Life Cycle Cost Analysis:

Application to an airport pavement

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Dissertation for obtaining the Master's Degree in

Civil engineering

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Resumo

Na construção ou reabilitação de pavimentos de estradas já é comum proceder a uma avaliação no ciclo de vida da sustentabilidade de soluções alternativas (LCA, Life-Cycle-Analysis) e/ou uma avaliação da solução mais eficiente economicamente através de uma análise de custos no ciclo de vida (LCCA, Life-Cycle-Cost-Analysis). No entanto, para pavimentos aeroportuários, estes tipos de avaliação não se fazem comummente. A dissertação descreve os dois tipos de avaliação referidos.

A LCA usa a pegada ecológica e a contribuição para o aquecimento global das alternativas em estudo enquanto que a LCCA é mais focada na eficiência financeira no final da vida dessas alternativas. A gestão dum aeroporto está mais focada na eficiência financeira pelo que a LCCA foi usada nesta dissertação. A aplicação foi feita para a pista principal do aeroporto de Lisboa considerando uma profunda reabilitação de 20 cm nas camadas betuminosas existentes. Foram comparadas duas soluções de pavimento flexível, uma em que as misturas betuminosas são um Stone Mastic Asphalt (SMA) e outra onde são um betão betuminoso (AC). Nos cálculos foram considerados custos diretos e indiretos. Os custos diretos estão relacionados com a construção inicial e as intervenções de reabilitação, e foram calculados com informação obtida junto da administração do aeroporto e de empreiteiros que trabalham para ela. Os custos indiretos estão relacionados com a perda de receita diária devido às atividades de reabilitação do pavimento. O valor usado na análise foi um valor aproximado proveniente de informação do tráfego e sobre as taxas aplicadas à operação no aeroporto. O cálculo foi feito pelo Software Aircost (AAPTP, 2011) para um período de 30 anos e taxas de desconto diferentes (2%; 2,5% and 3%).

Os resultados da LCCA permitem dizer, para as condições usadas, que a solução SMA é a mais eficiente economicamente e isto tanto para uma análise determinística, onde os parâmetros chave que definem a análise são fixos, como para uma probabilística, onde se admite uma variação segunda determinada lei para aqueles parâmetros.

Palavras-chave

Análise de Custos no Ciclo de Vida (LCCA) – Pavimentos Aeroportuários – Pistas – Betão Betuminoso (AC) – Stone Mastic Asphalt (SMA)

Abstract

In the construction or rehabilitation investments of highways' pavements it is already common to perform a Life-Cycle-Analysis (LCA) or Life-Cycle-Cost-Analysis (LCCA) for different alternatives, but for airport pavements is these kind of analysis quite new. In the dissertation are the different steps of both analysis types listed and represented.

LCA takes the different ecological footprints and global warming potentials of the alternatives in consideration, and LCCA is more focused on the final cost of the project. For the management of an airport is the cost tag more important, so this approach will be followed in the dissertation. The application is done on the main runway of the Lisbon airport for a deep rehabilitation of 20cm in the existing bituminous layers. There are two different flexible pavement types compared, one where the main bituminous mixture is a Stone Mastic Asphalt (SMA) and other where that is an Asphalt Concrete (AC). In the calculations are the different cost factors defined, the direct costs and the indirect costs. The direct costs are related to the initial construction and M&R activities and are calculated with information from the airport-agency and constructors that work for them. The indirect costs are related with the loss of daily revenue of the airport during work activities. This figure was used more as an assumption made on information of traffic and daily operational taxes for the airport, to get a clue for the value. For the application is an analysis period of 30 years chosen and different discount rates (2%; 2,5% and 3%) used to make the calculation in the Aircost software (AAPTP, 2011).

From the results and for the conditions used for the LCCA it can be decided that the SMA-option is the most cost-effective out of the deterministic analysis, where the key parameters have a fixed value, or the probabilistic analysis, where the key parameters can change over an adopted variation law.

Key-words

Life-Cycle-Cost-Analysis (LCCA) - Airport-pavements – Runways – Asphalt Concrete (AC) – Stone Mastic Asphalt (SMA)

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List of acronyms and symbols

AAPTP	Airport Asphalt Pavement Technology Program
AC	Asphalt Concrete
ACN	Aircraft Classification Number
AIP	Airport Improvement Program
CAA	Civil Aviation Authority
EUAC	Equivalent Uniform Annual Costs
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FOD	Foreign Object Damage
HMAC	High Modulus Asphalt Concrete
INAC	Instituto Nacional da Aviação Civil
LCA	Life Cycle Analysis
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
M&R	Maintenance and Rehabilitation
NPV	Net Present Value
PCC	Portland Cement Concrete
PCI	Pavement Condition/distress Indicators
PCN	Pavement Classification Number
PFC	Porous Friction Course
PFCs	Passenger Facility Charges
SCI	Structural Condition Index
SHAs	State Highway Agencies
SMA	Stone mastic asphalt
VOC	Vehicle Operating Costs

1. Introduction

1.1. Problem description

The first question is which analysis that will be used for the comparison of different pavement types for an airport pavement. There are two kind of analysis, Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA). Traditionally, the administration of an airport will choose LCCA but both analysis will be presented in the literature review.

When they choose LCCA, the decision regarding the investment of a new pavement on an airfield was normally made only on the base of agency costs, just related to own administrative involvement and first settlement costs, which in general means the initial construction cost of a new pavement. The other life-cycle costs like rehabilitation and reconstruction were not included in the decision making process. The user costs caused by the administration M&R interventions (or the lack of them) in the long-term are usually not considered in the decision making process of a new pavement.

All these kind of costs can be more crucial on the long-term than the costs of the initial construction and will be very useful for the administration to calculate and include them in the comparison.

So it is important for agencies to make their decisions on the long-term basis and include the user and agency costs because of the growing public scrutiny on major public expenditures and the budget constraints of the agencies. This will lead to the most cost-effective pavement solution.

1.2. Objective

The main purpose is to compare and evaluate pavement alternatives by carrying out a LCA or a LCCA to find the best alternative. There will be made a comparison between flexible pavement types for an analysis period of 30 years.

Basically, it will be used the information coming from the international airport of Lisbon in order to establish the analysis conditions and reach in the end to the more sustainable solution for the pavement taking to account those conditions. The choice between a LCA or a LCCA will be described in the following chapters.

1.3. Methodology

In a simple way, 3 steps could be defined in order to reach the objective.

The first step is to present the fundamental principles of the life cycle analysis and the life cycle cost analysis applied to pavements. Then will be chose the type of analysis that will be used on an airport pavement.

The next step will be collecting relevant data to do the analysis and compare the different alternatives over the analysis period. The data will come from the Lisbon airport and the software Aircost (AAPTP, 2011) is used.

The final step is to identify the most economical solution for the pavement on the main runway 03/21 of the Lisbon airport. This will be helpful for the agency of the airport for future decisions of pavement types.

The methodology of the dissertation is shown in Figure 1. Pavement alternatives are selected and their M&R strategy is scheduled. Based on that schedule, the life-cycle user and agency costs are computed by feeding the relevant input. Then, analysis will be done on the results of the net present values and equivalent uniform annual costs. Finally, the most economical pavement type will be identified.

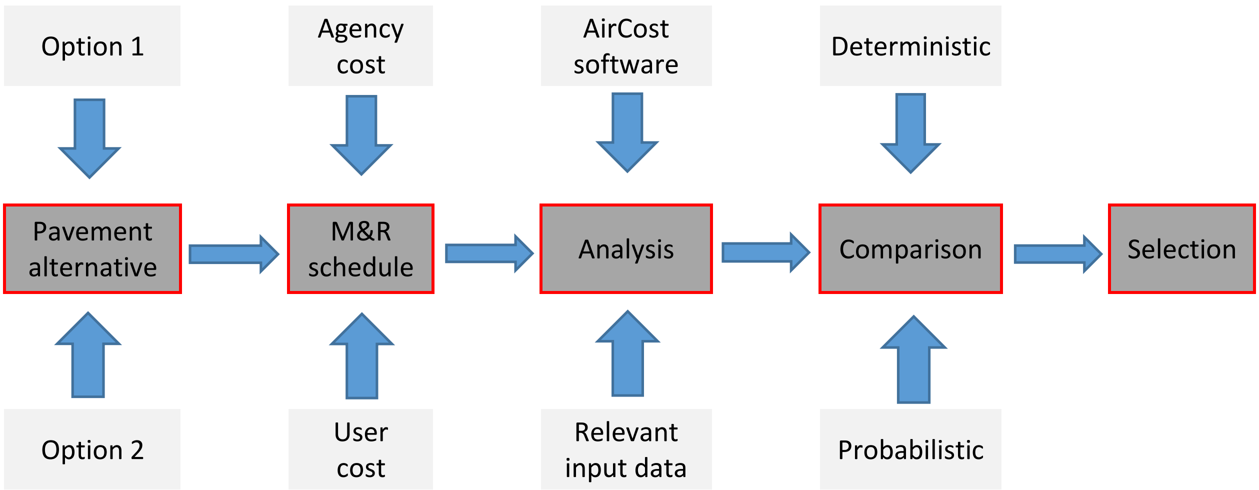

Figure 1: Methodology followed in the dissertation (adapted from Teklezghi, 2012) .

1.4. Structure of dissertation

The dissertation is structured into 9 chapters.

The first chapter is an introduction which defines the problem and the methodology and present the structure of the dissertation..

The next three chapters are a literature review about the different type of pavements on airports, LCA and LCCA in general. In chapter 2, the two pavements that are taken into consideration in the dissertation are presented. The differences between mixtures and structure are discussed. Chapter 3 gives a global view of LCA and all the different steps in the analysis. The fourth chapter gives a global view of LCCA and all the different steps in the analysis, but more applied to highways. These two previous chapters gives a good background to make the decision on what type of analysis will be used in the calculation part of the dissertation. In the end of chapter 4 is explained why LCCA is chosen instead of LCA to continue the dissertation.

Chapter five elaborates on the LCCA explicitly applied to airport pavements. It is also a literature review, but more in detail of all the items for airport pavements.

The sixth chapter gives more in detail an overview of the type of project. The dimensions, the amounts and the costs around the pavement types for the project are listed. The traffic approach on airports is short represented in this chapter with the calculation of a useful figure for the daily revenue in the Lisbon airport. Also, the input data for the LCCA in the software (Aircost, (AAPTP, 2011))e are discussed.

Chapter seven gives an overview of the deterministic and probabilistic results. There are values computed with only the agency costs included and with the agency and user costs included. The cost difference between the two alternatives is shown clearly.

The last chapter gives the main conclusion of the work. Also some recommendations are displayed for LCCA application in the future.

2. Pavement type selection for runways

2.1. Introduction

Generally, paved roads are surfaced with asphalt mixes, which gives good performance and durability under the most heavy traffic conditions. Asphalt mixes are also currently used in the construction of hard standing and parking areas for light and heavy vehicles. That's why they are eminently suitable for use in the construction and surfacing of access roads, perimeter roads and vehicle parking areas next to airfields.

Asphalt mixes give good durability and performance under the wide range of traffic and climatic conditions. In industrial areas or sites with specific applications they use more and more asphalt mixes, for example as base courses for railway tracks. In the airport construction, an asphalt mixture is also currently used.

In Europe, the construction and surfacing for the civil airports usually rests with the civil or municipal aviation authorities. These organisations often have their own standard specifications for this type of work. The responsibility of military airfields is the hands of the each nation’s Defence Ministry.

The following areas are approached differently on a typical airport:

- Runways
- Taxi-ways providing access to runways
- Aircraft parking, re-fuelling or servicing aprons hanger floors
- Car, bus or commercial vehicle parking areas
- Access roads

All of these areas require different considerations. For example, runways require good skid-resistance and surface water drainage for good braking while avoiding aquaplaning, an even surface regularity to ensure passenger comfort and minimum risk of damage to delicate electronic components and adequate strength to support the high wheel-loadings of modern aircraft.

Nowadays, it is common to use jet-engines in airplanes. So the freedom from loose particles on the surfacing is an additional, essential requirement to avoid the expensive damage that can be caused to jet engines from ingestion of foreign objects (known as Foreign Object Damage or FOD).

For paved areas where aircraft will undergo re-fuelling and servicing, the principal considerations are adequate stability under wheel-loads. Also heavy point loads from maintenance machinery as well as good resistance to oil and fuel spillage. This last characteristic is responsible for the general use of rigid pavements in this apron areas.

In the dissertation, the focus will be on the pavements of runways. Mostly the pavement type of the runways and the taxiways are the same. They need to be constructed with sufficient strength to carry the moving aircraft but from the surfacing point of view the difference between the two is that runways require a higher degree of resistance to skidding and aquaplaning in view of the higher speeds involved.

In Table 1, there is shown which pavement types are used in different countries in Europe. It is clear that the use of asphalt concrete (AC) and stone mastic asphalt (SMA) occurs often. (EAPA, 2003)

Table 1:Pavement types in different European countries (adapted from EAPA, 2003).

Country	Pavement on runways	Pavement on taxiways	Design period
Denmark	Dense AC SMA	Trad. AC	20 years
Finland	AC	AC	\
France	Airport AC HMAC	Airport or trad. AC HMAC	10 years
Germany	AC SMA	AC SMA	\
Italy	AC SMA	AC SMA	20 years
Norway	AC SMA PCC	AC SMA PCC	30 years
U.K.	Marshall asphalt PFC	Marshall asphalt	20 years

In Table 1 are also other pavement types named, High Modulus Asphalt Concrete (HMAC), Portland Cement Concrete (PCC), Marshall asphalt and Porous Friction Course (PFC). (EAPA, 2003)

2.2. Pavement types

In general, there are two big families of pavement types. There are the flexible and the rigid pavements. Further there is a mix of the two types, the semi-flexible or semi-rigid pavements. In the highway construction they use all of these types, but in the construction of runways of airports they usually use flexible pavements. In the following part the two most common types for runways are discussed. (U.S. Department of Transportation, Federal Aviation ministration, 2009)

The structure of a flexible pavement is composed of several bound and unbound layers that gives the pavement structural strength and also as drainage and frost protection. With respect to the bound layers, it consists essentially of a mineral skeleton and a bituminous binder, which may be supplemented with certain additives. The hot mixture is spread in successive layers in strips and mechanically compacted. The design of a suitable pavement requires the avoidance of permanent deformation (rutting) at moderate to high temperatures, and cracking at lower temperatures (U.S. Department of Transportation, Federal Aviation ministration, 2009). The unbound layers are mostly composed by a continuous crushed rock mineral skeleton.

In Figure 2 is shown how a flexible pavement distribute the load of a tire among his layers. The objective with the design of a flexible pavement is to avoid the excessive flexing of any layer. Failure to achieve this will result in the over stressing of a layer, which ultimately will cause a failure of the pavement.

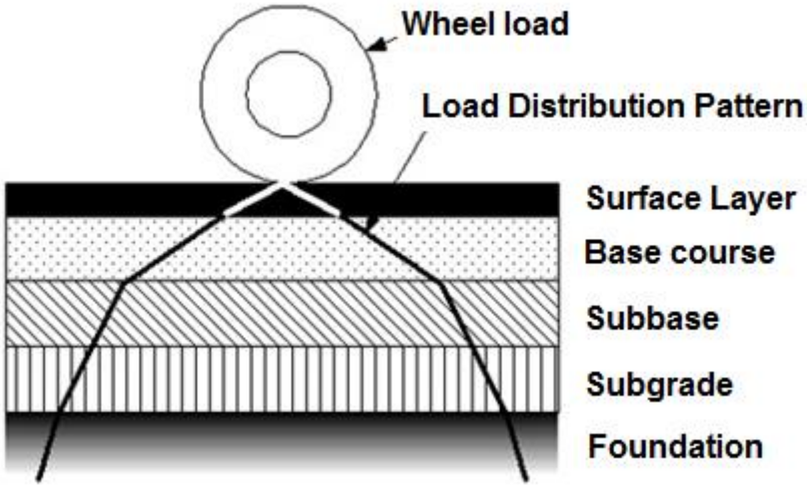

Figure 2: Load distribution (Adapted from SANRAL, n.d.)

In flexible pavements, the load distribution pattern changes from one layer to another, because the strength of the layers is different. The strongest material (least flexible) is on top and the weakest material (most flexible) is in the lowest layer. The reason for this is that at the surface the wheel load is applied to a small area, the result is high stress levels, deeper down in the pavement, the wheel load is applied to larger area, the result is lower stress levels thus enabling the use of weaker materials.

The surface layer or wearing course could be composed by two layers of bituminous mixtures and a binder course where can be used the same type of material indicated for the wearing course but without the same need of being a very good friction course. The base course could be a bituminous mixture (bound layer) follow up by an unbound continuous graded crushed rock layer, placed before the subs-base and often called "granular unbound base". The sub-base is generally composed by the same material (sometimes less controlled in quality) than the "granular unbound base". This "granular unbound base" layer could sometimes be bounded with a low content (3 to 4% in weight) of cement, forming in this case the so call "semi-flexible" pavement.

A common type of mixture, besides traditional asphalt concrete (AC), to constitute a wearing course of a flexible pavement for runways is the Stone mastic asphalt (SMA). It is a mixture with a stone skeleton, characterized by a very high content of stones. The individual stones touch each other and the loads are transferred by the stones. Because of the high contact stresses between the individual stones, the quality of the stone fraction is important. The space between the stones is filled with a mixture of fine sand, filler and bitumen. Even after compaction, there remains some significant voids. The amount of these voids specifies the subtype (4-6%). The composition of the aggregate in a percentage of mass is different for all mixtures, as shown in Table 2.

Table 2: Composition of the mineral aggregate (SMA) (Adapted from De Corte, 2013).

Name	Stone fraction	Sand fraction	Filler fraction
SMA-B	74-79	11-16	8,5-11,00
SMA-C	71-76	15-20	7,5-10,0
SMA-D	68-73	19-24	7,0-10,0

The most common bituminous mixture for a flexible pavement is a continuous graded one (all dimensions of the aggregate enter in the composition) call, Asphalt Concrete (AC). It is a mixture with a sand skeleton, characterized by a very high content of sand, about 35% of the all aggregate. The stone and sand (obtained by the crushing of an appropriate rock) forms in these mixtures the skeleton. The loads are transmitted by sand from grain to grain and the contact stresses are lower than in the case of the SMA but more spread in the mixture which can cause more deformation under the loads. The space between the sand and stones is filled with filler and bitumen. Even after compaction, there remains a certain amount of voids, which in general is under the SMA but reach similar figures (3-5% of voids). The composition of the aggregate in a percentage of mass could take several values, as shown in Table 3.

Table 3: Composition of the mineral aggregate (AC) (Adapted from De Corte, 2013).

Name	Stone fraction	Sand fraction	Filler fraction
AC – 1B	53 - 58	34 - 39	6,0 – 8,5
AC – 1B	55 - 60	32 - 37	6,0 – 8,5
AC – 1B	55 - 60	32 - 37	6,0 – 8,5
AC – 1B	45 - 55	41 - 46	4,5 – 8,5

3. Life Cycle Analysis (LCA)

3.1. Introduction

The concept of conducting a detailed examination of the life cycle of a process is a relatively recent way of approach which emerged in response to increased environmental awareness on the part of governments, industry and the general public.

