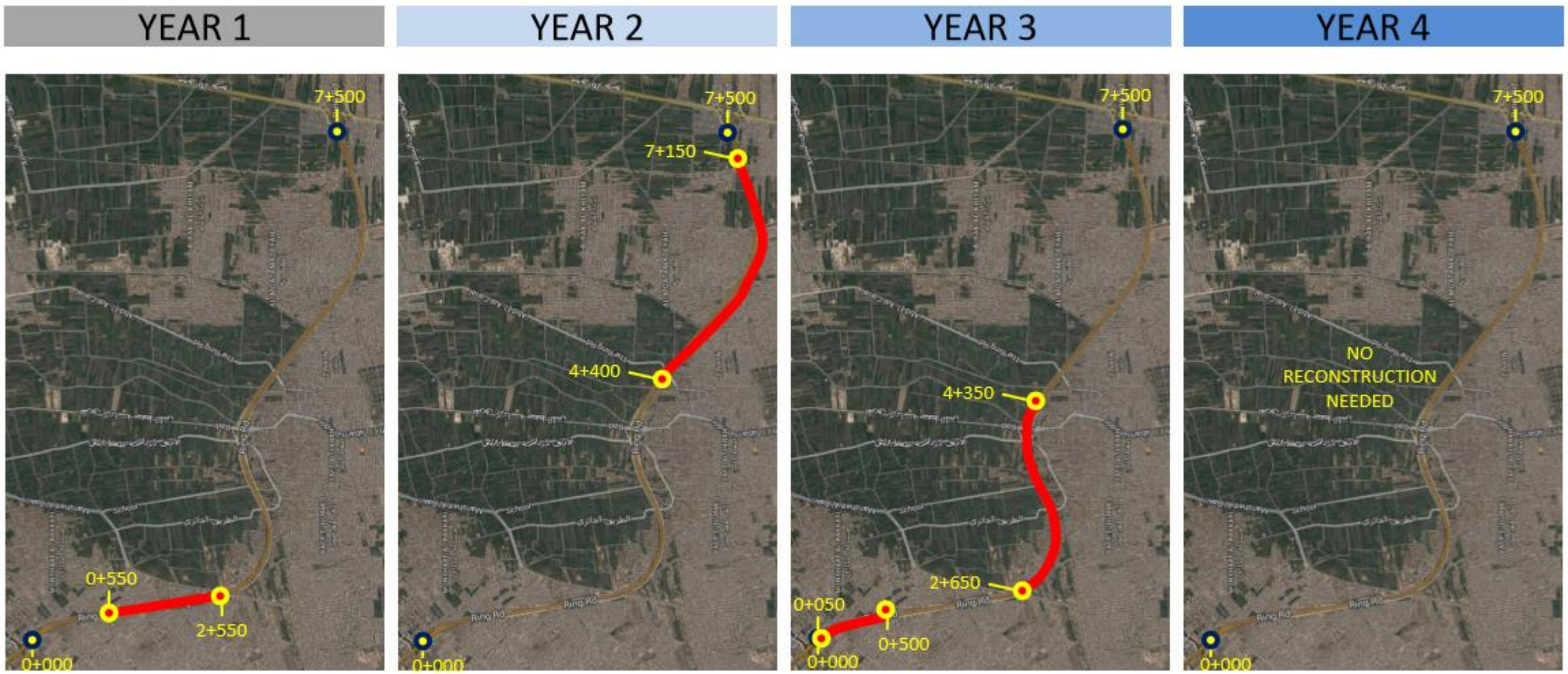



**Figure 31: Simulation concept.**

The objective is to select the minimal case scenario and therefore, setting the simulation to give minimal results. In order to verify the model, the maximum and mean simulation were performed. It is expected then that the minimum simulation will give the lowest costs.

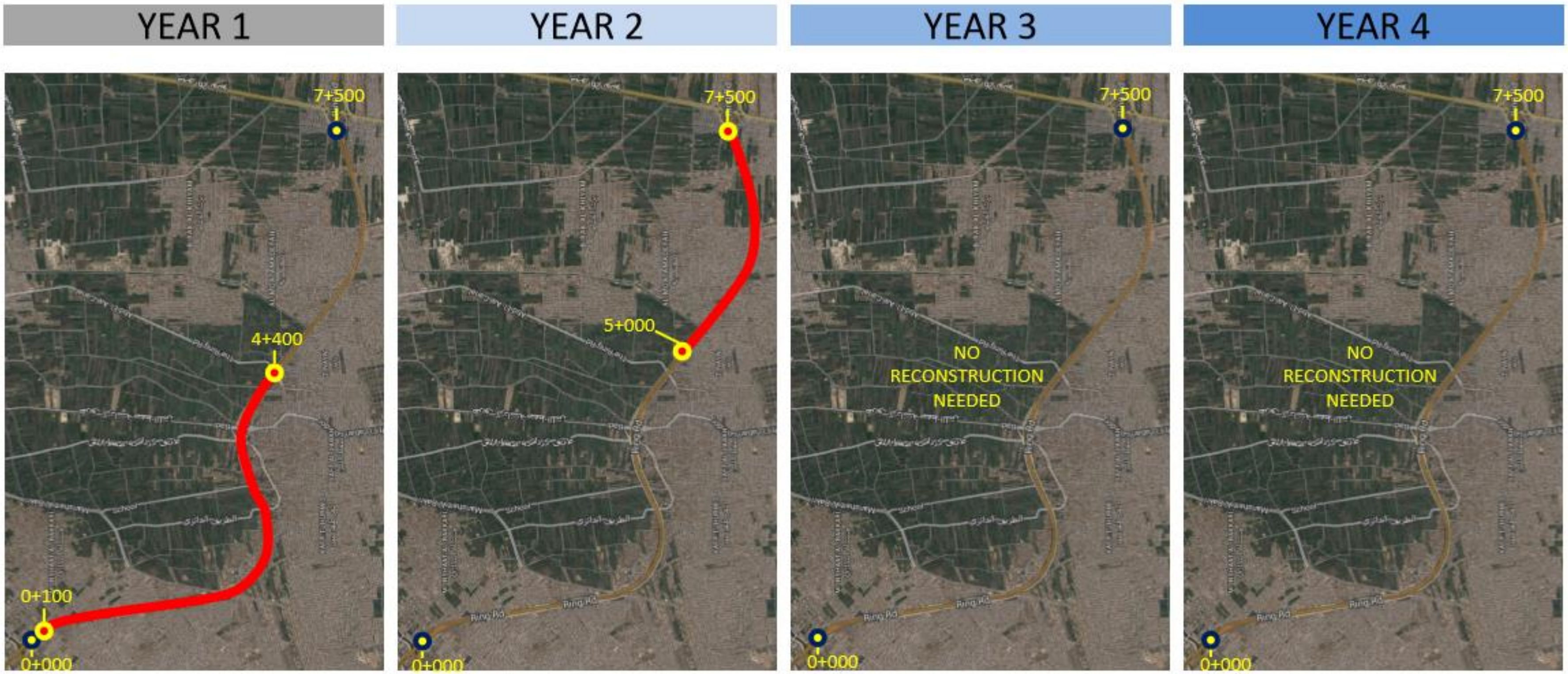
In this case, the results are presented in a different format; the use of action 7 for the 5 years is shown on the plan of the alignment under study. Figures 32, 33 and 34 are a representation of the mean, minimum and maximum simulation results respectively.

