Life Cycle Cost Analysis: Application to an airport pavement

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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 a discount rates of 2.5% 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)

1. Introduction

Runways are the most critical pavement areas of airports, so it is important to ensure the quality of these pavements. They need to be constructed with sufficient strength to carry the moving aircraft and have a high resistance to skidding and aquaplaning (EAPA, 2003). This is most of the time accomplished with reconstructions or deep rehabilitations. To do a reconstruction or rehabilitation, it is important to take some options in the consideration and to compare them. There are two types of analysis that are well known in the pavement industry, Life-Cycle analysis (LCA) and Life-Cycle cost analysis (LCCA). It is more likely to make a LCCA for an airport pavement, but the both types of analysis and the reason why to choose LCCA will be explained shortly in the next chapter.

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 cost factors like rehabilitation and reconstruction were not included in the analysis. 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. Ignoring these costs can lead to a wrong decision, because all these kind of costs can be more crucial on the long-term than the costs of the initial construction.
The application of the analysis is done on the main runway of the Lisbon airport. The purpose of the work activities is a deep rehabilitation of 20cm. The comparison between two pavement types, Asphalt Concrete (AC) and Stone Mastic Asphalt (SMA), will done to find the most cost-effective solution for the runway.

2. Pavements, LCA and LCCA overview

2.1. Pavement types

In general, there are two different options for pavements. 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 (U.S. Department of Transportation, Federal Aviation management, 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. The bound layers consists generally of a mineral skeleton and a bituminous binder, which may be supplemented with certain additives. The unbound layers are mostly composed by a continuous crushed rock mineral skeleton (U.S. Department of Transportation, Federal Aviation ministration, 2009).

One of the flexible pavement options 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%)(De Corte, 2013).

The second and most common bituminous mixture for a flexible pavement is a continuous graded one 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 forms in these mixtures the skeleton. The loads are transmitted by sand from grain to grain and the contact stresses are lower. It are the frictional properties of the sand and the mixture composition, which allows for an optimum stacking, which ensure the stability of the mixture. 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) (De Corte, 2013).

2.2. Life-cycle analysis (LCA)

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. When the definition of the aim and scope of the study is done, the next step 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)

In general, 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. Knowing that the use phase of the road is predominant with respect to energy consumption and also to gas emissions released to the atmosphere. One of the main factors for the use phase is the rolling resistance, this depends on the surface and structural characteristics of the different pavements (Araújo, Oliveira, & Silva, 2014).

The conceptual organization of the methodology is shown in Figure 1. The interactions between the various phases are shown 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 1: Energy/material interactions and flows between the phases of LCA (Adapted from Araújo, Oliveira, & Silva, 2014).](image)

The main structure of the LCA methodology is mostly done on base of worksheets in which the various phases and components of the pavement life cycle are considered. These worksheets are generally structured as followed: (Araújo, Oliveira, & Silva, 2014)

- Characterization of the road;
- Material characterization;
- Characterization of equipments and processes;
- Life-Cycle Inventory (LCI);
- LCCA (optional);
- Analysis of the road use phase.

2.3. Life-cycle cost analysis (LCCA)

LCCA is a useful tool to make a decision when selecting a pavement type, because to determine the most effective method and timing, all new construction, reconstruction and maintenance projects should
employ some level of economic evaluation (U.S. Department of Transportation, Federal Aviation
ministration, 2014). Defining the structure and mix type, ways of construction, as well as maintenance
and rehabilitation strategy are the most important steps in the beginning. The following steps are
basically followed: (Pavement Interactive, 2007)

- Initial strategy and analysis decisions

This includes the initial pavement design and the necessary supporting maintenance and
rehabilitation activities forms the pavement design strategy. The schedule for maintenance and
rehabilitations (M&R) needs to be made and the time period over which alternate design strategies will
be analyzed. 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.

- Estimate costs

First of all the agency costs, These 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. For example the costs of preliminary engineering, initial construction, M&R
activities, etc. The second cost item is the user cost, These costs arise by the users of the facility during
the construction, M&R activities and everyday use of the pavement.

- Compare the alternatives

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).

- Analyze 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.

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. 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.