The precursors of life cycle analysis and assessment (LCA's) were the global modelling studies and energy audits of the late sixties and early seventies. This way they wanted to assess the resource cost and environmental implications of different patterns of human behaviour.

LCAs were an extension, and became important to support the development of eco-labelling schemes which are operating or planned in a number of countries around the world. In order for eco-labels to be granted, the awarding authority needs to be able to evaluate the manufacturing processes involved, the energy consumption in manufacture and use, and the amount and type of waste generated.

To accurately assess the burdens placed on the environment by the manufacture of a project, the following of a procedure or the use of a certain process, two main stages are involved. The first stage is the collection of data, and the second is the interpretation of that data.

There are different terms to describe the processes, one of the first terms used was life cycle analysis. Recently there been coined two new terms to describe the processes: Life Cycle Inventory (LCI) and Life Cycle Assessment (LCA). These better reflect the different stages of the process. Other terms such as Cradle to Grave Analysis, Eco-balancing, and Material Flow Analysis are also used.

Which name is used to describe it, LCA is a tool which can assist regulators to formulate environmental legislation, help manufacturers analyse their processes and improve their products, and enable consumers to make more informed choices. The tool must be correctly used to make a relevant conclusion. (Global development research center, n.d.)

The difference between life cycle assessment and life cycle inventory is given in the following paragraphs.

Life cycle assessment (LCA) is a multi-step procedure for calculating the lifetime environmental impact of a product or service. The complete process of LCA includes goal and scope definition, inventory analysis, impact assessment, and interpretation. The process is naturally iterative as the quality and completeness of information and its plausibility is constantly being tested.

LCI is the life cycle inventory**,** which is the data collection portion of LCA. LCI is the straight-forward accounting of everything involved in the "system" of interest. It consists of detailed tracking of all the flows in and out of the product system, including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance. This kind of analysis can be extremely complex and may involve dozens of individual unit processes in a supply chain (e.g., the extraction of raw resources, various primary and secondary production processes, transportation, etc.) as well as hundreds of tracked substances. (Athena sustainable materials institute, 2015)

Life Cycle Assessment (LCA) has been created to evaluate a service throughout its life, considering the direct and indirect impacts. The ISO 14040 (2006) Standard divides the process of Life Cycle Assessment in four phases:

- The goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

After the definition of the aim and scope of the study, the main work is the development of an inventory in which all significant environmental burdens during the lifetime of the product or process are collected and quantified, followed by an assessment of impacts that are presented in order to allow its comparison or further analysis. (ISO14044, 2006)

The Life Cycle Inventory (LCI) includes different sub-steps such as raw materials extraction, transportation, production, consumption and waste disposal.

The life cycle of a pavement is divided into five phases:

- Raw materials and production
- Construction
- Use
- Maintenance
- End of life

Each phase comprises various components, each one representing a unique interaction between the pavement and the environment. There are several methodologies for LCA of road pavements, but after analysing and comparing these methods they realize that the analyses are still incomplete. (Santero, Masanet, & Horvath, 2011)

Most of the LCA methodologies ignore the road use phase, neglecting the supremacy of this phase with respect to energy consumption and gaseous emissions released during the life cycle of the road. These two aspects are in fact two of the main aspects to be taken account in the account in the analysis of life cycle.

There are some other important aspect during the use phase:

- The energy used for lightning the road

- The leachate production
- The carbonation of concrete that occurs in rigid pavements
- The albedo
- The rolling resistance

The type of material and the age of the pavement influence the reflectivity of light. The illumination needed to ensure the same visual conditions for each pavement will be different. Some studies concluded that flexible pavements spends 57% more energy than concrete mixture pavements to become enough lightning. The reflection in older pavement is less diverse, because concrete mixture pavements tend to darken and asphalt mixtures tend to lighten with time. (Santero, Masanet, & Horvath, 2011)

The leachate from road pavements is an important issue in terms of drainage and the use of rainwater in the ecosystem. When the pavement induces a pollution of the water, then this subject should be taken into account. Some published studies show a small risk of leaching of contaminants in dangerous concentrations in the runoff of storm water.

The phenomenon of carbonation of concrete in rigid pavements corresponds to carbon capture by the concrete, which can partially offset the carbon dioxide that was released during the cement production. This process goes very slow and the rate of absorption depends of aspects such as water cement ratio, cement content, the porosity of concrete and the relative humidity and the temperature of the surrounding environment.

The measure of the ability of the pavement surface to reflect the solar radiation that is coming in is called albedo. This value can vary from 0 (for total absorption) to 1 (for total reflection). For asphalt mixtures pavement is the expected value ranges between 0.05 and 0.20, while for concrete mixtures pavements the value is expected between 0.25 and 0.40. There are some factors that can influence its albedo, such as type and age of pavement surface. In case of concrete mixture pavements the albedo tends to decrease due to the darkening of the surface, as opposed to asphalt mixture pavements for which the albedo tends to increase with age, since they tend to become clearer. (Araújo, Oliveira, & Silva, 2014)

The factor of rolling resistance is in fact the energy loss due to the interaction of the pavement and the vehicle. There are many factors that can influence the rolling resistance, which can be related to the pavements, the environment and the tires. Material stiffness and surface characteristics can influence the pavement characteristics and the rolling resistance. It is logical that a portion of the vehicle's power must be used to overcome rolling resistance. The lower the rolling resistance, the lower the capacity to overcome this resistance, so the lower the power of the vehicle must be. This results in a lower fuel consumption.

Thus, it is important to choose a pavement that will maximize the fuel economy, reducing the gaseous emissions released to the atmosphere and the energy consumption. Several studies show that rigid pavements can lead to fuel savings, because flexible pavements deform under the action of vehicles.

This leads to a higher energy expenditure is necessary for the movement. Other studies claim that pavements with improved surface characteristics require a lower energy consumption in contrast to more irregular and rougher pavements. (Araújo, Oliveira, & Silva, 2014)

3.2. Developed LCA methodologies

Most of the methodologies that exist for life cycle analysis of pavements are focused on the activities of extraction, production, transportation and application of materials, concisely the construction of the road. Because it's difficult to obtain other relevant data. Is a fact that the use phase of the road is predominant with respect to energy consumption and also to gas emissions released to the atmosphere. When analysing the use phase, one of the main factors is the rolling resistance. The rolling resistance depends on the surface and structural characteristics of the different pavements. (Araújo, Oliveira, & Silva, 2014)

3.3. Conceptual organization of the methodology

1) Materials extraction and production

In this phase all the inputs and outputs of the system are considered , including extraction and crushing of aggregates, production of binders (cement, bitumen or bitumen emulsion) and production of mixtures (bituminous or hydraulic). The transport at the jobsite and a the production plant for materials and mixtures are also considered , as well as the activities and equipment inherent to loading the trucks.

2) Construction

All activities necessary for pavement construction are considered in this phase such as earthworks, foundation reinforcement (not always necessary) and application of the pavement layers. This for all types of pavement with their specific activities.

3) Use

This phase is in most of the methodologies not integrated, but no less important. Here will be the difference in rolling resistance, energy consumption and emissions compared, which depend on the type of pavement and characteristics. This methodology enables the introduction of different consumption values, which may be obtained experimentally.

4) Maintenance

Here, the operations are described that will be made on the road to ensure that adequate pavement conditions are maintained throughout its life. This all depends on the strategy that is chosen by the road administration, preventive maintenance operations or other more complex rehabilitation techniques can be integrated. Including the replacement of the pavement overlay or surface course.

5) End of life

When the road reach the end of his useful life (for which it was designed in the beginning) the last phase occurs. In this phase it also depends on the chosen strategy by the road administration. It is possible to proceed to its recovery (reconstruction of the pavement), demolition and removal of the used materials that may still be recycled or just leave the road on site. The last solution would also lead to a certain environmental burden.

In Figure 3, the interactions between the various phases described and the energy/material flows are schematically represented. The filled arrows indicate the movement of the phases in the time. The other arrows indicate the correlation between certain aspects that coincide in time. The three solutions after the end of life are shown and the arrows give the place where they can take place afterwards.

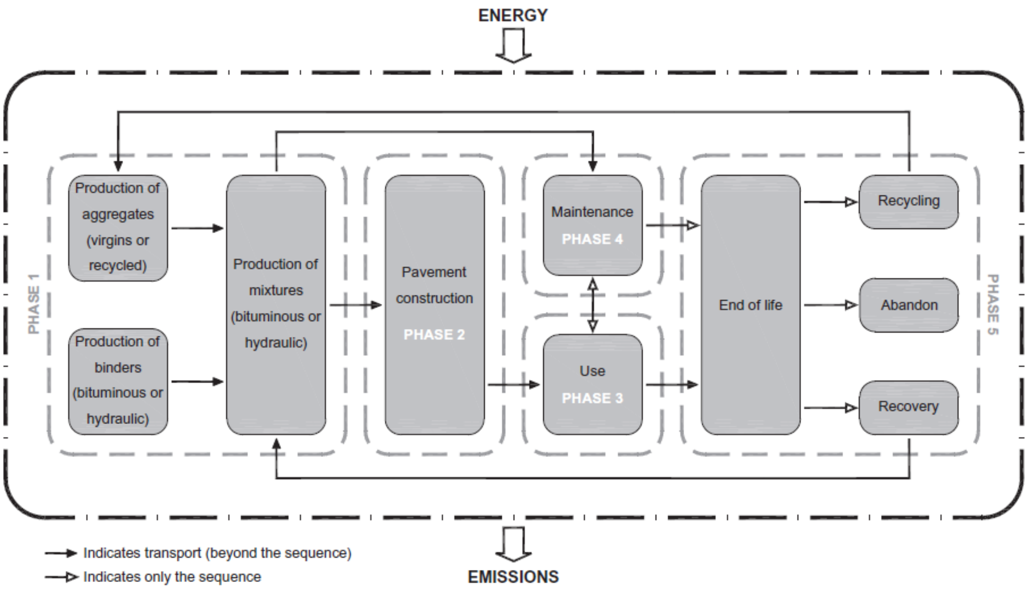

Figure 3: Energy/material interactions and flows between the phases of LCA (Adapted from Araújo, Oliveira, & Silva, 2014).

In every life cycle assessment they use a reference unit, known as the functional unit to allow that the results can be compared of the different analyses (for the different pavement solutions) . The functional unit describes the geometry, service life and levels of traffic. So, to compare the different pavements, the width and length of the road must be the same for all the options. The thickness of the layers can vary and is determined (by conventional design methods for pavements) so that all analysed options are capable of withstanding the same design traffic within a comparable service life.

It should be understood that in case of pavements, the definition of the functional unit will depend on the characteristics of each road, design traffic and its lifetime. Thus it is not the intention to compare solutions with different functional units, for example to compare a railway with a roadway is not relevant. (Araújo, Oliveira, & Silva, 2014)

3.4. Structure of the LCA methodology

To set up an analysis they use worksheets in which the various phases and components of the pavement life cycle are considered. The worksheets mostly used are organized as follows:

1) Characterization of the road:

First of all a characterization of the road and pavement is made, mainly by the geometric characteristics and the type and thickness of each pavement layer. Furthermore the indication of the average transport distances within the production plant, the jobsite and between both.

2) Material characterization:

In this worksheet the mixtures and materials are characterized, i.e. their composition, through the definition of the percentages (by mass) of each constituent and also their densities (loose and compacted). These values are used to make the calculation for the number of trips to be made by trucks for transportation.

3) Characterization of equipment's/processes:

In the third worksheet, the characterization of the different activities/processes and the equipment that is required. The unitary consumption and emissions for the activities that makes up the life cycle can be determined in this worksheet.

4) Life Cycle Inventory (LCI):

This worksheet is the inventory itself and is the main output of the methodology. It begins by presenting a summary of the characteristics of the road and a detailed map of the quantities of materials and mixtures needed. Subsequently the presentation of consumptions and emissions that result from each activity, which are after presented in overall terms and grouped by impact categories, for analysis and comparison purposes.

One of the most important categories to be taken into account is Global Warming Potential (GWP). The GWP will be determined by converting CO_2, CH_4 and N_2O, because of their potential for the greenhouse effect, in CO_2-equivalent emissions using the conversion factors of 1, 23 and 296, respectively.

GWP = $CO_2 + 23CH_4 + 296N_2O$

Total energy consumption (TEC) = $\sum_{i=1}^{n}\sum_{j=1}^{m} \left(UFC_i * UEFC_i * V_j \right)$ $[J]$

In this equation: UFC_i = Unitary fuel consumption of equipment i (l/m³)

$UEFC_i$ = Unitary energy consumption conversion factor of the fuel used in the equipment (l/m)

V_j = Volume of the material/mixture j used (m³)

Total emissions of the gas g released ($TER_{(g)}$) = $\sum_{i=1}^{n}\sum_{j=1}^{m} (UER_{(g)_i} * UFC_i * V_j)$ [kg]

In this equation: $UER_{(g)_i}$ = Unitary emissions of the gas g released by the equipment i (kg/l)

UFC_i = unitary fuel consumption of equipment i (J/l)

V_j = Volume of the material/mixture j used (m^3)

5) Life Cycle Cost Analysis (LCCA):

This worksheet includes the costs of each alternative. This type of analysis will be discussed in the next chapter of the dissertation.

6) Analysis of the road use phase:

The last worksheet is not always included in existing methods, by analysing the use phase of the road. This mainly keep quantifying the impact that result from the traffic on the pavement. There will be made a prediction of the fuel consumed by the design traffic during the lifetime of the road and also gaseous emissions released as a result of that fuel combustion. This is possible with experimental data to compare the fuel consummation between the possible pavements and also determines the differences of the fuel, costs and emissions compared with a reference pavement. The calculation will be made for the total fuel consumption between 0 and n years ($\mathrm{TFCV}_{(y_0 - y_n)}$) and for the total of emissions of the gas between 0 and n years ($TERV_{(g)_{(y_0 - y_n)}}$). (Araújo, Oliveira, & Silva, 2014)

4. Life Cycle Cost Analysis (LCCA)

4.1. Introduction

To determine the most effective method and timing, all new construction, reconstruction and maintenance projects should employ some level of economic evaluation. The Federal Highway Administration (FHWA), U.S. department of transportation, defines it as:

"...an analysis technique that builds on the well-founded principles of economic analysis to evaluate the over-all-long-term economic efficiency between competing alternative investment options. It does not address equity issues. It incorporates initial and discounted future agency, user, and other relevant costs over the life of alternative investments. It attempts to identify the best value (the lowest long-term cost that satisfies the performance objective being sought) for investment expenditures." (U.S. Department of Transportation, Federal Aviation administration, 2014).

Life cycle cost analysis is useful as an decision tool when selecting a pavement type, defining structure and mix types, ways of construction, as well as maintenance and rehabilitation strategy. LCCA follows basically the following steps:

1) Initial strategy and analysis decisions:

First of all there need to be some baseline decisions, estimates and assumptions to establish the parameters under which a LCCA can be conducted.

2) Estimate costs:

For every alternative the costs associated with the owning agency and users are set up and calculated.

3) Compare the alternatives:

The part of comparison involves expressing every alternative using a common metrics such as net present value (NPV) or Equivalent Uniform Annual Costs (EUAC).

4) Analyse the results and re-evaluate the alternatives:

Results should be examined for the most influential costs, factors and assumptions. Usually they use a sensitivity analysis to do this. The original design strategy alternatives need to be re-evaluated on base of the results in order to improve the cost-effectiveness of each alternative.

At the end of a successful life cycle cost analysis they need to select the most cost-effective design strategy for a particular situation and a greater understanding of the factors that influence cost effectiveness, and not just select one alternative over another. (Pavement Interactive, 2007)

4.2. Initial strategy and analysis decisions more in detail

- Alternative pavement design strategies:

The initial pavement design and the necessary supporting maintenance and rehabilitation activities forms the pavement design strategy. It is useful to evaluate two or more different pavement design strategies and determine their relative value.

- Determine performance periods and activity timing:

The analysis is done before the actual pavement construction, therefore they need to make estimates of pavement performance (how will a pavement deteriorate over time) and maintenance and rehabilitation effort timing (when should maintenance and rehabilitation activities be scheduled) so they can choose an appropriate analysis period and appropriate cost estimates. Agencies can use past local experience to estimate these parameters.

- Analysis period:

This is the time period over which alternate design strategies will be analysed. this period has to be sufficiently long to compare the cost differences between alternatives on long-term. In general the chosen analysis period should include at least one rehabilitation activity for each alternative. For example, if a pavement design alternative requires rehabilitation at the 15-year point and another requires rehabilitation at the 25-year point, an 20-year analysis period would not provide a fair comparison between the two alternatives since it would include rehabilitation costs for one alternative but not for the other. In this case it is better to choose a period of 30 years or even 50 years, this depends upon the rehabilitation activity timing and, of course, the pavement types.

It's important to keep in mind that the nature of these initial decisions, estimates and assumptions can be critical to the conclusion of the LCCA afterwards. When the input parameters are changed, the cost-effectiveness of alternatives will change. (Pavement Interactive, 2007)

4.3. Estimate costs more in detail

4.3.1. Agency costs

This are the costs incurred by the owning administration over the life of the project. Items that are the same for all alternatives do not need to be considered because their costs will cancel one another out. What the agency costs include is listed below.

- Preliminary engineering:

The feasibility studies of alternative designs, permitting, engineering design and consultation for each alternative are costs that are placed here.

- Contract administration:

All the costs that are related with paperwork and contract administration fall under this heading.

- Initial construction:

For every alternative the construction costs are listed. Only the costs which are unique to each alternative should be counted in the analysis. For instance, each alternative has different pavement sections and material quantities and should be accounted for the analysis.

- Construction supervision:

Costs associated with construction inspectors, construction management consultant costs, materials testing costs, or other costs associated with construction supervision are described here.

- Maintenance costs:

The maintenance of the pavement surface to keep it at some acceptable level generates also costs. Routine reactive-type maintenance cost data are generally difficult to find. But, these costs are generally small and do not vary greatly from alternative to alternative. They have a negligible effect on NPV and can most of the time be ignored. When there are maintenance costs available for the alternatives , they should be incorporated into the life-cycle cost analysis.

- Rehabilitation costs:

Costs associated with each rehabilitation alternative, typically they are resurfacing costs, fall under this heading. They are calculated in a manner consistent with the initial construction costs.

- Administrative costs:

Sometimes there are other administrative or overhead costs unique to each alternative that need to be included in the analysis.

- Salvage value:

This is the value of an investment alternative at the end of the analysis period. Generally this is included as a negative agency cost (an agency benefit) and is comprised of two major components:

  - Residual value:

  This is the net value from rehabilitation strategy of the pavement during the analysis period. The difference between residual values for different strategies is generally not very large, and, when it is seen over long periods of time (e.g., 30 years) it tends to have little effect on LCCA results.