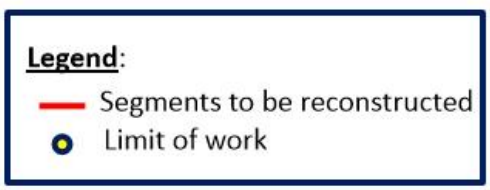



**Legend**:
- Segments to be reconstructed
- Limit of work

| Segments to Be Reconstructed by Station | | |
|---|---|---|
| Year | Start Station | End Station |
| 1 | 0+550 | 2+550 |
| 2 | 4+400 | 7+150 |
| 3 | 0+050 | 0+500 |
| | 2+650 | 4+350 |

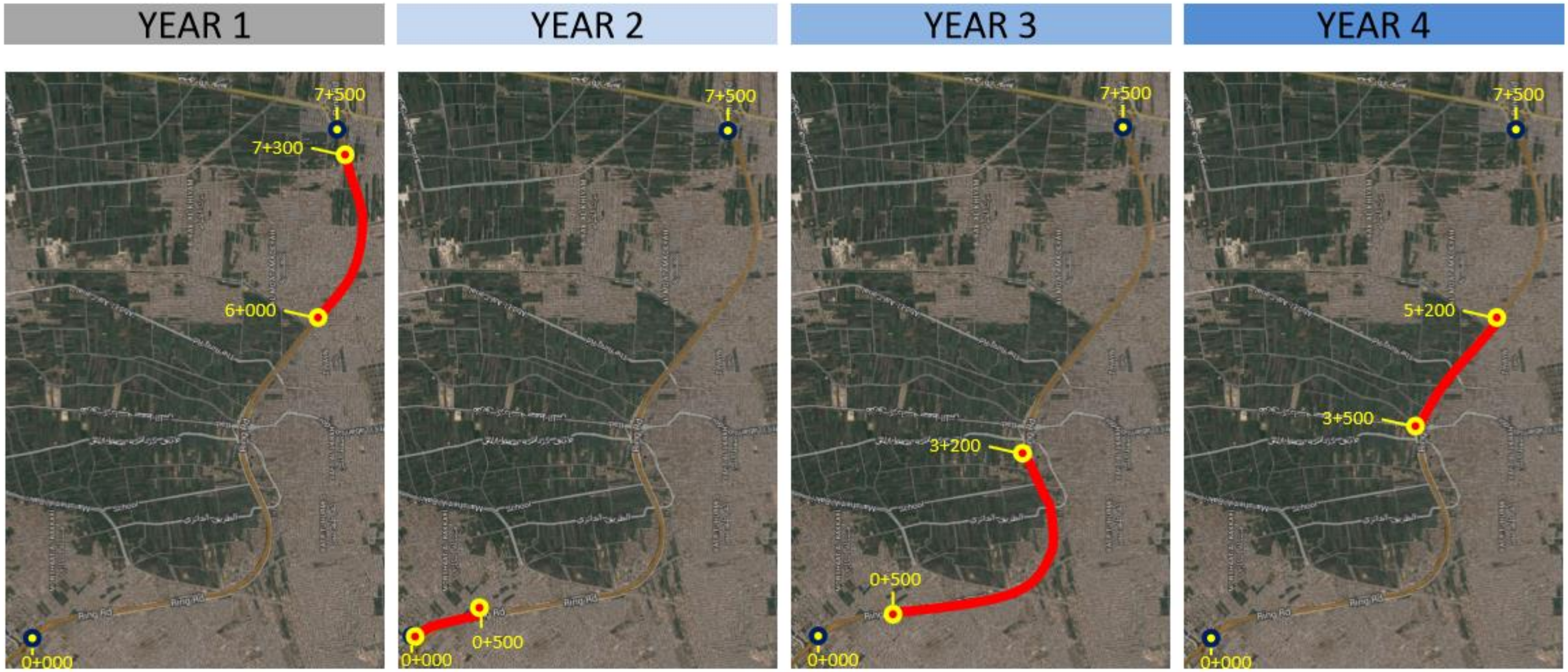
**Figure 32: Segments to Be Reconstructed – Mean Simulation Results**




| Segments to Be Reconstructed by Station | | |
|---|---|---|
| Year | Start Station | End Station |
| 1 | 0+100 | 4+400 |
| 2 | 5+000 | 7+500 |