➢ Serviceable life:

This is the remaining life in a pavement alternative at the end of the analysis period. The serviceable life stands for the differences in remaining pavement life between different alternatives.

For example, alternative A reaches a terminal serviceability at year 30 and alternative B needs a rehabilitation at year 25 that will give the pavement another 10 year of service life. If the used period of analysis is 30 years, then alternative A has no remaining serviceable life at the end of the analysis period while alternative B has 5 years of remaining service life. An additional serviceable life must be accounted for in LCCA and is usually done so under the "agency cost" category. So in this case alternative B will be credited with a monetary value equivalent to 5 years of service life.

Then there are sunk costs that are a special category. They are those costs that are irrevocable and should not be used to influence the alternative selection decision.

4.3.2. User costs

The costs that arise by the users of the facility during the construction, maintenance and/or rehabilitation and everyday use of a runway or taxiway section are the user costs. They should be included in de analysis because they tend to be several orders of magnitude larger than agency costs and are generally the major driving force in the analysis. The user costs are distributed into two basic categories:

- Normal operation:

The use of the facility during periods free of construction, maintenance, and/or rehabilitation activities that restrict the capacity of the facility are classed in this category. The pavement roughness is generally the most important parameter for these costs.

- Work zone:

The use of the facility during periods of construction, maintenance, and/or rehabilitation activities that normally restrict the capacity of the facility and hinder normal traffic flow are classed in this category. The level, duration and character of capacity restriction (e.g., number of closed runways, traffic during closure, etc.) will influence the costs.

The costs of normal operation are assumed to be equal for all options involved and it is only useful to analyse the work zone costs in the LCCA. According to the approach by FHWA , user costs are generated of three separate cost components: (Pavement Interactive, 2007)

- Vehicle operating costs (VOC):

This item includes the costs associated with operating vehicles including fuel, oil, part replacement, upkeep and maintenance. These costs will vary depending upon runway and taxiway conditions. In the LCCA of roadways, there is data that gives the relationship between VOC and roughness for a stretch of a roadway.

- User delay costs:

These are the costs associated with the users time. When there are slowdowns due to construction and maintenance activities, the costs fall under this heading. User delay costs are difficult to calculate and the most controversial costs of the LCCA, because they involve assigning a money value to individuals' delay time. This value also depends on the type of transportation (Cargo or passengers).

- Crash costs:

The costs associated with accidents. Crash costs are categorized into fatality, non-fatal injury and property damage only on roadways.

The vehicle operating costs and the crash costs are only used in the analysis for highways, these are not relevant for the runway pavements of airports. But the user delay costs are also useful for airports and will be discussed in the next chapters.

4.4. Compare the alternatives more in detail

When the performance period, activity timing, and costs associated with each alternative have been defined, the next step is the comparison over the chosen analysis period. This is generally done in one of two ways: net present value (NPV) or equivalent uniform annual costs (EUAC). (Pavement Interactive, 2007)

- Net present value (NPV):

The NPV is a calculation of the value of an investment based on a time axis with just the cash flows relevant to the project. Thus the project can be expressed as a single base year, or present year, cost. Then it is possible to compare the different alternatives with by comparing these base year costs. NPV is an economic calculation and, can be expressed by the following equation:

$$\text{NPV} = \text{initial cost} + \sum_{k=1}^{N} Rehab\ cost \left[\frac{1}{(1+i)^n}\right]$$

In this equation: i = Discount rate

n = Year of expenditure

- Equivalent Uniform Annual Costs (EUAC):

This way to compare alternatives is determined by converting all project costs to a uniform recurring annual cost over the analysis period. EUAC discounts all projects to a recurring yearly cost and then compares these costs and is a useful indicator when budgets are established on an annual basis. Generally, they first figuring the NPV and then using the following equation to convert it to EUAC:

$$EUAC = \frac{NPV}{\left[\frac{\left(1 - \frac{1}{(1+i)^n}\right)}{i}\right]}$$

In this equation: NPV = Net present value

i = Discount rate

n = analysis period (the number of years over which you wish to compare the alternatives)

(Pavement Interactive, 2007)

4.5. Analyse the results and re-evaluate the alternatives

After that the initial NPV's and EUACs have been calculated for all options they should be analysed to define the relative effects of inputs, the distribution of likely input values and the probability distribution of resultant NPV’s and EUACs. To determine which alternatives are better in which situations and also where improvements can be made to each alternative to make it more cost effective is the purpose of this analysis. In general, it should involve a sensitivity analysis and a risk analysis.

- Sensitivity Analysis:

Sensitivity analysis looks how variations in key input parameters affect its NPV. For each major input parameter (the determination of which input parameters are significant is subjective but can include discount rate, agency costs, pavement performance life and rehabilitation costs)the parameter in question is varied over a reasonable range (either within some percentage of the initial value or over a range of values) and all other parameters are held constant. The resultant NPVs should give a feel for the impact of input parameter variability on overall life cycle cost analysis. There is no credit for the relative likelihood of input values and that's the major disadvantage of the sensitivity analysis. For this reason there is given an equal weight to all input value assumptions regardless of their occurrence likelihood.

- Probability Analysis:

The risk analysis or probability analysis is a term that describes an analytical method used to account for the potential variability of input parameters. It's important to do the analysis because it can give a range of potential life-cycle costs and their associated probabilities of occurring. With information, an administration can assess the risks associated with a particular probability distribution of life-cycle costs. (Pavement Interactive, 2007)

4.6. Selection of analysis type.

The decision on which type of analysis that would be chosen for the application of the Lisbon airport runway was clear from the beginning, but here are some arguments cited to explain the choice.

The choice of LCCA is mainly due to the availability of certain parameters. For LCA certain values are required in the analysis that are not available, for example, the total energy consumption or the total fuel consumption of between 0 and n years. This data is also not relevant for the management of the pavements at an airport.

An LCA is more applicable to ordinary roads and highways. This analysis take into account the different ecological footprints and Global Warming Potentials of the alternatives. These are things that are important for the government in the tender of major road works. For the management of an airport is ultimately the price tag more important than the environmental impact. This impact is also much smaller compared with highway projects.

Further, this is a deep rehabilitation of an existing runway and not the construction of a new one. So, there is no use of existing green zone in the project that will have any influence on the environment.

5. LCCA explicitly applied to airport pavements

5.1. Introduction

It often takes several years to complete an airport pavement project (planning, designing, contracting and constructing). When a particular pavement is needed to be built or improved, it is assigned a general scope and cost is scheduled with other airport projects as part of a proposed multi-year improvement plan. When the funding is arranged for the project, the preliminary design plans are be made based on latest information concerning the goals, needs, and constraints of the project. In this stage of the process the type of pavement or rehabilitation to use on the project will be chosen.

Despite of they use a traditional or an alternate bidding approach for the selection of the contractor, two or more feasible pavement design strategies should be developed for consideration. The decision of which alternatives will be chosen depends on past experiences to satisfy the regional and/or local conditions (traffic, climate, and subgrade characteristics, materials and equipment availability, contractor experience, etc.). But, sometimes they include revised and/or innovative strategies, design and/or material modifications, that have better expectations or promising performance characteristics.

The selection of a pavement type or a rehabilitation for airport pavement projects asks the collection and evaluation of a large amount of data. This data pertain to past experiences and to the project at hand. Such data need to have some degree of relevance in terms of the various factors considered in the selection process (pavement structure design, costs, performance, traffic characteristics, materials, subgrade, climate, etc.).

The data of past experiences could be manifest as practical experience information held by the airport sponsor, its engineering consultants, paving contractors, or various other project stakeholders or this data may consist of direct source data. (AAPTP, 2011)

5.2. Applications

The applications of the analysis will most of the time depend on the type of contracting approach, traditional or alternate bid, planned for the project, the availability of data and the level of detail that can be used. when traditional bidding is used, it's recommended that they perform a probabilistic LCCA or a deterministic LCCA with sensitivity testing. If they can define the variation or uncertainty of each of the inputs (e.g., discount rate, pay item unit costs, pavement service lives) with sufficient data, then probabilistic LCCA should be used. otherwise a deterministic LCCA should be performed along with sensitivity testing to define the effects of varying key inputs (e.g., discount rate, initial pavement service life, the analysis period).

When they use alternate bidding procedures , it's important that the alternative strategies are "equivalent", i.e., their initial structures are based on the same design life with the same reliability level and the same levels of serviceability over the same chosen analysis period will be maintained (the design life will be substantially shorter than the analysis period). It's also important that there are no initial construction factors or non-economic factors that would dictate an advantage for any one of the alternatives.

When the equivalent alternative strategies have been defined, the next step is to perform a preliminary deterministic LCCA that includes the initial and future costs of each alternative. These results should be examined and acted.

When they choose a strategy based solely on initial costs it is possible to accomplish more with a specified annual budget, it does not account for the long-term costs that are paid by facility users and taxpayers. The perfect way for taking into consideration initial and future costs and comparing them against non-economic factors to become the preferred pavement alternative is LCCA. (AAPTP, 2011)

5.3. Recommended LCCA practice

5.3.1. Overview

The LCCA process for conducting on project of a highway pavement is the sequence of 8 steps, the first six of which are performed for each alternative strategy:

1) Establish alternative pavement strategies for the analysis period.
2) Determine pavement performance periods and establish M&R activity timing.
3) Estimate agency costs.
4) Estimate user costs.
5) Develop expenditure stream diagrams.
6) Compute NPV.
7) Analyse results.
8) Re-evaluate pavement strategies.

(Teklezghi, 2012)

A slightly expanded version of this procedure is recommended for use in the airports arena. The procedure is shown in Figure 4 and contains 10 steps. The guidance and description for completing the steps are listed in the sections below. Because of the use of experience-based estimates in quantifying the many LCCA inputs, it is important to use all available, applicable and reliable data in this effort.

The process described is useful to both bidding approaches (traditional and alternate). In the alternate bidding approach, all of the steps used in the traditional approach are followed, except that the initial cost in the LCCA is substituted by the actual bid price. So it's not necessary to estimate this cost for each of the alternative strategies. Also, because they use a discrete life cycle cost adjustment factor for each alternative strategy in the alternate bidding approach, there is only a deterministic computation of the life cycle costs associated with future expenditures needed.

The best application of the alternate bidding approach requires that the used LCCA process be largely acceptable and totally transparent to both pavement industries. Generally it's recommended to use it in situations where there are no primary or secondary factors that would give an advantage for the use of one pavement strategy over the others. (AAPTP, 2011)

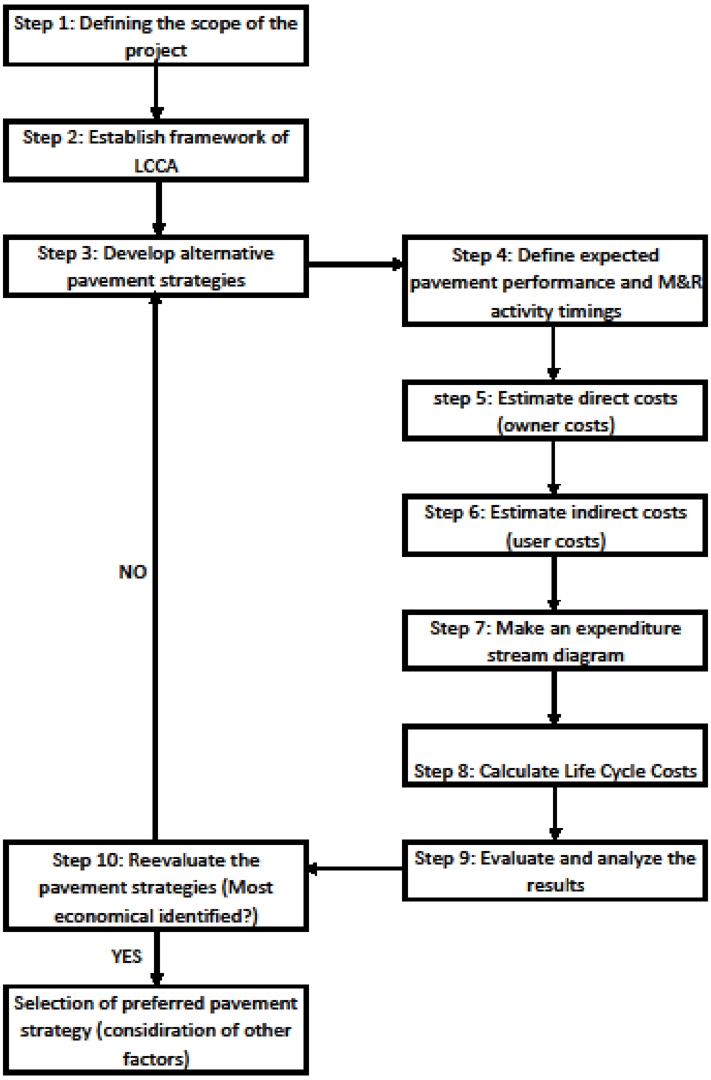

Figure 4: Process for conducting airport pavement LCCA (Adapted from AAPTP, 2011).

5.3.2. Step 1 – Defining the scope of the project

The first step of a LCCA of airport pavement project involves defining the physical scope of the cost analysis. These projects have a great variance in terms of the type of facility (apron, taxiway or runway), the specific branch(es) and specific section(s) that are to be constructed or rehabilitated. For projects consisting of just one section, it is easy to define the scope of the analysis. But projects that include work on multiple facilities or branches require thoughtful consideration of whether all the sections involved can be integrated to one analysis or if two or more separate analysis's are warranted. The focus in traditional bidding is on differential costs. In alternate bidding, all the items of payment in the project need to be included (drainage structures, lighting, ...). Bid costs that are received from constructors need to be analysed carefully to ensure they are reasonable.

it's a good habit to do separate LCCAs for the different sections located on different facilities. Because, when there are significant design differences and/or forecasted traffic applications between pavement sections located on the same branch, it's useful to have separate LCCAs for those sections. There are exceptions on this guidance, such as when one section is significant smaller in size than another section. An analysis for the smaller section may not be warranted, because the mobilization and different advantages of using the same type of pavement (material and layers) for both sections as determined by the LCCA for the larger section.

In highway projects, they often perform the analysis on the base of a unit representative of the project limits. The costs and quantities are defined for a short representative segment (1 mile or 1 kilometer) and sometimes for the lanes in one direction, instead of the entire project length and width. It's possible to use this approach in airport pavement LCCA, but airport projects have shorter lengths and have unique design characteristics that occur throughout the project (transition sections, electrical/lighting issues). So, it's better to make the LCCA over the full representation of quantities and costs.

5.3.3. Step 2 – Establish framework of the LCCA

1) Analysis period:

Recent research has found that airport pavements largely exceed the design life value, that is recommended by the FAA (20 years). the typical design lives for new/reconstructed highway pavements surfaces range from 10 to 20 years for asphalt mixture structures and 20 to 30 years for concrete mixture structures.

For airport pavement LCCA it is recommended to choose an analysis period of 40 years or more for new/reconstruction projects, and an analysis period of at least 30 years for rehabilitation projects. When longer periods are warranted for long-life pavement designs, it is important to know that the LCCA should not extend beyond the period of reliable forecasts. A good approach is to use an analysis period of one of the alternatives that results in zero salvage for that alternative, and use this period to the other alternatives, salvage for the others would then be linearly adjusted.

It must be clear that the chosen period needs to be applied to all the different pavement strategies. No alternative should be analysed over a different period than the other alternatives.

2) Economic Analysis Technique:

Like discussed in the previous chapter, They use the net present value (NPV) and equivalent uniform annual costs (EUAC) as economic analysis technique.

$$\text{NPV} = \text{initial cost} + \sum_{k=1}^{N} Rehab\ cost \left[\frac{1}{(1+i)^n}\right]$$

In this equation: i = Discount rate

n = Year of expenditure

$\left[\frac{1}{(1+i)^n}\right]$ = Present value factor

$$EUAC = \frac{NPV}{\left[\frac{\left(1 - \frac{1}{(1+i)^n}\right)}{i}\right]}$$

In this equation: NPV = Net present value

i = Discount rate

n = analysis period (the number of years over which you wish to compare the alternatives)

3) Discount rate:

The discount rate is an important and controversial piece of the LCCA framework, because it can influence the result significantly. It shows the real value of money over time and is used to convert future costs to present-day costs.

The discount rate is a value in function of interest rate and de inflation rate. The interest rate is associated with the cost of borrowing money and stands for the earning power of money. It is often referred to the market interest rate. Lower interest rates benefits those alternatives that combine large capital investments with low maintenance or user costs and higher interest rates benefits smaller capital investments with higher maintenance or user costs.

The inflation rate is the rate of increase in the costs of services and goods (construction and upkeep) and shows changes in the purchasing power of money. The discount rate is just about the difference of the interest and inflation rates, representing the real value of money over time.

Recent studies indicate (AAPTP, 2011) the predominant use of discount rates in the 2 to 5 percent range for the application of LCCA for airport pavements. The most current annual real discount rate based on a long-term (10-, 20-, or 30-year) Treasury rate should be used for deterministic analysis and as the mean value for probabilistic normal-distribution LCCA.

4) Cost factors:

In the airport business, they have many users, the aircraft crew and passengers, the airlines, air charter companies, air cargo, the airport owner/operator, and the community of businesses tied to airport operations (rental car companies, vendors/concessionaires, hotels, etc.). The costs generated by these users as a result of choosing a pavement strategy over another can be evaluated in terms of the following components:

- Normal operating conditions

  Aircraft operating costs caused due to added fatigue damage by rough pavements. The alternatives with more M&R events could have a longer cumulative period of being in a “rough” condition, resulting in extra upkeep costs.

- Construction zone operating conditions

  The costs of aircraft time delay due to construction and M&R activities with partial or full pavement facility closures. Strategies with longer and/or more interventions could result in greater lost time/productivity of crew and passengers.

  Aircraft operating costs due to the same reason. Pavement strategies with longer and/or more interventions could result in increased business costs (fuel, maintenance, crew, upkeep, etc.) for airlines, air cargo, and air charter companies.

  Aircraft crash/accident costs due to the same reason. Pavement alternatives with longer and/or more interventions yield greater risk for crashes.

  Environmental costs due to the same reason. Pavement alternatives with longer and/or more interventions could result in increased air pollution and energy consumption.

To estimate these costs they have not developed standardized procedures, but there have been some preliminary evaluations and work in the past years to correlate runway roughness/profile with aircraft fatigue damage, estimating amounts of air pollution and energy consumption associated with construction operations. For example, the Air Transport Association (ATA) projected the overall cost of delay to be $72.13/minute (€ 67.48/minute) based on data of 77 airports in 2008.

When the normal flow of the airport operations is changed because of construction or M&R activities, the business cycles of the airport and the aircraft operators are affected. Full or partial closures of any section for any duration can result in significant rescheduling of aircraft operations and/or re-routing of flights to alternate airports. Airlines, air cargo companies, etc. are the first to feel cost impacts and the airport owner/operators are next.

However it is very hard to estimate the added costs incurred by the various aircraft operators as a result of airfield construction and M&R activities, a better solution to estimate can be made of the airport owner/operator's costs in terms of reduced daily operating revenues. Pavement alternatives entailing longer and/or more intensive restrictions on airport operations, particularly when a runway is involved, the losses of daily revenue will be big due to reduced passengers and/or cargo, and possibly fewer aircraft operations.

The loss-of-daily-operating-revenue approach is recommended as one form of user cost that a pavement designer/analyst can consider including in an airport pavement LCCA. Other user cost components, such as airline delay and operating costs and passenger delay costs, appear to be also relevant to LCCA.

5) Statistical computation approach:

As discussed above, there are two approaches possible for computing life cycle costs, deterministic and probabilistic. In the deterministic approach a value is selected for each input parameter (generally the value considered most likely to occur, based on historical evidence or professional experience), and the group of selected values is then used to compute a single projected life cycle cost. Because each parameter is represented by just one value, the variations and uncertainties known to exist in these variables in the real world are not fully accounted for.

The variability associated with input estimates, projections, and assumptions can be accounted to some degree for through a deterministic sensitivity analysis. In this type of process, a given input parameter is varied over a practical range while holding all other inputs at their chosen value, so there can be computed a series of projected life cycle costs. In Figure 5 is shown an example, the projected costs are plotted as a function of the variable input parameter, to reveal the relative impact of input parameter variation on life cycle costs.

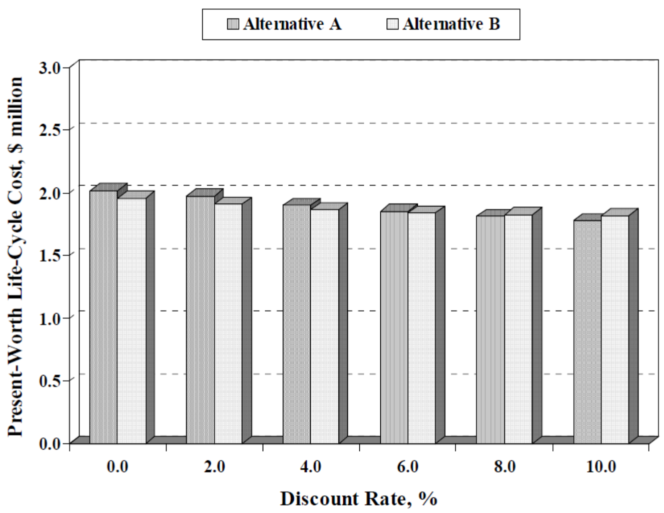

Figure 5: An example of deterministic analysis (Adapted from AAPTP, 2011).

The probabilistic approach simulates and accounts for the inherent variability of the input parameters. As shown in Figure 6 ,for a certain pavement strategy, sample input values are randomly drawn from the defined frequency distributions and the selected values are used to compute a forecasted life cycle cost value.

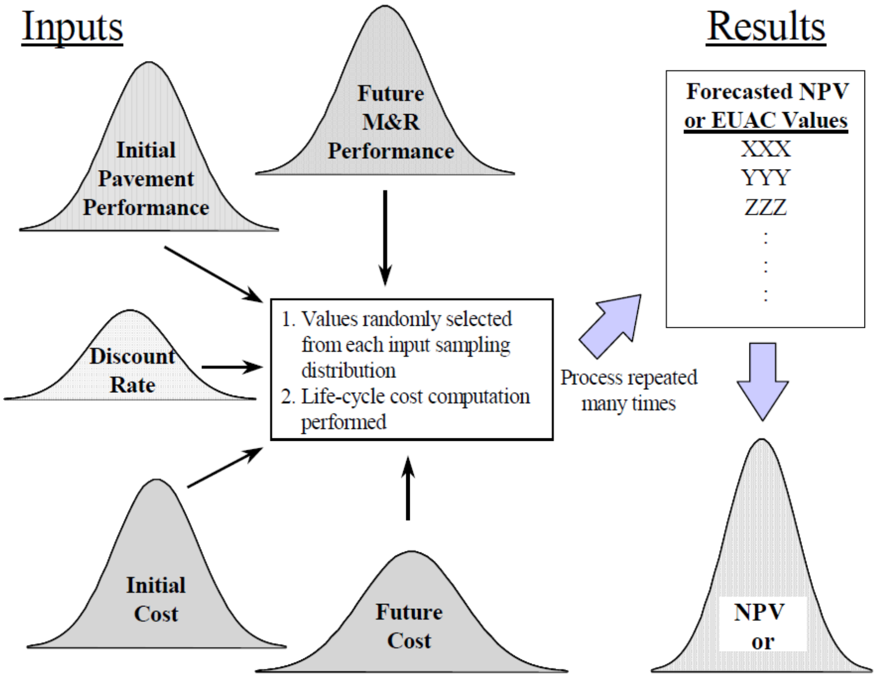

Figure 6: Illustration of the probabilistic approach (Adapted from AAPTP, 2011).

The sampling process is repeated over and over again, thereby generating many forecasted life cycle cost values for the pavement strategy. The resulting forecasted costs can then be compared and analysed with the forecasted results of competing alternatives to identify the most relevant and economical strategy.

It is recommended for airport pavement LCCA to use the probabilistic computation approach when reliable historical data exist to model one or more of the input parameters. If they do not have access to such data, then a deterministic approach should be used, supplemented with sensitivity testing of key input parameters, like the discount rate, the service life estimates of the initial structures and major unit costs associated with the initial pavement structures.

5.3.4. Step 3 – Develop alternative pavement strategies

There must be at least two feasible pavement alternatives identified for evaluation in the LCCA of a given project. Here will each alternative be assigned to a strategy consisting of the initial structure (whether new or rehabilitated) and the probable M&R activities covering the selected analysis period.

The traditional approach of establishing M&R activities is to use the experiences of the past. Most airports have pavement management systems in place to record and track important pavement information. Generally, this information includes year of original construction, years and types of M&R treatments, structural composition (material layers and thicknesses), historical traffic applications (number of operations and types of aircraft), and historical pavement conditions (PCI or other pavement condition/distress indicators). It is necessary that a general indication of the types of M&R treatments that have been applied to specific types of pavement is included in the airport pavement management system. Sometimes there is individual distress data available, then critical forms of distress and modes of failure may be identified, so there is a greater perspective on appropriate M&R treatments. allowing for an equation between the current and/or past M&R practices, and they can prove the treatments are acceptable or there are deviations needed.

5.3.5. Step 4 – Define expected Pavement Performance and M&R Activity Timing

Pavements (New, reconstructed and rehabilitated) deteriorate due to a combination of traffic- and environmental-related stresses. This process of deterioration needs various forms of upkeep over a long time period to sustain the structural integrity and capacity of the pavement, as well as its functional characteristics (smoothness, friction). In this step of the analysis they list up for each alternative pavement strategy, the expected performance life of the initial pavement structure and each future rehabilitation treatment projected to occur over the chosen analysis period. It also involves identifying the timings and extents of anticipated maintenance treatments.

All these information can be used to establish the sequence and timings of future M&R activities treatments, as shown by the life cycle model in Figure 7. It illustrates the difference between maintenance (surface sealing, surface patching and surface treatment) and resurfacing project over the chosen analysis period.

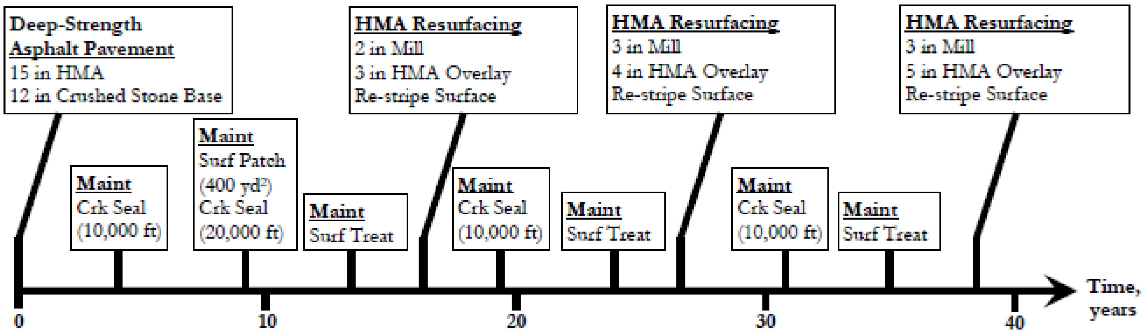

Figure 7: Example pavement life cycle model (Adapted from AAPTP, 2011).

1) Service Lives of Initial Pavement and Future Rehabilitation Treatments:

The service life of a pavement is the period of time from the construction until the structural integrity of the pavement to be unacceptable and structural rehabilitation or replacement is required. In Figure 7, the service life of the initial asphalt mixture pavement structure is about 17 years. The service life of the first resurfacing is about 10 year, so then they plans the second HMA resurfacing. In LCCA the service life is taken to mean the average or median life of the pavement, this is the time associated with 50 percent probability of the need for structural rehabilitation. This is completely different than the design life, which represents a time period with a relatively low probability of the need for structural rehabilitation or reconstruction.

There are different ways to estimate the pavement life time, from expert modelling using the opinions of experienced engineers to detailed performance prediction modelling using historical pavement performance data. It is only useful to follow the first option when reliable historical performance data are not available or are greatly limited, for example if the pavement or rehabilitation types being considered are substantially different, due to changes in traffic or use of new materials or technologies. Experience-based estimates can be made in conjunction with data trends from other locations or projects.

The airport pavement management system should foremost source for developing service life estimates of the pavement structures and rehabilitation treatments anticipated for the different strategies. Depending on the useful data, a variety of analysis can be made to develop service life estimates. The accuracy and reliability of results depend greatly on the number of data points available for analysis. The more pavement sections representative of a particular pavement type, the better. When they do a performance trend analysis, the more time-series condition measurements, the better.

- Performance Trend Analysis

In performance trend analysis, condition data from the past for pavements similar to those comprising each pavement strategy are compiled and plotted as a function of time. Then the best-fit regression curve is calculated and is used for the average age at time of rehabilitation or the estimated service life of the pavement.

The analysis is a four-step process. In step one, they search for existing pavement sections with structural designs, traffic loadings, and functional purposes (runway, taxiway, apron) that are similar to the pavement alternatives being considered. Then the historical data will be extracted from the pavement management system. The best case is to use data from sections in the current airport, but if insufficient sections exist, they can use data from sections at other airports with similar climatic conditions.

An important part of this step is to be careful with the acceptability of the pavement sections:

- Were they built with drastically different materials than the pavement alternatives currently being evaluated?

- Were there design and/or construction issues that substantially influenced performance?
- Was traffic loadings significantly altered, thereby influencing performance?

When there are sections with these kinds of issues, they should be removed from the analysis.

Step two contains creating time-series plots of pavement performance using the available condition data for each family or group of pavements, and developing best-fit linear or non-linear models relating pavement condition to age. The condition data will generally consist of Pavement Condition/distress Indicators (PCI) data, but Structural Condition Index (SCI) data also may be available. Most of the pavement management programs have the ability to develop customized performance/condition models for a family of pavements, but there may be imitations on use of the surface condition data for prediction of pavement life, since other modes of failure may be ignored. That is the reason that these programs cannot be used for decisions related to reconstruction and rehabilitation.

When the time-series condition plots are created, it may be necessary to filter the data, for example when a significant increase is observed in PCI from one year to the next. This kind of increases likely indicate a rehabilitation or significant maintenance intervention. It is better to remove tis PCI data, to negate their influence. Figure 8 is an illustration of a PCI deterioration curve for a family of pavements.

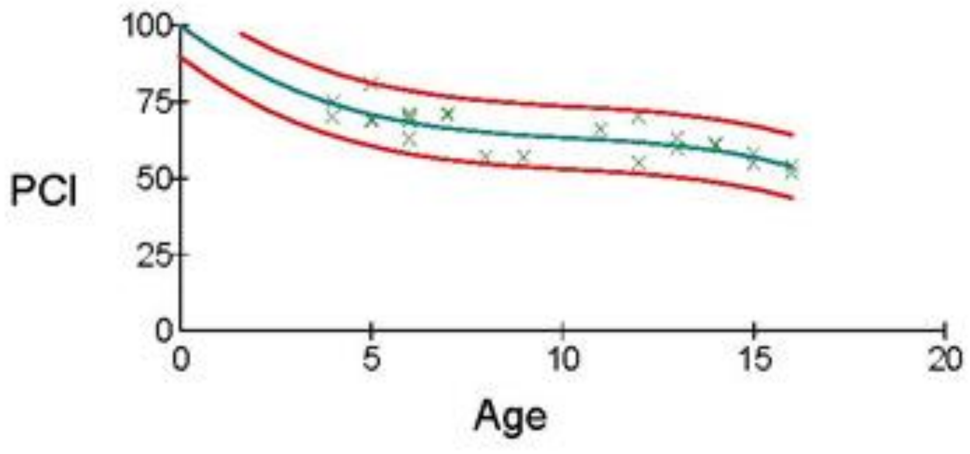

Figure 8: PCI deterioration curve for a family of pavements (Adapted from Paver TM, 2014).

In step three, an acceptable threshold condition level must be defined to use as the trigger for structural rehabilitation. A level of 60 to 70 are typical PCI levels when airport pavements receive some form of structural rehabilitation. The lower end of this range being more suitable for aprons and the higher for runways.

In the last step, according to the development of pavement performance/condition trends and the establishment of a specific condition threshold, an estimate of service life can be made for each pavement family. Sometimes there may be a need to project the model forward so that it reaches the threshold condition level, this depends on the nature of each performance/condition model.

When they use a probabilistic LCCA, then an estimate of the variation in expected pavement life will be needed. In the development of the performance/condition model, the can define a confidence level that allows for the development of confidence bands around the model trend line.

- Survival Analysis

This is a procedure used in the highways arena to estimate the pavement service life. It uses construction and rehabilitation data from projects in the past for a family of pavements to construct a survival curve that depicts the probability of survival with time. In survival analysis they define the non-occurrence of structural rehabilitation, such as a substantive overlay or extensive concrete mixture pavement restoration.

This survival analysis approach is most of the time not useful for airport pavements because they do not possesses a sufficient number of sections at a given airport from which to develop a pavement family survival curve. In such cases, pavement sections from other airports with similar conditions should be utilized, if available, or performance trend or other types of analysis should be used.

2) Timing and Extent of M&R Treatments

Sometimes in airports, the management are faced with the need to improve only the functional characteristics of pavements. For example thin overlays to address smoothness and/or friction deficiencies or transverse grooving to restore texture for improved friction. The expected timings and extents of these actions, if needed, should be calculated with structural rehabilitation treatments, pavement management and/or history records.

In the time between construction and rehabilitation of an airport pavement or between two rehabilitations, there are sure to occur multiple maintenance interventions. These interventions can vary from routine activities (pothole/spall repairs, removal of foreign objects) to preventive activities (crack sealing, joint resealing, surface treatments) to major repairs (slab replacements, full-depth repairs, localized skin patching). This is not the case on highways. On airports is the routine maintenance considered extremely important and are done very frequently to maintain high levels of safety.

The perfect LCCA for airport pavements includes all forms of maintenance costs, since the types, timings, and extents of maintenance activities will be different for each pavement alternative. The routine reactive-type maintenance costs generally are relative low and not substantially different between pavement types, so they can be ignored. The focus of maintenance costs will be on the timing and extent of preventive and major forms of maintenance.

5.3.6. Step 5 – Estimate direct costs (owner costs)

Also an important element of LCCA are the costs of building, maintaining, and rehabilitating pavements as part of each alternative pavement strategy. The use of reliable, up-to-date unit price estimates for each activity/material pay item associated with the initial structure and also for M&R treatments will give a good view of the life cycle costs. In step five will be made an estimating of these unit costs and combining them with estimated pay item quantities to develop the physical costs of pavement activities, and use them in the LCCA. The salvage value of the pavement structure at the end of the analysis period will be accounted, if so, an estimate of that benefit or cost will be made.

A third and last aspect of direct costs is the extra costs associated with construction and M&R activities, these costs can be administrative, engineering, and traffic control costs. Their inclusion in the analysis depends on whether substantive differences can be identified among the alternative pavement strategies.

1) Physical costs of pavement activities

The most important issue is identifying and obtaining sufficient and reliable unit cost data for the pay items that will go into the initial structure and individual M&R treatments. These data can be obtained of historical bid tabulations for projects undertaken in recent years at the subject airport or at other airports in the region. This data is compiled on a regular base and are available for project estimating purposes. Another source for this data are the highway agencies that are connected this kind of costs. But a good comparison should be made to ensure the pay items represent the same work activities as those of the subject airport.

Unit cost estimates can be made of the unit price data from the lowest bid or three lowest bids tendered on projects of comparable nature. The average unit price must be compared to present day to account for the effects of inflation, and consideration should be given to filtering out prices biased by projects that included small quantities of a particular pay item.

When there is a use of new materials/technologies and little or no regional cost information is available, they should estimate using data available from other sources. Pavement industry groups can be contacted to help identify appropriate sources. Unit cost data received from other sources may need to be corrected to account for geographical differences in construction costs.

2) Salvage value

The salvage value gives the remaining worth of a pavement alternative at the end of the analysis period. It can be positive or negative, positive means useful and salvageable material, negative means the cost to remove and dispose of the material that exceeds any possible positive salvage value. Some project-specific factors, for example age, durability, quantity, and location of existing materials, must be considered in estimating this component of salvage and, that is why it requires extensive input data and very detailed analyses.

Figure 9 shows an example of remaining life salvage value. The remaining life method prorated the cost of the last rehabilitation event using the ratio of its remaining life at the end of the analysis period to its total expected life.

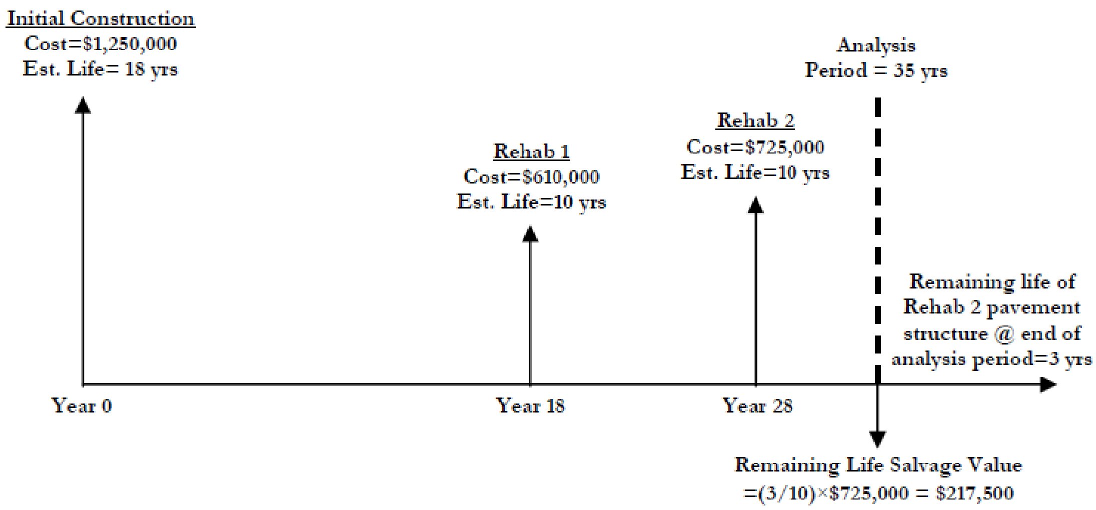

Figure 9: An example of remaining life salvage value (Adapted from AAPTP, 2011).