**Figure 33: Segments to Be Reconstructed – Minimum Simulation Results**





| Segments to Be Reconstructed by Station | | |
|---|---|---|
| Year | Start Station | End Station |
| 1 | 6+000 | 7+300 |
| 2 | 0+000 | 0+500 |
| 3 | 0+500 | 3+200 |
| 4 | 3+500 | 5+200 |

**Figure 34: Segments to Be Reconstructed – Maximum Simulation Results**

The results for the mean case can be summarized as shown in Figure 32, that the reconstruction works only took place in the first three years. This action was not taken in years 4 and 5. The segments to be reconstructed were grouped at each year as shown. The total agency cost was 9,913,386 EGP which meets the set constraints. As for the minimum simulation results, Figure 33 depicts the fact that action 7 was used during the first 2 years only and that once again the model grouped the segments on which action 7 was applied. The total cost in this case was 8,725,428. Finally for the maximum simulation, the reconstruction works took place over a period of 4 years as shown in Figure 33 and resulted with a total agency cost of 9,986,534.

The spread of action 7 over different years depending on the simulation mode is due to the fact that when the simulation is maximized, the large probabilities are selected and therefore the assets have the tendency to remain in their condition rather than move to another one and when minimized, the small probabilities are selected and therefore the model becomes more dynamic at earlier years.

The hypothesis made for the verification of the model is therefore confirmed and that in order to obtain the optimum minimal solution, the simulation should be set to give the minimum.

For all three runs, the optimization duration was around 40 hours, which exceeds all the previous models running duration, which is expected given the complexity of the model as well as the simulation process that took place for the *Rand* variables.

It is important to note that in all three cases most of the alignment under study has been reconstructed over the five years horizon, and this is due to the initial condition of this stretch that is poor.

# VIII- Conclusion and Recommendations

## A. Conclusion

Based on the previous findings, a set of conclusions can be drawn. First, the application of the model in a linear or nonlinear method affect both the duration of the optimization exercise and the final results obtained. It was found that the linear models give more economical solutions. The linear models have the tendency to allocate all the interventions at early years to dramatically decrease the user cost over the five years plan as well as incurring only the first year the major agency costs. As for the integration of uncertainties in the model, the Robust model implementation resulted in the highest costs in comparison with the others. The later is due to the fact that Robust model customized itself on the worst case Scenario. The results of the Hurwics criterion were then recorded and it was noted that they produced figures that fall between the Standard and Robust model results (i.e. worst and best case scenarios). This outcome is also a verification of the models as it confirms the hypothesis of the possible scenarios and the implication they have on the costs. Finally, the upgrade of these models to account for the distances between a stretch and the other was developed. This was performed on two stages, first a set of equation was done followed by its translation into an Excel model. Three simulations were carried out for this model –minimum, mean and maximum. The former resulted in the least cost given it selected the deterioration probabilities to give the minimum of the minimum score of total costs and distance factor, whereas the two others were for the verification and resulted in higher costs respectively. In all cases, linear, nonlinear or spatial, the reduction of the cost occurred when the models had the tendency to reconstruct most of the asset at early years of the plan; in other words, when actions are spread over the five years, the costs incurred were higher (mainly due to user costs).

## B. Recommendations for Future Works

A set of recommendations are made hereunder for future works that could continue the chain of research already initiated by this thesis:

- Develop both the Robust and Hurwics criterion models to account for distances and evaluate the findings as compared to the original ones.
- Develop the Spatial model using the linear integer technique.
- Take each of the models that include uncertainties (Robust and Hurwics criterion) and try different combinations of uncertainty and optimism levels and evaluate the results.
- Further develop the data inventory modules to account for different assets, in other words provide a breakdown of the elements composing other assets.
- Further develop the deterioration model module to include other technique such as fuzzification, regression and linear.
- Develop models on different tools than the ones used in this thesis and minimize the optimization duration.
- Apply the Robust and Hurwics Criterion concepts on the cost to account for costs fluctuations and markets uncertainties.

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# Appendix A: Deterioration Matrices

| Action 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.7 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 2 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.6 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 3 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.8 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 4 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 5 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.6 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 6 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 0.95 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.2 | 0.7 | 0.1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0.3 | 0.6 | 0.1 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0.4 | 0.5 | 0.1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 | 0.1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

| Action 7 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

# Appendix B: Model Engine of All Models

## Standard – Nonlinear model

| Year | Condition | Fraction 1 | Fraction 1 Check | Action | Fraction 2 | Fraction 2 check | User Cost | Agency cost | Total Costs |
|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 1 | 1 | 0.000 | 1 | - | 0.000 | 1 | 0 | 0 | 0 |
| | 2 | 0.000 | | - | 0.000 | | 0 | 0 | 0 |
| | 3 | 0.000 | | - | 0.000 | | 0 | 0 | 0 |
| | 4 | 0.025 | | 1 | 0.015 | | 42000 | 0 | 42000 |
| | 5 | 0.945 | | 1 | 0.483 | | 3183600 | 0 | 3183600 |
| | 6 | 0.030 | | 1 | 0.485 | | 176400 | 0 | 176400 |
| | 7 | 0.000 | | - | 0.018 | | 0 | 0 | 0 |
| | 8 | 0.000 | | - | 0.000 | | 0 | 0 | 0 |
| 2 | 1 | 0.000 | 1 | - | 0.309 | 1 | 0 | 0 | 0 |
| | 2 | 0.000 | | - | 0.000 | | 0 | 0 | 0 |
| | 3 | 0.000 | | - | 0.004 | | 0 | 0 | 0 |
| | 4 | 0.009 | | 4 | 0.004 | | 15120 | 50198 | 65318 |
| | 5 | 0.247 | | 1 | 0.125 | | 832860 | 0 | 832860 |
| | 6 | 0.435 | | 1 | 0.298 | | 2564709 | 0 | 2564709 |
| | 7 | 0.296 | | 7 | 0.261 | | 2742894 | 6475723 | 9218617 |
| | 8 | 0.013 | | 7 | 0.000 | | 132300 | 274866 | 407166 |
| 3 | 1 | 0.278 | 1 | 1 | 0.690 | 1 | 0 | 0 | 0 |
| | 2 | 0.031 | | 2 | 0.057 | | 0 | 3899 | 3899 |
| | 3 | 0.003 | | 3 | 0.006 | | 2646 | 5821 | 8467 |
| | 4 | 0.004 | | 4 | 0.002 | | 5897 | 19577 | 25474 |
| | 5 | 0.064 | | 1 | 0.032 | | 214565 | 0 | 214565 |
| | 6 | 0.181 | | 1 | 0.104 | | 1068877 | 0 | 1068877 |
| | 7 | 0.257 | | 7 | 0.109 | | 2379817 | 5618533 | 7998350 |
| | 8 | 0.183 | | 7 | 0.000 | | 1923532 | 3996330 | 5919861 |
| 4 | 1 | 0.621 | 1 | 1 | 0.730 | 1 | 0 | 0 | 0 |
| | 2 | 0.115 | | 2 | 0.173 | | 0 | 14485 | 14485 |
| | 3 | 0.016 | | 3 | 0.019 | | 13215 | 29072 | 42287 |
| | 4 | 0.003 | | 5 | 0.011 | | 4812 | 25094 | 29906 |
| | 5 | 0.017 | | 5 | 0.007 | | 56541 | 181780 | 238322 |
| | 6 | 0.058 | | 1 | 0.025 | | 341022 | 0 | 341022 |
| | 7 | 0.095 | | 7 | 0.035 | | 882475 | 2083443 | 2965918 |
| | 8 | 0.076 | | 7 | 0.000 | | 801658 | 1665524 | 2467181 |
| 5 | 1 | 0.657 | 1 | 1 | 0.641 | 1 | 0 | 0 | 0 |
| | 2 | 0.212 | | 2 | 0.256 | | 0 | 26716 | 26716 |
| | 3 | 0.048 | | 1 | 0.055 | | 40291 | 0 | 40291 |
| | 4 | 0.013 | | 2 | 0.026 | | 21054 | 6842 | 27896 |
| | 5 | 0.008 | | 4 | 0.014 | | 27137 | 61465 | 88602 |
| | 6 | 0.013 | | 6 | 0.006 | | 79153 | 206929 | 286082 |
| | 7 | 0.025 | | 7 | 0.001 | | 234404 | 553407 | 787811 |
| | 8 | 0.024 | | 7 | 0.000 | | 255767 | 531381 | 787148 |

| Budget |
|---|
| 25,000,000 |

| Agency Cost |
|---|
| 21,831,088 |

| Total Cost |
|---|
| 39,873,834 |

* Minimize the total cost.
*Initial conditions are known.
*All fractions should be positive
*The folowing fractions should equal to zero:
(1) condition 8 year 2,
(2)condition 8 year 3,
(3)condition 8 year 4,
(4)conditions 8 year 5.
*At year 5, condition 1 should have at least 0.5 of the segments
*Action 7 can only be used in conditions 7 and 8
*The sum of all fractions after optimization each year should equal 1.
*The total agency cost should range between the budget and 80% of it

## Standard – Linear model

| Year | Condition | Fraction 1 | Fraction 1 Check | Action | Fraction 2 | Fraction 2 check | User Cost | Agency cost | Total Costs |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.000 | 1.000 | 1 | 1.000 | 1.000 | 0 | 0 | 0 |
| | 2 | 0.000 | | 5 | 0.000 | | 0 | 0 | 0 |
| | 3 | 0.000 | | 6 | 0.000 | | 0 | 0 | 0 |
| | 4 | 0.025 | | 7 | 0.000 | | 42000 | 545370 | 587370 |
| | 5 | 0.945 | | 7 | 0.000 | | 3183600 | 20669523 | 23853123 |
| | 6 | 0.030 | | 7 | 0.000 | | 176400 | 654444 | 830844 |
| | 7 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| | 8 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| 2 | 1 | 0.900 | 1.000 | 2 | 0.855 | 1.000 | 0 | 30316 | 30316 |
| | 2 | 0.100 | | 2 | 0.135 | | 0 | 12632 | 12632 |
| | 3 | 0.000 | | 5 | 0.010 | | 0 | 0 | 0 |
| | 4 | 0.000 | | 1 | 0.000 | | 0 | 0 | 0 |
| | 5 | 0.000 | | 1 | 0.000 | | 0 | 0 | 0 |
| | 6 | 0.000 | | 1 | 0.000 | | 0 | 0 | 0 |
| | 7 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| | 8 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| 3 | 1 | 0.770 | 1.000 | 2 | 0.731 | 1.000 | 0 | 25920 | 25920 |
| | 2 | 0.194 | | 2 | 0.223 | | 0 | 24442 | 24442 |
| | 3 | 0.034 | | 5 | 0.041 | | 28631 | 226474 | 255106 |
| | 4 | 0.003 | | 4 | 0.005 | | 5053 | 16775 | 21827 |
| | 5 | 0.000 | | 5 | 0.000 | | 0 | 0 | 0 |
| | 6 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| | 7 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| | 8 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| 4 | 1 | 0.658 | 1.000 | 2 | 0.625 | 1.000 | 0 | 22161 | 22161 |
| | 2 | 0.251 | | 3 | 0.274 | | 0 | 423345 | 423345 |
| | 3 | 0.073 | | 6 | 0.084 | | 61844 | 724810 | 786653 |
| | 4 | 0.015 | | 4 | 0.014 | | 25490 | 84628 | 110118 |
| | 5 | 0.002 | | 5 | 0.002 | | 6703 | 21551 | 28254 |
| | 6 | 0.000 | | 5 | 0.000 | | 884 | 1830 | 2715 |
| | 7 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| | 8 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| 5 | 1 | 0.563 | 1.000 | 1 | 0.515 | 1.000 | 0 | 0 | 0 |
| | 2 | 0.282 | | 1 | 0.338 | | 0 | 0 | 0 |
| | 3 | 0.114 | | 3 | 0.102 | | 95696 | 210532 | 306229 |
| | 4 | 0.034 | | 2 | 0.035 | | 57043 | 18539 | 75582 |
| | 5 | 0.007 | | 7 | 0.010 | | 23383 | 151816 | 175199 |
| | 6 | 0.001 | | 7 | 0.000 | | 7630 | 28307 | 35936 |
| | 7 | 0.000 | | 7 | 0.000 | | 1565 | 3694 | 5258 |
| | 8 | 0.000 | | 7 | 0.000 | | 111 | 230 | 340 |