It is useful that salvage value be counted in the airport LCCA, particularly when shorter analysis periods (30 to 40 years) are used. Because of the complexity in evaluating the recyclable value of a pavement structure at the end of the analysis period, it is better that only the remaining life component be considered when including salvage value in the LCCA.

3) Supplemental Costs

The supplemental costs are applicable only to the series of anticipated future M&R events. When these costs of the different alternatives are approximately the same, then these costs can be ignored and only the physical costs should be counted. In case of significant differences, the process of developing estimates for all events should proceed.

- Administrative costs (Contract management and administrative overhead).

- Engineering costs (Design and construction engineering, construction supervision, and materials testing and analysis)

- Ground traffic control costs (Traffic control setup and communications)

5.3.7. Step 6 – Estimate indirect costs (user costs)

If it is decided in step 2 that indirect/user costs should be included in the airport pavement LCCA, this step should be performed. The reductions in airport daily revenue will be estimated in this step for each event in the life cycle of each pavement alternative (initial construction/rehabilitation and future M&R treatments).

1) Type and duration of pavement facility restrictions

Every airport is different in its airfield pavement system layout, how it manages air and ground traffic operations, and how it facilitates construction and M&R practices. Therefore it is necessary that each event in the life cycle of a pavement alternative must be examined carefully to identify the most probable construction zone scenario. It is important that each scenario defined if daily capacity will be exceeded and for how long.

2) Reductions in aircraft operations, passengers, and/or cargo

When they expect that the capacity will be exceeded for a given scenario, then estimates of the daily reduction in aircraft operations, passengers, and/or cargo must be developed. These estimates should display what would most likely occur in terms of how aircraft operators might alter their services.

If they do not expect that the capacity will be exceeded, but the construction zone is such that airlines and/or air cargo companies must reduce their operational loads due to shortened runways, then they should develop estimates of reduced passengers and/or reduced landing weights.

3) Loss of daily operating revenue

The owner and operators of a commercial airport gets most of the revenues either directly or indirectly from aeronautical activities (passenger, cargo, fuel taxes/fees collected through the Airport Improvement Program (AIP), passenger facility charges (PFCs), and aircraft take-off/landing fees). To calculate the loss of daily operating revenue for a given construction zone scenario entails:

- Multiplying the appropriate fee or tax rates by the daily reductions in aircraft, passengers, and cargo
- Summing the individual daily revenue losses
- Multiplying the overall daily revenue loss by the number of days the construction zone scenario is expected to be in-place

5.3.8. Step 7 – Make an expenditure stream diagram

Expenditure stream diagrams give a graphical or tabular representation of expenditures in time. It is the intention to help the designer/analyst visualize the magnitudes and timings of all expenditures projected for the analysis period for each alternative pavement strategy.

In Figure 10 is shown that costs normally depicted by upward arrows and benefits by downward arrows. So a visual image is given of the cost and benefits of certain aspects of the analysis period of the different alternatives.

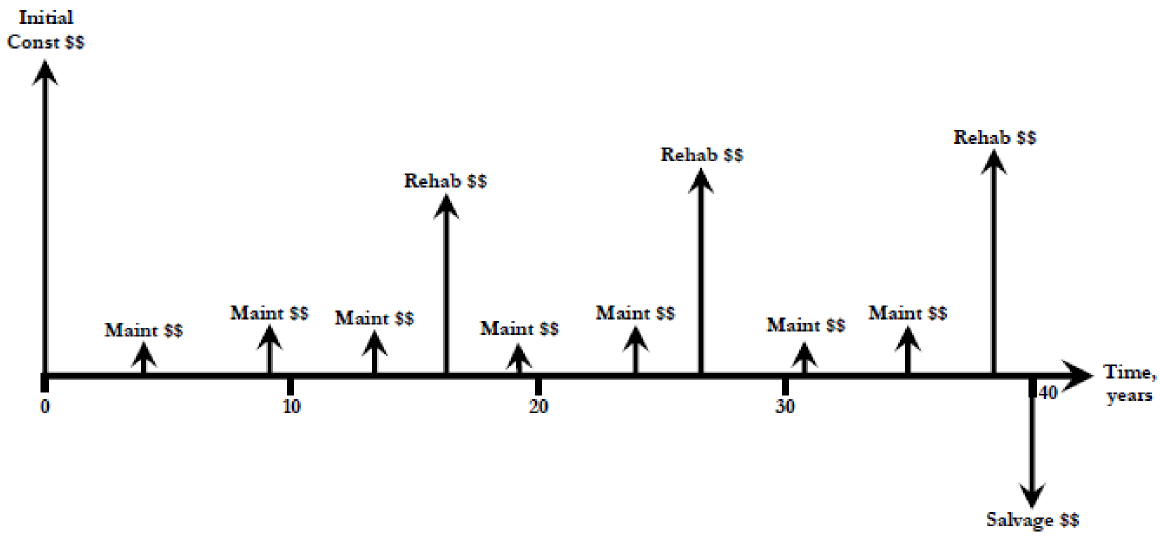

Figure 10: Illustration of an expenditure diagram (Adapted from AAPTP, 2011).

5.3.9. Step 8 – Calculate Life Cycle Costs

When the expenditure stream for each alternative pavement strategy has been made, the part of computing projected life cycle costs is done. For deterministic analysis, they have to convert all future costs projected to occur over the chosen analysis period to present worth values using a specified discount rate. All the costs of initial construction and all converted costs are then summed together to produce the NPV. Then they can convert this cost to EUAC by use of the discount rate and analysis period, if desired.

As said before, probabilistic LCCA is about selecting a random value from each input parameters sampling distribution. With these selected values and the NPV/EUAC formula they can calculate a single life cycle cost. When they are repeating this steps for hundreds or thousands of iterations, they can generate an array of forecasted costs. These costs are then compared with the forecasted costs of the alternative pavement strategies to find the most economical strategy. This simulation requires a specific software package.

It is important to ensure that each iteration represents a scenario that can actually occur when performing a probabilistic simulation. Two particular modelling errors can be:

- A lack of appropriate pre-defined relationships between different input parameters

- A lack of fixed limits on input sampling distributions

5.3.10. Step 9 – Evaluate and analyse the results

After the computation of the deterministic or probabilistic life cycle costs, it is necessary to analyse and interpret carefully the results to identify the most economical pavement strategy. This ways of evaluation and interpretation are different for the two approaches, because the outputs are different (probabilistic yields a distribution of NPV/EUAC values, deterministic yields a single NPV/EUAC value).

In the deterministic approach, they compute the percent difference in life cycle costs of the alternative strategies. When the difference between the two lowest cost strategies is greater than an established minimum requirement (set according to the tolerance for risk, 5 and 10 percent are common) then the lowest cost strategy is accepted as the most economical one. Otherwise, when the difference is less than the established minimum requirement, then the life cycle costs of the two strategies are deemed equivalent, And so the analyst can analyse the two strategies in the difference in quality without looking at the costs.

The probabilistic results can be analysed and interpreted in different ways. A simple, comprehensive approach recommended for use is given below in three steps:

1) Evaluation 1 - Trial-By-Trial Comparisons

A first indication of the most economical pavement strategy can be made by examining the life cycle cost results associated with each iteration or trial computation. By counting the number of "wins" for each option, i.e. trials in which one strategy had the lowest life cycle cost compared to all other strategies. The ratio of number of wins of a particular strategy and the total number of trials performed in the simulation, and multiplying by 100, gives the probability for each alternative to have the lowest life cycle cost. The alternative with the highest overall probability, becomes the advantaged strategy, but additional evaluation is needed to find out if it is the most economical one.

2) Evaluation 2 - Statistical Analysis

In this step the mean and standard deviation of the life cycle costs will be computed for each alternative. So they can determine if significant differences exist between the means of each strategy. When the strategy with the lowest mean seems to be statistically significantly lower than all other alternatives, then this strategy can be accept as the most economical one. in the other case, the third and final evaluation option must be done.

To evaluate two competing alternatives, they use the t-test to investigate the difference in means. When there are more than two competing alternatives, an analysis of variance (ANOVA) can be done or they can do the t-test on the two seemingly lowest cost alternatives.

3) Evaluation 3 - Risk Assessment

If the previous steps are not definitive with respect to identifying the most economical strategy, then a risk assessment is necessary. The purpose of this assessment is to identify any distinguishing probability characteristics that play to or against an administrations propensity for risk-taking. Because the statistical analysis did not show a statistically significant difference between the expected means of the lowest-cost alternatives, they should look in the tails of the frequency distribution curves to find such distinguishing characteristics.

5.3.11. Step 10 – Re-evaluate the pavement strategies (Most economical identified?)

In the last step, the information received from the LCCA will be evaluated to define if any modifications to the alternative strategies are needed before the final decision on which alternative to use. This adjustments can be changes to the original structure or rehabilitation treatment, revisions to the maintenance of traffic plans, reductions in construction periods, or changes in future M&R activities. (AAPTP, 2011)

6. Application of analysis to the runway of the Lisbon airport

6.1. Description of the runway

In Lisbon there are two runways, a short one for smaller airplanes (RWY17/35) of 2304m long and the main runway (RWY03/21) of 3805m long for the usual air traffic, the both are 45m wide. In this dissertation is a LCCA applied to the main runway, RWY03/21, with an area of 171.225 m² or 204.790,1 yd². In Figure 11 is a map of the airport shown with the location of the main runway in the red rectangle.

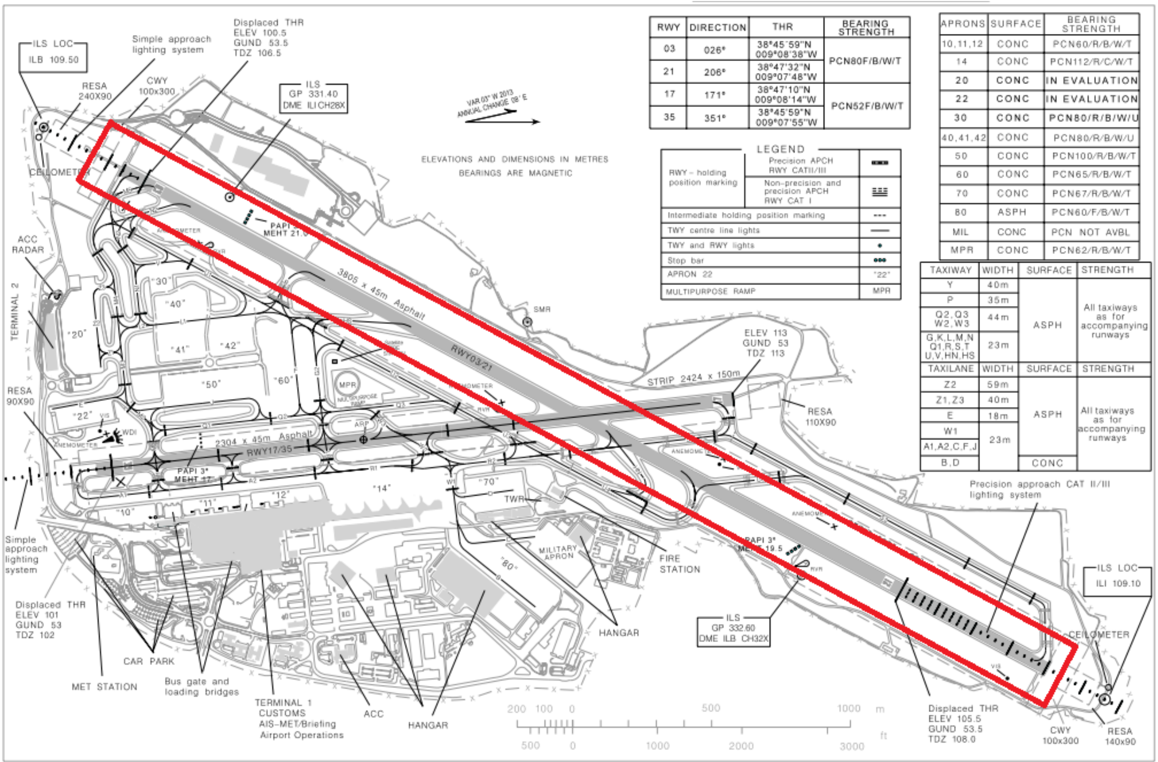

Figure 11: Map of the Lisbon airport with the location of the main runway.

The bearing strength of airfield pavements must be measured, analysed, evaluated and reported so that the operating weight of aircraft allowed to use the pavements can be controlled. The Pavement Classification Number (PCN) indicates the suitability of a pavement area for unrestricted operations by any aircraft that has an Aircraft Classification Number (ACN) and tire pressure not exceeding the limits reported in PCN format of stated pavement type and subgrade strength category. The method of PCN pavement evaluation is left up to the airport, under the approval of the regulating Civil Aviation Authority (CAA).

PCN 80 F/B/W/T is the pavement classification number of the main runway of the Lisbon airport. The first number is the reported PCN value on a scale of 1 to about 130, with 1 representing a weak pavement and 130 a very strong pavement. The second part of the code is either an "F" for flexible pavement systems or "R" for rigid pavement systems. The third part is a letter code A, B, C, or D indicating the subgrade/bearing strength, with A representing a high supporting strength and D a very low strength. The fourth part indicates the tire pressure limitation in MPa if applicable (X, Y, Z otherwise W). The fifth and final part of the PCN code indicates the evaluation method used to determine the pavement strength – "T" if derived from an engineering study or "U" if based on satisfactory aircraft usage. In Table 4 are all the different parameters of the PCN summarized. (Crow, 2013)

Table 4: Summary of PCN parameters (Adapted from Crow, 2013).

PCN	Pavement type	Subgrade category	Tire pressure	Evaluation method
	R – Rigid F – Flexible	A – Unlimited B – High C – Medium D –Very Low	Unlimited, no limit – W High, limited to 1.75 MPa – X Medium, limited to 1.25 MPa – Y Low, limited to 0.5 MPa – Z	T – Technical U – Using Aircraft

Because of historical reasons is the structure of the runway not equal over the whole length. The runway is split in three zones with different thicknesses of the layers. For simplicity, is assumed that there are no different zones in the runway and one specific structure is chosen for the analysis. In Table 5 the different zones are listed.

Table 5: Different zones of RWY03/21.

RWY 03/21 zone 1 (0m to 850m)			RWY 03/21 zone 2 (850m to 2700m)			RWY 03/21 zone 3 (2700m to 3805m)		
Layer	**h (m)**	**E (MPa)**	**Layer**	**h (m)**	**E (MPa)**	**Layer**	**h (m)**	**E (MPa)**
AC	0,100	5500	**AC**	0,080	4900	**AC**	0,080	4500
AC	0,170	4500	**AC**	0,190	3800	**AC**	0,120	4000
AC	0,110	1000	**AC**	0,080	800	**AC**	0,100	2300
Unbound Material	0,300	700	**Unbound Material**	0,300	400	**Unbound Material**	0,300	280
Unbound Material	0,300	350	**Unbound Material**	0,300	250	**Unbound Material**	0,300	280
Subgrade	∞	100	**Subgrade**	∞	90	**Subgrade**	∞	80

Zone 1 is chosen to proceed in the dissertation, because this section has the thickest layers and this is an important zone for the take-off and touch-down of the airplanes. It is a package of 98cm with two unbound layers of 30 cm and three bound layers of asphalt concrete. Two layers of the asphalt concrete as base course (11cm and 17cm) and one layer as wearing/surface course of 10cm. Foundation, including subgrade, is located under this package of 98cm.

6.2. LCCA methodology and software

The used LCCA methodology is based on the strategy developed by the AAPTP. The final report published by AAPTP in 2011 has outlined the steps of LCCA on airfields, which are consistent to the principles of the technical bulletin. The different steps are listed in the literature review (chapter 5).

AAPTP has also developed LCCA software called "Aircost" in 2011 to implement its LCCA principles according to the outlined steps. The software is used for carrying out the LCCA of a runway, taxiway or apron at hand. Aircost also allow conducting LCCA in both deterministic and probabilistic approach.

6.3. Pavement alternatives

The pavement alternatives analysed are both flexible pavements, one where the main bituminous mixture is an SMA and other that is an AC. The reason for their selection is that they are the common ones in airport construction, i.e. they are the main candidates for a runway project.
Like stated in Chapter 2 (Table 1), AC and SMA are the most used pavement types for runways in Europe. AC is more applied than SMA in the airports because of the lower initial costs and the know-how in the past about SMA was not that big. Now they use more and more SMA in other facilities, so the knowledge about the alternative rises. That is why the life-cycle cost analysis for both alternatives will make a reasonable comparison of their relative cost effectiveness.
The comparison will be made for a deep rehabilitation of the main runway. The intention of the rehabilitation is milling 20cm of the old structure (the full wearing course and a part of the of the remain bound layers, namely the binder course and part of the base) and refill these 20cm with a new material. The new structure is the same for both alternatives, a base course of 15cm (two layers of 8cm and 7cm) and a wearing/surface course of 5cm. In Figure 12 is the structure shown of the different alternatives with the thickness of the different layers of the new and the old structure.
Normally, a rehabilitation like this will be done for 12-14cm, but in this case there is chosen for 20cm to become a clear distinction between the alternatives.

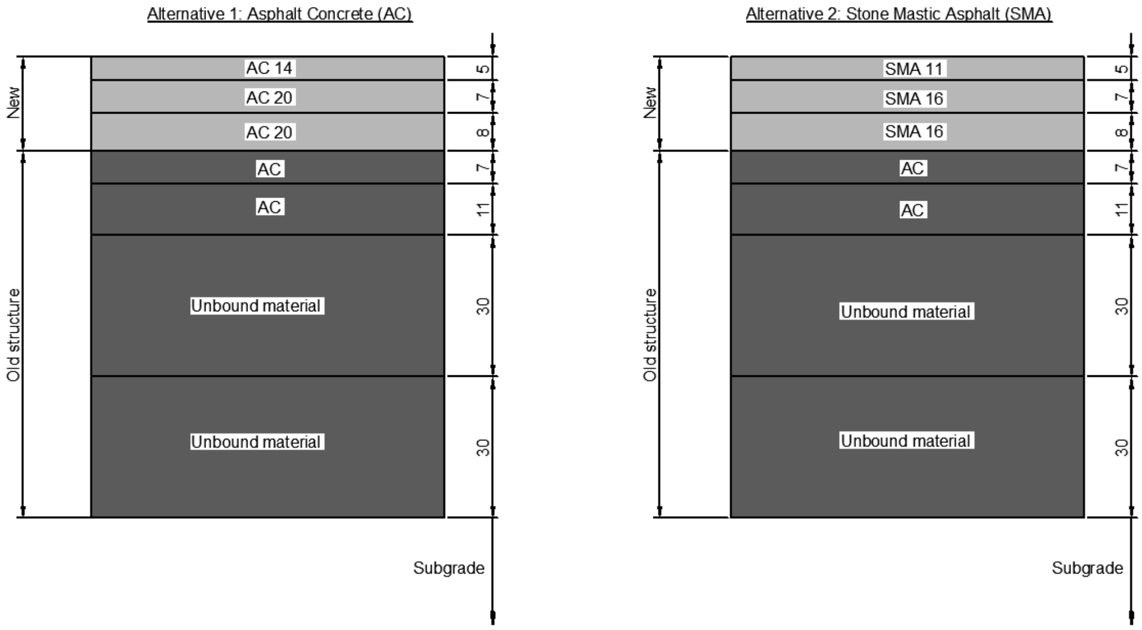

Figure 12: Structure of the alternatives.