| Budget |
|---|
| 25,000,000 |

| Agency Cost |
|---|
| 23,897,336 |

| Total Cost |
|---|
| 27,613,369 |

## Robust – Nonlinear model

| Year | Condition | Fraction 1 | Fraction 1 Check | Action | Fraction 2 | Fraction 2 check | User Cost | Agency cost | Total Costs |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.000 | 1.00 | 5 | 0.000 | 1.000 | 0 | 0 | 0 |
| | 2 | 0.000 | | 6 | 0.000 | | 0 | 0 | 0 |
| | 3 | 0.000 | | 6 | 0.000 | | 0 | 0 | 0 |
| | 4 | 0.025 | | 1 | 0.017 | | 42000 | 0 | 42000 |
| | 5 | 0.945 | | 2 | 0.368 | | 3183600 | 660597 | 3844197 |
| | 6 | 0.030 | | 3 | 0.615 | | 176400 | 221256 | 397656 |
| | 7 | 0.000 | | 1 | 0.000 | | 0 | 0 | 0 |
| | 8 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| 2 | 1 | 0.000 | 1.00 | 5 | 0.160 | 1.001 | 0 | 0 | 0 |
| | 2 | 0.000 | | 1 | 0.000 | | 0 | 0 | 0 |
| | 3 | 0.000 | | 1 | 0.009 | | 0 | 0 | 0 |
| | 4 | 0.011 | | 4 | 0.142 | | 18573 | 61664 | 80237 |
| | 5 | 0.341 | | 3 | 0.134 | | 1148111 | 2052249 | 3200360 |
| | 6 | 0.488 | | 2 | 0.311 | | 2879365 | 575873 | 3455239 |
| | 7 | 0.160 | | 7 | 0.244 | | 1484692 | 3505224 | 4989916 |
| | 8 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| 3 | 1 | 0.160 | 1.00 | 1 | 0.485 | 1.003 | 0 | 0 | 0 |
| | 2 | 0.000 | | 1 | 0.001 | | 0 | 0 | 0 |
| | 3 | 0.009 | | 1 | 0.103 | | 7615 | 0 | 7615 |
| | 4 | 0.094 | | 5 | 0.100 | | 158547 | 826823 | 985370 |
| | 5 | 0.172 | | 6 | 0.032 | | 578017 | 2408887 | 2986904 |
| | 6 | 0.242 | | 1 | 0.219 | | 1429422 | 0 | 1429422 |
| | 7 | 0.325 | | 7 | 0.063 | | 3012289 | 7111740 | 10124029 |
| | 8 | 0.000 | | 7 | 0.000 | | 0 | 0 | 0 |
| 4 | 1 | 0.484 | 1.00 | 1 | 0.603 | 1.004 | 0 | 0 | 0 |
| | 2 | 0.002 | | 1 | 0.003 | | 0 | 0 | 0 |
| | 3 | 0.103 | | 4 | 0.102 | | 86437 | 355257 | 441694 |
| | 4 | 0.067 | | 6 | 0.066 | | 112022 | 798157 | 910179 |
| | 5 | 0.064 | | 1 | 0.059 | | 217048 | 0 | 217048 |
| | 6 | 0.165 | | 1 | 0.128 | | 973596 | 0 | 973596 |
| | 7 | 0.120 | | 7 | 0.043 | | 1112093 | 2625551 | 3737644 |
| | 8 | 0.000 | | 2 | 0.000 | | 0 | 0 | 0 |
| 5 | 1 | 0.602 | 1.00 | 1 | 0.601 | 1.005 | 0 | 0 | 0 |
| | 2 | 0.004 | | 2 | 0.033 | | 0 | 567 | 567 |
| | 3 | 0.102 | | 6 | 0.093 | | 85840 | 1006048 | 1091889 |
| | 4 | 0.044 | | 3 | 0.022 | | 73985 | 174974 | 248958 |
| | 5 | 0.077 | | 1 | 0.073 | | 258083 | 0 | 258083 |
| | 6 | 0.100 | | 1 | 0.081 | | 589627 | 0 | 589627 |
| | 7 | 0.076 | | 1 | 0.102 | | 706110 | 0 | 706110 |
| | 8 | 0.000 | | 1 | 0.000 | | 0 | 0 | 0 |

| Budget |
|---|
| 25,000,000 |
| **Uncertainity Level** |
| 0.3 |
| **Agency Cost** |
| 22,384,867 |
| **Total Cost** |
| 40,718,342 |

Robust – Linear model

| Year | Condition | Fraction 1 | Fraction 1 Check | Action | Fraction 2 | Fraction 2 check | User Cost | Agency cost | Total Costs |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.000 | 1.000 | 6 | 0.945 | 1.000 | - | - | - |
| | 2 | 0.000 | | 5 | 0.000 | | - | - | - |
| | 3 | 0.000 | | 6 | 0.000 | | - | - | - |
| | 4 | 0.025 | | 1 | 0.011 | | 42,000 | - | 42,000 |
| | 5 | 0.945 | | 7 | 0.014 | | 3,183,600 | 20,669,523 | 23,853,123 |
| | 6 | 0.030 | | 1 | 0.016 | | 176,400 | - | 176,400 |
| | 7 | 0.000 | | 7 | 0.014 | | - | - | - |
| | 8 | 0.000 | | 7 | 0.000 | | - | - | - |
| 2 | 1 | 0.879 | 1.000 | 1 | 0.858 | 1.000 | - | - | - |
| | 2 | 0.066 | | 2 | 0.114 | | - | 8,357 | 8,357 |
| | 3 | 0.000 | | 5 | 0.013 | | - | - | - |
| | 4 | 0.005 | | 1 | 0.004 | | 7,766 | - | 7,766 |
| | 5 | 0.010 | | 3 | 0.008 | | 33,995 | 60,766 | 94,761 |
| | 6 | 0.019 | | 7 | 0.003 | | 109,880 | 407,653 | 517,533 |
| | 7 | 0.010 | | 7 | 0.000 | | 96,410 | 227,616 | 324,026 |
| | 8 | 0.011 | | 7 | 0.000 | | 116,960 | 242,995 | 359,955 |
| 3 | 1 | 0.798 | 1.000 | 1 | 0.743 | 1.000 | - | - | - |
| | 2 | 0.145 | | 2 | 0.172 | | - | 18,282 | 18,282 |
| | 3 | 0.040 | | 1 | 0.061 | | 33,862 | - | 33,862 |
| | 4 | 0.004 | | 6 | 0.013 | | 7,285 | 51,907 | 59,192 |
| | 5 | 0.004 | | 6 | 0.003 | | 14,526 | 60,537 | 75,063 |
| | 6 | 0.007 | | 1 | 0.005 | | 43,744 | - | 43,744 |
| | 7 | 0.001 | | 7 | 0.003 | | 13,181 | 31,120 | 44,302 |
| | 8 | 0.000 | | 7 | 0.000 | | - | - | - |
| 4 | 1 | 0.691 | 1.000 | 1 | 0.643 | 1.000 | - | - | - |
| | 2 | 0.179 | | 1 | 0.197 | | - | - | - |
| | 3 | 0.093 | | 5 | 0.122 | | 78,338 | 619,657 | 697,996 |
| | 4 | 0.018 | | 6 | 0.019 | | 30,887 | 220,067 | 250,953 |
| | 5 | 0.008 | | 6 | 0.008 | | 27,196 | 113,341 | 140,537 |
| | 6 | 0.005 | | 3 | 0.006 | | 27,435 | 34,412 | 61,847 |
| | 7 | 0.003 | | 4 | 0.002 | | 27,663 | 30,957 | 58,620 |
| | 8 | 0.003 | | 6 | 0.003 | | 29,004 | 47,511 | 76,515 |
| 5 | 1 | 0.598 | 1.000 | 1 | 0.564 | 1.000 | - | - | - |
| | 2 | 0.191 | | 2 | 0.219 | | - | 24,066 | 24,066 |
| | 3 | 0.148 | | 5 | 0.159 | | 124,501 | 984,800 | 1,109,300 |
| | 4 | 0.034 | | 6 | 0.034 | | 57,283 | 408,138 | 465,421 |
| | 5 | 0.013 | | 6 | 0.016 | | 44,522 | 185,547 | 230,069 |
| | 6 | 0.009 | | 6 | 0.006 | | 51,995 | 135,931 | 187,926 |
| | 7 | 0.003 | | 7 | 0.001 | | 29,940 | 70,686 | 100,627 |
| | 8 | 0.005 | | 7 | 0.000 | | 48,126 | 99,986 | 148,111 |