6.4. Schedule of M&R activity timings

The schedule for the rehabilitations of the different alternatives is made by the experience in design of past projects and on the engineering judgement of pavement experts. In pavements for runways it is likely to choose an analysis period of 30 to 40 years. In the dissertation is a period of 30 years used.

For the first alternative is a resurfacing of the wearing course needed every 10 years, so there are two rehabilitations required. For the second alternative is only one resurfacing required after 15 years for the chosen analysis period.

In Figure 13 is a timetable drawn for the different alternatives over the analysis period. There are no indications for normal maintenance operations on the timetable, because these are likely to be of the same type at the same date for the both alternatives. So, these interventions will be required at the same time on the different type of pavements and will cause the same costs, so it is not be relevant to include these interventions and costs in the analysis.

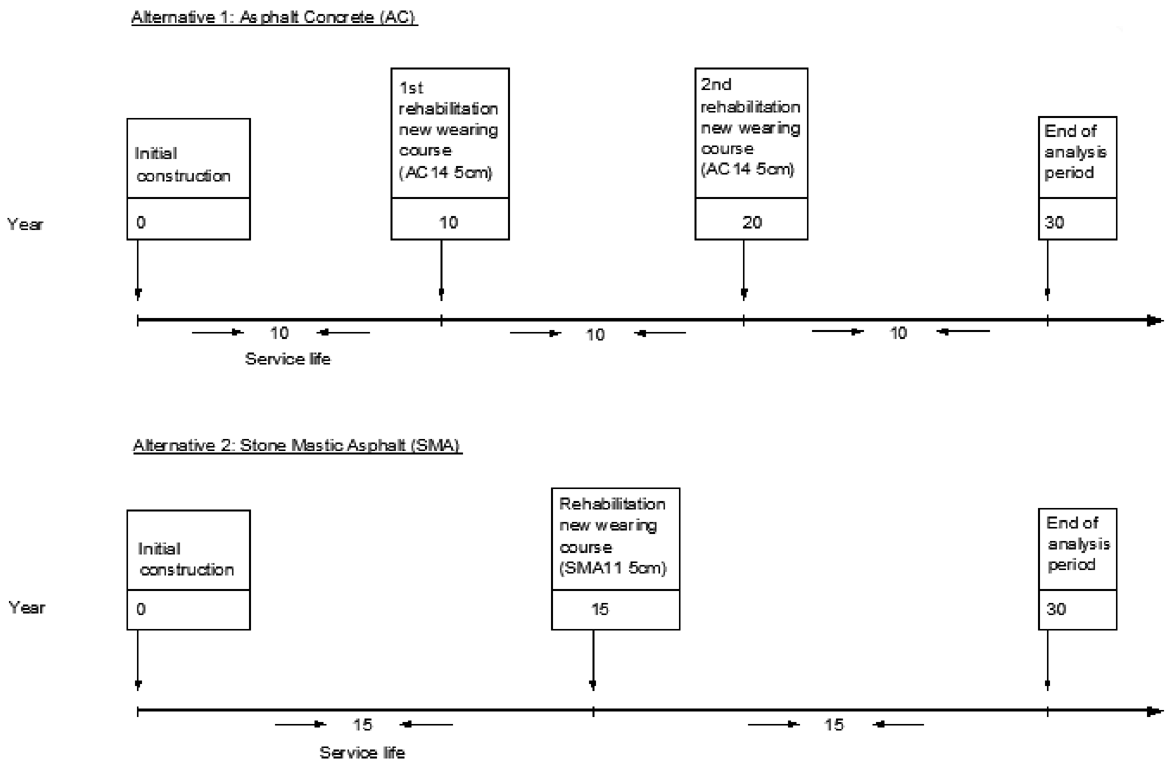

Figure 13: Schedule of the rehabilitations on the alternatives.

The difference between analysis period of the pavement and the service life of the pavement is also displayed in Figure 13 . The pavement has a specific service life for the quality of the wearing course and is completely different from the analysis period that is used for the calculations.

6.5. Direct costs

The agency cost includes the costs of initial construction and future M&R activities during the analysis period. The costs are calculated based on the unit cost rates and quantities of the items of work in each activity. In Table 6 are the unit prices listed and converted to dollar for the Aircost software. This costs were obtained directly from recent works at Lisbon airport and were supplied by the contractor. Also some practical orientations used in the next paragraphs, related to construction details for instance, also were stated by the contractor.

Table 6: Unit prices of the layers for the different alternatives.

Pay item	€/m²	$/m²
Wearing course AC14 (5cm)	6,86	7,75
Base course AC20 (7cm)	7,15	8,08
Base course AC20 (8cm)	8,15	9,20
Wearing course SMA11 (5cm)	8,15	9,21
Base course SMA16 (7cm)	8,28	9,35
Base course SMA16 (8cm)	9,46	10,68

In these unit prices are already included the extra costs of the night work and everything related with this. It is also clear that the unit costs of SMA are higher than AC, this because of the higher costs of the materials in the mixture. Also the complexity to finish the wearing course is higher for SMA than AC, and this increases the unit prices.

Beside the unit costs of the materials for the initial construction and the rehabilitations, there are some other costs to be included. The milling of the old materials, the binder between the different layers, restriping of the runway after the resurfacing and the work on the lighting in the surface of the runway also involve several costs. It is assumed that these costs can be calculated as 30% of the initial construction costs of the most expensive alternative, in this case the SMA. The calculation is done as followed:

Surface area: 3.805m * 45m = 171.225m² = 204.790,1 yd²

Cost for initial construction with SMA: ($ 9,21 + $9,35 + $10,68) * 204 790,1 yd² = $ 5.988.906,03

Extra costs for milling, binder, striping and lightning: $ 5.988.906,03 * 30% = $ 1.796.671,81

This extra cost of $ 1.796.671,81 needs to be counted in the initial construction, but also in the rehabilitations. The milling, the binder, the striping and the lightning are also necessary in the resurfacing of the wearing course during the analysis period.

When all the costs of the different layers and extra costs are taken together for the initial construction and the rehabilitations, a first impression can be made of the most cost-effective alternative. The user costs and the discount rate also need to be counted, but this is a good start. In Table 7 are the total agency costs calculated for the two alternatives.

Table 7: Agency costs of the two alternatives.

Alternative 1: AC						
Activity	Description	Year	Service life	Duration (nights)	Cost	meter/night
1	Deep rehabilitation	0	10	50	$6.922.982,02	100
2	New wearing course	10	10	25	$3.384.245,95	200
3	New wearing course	20	10	25	$3.384.245,95	200
				Total	$13.691.473,92	
Alternative 2: SMA						
Activity	Description	Year	Service life	Duration (nights)	Cost	meter/night
1	Deep rehabilitation	0	15	50	$7.785.577,84	100
2	New wearing course	15	15	25	$3.682.494,33	200
				Total	$11.468.072,17	

For alternative 1, the cost of the initial activity ($ 6.922.982,02) is about 50% of the total undiscounted cost over the 30-years period ($ 13.691.473,92). On the contrary, alternative 2 has higher initial cost ($ 7.785.577,84) which is about 70% of the total undiscounted cost over the 30-year period ($ 11.468.072,17). This calculation of the agency costs does not include the effect of the discount rate. And so there is no deterministic or probabilistic approach applied for the different alternatives. This gives a first global impression.

Nevertheless, Alternative 2 is the most cost-effective alternative with only the agency costs in the consideration. This because of there is only one rehabilitation necessary instead of two rehabilitations for alternative 1. This makes already a big difference between the two alternatives with only the agency costs in the calculation.

In the literature review, is spoken about salvage value of pavement alternatives. In this case there is no salvage value for both of the alternatives. This is because for the both alternatives the service life after the last rehabilitation ends at the same time of the analysis period.

Further, there is also spoken about supplemental costs (administrative costs, engineering costs and ground traffic control costs) to include in the LCCA. These costs are already settled in the unit price of the extra costs for milling, binder, striping and lightning.

6.6. Indirect costs

In airports the user costs are related to the reduction of the daily revenue. This value has a wide scope of parameters, but for the analysis only the parameters involved with the pavement. This value was not available for the Lisbon airport. So there had to be sought for another way to obtain this value.

With a document from the ANA GROUP (ANA GROUP AIRPORTS, 2015) which main directives are shown in Appendix A, that gives an overview of all different charges on the airports in their group, it is possible to make an estimate of the total daily revenue of the Lisbon airport. The calculation of this value is shown below.

The traffic on runways is logically the departures and arrivals of the planes. There is no other traffic possible on runways in normal conditions because of the safety guidelines. On highways there is a difference between the heavy traffic of the trucks and the normal traffic of the cars. These different kinds of traffic have their specific influence on the pavements, but on airfields there is a different approach used. Especially the departures of the planes is relevant, because the planes are much heavier by the full tank of fuel. The impact of the departures are approximately three times as big as the arrivals.

On an international airport come several types of airplanes. The data given by the Lisbon airport of the departures in 2013 gives a range of 147 different types of planes. For every type is the number of departures tracked to convert all these different departures to an equivalent number of departures of the critical airplane. This is in most of the cases the plane that has the most departures on the airport. For example in the airport of Porto this is the A320 and in the Lisbon airport this is the A340 or A332. This data (and all other data related do traffic in the airport) was supplied by the research group where the author has been integrated to do the dissertation and coming from their involvement in the establishment of the pavement management system of the airport.

The equivalent traffic for the A332 is 12.758 departures per year, which is calculated in terms of the equivalence for the damage on the pavement to all type of other aircrafts that operate in the Lisbon airport. In the dissertation this figure is taken has the reference figure to computed departures and in this sense make the calculation of the total daily revenue of the airport. Of course, the computation of all set of type of planes that depart or land in Lisbon will gives us a more accurate result. However, the objective is to demonstrate the framework and in this sense the simplification used was considered enough to have the insight about this subject. The charges for the landing and take-off are calculated with the maximum take-off weight of the planes. For the A332 is this a weight of 230 tons. So, the minimum charge per landing amounts € 182,94 and the A332 is in the category of planes above 150 tons. This gives the next calculation:

$[12.758 \times (182{,}94 + (82 \times 6{,}27))] =$ 8.733.361,32 euro/year

It is assumed, that for every departure there is an arrival needed. So, the value above must be doubled and gives € 17.466.722,64 per year. Charges for the parking, air bridge and GPS are not counted.

In an A332 can sit 320 passengers, so there would be arrive 4.091.200 passengers per year at the airport of Lisbon. It is true that not all planes are always full, so there is counted with 80% of this number. This gives a number of 3272960 passengers per year.

The cost for passenger service vary depending on the origin of the flight. It is assumed that 50% of the flights is coming from a country in the Schengen zone, 30% of flights are Intra EU flights outside the Schengen zone and 20% are international flights. The calculations of the cost is given below.

Schengen zone: € 9,28 x (3272960 x 50%) = € 15.186.534,40

Intra EU: € 12,10 x (3272960 x 30%) = € 11.880.844,80

International: € 17,19 x (3272960 x 20%) = € 11.252.436,48

This gives a total of € 38.319.815,68 per year for the passenger service for the departing passengers. This value also needs to be doubled and gives a figure of € 76.639.631,36 per year.

There are also charges for the security, the calculation is done as followed:

Schengen zone: (€ 1,53 + € 2,50) x (3272960 x 50%) = € 6.595.014,40

Intra EU: (€ 3,20 + € 2,50) x (3272960 x 30%) = € 5.596.761,60

International: (€ 6,22 + € 2,50) x (3272960 x 20%) = € 5.708.042,24

This gives a total of €17.899.818,24 per year for the security check of the departing passengers. The rest of the charges are not taken into count, because these are the most influential.

When all these charges are summed, it gives a total of € 112.006.172,24 per year. So, for the Aircost software is the daily revenue of the airport required and these is € 306.866,23 ($ 341.081,81).

When they plan to work on a runway, a good planning of the work is necessary. If there are more runways on the airport it is possible to reschedule the departures and arrivals of that particular runway to other runways that are not in the work zone. If this scenario is possible they can plan the work in a 24hours/7days schedule. During this period of time there will also be a reduction in the daily revenue because the other runways have also a capacity they cannot exceed. This is the most effective way to work on runways. This is because when they can work on a continuous way on the runway, they do not have the pressure of time during the night and they can finish the wearing course in one piece or in more bigger pieces. These things can only be a benefit for the flatness of the runway.

In the Lisbon airport this scenario of rescheduling the departures and arrivals to other runways is not possible, because of the simple reason that there is only one big runway. To work on this single runway they need to plan the actions during the least busy hours of the airport traffic.

This time span is approximately between 01.00 AM and 05.00 AM. In these 4 hours they close the runway and have the time to do a piece of the runway. During the initial construction (deep rehabilitation of 20cm) they are able to do 100m in one night and during a rehabilitation (resurfacing of the wearing course) they can do 200m per night. The initial construction for both alternatives takes with this speed approximately 50 nights. A rehabilitation takes approximately 25 nights of work for the both pavement types.

Over this particular distance they need to do the milling, the rebuilding of the structure, the delicate finishing of the surface, the lighting and restriping. This kind of work is very unpredictable because of the weather influences and difficult to manage. Also the setting up and removing of the machines and tools takes a valuable time every night. The danger for FOD on the runway in reconstruction is also an important issue.

When they want to connect the new piece to the piece that was previously constructed, they need to create a smooth transition. This by milling in the previous piece for about 2 meters and start the connection at that point. The critical surface areas are the most likely places where the planes have their touch down or take off with the wheels and the vibrations caused by the suspensions take place. So, It is necessary to do these areas in one piece or pay extra attention in these areas.

6.7. Expenditure stream diagram

In Figure 14 is the expenditure stream diagram drawn for both alternatives, but only for the agency costs. It gives a graphical representation of the expenditures in time. Because there is no salvage value, all the arrows are point upwards and the height of the arrows is in proportion with the actual costs.

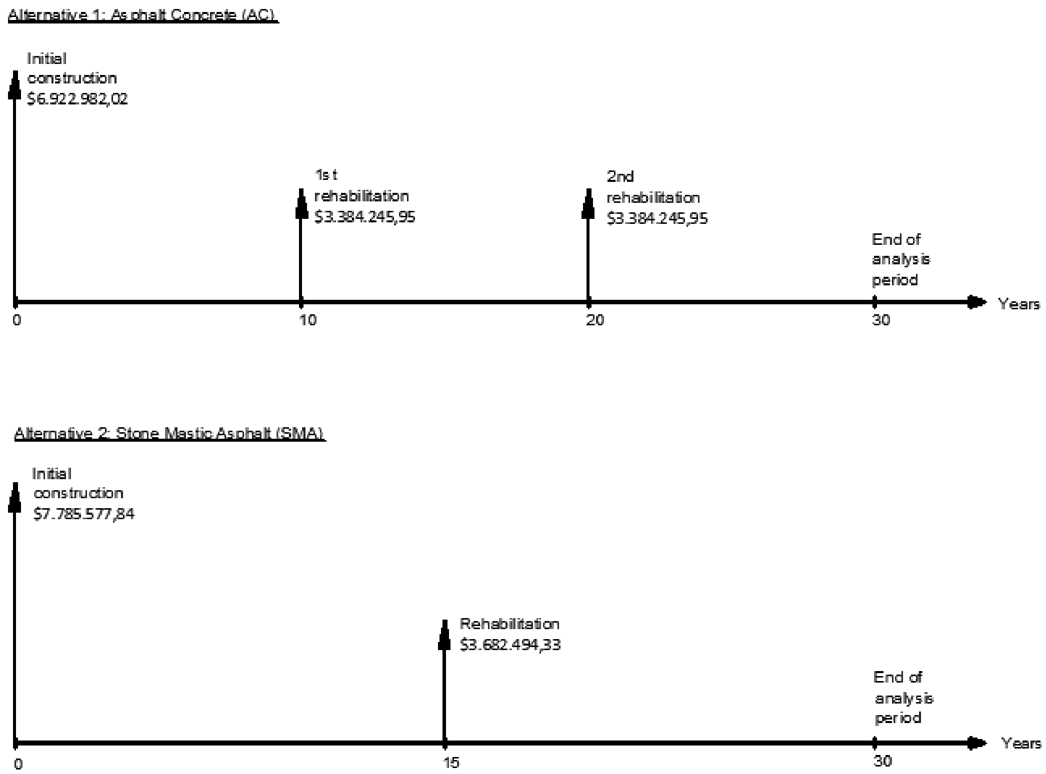

Figure 14: Expenditure stream diagram of the both alternatives.

On the diagram is clear that with only the agency costs in the consideration, the second alternative is the best cost-effective option. When the user costs would be integrated the difference between the alternatives become just bigger.

It is possible to include all the other types of maintenance on the expenditure stream diagram, but these are the same for the both alternatives as described above. So these arrows (costs) are not integrated in the diagram.

6.8. LCCA input data

Having relevant input data is crucial for achieving the intended result from LCCA. Unfortunately, historical data that can serve this purpose is not easily available. As a result, most of the input data are either estimated or assumed with the help of the Lisbon airport. Anyway, a probabilistic-based LCCA will be carried out considering the uncertainty and variability of the input data. The most important parameters are discussed below.

6.8.1. Analysis period

Nevertheless, the pavement alternatives have different design lives, they have to be compared for the same analysis period; otherwise the comparison will be among alternatives of different benefits, which is not the case of LCCA. The period should be long enough to show cost differences of the alternatives. So, the analysis period is taken 30 years for our analysis. This period is long enough as it includes major rehabilitation activities of both the flexible and rigid pavement alternatives.

6.8.2. Discount rate

For the probabilistic analysis, there are three option for the type of probabilistic approach:

- Normal probabilistic with a mean value and a standard deviation.
- Uniform probabilistic with a minimum and maximum value.
- Triangular probabilistic with a minimum, maximum and most likely value.

In the dissertation is the normal probabilistic approach used with different values for the mean (2%, 2,5% and 3%) and a standard deviation of 0,5%, to see what the impact is of a different discount rate on the result.

For the deterministic analysis are discount rates used of 2%, 2,5% and 3% to also see the difference in the result with this different values.