| Budget |
|---|
| 25,000,000 |

| Uncertainity level |
|---|
| 0.30 |

| Agency Cost |
|---|
| 24,753,855 |

| Total Cost |
|---|
| 29,210,354 |

## Hurwics Criterion – Nonlinear model

| Year | Condition | Fraction 1 | Fraction 1 Check | Action | Fraction 2 (worst) | Fraction 2 worst check | Fraction 1 (Best) | Fraction 1 Best Check | Fraction 2 (Best) | Fraction 2 best check | User Cost | Agency cost | Total Costs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 0 | | 1 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 2 | 0 | | 1 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 3 | 0 | | 1 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| 1 | 4 | 0.024938 | 1 | 1 | 0.012733 | 1 | 0.025 | 1 | 0.015 | 1 | 42000 | 0 | 42000 |
| | 5 | 0.945137 | | 1 | 0.347680 | | 0.945 | | 0.498 | | 3183600 | 0 | 3183600 |
| | 6 | 0.029925 | | 6 | 0.632167 | | 0.030 | | 0.485 | | 176400 | 461160 | 637560 |
| | 7 | 0 | | 1 | 0.003002 | | 0.000 | | 0.003 | | 0 | 0 | 0 |
| | 8 | 0 | | 7 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 1 | 0 | | 1 | 0.635170 | | 0.000 | | 0.635 | | 0 | 0 | 0 |
| | 2 | 0 | | 1 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 3 | 0 | | 4 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| 2 | 4 | 0.006501 | 1 | 1 | 0.003319 | 1 | 0.008 | 1 | 0.004 | 1 | 11907.9234 | 0 | 11907.923 |
| | 5 | 0.124544 | | 2 | 0.152754 | | 0.177 | | 0.146 | | 507356.577 | 87049.455 | 594406.03 |
| | 6 | 0.22778 | | 4 | 0.194856 | | 0.326 | | 0.186 | | 1632000.42 | 2050486.8 | 3682487.2 |
| | 7 | 0.63517 | | 7 | 0.006335 | | 0.488 | | 0.023 | | 5199844.61 | 13890737 | 19090582 |
| | 8 | 0 | | 1 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| | 1 | 0.63517 | | 1 | 0.635170 | | 0.635 | | 0.572 | | 0 | 0 | 0 |
| | 2 | 0 | | 1 | 0.000000 | | 0.000 | | 0.064 | | 0 | 0 | 0 |
| | 3 | 0 | | 2 | 0.000000 | | 0.000 | | 0.000 | | 0 | 0 | 0 |
| 3 | 4 | 0.001695 | 1 | 1 | 0.024113 | 1 | 0.002 | 1 | 0.022 | 1 | 3104.32989 | 0 | 3104.3299 |
| | 5 | 0.053661 | | 6 | 0.026383 | | 0.052 | | 0.028 | | 177132.274 | 753288.03 | 930420.3 |
| | 6 | 0.100076 | | 1 | 0.005312 | | 0.095 | | 0.045 | | 576220.901 | 0 | 576220.9 |
| | 7 | 0.201191 | | 1 | 0.301267 | | 0.209 | | 0.120 | | 1901040.26 | 0 | 1901040.3 |
| | 8 | 0 | | 1 | 0.000000 | | 0.000 | | 0.141 | | 0 | 0 | 0 |
| | 1 | 0.63517 | | 1 | 0.941748 | | 0.572 | | 0.878 | | 0 | 0 | 0 |
| | 2 | 0 | | 1 | 0.000000 | | 0.052 | | 0.064 | | 0 | 0 | 0 |
| | 3 | 0 | | 1 | 0.006025 | | 0.012 | | 0.006 | | 4910.8992 | 0 | 4910.8992 |
| 4 | 4 | 0.012312 | 1 | 4 | 0.001779 | 1 | 0.011 | 1 | 0.005 | 1 | 20034.0127 | 68842.605 | 88876.617 |
| | 5 | 0.020212 | | 1 | 0.011370 | | 0.020 | | 0.011 | | 67452.379 | 0 | 67452.379 |
| | 6 | 0.017285 | | 1 | 0.013242 | | 0.018 | | 0.017 | | 104061.452 | 0 | 104061.45 |
| | 7 | 0.306578 | | 7 | 0.017285 | | 0.166 | | 0.010 | | 2187839.65 | 6704662.8 | 8892502.5 |
| | 8 | 0 | | 1 | 0.000000 | | 0.141 | | 0.000 | | 741224.132 | 0 | 741224.13 |
| | 1 | 0.941748 | | 1 | 0.941748 | | 0.878 | | 0.848 | | 0 | 0 | 0 |
| | 2 | 0 | | 1 | 0.000000 | | 0.052 | | 0.094 | | 0 | 0 | 0 |
| | 3 | 0.003762 | | 1 | 0.002349 | | 0.016 | | 0.003 | | 8113.37617 | 0 | 8113.3762 |
| 5 | 4 | 0.003162 | 1 | 1 | 0.003022 | 1 | 0.005 | 1 | 0.003 | 1 | 6719.24662 | 0 | 6719.2466 |
| | 5 | 0.004707 | | 1 | 0.003076 | | 0.006 | | 0.004 | | 18298.116 | 0 | 18298.116 |
| | 6 | 0.007449 | | 1 | 0.003084 | | 0.007 | | 0.005 | | 43847.188 | 0 | 43847.188 |
| | 7 | 0.030527 | | 1 | 0.037976 | | 0.027 | | 0.014 | | 268248.503 | 0 | 268248.5 |
| | 8 | 0 | | 3 | 0.000000 | | 0.000 | | 0.021 | | 0 | 0 | 0 |

| Budget |
|---|
| 25,000,000 |

| Uncertainity Level |
|---|
| 0.3 |

| Optimisim Level |
|---|
| 0.5 |

| Agency Cost |
|---|
| 24,016,227 |

| Total Cost |
|---|
| 40,897,583 |

# Hurwics Criterion – Linear model

| Year | Condition | Fraction 1 (worst) | Fraction 1 Check (worst) | Action | Fraction 2 (worst) | Fraction 2 check (worst) | Fraction 1 (best) | Fraction 1 Check (best) | Fraction 2 (best) | Fraction 2 check (best) | User Cost | Agency cost | Total Costs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.000 | 1.000 | 6 | 0.945 | 1.000 | 0.000 | 1.000 | 0.945 | 1.000 | - | - | - |
| | 2 | 0.000 | | 5 | 0.000 | | 0.000 | | 0.000 | | - | - | - |
| | 3 | 0.000 | | 6 | 0.003 | | 0.000 | | 0.010 | | - | - | - |
| | 4 | 0.025 | | 5 | 0.012 | | 0.025 | | 0.012 | | 42,000 | 219,030 | 261,030 |
| | 5 | 0.945 | | 7 | 0.018 | | 0.945 | | 0.014 | | 3,183,600 | 20,669,523 | 23,853,123 |
| | 6 | 0.030 | | 5 | 0.021 | | 0.030 | | 0.015 | | 176,400 | 365,148 | 541,548 |
| | 7 | 0.000 | | 7 | 0.000 | | 0.000 | | 0.003 | | - | - | - |
| | 8 | 0.000 | | 7 | 0.000 | | 0.000 | | 0.000 | | - | - | - |
| 2 | 1 | 0.898 | 1.000 | 1 | 0.853 | 1.000 | 0.898 | 1.000 | 0.810 | 1.000 | - | 180 | 180 |
| | 2 | 0.047 | | 3 | 0.074 | | 0.047 | | 0.135 | | - | 79,590 | 79,590 |
| | 3 | 0.003 | | 5 | 0.021 | | 0.009 | | 0.013 | | 5,103 | 40,365 | 45,468 |
| | 4 | 0.007 | | 5 | 0.008 | | 0.008 | | 0.010 | | 12,894 | 67,242 | 80,136 |
| | 5 | 0.011 | | 5 | 0.012 | | 0.010 | | 0.010 | | 34,709 | 111,589 | 146,298 |
| | 6 | 0.016 | | 5 | 0.026 | | 0.013 | | 0.014 | | 84,260 | 174,419 | 258,679 |
| | 7 | 0.017 | | 6 | 0.003 | | 0.013 | | 0.007 | | - | 259,375 | 259,375 |
| | 8 | 0.000 | | 7 | 0.003 | | 0.002 | | 0.001 | | 11,435 | 23,756 | 35,191 |
| 3 | 1 | 0.811 | 1.000 | 2 | 0.755 | 1.000 | 0.770 | 1.000 | 0.758 | 1.000 | - | 188 | 188 |
| | 2 | 0.108 | | 3 | 0.165 | | 0.161 | | 0.188 | | - | 226,493 | 226,493 |
| | 3 | 0.027 | | 6 | 0.055 | | 0.027 | | 0.035 | | 22,739 | 266,500 | 289,239 |
| | 4 | 0.006 | | 7 | 0.008 | | 0.007 | | 0.006 | | 11,076 | 143,826 | 154,903 |
| | 5 | 0.007 | | 6 | 0.006 | | 0.007 | | 0.007 | | 24,072 | 100,321 | 124,394 |
| | 6 | 0.013 | | 5 | 0.010 | | 0.009 | | 0.005 | | 65,912 | 136,439 | 202,351 |
| | 7 | 0.023 | | 7 | 0.000 | | 0.014 | | 0.001 | | - | 398,928 | 398,928 |
| | 8 | 0.005 | | 7 | 0.000 | | 0.006 | | 0.000 | | 56,062 | 116,474 | 172,536 |
| 4 | 1 | 0.717 | 1.000 | 2 | 0.653 | 1.000 | 0.720 | 1.000 | 0.693 | 1.000 | - | 174 | 174 |
| | 2 | 0.185 | | 2 | 0.238 | | 0.206 | | 0.247 | | - | 24,660 | 24,660 |
| | 3 | 0.068 | | 3 | 0.085 | | 0.052 | | 0.041 | | 50,431 | 110,949 | 161,380 |
| | 4 | 0.010 | | 2 | 0.016 | | 0.007 | | 0.010 | | 14,110 | 4,586 | 18,695 |
| | 5 | 0.005 | | 7 | 0.004 | | 0.005 | | 0.005 | | 16,830 | 109,266 | 126,096 |
| | 6 | 0.006 | | 6 | 0.003 | | 0.006 | | 0.002 | | 34,651 | 90,588 | 125,239 |
| | 7 | 0.009 | | 7 | 0.001 | | 0.005 | | 0.001 | | - | 147,307 | 147,307 |
| | 8 | 0.000 | | 6 | 0.000 | | 0.001 | | 0.001 | | 3,666 | 6,006 | 9,672 |
| 5 | 1 | 0.620 | 1.000 | 2 | 0.558 | 1.000 | 0.658 | 1.000 | 0.632 | 1.000 | - | 158 | 158 |
| | 2 | 0.244 | | 3 | 0.233 | | 0.255 | | 0.288 | | - | 419,999 | 419,999 |
| | 3 | 0.103 | | 4 | 0.172 | | 0.064 | | 0.058 | | 70,322 | 289,025 | 359,347 |
| | 4 | 0.018 | | 2 | 0.028 | | 0.010 | | 0.016 | | 22,966 | 7,464 | 30,430 |
| | 5 | 0.008 | | 6 | 0.007 | | 0.006 | | 0.006 | | 24,128 | 100,555 | 124,683 |
| | 6 | 0.004 | | 7 | 0.002 | | 0.004 | | 0.001 | | 22,319 | 82,804 | 105,123 |
| | 7 | 0.003 | | 7 | 0.000 | | 0.002 | | 0.000 | | - | 56,918 | 56,918 |
| | 8 | 0.000 | | 2 | 0.000 | | 0.001 | | 0.001 | | 7,750 | 1,476 | 9,227 |

| Budget |
|---|
| 25,000,000 |

| Uncertainity level |
|---|
| 0.30 |

| Optimism level |
|---|
| 0.50 |

| Agency Cost |
|---|
| 24,851,322 |

| Total Cost |
|---|
| 28,848,758 |

# Appendix C: Interviews Credits

AbdelRaouf, Mohamed. (2010). Assitant Professor at the American Univeristy in Cairo (S. Omar, Interviewer)

Behairy, A. (2013, October). Construction Engineering Professor at the American University in Cairo (AUC). (S. Omar, Interviewer)

Hazem, A. (2014). Senior Transportation Engineer at Dar Al Handasah Shair & Partners (S. Omar, Interviewer)

Sherine, A. (2014). Senior Transportation Engineer at Dar Al Handasah Shair & Partners (S. Omar, Interviewer)