6.8.3. Service life

For the probabilistic approach it is necessary to give a standard deviation to the service life for the different alternatives. The AC pavement have a service life of 10 years and the SMA pavement have a service life of 15 years. In the dissertation is a standard deviation used of 2 years on these service life's, but there is also a calculation done with 1 year and 3 years for the standard deviation to see the influence of these parameters.

6.8.4. Daily airport revenue

The daily revenue of the airport that is related to the runway is calculated above and amounts € 306,866.23 ($ 341.081,81). This is an assumption that was made on the basis of the data from Appendix A. This value is determined to get a clue of daily revenue. So this is not an exact value, but an approximation.

6.8.5. Revenue growth rate

The revenue growth rate gives the opportunity to calculate the revenue of the airport in the following years. Actually it is a supposition of the growth over a certain period. In the Aircost software it is possible to a compound or a simple growth rate.

The compound growth rate goes over the long range revenue projection. It is applied to on base of the growth rate of the previous year's revenue and represents exponential growth. The simple growth rate goes over the short range revenue projection. It is applied as a uniform growth rate over the years and represents the linear growth.

In the dissertation are the both types of growth rates used to see the difference between them. The typical revenue growth rate used in the case of the Lisbon airport can be deduced from the growth rate of the air traffic, this is about 2% or 2,5%. These two values are used in the LCCA to also see the difference between them.

6.8.6. Daily revenue reduction

To calculate the user costs in the Aircost software, the total daily revenue is asked. This figure will be used to obtain the user costs by multiplying this revenue with the number of work days. This calculated value is the total loss of the work activities related to closing the runway.

The runway is not closed for whole days, but only 4 or 5 hours during the night. At this time there is no traffic, so during this period there is no impact on the daily revenue. There is always a chance that during work activities something goes wrong, and that the first flights in the morning will have a delay or need to be relocated to other airports in the area. For this issue, it is possible to give a daily revenue reduction (%) in the Aircost software. In the LCCA is a value assumed of 10% to cover these problems. For example, with a daily revenue of € 306.866,23 the loss for one night of work is € 30.686,62.

7. LCCA result analysis

7.1. Deterministic output

The deterministic approach gives one value to compare the alternatives. There are different discount rates used in the calculations with only the agency costs. In the computation with the agency and user costs there are different discount rates and also different growth revenues for the daily revenue of the airport (simple or compound) used.

7.1.1. Only agency costs

The NPV's and EUAC values are calculated for a discount rates of 2% , 2,5% and 3%. Figure 15 gives a visual image of the NPV's of the different alternatives with the different discount rates and Figure 16 gives the EUAC values for the alternatives with the different discount rates. Table 12 in Appendix B give the calculated values.

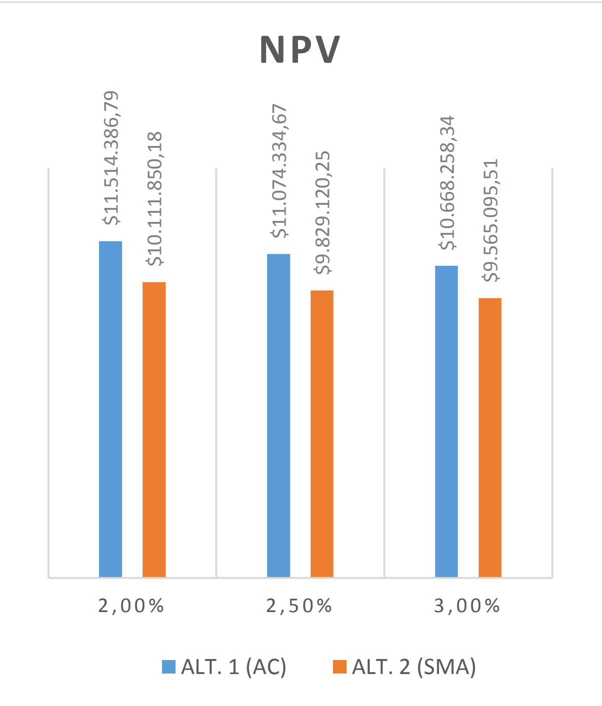

Figure 15: NPV of only agency costs (deterministic).

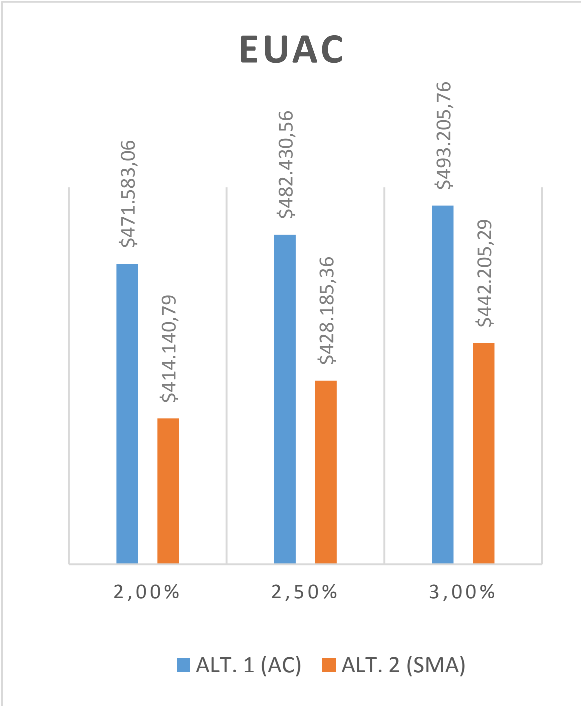

Figure 16: EUAC for only agency costs (deterministic).

The second alternative is clearly the least expensive option when only the agency costs are included for the deterministic approach. With an increasing discount rate the NPV's reduce and the EUAC values rise. The ratio of the differences between the alternatives is identical under the NPV’s and the EUAC values.

7.1.2. Agency and user costs

When the user costs are integrated in the deterministic approach, there are other parameters that influence the results. Figure 17 gives the NPV's and Figure 18 gives the EUAC values for the alternatives with the different discount rates. There are several calculations done with different growth rates for the daily revenue, but here is only one result shown. These values are for a compound growth rate of 2% and a daily reduction of 10% for the daily revenue. Table 13 in Appendix B give also the other values.

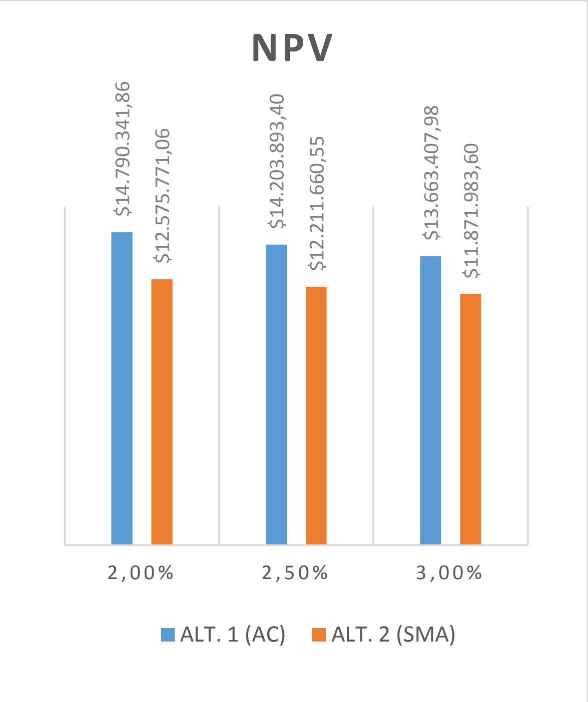

Figure 17: NPV of agency and user costs (deterministic).

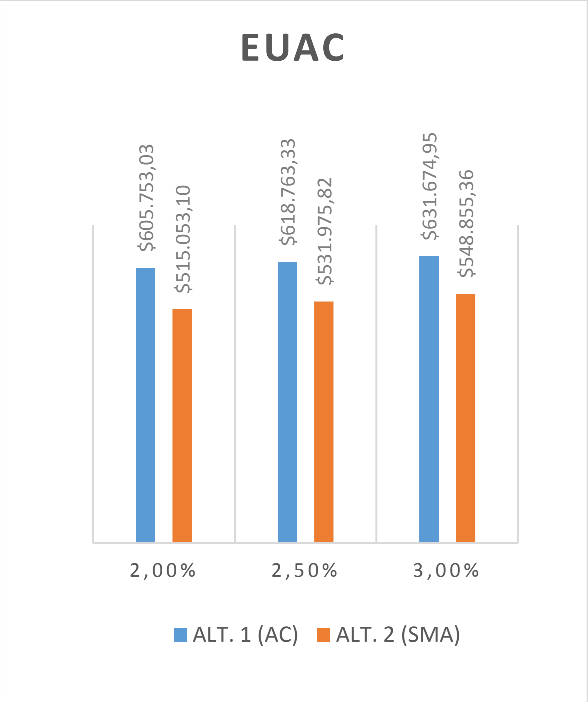

Figure 18: EUAC for agency and user costs (deterministic).

Alternative 2 is again the most economical option with now the agency and user costs included. The NPV's and the EUAC values behave with the same trend. When the discount rate rises, the NPV's reduce and the EUAC values rise.

For example with a discount rate of 2,5%, the NPV for alternative 1 with only the agency costs is $ 11.074.334,67 and with the agency and user costs is $ 14.203.893,40. So the difference of $ 3.129.558,73 is due to the user costs and is approximately 22% of the total cost. For alternative 2 with only the agency costs is $ 9.829.120,25 and with the agency and user costs is $ 12.211.660.55. The difference here is $ 2.382.540,30 and is approximately 20% of the total cost. It is obvious that the greatest impact with the considered conditions on the total costs comes out of the agency costs (initial construction and rehabilitations) with approximately 80% of the total cost.

With all the costs into consideration, for a discount rate of 2,5%, alternative 1 is 1.992.232,85 more expensive than alternative 2, meaning that alternative 1 is approximately 17% more expensive than alternative 1 for the deterministic approach.

7.2. Probabilistic output

In contrast to the deterministic approach, the probabilistic approach provides a range of values. The result of a probabilistic calculation can be shown in a bell curve with a mean and a standard deviation. The Aircost software also gives the minimum and the maximum value, and it is possible to calculate four percentiles in the bell curve.

In this approach there are some standard deviations required for some parameters. For the discount rate is a standard deviation of 0,5% chosen and for the service life of the pavements a standard deviation of 2 years.

Like in the deterministic approach, in the calculations with the agency and user costs there are several calculations done. Different growth rates for the daily revenue are used to show the influence of these parameters on the result.

7.2.1. Only agency costs

In the calculations with only the agency costs there is a comparison made with different standard deviations for the service life of the pavements. The main standard deviation is 2 years, but also 1 year and 3 years are used to define the difference in the results. The values of these calculations are in tables 14 and 15 in Appendix B. The main trend in this comparison is that the cost difference rises in proportion as the standard deviation of the service life increases.

Table 8 shows the results of the NPV's with a standard deviation of 2 years and a discount rate of 2,5% ± 0,5%. Table 9 gives the EUAC values for the same input parameters. The tables gives the means, standard deviations, minimum values and maximum values of the distribution. The chosen percentiles are also listed (5%, 50%, 75% and 95%).

Table 8: NPV of only agency costs (probabilistic).

Statistic	ALT. 1 (x 1000)	ALT. 2 (x 1000)
Mean	$11.910	$10.663
Stand. Dev.	$1.165	$1.060
Minimum	$9.203	$9.084
Maximum	$15.565	$13.271
Perc. 1 (5%)	$10.392	$9.411
Perc. 2 (50%)	$11.666	$10.157
Perc. 3 (75%)	$12.906	$11.641
Perc. 4 (95%)	$13.790	$12.402

Table 9: EUAC of only agency costs (probabilistic).

Statistic	ALT. 1 (x 1000)	ALT. 2 (x 1000)
Mean	$518	$463
Stand. Dev.	$47	$43
Minimum	$374	$389
Maximum	$661	$551
Perc. 1 (5%)	$460	$406
Perc. 2 (50%)	$499	$444
Perc. 3 (75%)	$560	$507
Perc. 4 (95%)	$582	$521

Figure 19 gives a simple visual image of the results with just the mean value of alternatives. The second alternative is also for the probabilistic approach with only the agency costs in the consideration the best option. The cost difference of the mean values for the NPV is $ 1.248.000 and for the EAUC $ 55.000.

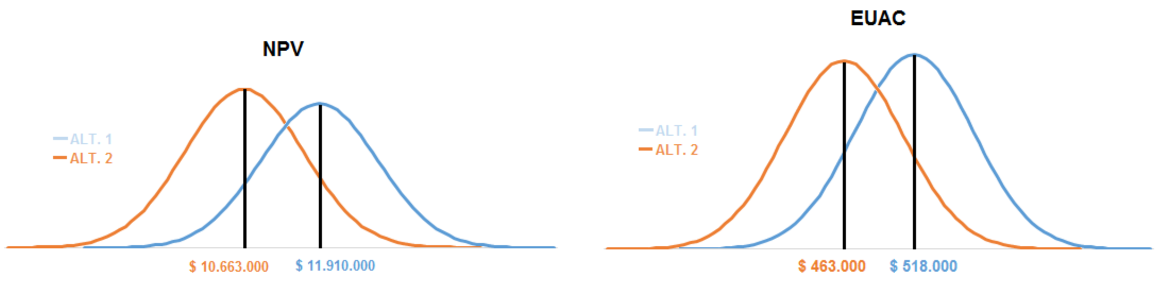

Figure 19: Visual image of the results for only agency costs (probabilistic).

7.2.2. Agency and user costs

In the comparison of the agency and user costs, there are again different growth rates for the daily revenue used. For every different value and type of growth rate there are also different discount rates used. The values of these calculations are in tables 16, 17, 18 and 19 in Appendix B.

These results show, as expected, that if the growth rate increases the costs also rises for the different alternatives. The difference in cost between simple and compound growth rate is also like expected. The values of the compound growth rate are higher than these of the simple growth rate.

Table 10 shows the results of the NPV's with a standard deviation of 2 years, a discount rate of 2,5% ± 0,5%, a compound growth rate of 2% and a daily revenue reduction of 10% during work activities. Table 11 gives the EUAC values for the same input parameters. The tables gives also the means, standard deviations, minimum values and maximum values of the distribution. The chosen percentiles are also listed (5%, 50%, 75% and 95%).

Table 10: NPV of agency and user costs (probabilistic).

Statistic	ALT. 1 (x 1000)	ALT. 2 (x 1000)
Mean	$15.359	$13.293
Stand. Dev.	$1.578	$1.424
Minimum	$12.266	$11.052
Maximum	$20.786	$16.882
Perc. 1 (5%)	$13.324	$11.648
Perc. 2 (50%)	$14.905	$12.635
Perc. 3 (75%)	$16.701	$14.646
Perc. 4 (95%)	$18.028	$15.661

Table 11: EUAC of agency and user costs (probabilistic).

Statistic	ALT. 1 (x 1000)	ALT. 2 (x 1000)
Mean	$668	$578
Stand. Dev.	$61	$59
Minimum	$568	$485
Maximum	$871	$683
Perc. 1 (5%)	$594	$506
Perc. 2 (50%)	$636	$548
Perc. 3 (75%)	$727	$641
Perc. 4 (95%)	$749	$658

A visual image is given in Figure 20 of the computed values of the total cost for the different alternatives. Once more, it is clear that the second alternative is the most cost effective solution. The mean of the NPV for alternative 1 is $ 15.359.000 and for alternative two $ 13.293.000, so this gives a cost difference of $ 2.066.000. For the EUAC the mean of alternative 1 is $ 668.000 and for alternative $ 2 578.000, and gives a cost difference of $ 90.000. So, alternative 1 is approximately 16% more expensive than alternative 2.

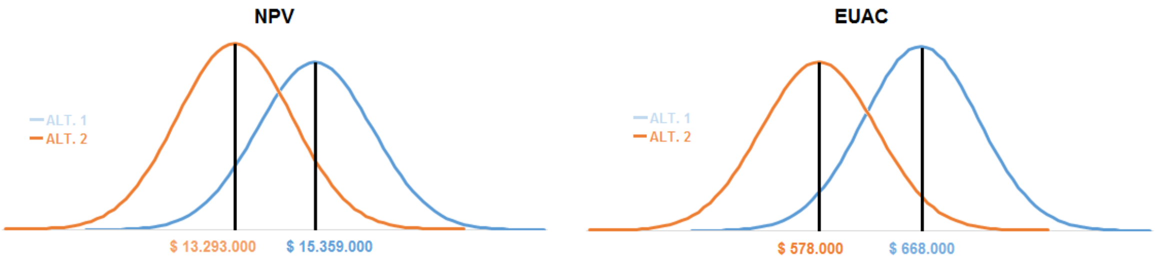

Figure 20: Visual image of the results for agency and user costs (probabilistic).

In tables 14, 15, 16, 17, 18 and 19 of the probabilistic approach in Appendix B, are also the number of iterations to reach convergence and the number of iterations with repeated events given. The tolerance to reach convergence is defined as 2,5% in these calculations.

8. Conclusion and recommendations

8.1. Conclusion

In case that the main runway of the Lisbon airport needs to be reconstructed, the most probable option will be the reclamation of 20cm of the old structure and rebuild it with new layers of 20cm. There are two usual flexible pavement options to do this work: one where the bound layers are formed by AC; other where they are formed by SMA. A life-cycle cost analysis (LCCA) was done to find among the two options the most cost effective solution for an analysis period of 30-years. The agency and user costs are included in the consideration, but the common costs are neglected.

The agency costs covers the initial construction and rehabilitations during the analysis period, but small maintenance operations are ignored because they are the same for the both alternatives. For the user costs, the daily revenue related to the pavements of the airport is used in the analysis with a reduction factor according to the influence of the work activities on the daily revenue. Other costs, like accidental and environmental costs are not included in the analysis.

To make the comparison, AAPTP's LCCA practice for airport pavements and Aircost software was used. A deterministic and probabilistic LCCA was carried to compute the NPV and the EUAC for the different alternatives.

After analysing the result out of the deterministic and probabilistic approach, it was for the analysis conditions used that the user cost is quite low when compared with the agency cost. The user cost covers approximately 20% of the total cost. The reason is that the work activities are planned outside of the operating time of the airport, so the impact on the daily revenue is reduced to exceptional cases. For example when the first receiving flight in the morning needs to be rescheduled.

So the most influential factor is the agency cost, with approximately 80% of the total cost. The initial construction cost is the highest for the SMA-option because of the higher unit cost of the materials and the higher difficulty. When the rehabilitations are taken in consideration, the SMA-option becomes more interesting than the one with AC. This because AC needs two rehabilitations and SMA only one.

The results of the deterministic approach with all the costs included show that the SMA-option is the most cost-effective solution and the results of the probabilistic approach with all the costs included show the same trend. Even with all the different input parameters (discount rates, standard deviation of the service life’s, growth rates of the daily revenue) the cost difference between the two alternatives changes slightly and the conclusion of the most cost-effective solution stays the same.

In general, the flexible pavement (SMA) is the best option according to this LCCA. Although other factors may be taken into consideration for the decision, the difference of the life-cycle costs between the alternatives will make the selection of the flexible pavement with SMA most likely.

8.2. Recommendations

Life-cycle cost analysis is certainly a very good and important technique to find the most cost-effective solution for pavements, not only for airport pavements but also other transport infrastructures. For its proper application and reliable results, it should be pointed out that:

- The need of relevant data to use in the LCCA. When the input data is not plausible, the results of the analysis are useless. Mainly the most influential ones such as the discount rate, construction and rehabilitation costs and work zone duration of the different activities. Therefore, determination of such variables for a specific pavement should be subject to extensive investigation. In this case for the runway, the best way to collect this data is to get it by the airport-agency and by the construction working for it.
- The value out of the computation of the daily revenue of the Lisbon airport is more an assumption than a precisely known value. The figure is more a guide value to get an acceptable value for the user costs out of the Aircost software. So, once more, the proper figures should be used and these are, for sure, available for the airport-agency.

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Appendix

Appendix A: Regulated charges 2015 ANA group (ANA GROUP AIRPORTS, 2015)

Traffic charges:

LANDING/TAKE OFF - per tonne Mainland Airports	LISBON	PORTO	FARO Jan., Feb. and Dec. 2015	FARO Nov. and Mar. 2015	FARO From April until Oct. 2015
Aircrafts up to 25 tonnes, per tonne	5,91	4,92	2,30	3,45	5,11
25 to 75 tonnes, per tonne above 25 tonnes	7,03	5,97	2,80	4,19	6,21
75 to 150 tonnes, per tonne above 75 tonnes	8,27	7,03	3,29	4,93	7,30
over 150 tonnes, per tonne above 150 tonnes	6,27	4,95	2,80	4,19	6,21
Minimum charge per landing	182,94	98,42	46,01	69,01	102,23

Figure 21: Landing/Take off charges (Adapted from ANA GROUP AIRPORTS, 2015).

Passenger service charges:

PASSENGER SERVICE CHARGE	LISBON	PORTO	FARO	BEJA	A.R. AÇORES	A.R. MADEIRA
O/D Passengers						
Flights inside Schengen Area	9,28	8,12	7,89	7,25	6,81	14,27
Intra EU flights outside Schengen Area	12,10	10,58	10,26	9,19	11,05	17,86
International flights	17,19	14,41	14,02	12,32	15,05	23,81
Flights between Madeira and Porto Santo						11,43
Transfer Passengers						
Flights inside Schengen Area	7,68	8,12	7,89	7,25	6,81 a)	14,27
Intra EU flights outside Schengen Area	10,01	10,58	10,26	9,19	11,05 a)	17,86
International flights	13,59	14,41	14,02	12,32	15,05 a)	23,81
Flights between Madeira and Porto Santo						11,43

Figure 22: Passenger service charges (Adapted from ANA GROUP AIRPORTS, 2015).

Security charge:

a) A part corresponding to the amounts received by the official entities, to be charged by Instituto Nacional da Aviação Civil (INAC) per departing passenger.

SECURITY CHARGE	Flights inside Schengen Area	Intra EU flights outside Schengen Area	International flights
Official entities	1,53	3,2	6,21

Figure 23: Security charges (Adapted from ANA GROUP AIRPORTS, 2015).

b) Another part of security charge is related to the amounts allocated to the airport operator and to be directly charged to the users of the airports by managing body, per departing passenger.

€2,50 / departing passenger

Appendix B: All Aircost output data

Deterministic output:

a) Only agency costs.

Table 12: NPV and EUAC output data, only agency costs (deterministic).

Discount rate	NPV		EUAC	
	ALT. 1	**ALT. 2**	**ALT. 1**	**ALT. 2**
2,0%	$11.514.386,79	$10.111.850,18	$471.583,06	$414.140,79
2,5%	$11.074.334,67	$9.829.120,25	$482.430,56	$428.185,36
3,0%	$10.668.258,34	$9.565.095,51	$493.205,76	$442.205,29

b) Agency and user costs.

Table 13:NPV and EUAC output data, agency and user costs (deterministic).

	Discount rate	NPV		EUAC	
		ALT. 1	**ALT. 2**	**ALT. 1**	**ALT. 2**
Revenu growth rate : 2% (simple)	2,0%	$14.730.165,70	$12.547.838,70	$603.288,45	$513.909,10
	2,5%	$14.149.280,17	$12.185.956,31	$616.384,22	$530.856,07
	3,0%	$13.613.799,79	$11.848.320,16	$629.381,51	$547.761,37
Revenu growth rate : 2% (compound)	2,0%	$14.790.341,86	$12.575.771,06	$605.753,03	$515.053,10
	2,5%	$14.203.893,40	$12.211.660,55	$618.763,33	$531.975,82
	3,0%	$13.663.407,98	$11.871.983,60	$631.674,95	$548.855,36
Revenu growth rate : 2,5% (simple)	2,0%	$14.818.939,33	$12.593.511,32	$606.924,26	$515.779,67
	2,5%	$14.230.512,25	$12.227.985,70	$619.922,93	$532.686,99
	3,0%	$13.688.205,11	$11.887.012,59	$632.821,35	$549.550,16
Revenu growth rate : 2,5% (compound)	2,0%	$14.915.622,14	$12.638.147,57	$610.884,00	$517.607,79
	2,5%	$14.318.244,19	$12.269.061,40	$623.744,79	$534.476,37
	3,0%	$13.767.884,68	$11.924.827,04	$636.505,03	$551.298,37

Probabilistic output:

a) Only agency costs.

Table 14: NPV output data, only agency costs (probabilistic).

		NPV					
	Statistic	Discount rate: 2,0% ± 0,5%		Discount rate: 2,5% ± 0,5%		Discount rate: 3,0% ± 0,5%	
		ALT. 1	**ALT. 2**	**ALT. 1**	**ALT. 2**	**ALT. 1**	**ALT. 2**
Service life ± 2 year	Mean	$12.385	$11.063	$11.910	$10.663	$11.357	$10.201
	Stand. Dev.	$1.274	$1.157	$1.165	$1.060	$1.039	$925
	Minimum	$10.258	$9.219	$9.203	$9.084	$9.256	$8.703
	Maximum	$17.831	$14.150	$15.565	$13.271	$14.635	$12.697
	Perc. 1 (5%)	$10.752	$9.715	$10.392	$9.411	$9.949	$9.142
	Perc. 2 (50%)	$11.988	$10.485	$11.666	$10.157	$11.111	$9.781
	Perc. 3 (75%)	$13.503	$12.143	$12.906	$11.641	$12.267	$11.055
	Perc. 4 (95%)	$14.503	$12.910	$13.790	$12.402	$13.027	$11.772
# iterations		600	700	900	600	900	800
# iterations with repeated events		260	313	423	267	424	327
Service life ± 1 year	Mean	$12.257	$10.832	$11.695	$10.508	$11.239	$10.084
	Stand. Dev.	$1.151	$1.108	$1.034	$947	$911	$835
	Minimum	$10.163	$9.181	$9.896	$9.086	$9.589	$8.733
	Maximum	$16.446	$14.155	$15.080	$13.002	$14.131	$12.621
	Perc. 1 (5%)	$10.843	$9.692	$10.418	$9.449	$10.065	$9.190
	Perc. 2 (50%)	$11.887	$10.302	$11.325	$10.061	$11.000	$9.726
	Perc. 3 (75%)	$13.155	$11.892	$12.540	$11.385	$11.950	$10.822
	Perc. 4 (95%)	$14.368	$12.729	$13.572	$12.187	$12.891	$11.675
# iterations		1000	300	800	900	900	800
# iterations with repeated events		384	107	303	346	357	280
Service life ± 3 year	Mean	$12.516	$11.014	$12.050	$10.722	$11.471	$10.332
	Stand. Dev.	$1.637	$1.246	$1.470	$1.116	$1.345	$1.021
	Minimum	$8.577	$9.183	$8.180	$8.762	$8.271	$8.733
	Maximum	$18.897	$15.986	$17.914	$13.377	$17.600	$15.497
	Perc. 1 (5%)	$10.614	$9.650	$10.101	$9.351	$9.752	$9.072
	Perc. 2 (50%)	$12.076	$10.396	$11.836	$10.236	$11.256	$9.905
	Perc. 3 (75%)	$13.675	$12.190	$13.168	$11.766	$12.432	$11.248
	Perc. 4 (95%)	$15.151	$13.072	$14.372	$12.461	$13.625	$11.979
# iterations		700	500	1000	1100	1000	900
# iterations with repeated events		321	209	497	518	478	412

Table 15: EUAC output data, only agency costs (probabilistic).

		EUAC					
	Statistic	Discount rate: 2,0% ± 0,5%		Discount rate: 2,5% ± 0,5%		Discount rate: 3,0% ± 0,5%	
		ALT. 1	**ALT. 2**	**ALT. 1**	**ALT. 2**	**ALT. 1**	**ALT. 2**
Service life ± 2 year	Mean	$505	$452	$518	$463	$526	$472
	Stand. Dev.	$47	$47	$47	$43	$43	$41
	Minimum	$441	$369	$374	$389	$455	$400
	Maximum	$663	$540	$661	$551	$663	$565
	Perc. 1 (5%)	$451	$395	$460	$406	$470	$421
	Perc. 2 (50%)	$480	$428	$499	$444	$511	$454
	Perc. 3 (75%)	$553	$500	$560	$507	$566	$515
	Perc. 4 (95%)	$568	$513	$582	$521	$587	$531
# iterations		600	700	900	600	900	800
# iterations with repeated events		260	313	423	267	424	327
Service life ± 1 year	Mean	$501	$445	$509	$458	$519	$467
	Stand. Dev.	$41	$42	$39	$41	$37	$37
	Minimum	$434	$378	$451	$390	$457	$404
	Maximum	$575	$519	$588	$532	$595	$547
	Perc. 1 (5%)	$454	$397	$464	$408	$475	$421
	Perc. 2 (50%)	$478	$425	$489	$440	$501	$452
	Perc. 3 (75%)	$549	$494	$553	$503	$559	$510
	Perc. 4 (95%)	$559	$506	$566	$516	$573	$525
# iterations		1000	300	800	900	900	800
# iterations with repeated events		384	107	303	346	357	280
Service life ± 3 year	Mean	$513	$451	$523	$467	$528	$477
	Stand. Dev.	$61	$49	$60	$46	$56	$45
	Minimum	$350	$372	$355	$379	$363	$393
	Maximum	$758	$596	$778	$563	$777	$639
	Perc. 1 (5%)	$446	$391	$453	$407	$461	$418
	Perc. 2 (50%)	$488	$427	$514	$450	$516	$460
	Perc. 3 (75%)	$558	$502	$567	$510	$570	$519
	Perc. 4 (95%)	$637	$520	$609	$531	$611	$542
# iterations		700	500	1000	1100	1000	900
# iterations with repeated events		321	209	497	518	478	412

b) Agency and user costs.

Table 16:NPV output data, agency and user costs, growth rate of 2% (probabilistic).

		NPV					
	Statistic	Discount rate: 2,0% ± 0,5%		Discount rate: 2,5% ± 0,5%		Discount rate: 3,0% ± 0,5%	
		ALT. 1	**ALT. 2**	**ALT. 1**	**ALT. 2**	**ALT. 1**	**ALT. 2**
Revenu growth rate : 2% (simple) Daily revenu reduction: 10%	Mean	$15.961	$13.765	$15.265	$13.336	$14.634	$12.781
	Stand. Dev.	$1.720	$1.559	$1.559	$1.391	$1.517	$1.254
	Minimum	$12.783	$11.266	$12.395	$11.159	$11.227	$10.644
	Maximum	$22.626	$17.328	$21.216	$16.596	$20.999	$15.695
	Perc. 1 (5%)	$13.838	$11.939	$13.265	$11.675	$12.729	$11.298
	Perc. 2 (50%)	$15.545	$13.027	$14.845	$12.675	$14.313	$12.209
	Perc. 3 (75%)	$17.297	$15.292	$16.529	$14.587	$15.877	$13.942
	Perc. 4 (95%)	$18.833	$16.267	$17.859	$15.546	$17.154	$14.904
# iterations		600	500	1000	600	800	700
# iterations with repeated events		264	219	460	278	360	305
Revenu growth rate : 2% (compound) Daily revenu reduction: 10%	Mean	$16.249	$13.840	$15.359	$13.293	$14.556	$12.765
	Stand. Dev.	$1.768	$1.633	$1.578	$1.424	$1.404	$1.268
	Minimum	$13.157	$11.351	$12.266	$11.052	$11.991	$10.967
	Maximum	$20.465	$18.052	$20.786	$16.882	$18.325	$16.019
	Perc. 1 (5%)	$13.851	$12.063	$13.324	$11.648	$12.811	$11.347
	Perc. 2 (50%)	$16.011	$12.981	$14.905	$12.635	$14.124	$12.224
	Perc. 3 (75%)	$17.754	$15.366	$16.701	$14.646	$15.800	$13.887
	Perc. 4 (95%)	$19.053	$16.655	$18.028	$15.661	$17.019	$15.003
# iterations		500	800	1300	800	600	600
# iterations with repeated events		249	345	598	339	254	247

Table 17:EUAC output data, agency and user costs, growth rate of 2% (probabilistic).

	EUAC						
	Statistic	Discount rate: 2,0% ± 0,5%		Discount rate: 2,5% ± 0,5%		Discount rate: 3,0% ± 0,5%	
		ALT. 1	**ALT. 2**	**ALT. 1**	**ALT. 2**	**ALT. 1**	**ALT. 2**
Revenu growth rate : 2% (simple) Daily revenu reduction: 10%	Mean	$651	$565	$664	$580	$673	$590
	Stand. Dev.	$62	$61	$61	$58	$61	$54
	Minimum	$559	$472	$576	$479	$581	$503
	Maximum	$866	$668	$850	$679	$892	$692
	Perc. 1 (5%)	$580	$490	$590	$506	$601	$521
	Perc. 2 (50%)	$616	$535	$631	$553	$640	$565
	Perc. 3 (75%)	$714	$629	$722	$639	$727	$645
	Perc. 4 (95%)	$733	$643	$745	$656	$755	$664
# iterations		600	500	1000	600	800	700
# iterations with repeated events		264	219	460	278	360	305
Revenu growth rate : 2% (simple) Daily revenu reduction: 10%	Mean	$662	$566	$668	$578	$672	$590
	Stand. Dev.	$64	$62	$61	$59	$58	$55
	Minimum	$568	$462	$568	$485	$582	$504
	Maximum	$858	$667	$871	$683	$851	$704
	Perc. 1 (5%)	$584	$492	$594	$506	$604	$521
	Perc. 2 (50%)	$671	$533	$636	$548	$643	$564
	Perc. 3 (75%)	$722	$633	$727	$641	$732	$650
	Perc. 4 (95%)	$737	$648	$749	$658	$754	$668
# iterations		500	800	1300	800	600	600
# iterations with repeated events		249	345	598	339	254	247

Table 18: NPV output data, agency and user costs, growth rate of 2,5% (probabilistic).

	NPV						
	Statistic	Discount rate: 2,0% ± 0,5%		Discount rate: 2,5% ± 0,5%		Discount rate: 3,0% ± 0,5%	
		ALT. 1	**ALT. 2**	**ALT. 1**	**ALT. 2**	**ALT. 1**	**ALT. 2**
Revenu growth rate : 2,5% (simple) Daily revenu reduction: 10%	Mean	$16.122	$13.847	$15.333	$13.202	$14.621	$12.859
	Stand. Dev.	$1.708	$1.602	$1.613	$1.345	$1.482	$1.257
	Minimum	$12.735	$11.428	$11.042	$11.202	$11.746	$10.957
	Maximum	$20.529	$18.209	$20.262	$17.309	$20.813	$15.873
	Perc. 1 (5%)	$13.891	$12.032	$13.211	$11.713	$12.675	$11.378
	Perc. 2 (50%)	$15.737	$12.993	$14.862	$12.514	$14.150	$12.232
	Perc. 3 (75%)	$17.623	$15.390	$16.662	$14.416	$15.839	$14.090
	Perc. 4 (95%)	$18.886	$16.544	$18.070	$15.487	$17.087	$14.855
# iterations		900	600	700	400	600	400
# iterations with repeated events		428	252	314	161	267	175
Revenu growth rate : 2,5% (simple) Daily revenu reduction: 10%	Mean	$16.239	$13.931	$15.507	$13.421	$14.730	$12.842
	Stand. Dev.	$1.812	$1.651	$1.561	$1.488	$1.430	$1.287
	Minimum	$11.560	$11.570	$13.047	$11.160	$11.966	$11.043
	Maximum	$22.701	$19.088	$19.536	$17.254	$18.699	$15.804
	Perc. 1 (5%)	$13.918	$12.114	$13.492	$11.746	$12.844	$11.403
	Perc. 2 (50%)	$15.670	$13.050	$15.052	$12.642	$14.334	$12.166
	Perc. 3 (75%)	$17.765	$15.488	$16.835	$14.819	$15.899	$14.189
	Perc. 4 (95%)	$19.357	$16.656	$18.188	$15.865	$17.195	$14.970
# iterations		900	1300	500	700	800	400
# iterations with repeated events		408	557	235	300	348	162

Table 19: EUAC output data, agency and user costs, growth rate of 2,5% (probabilistic).

	EUAC						
	Statistic	Discount rate: 2,0% ± 0,5%		Discount rate: 2,5% ± 0,5%		Discount rate: 3,0% ± 0,5%	
		ALT. 1	**ALT. 2**	**ALT. 1**	**ALT. 2**	**ALT. 1**	**ALT. 2**
Revenu growth rate : 2,5% (simple) Daily revenu reduction: 10%	Mean	$662	$564	$666	$576	$677	$592
	Stand. Dev.	$63	$62	$62	$58	$60	$55
	Minimum	$564	$456	$490	$483	$587	$500
	Maximum	$865	$670	$863	$683	$886	$710
	Perc. 1 (5%)	$584	$491	$595	$507	$605	$522
	Perc. 2 (50%)	$631	$530	$634	$544	$646	$567
	Perc. 3 (75%)	$723	$631	$727	$641	$734	$650
	Perc. 4 (95%)	$741	$647	$748	$655	$756	$666
# iterations		900	600	700	400	600	400
# iterations with repeated events		428	252	314	161	267	175
Revenu growth rate : 2,5% (compound) Daily revenu reduction: 10%	Mean	$665	$570	$675	$583	$679	$594
	Stand. Dev.	$66	$65	$63	$60	$60	$56
	Minimum	$455	$463	$587	$481	$595	$507
	Maximum	$871	$686	$861	$705	$826	$702
	Perc. 1 (5%)	$591	$495	$599	$510	$608	$525
	Perc. 2 (50%)	$626	$534	$642	$550	$645	$565
	Perc. 3 (75%)	$730	$641	$736	$648	$741	$653
	Perc. 4 (95%)	$749	$655	$755	$664	$763	$675
# iterations		900	1300	500	700	800	400
# iterations with repeated events		408	557	235	300	348	162