The LCCA process for conducting on project of an airport pavement is a slightly expand version of
procedure than for a highway pavement, and contains 10 steps. The guidance and short description for
completing the steps are listed below. Because of the use of experience-based estimates in quantifying
the many LCCA inputs, it is important to use relevant data in this effort (AAPTP, 2011).
**- Step 1: Defining the scope of the project**

The first step 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 (AAPTP, 2011).

**- Step 2: Establish framework of the LCCA**

First of all, the analysis period of the project needs to be defined. 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. In this research is calculated with an analysis period of 30 years for the deep rehabilitation.

The economic analysis technique needs to be selected. Mostly they use the NPV and EUAC to compare the alternatives.

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

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

In these equations: 
- \(i\) = Discount rate
- \(n\) = Year of expenditure

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- \(i\) = Discount rate
- \(n\) = Analysis period

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

Another important and controversial parameter for the approach is the discount rate, 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. Recent studies indicate the predominant use of discount rates in the 2 to 5 percent range for the application of LCCA for airport pavements. In this research is calculated with values of 2%, 2.5% and 3% for the discount rate.

The choice of the statistical computation approach is between 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 probabilistic approach simulates and accounts the inherent variability of the input parameters. It is a sampling process where the input values are randomly drawn from the defined frequency distributions and the selected values are used to compute a forecasted life cycle cost value. The sampling process is repeated over and over again, thereby generating many forecasted life cycle cost values for the pavement strategy (AAPTP, 2011).
- 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 each alternative be assigned to a strategy consisting of the initial structure and the probable M&R activities covering the selected analysis period (AAPTP, 2011).

- Step 4: Define expected Pavement Performance and M&R Activity Timing

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, and can be visually represented by a life cycle model. It illustrates the difference between maintenance and resurfacing projects over the chosen analysis period (AAPTP, 2011).

- Step 5: Estimate direct costs (owner costs)

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. 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 (AAPTP, 2011).

- Step 6: Estimate indirect costs (user costs)

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 and future M&R treatments) (AAPTP, 2011).

- 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 (AAPTP, 2011).

- Step 8: Calculate Life Cycle Costs

The results of the analysis are generally achieved by a software package (Aircost), for the deterministic and probabilistic approach (AAPTP, 2011).

- Step 9: Evaluate and analyse the results

After the computation of the 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 (AAPTP, 2011).
Step 10: Re-evaluate the pavement strategies

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).

3. Application and results discussion

The application of the analysis is made on the main runway RWY03/21 of the Lisbon airport. The runway is 3805m long and 45m wide, so work area is 171,225m² or 204,790,1yd². The deep rehabilitation is a resurfacing of 20cm with new bounded layers of AC or SMA. In Figure 2 is the structure of both alternatives shown, and in Figure 3 is the schedule of the M&R represented.

In Table 1 are the unit prices of the different layers for the both alternatives given. The extra costs for milling, binder, striping and lighting are calculated on $1,796,671,81. For the application of the indirect costs is an assumption made of total daily revenue of the airport, based on the information obtained by the ANA group (Regulated charges 2015), this value is $341,081,81. Figure 4 shows the expenditure diagram for the both alternatives, but only for the agency costs, this gives a graphical representation of the expenditure in time.

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

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. 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 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%. There is also a daily revenue reduction factor (%) included to set the reduction of the revenue during work activities, this value is 10%.

The deterministic approach for only the agency costs with a discount rate of 2,5% give a NPV for AC of $11,074,334,67 and for SMA of $9,829,120,25; and a EUAC for AC of $482,430,56 and for SMA of $428,185,36. In this case is SMA clearly the least expensive option. When the user costs are also included with the same discount rate the results give a NPV for AC of $14,203,893,40 and for
SMA of $12.211.660,55; and a EUAC for AC of $618.763,33 and for SMA of $531.975,82. So, when all the costs are included in the deterministic approach, SMA is the most economical solution.

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Table 2 shows the results of the NPV’s with a standard deviation of 2 years and a discount rate of 2.5% ± 0.5% and Table 3 gives the EUAC values with the same input parameters, for the probabilistic approach with only the agency costs in the consideration. When the user costs are included, the result of the NPV’s are shown in Table 4 and the EUAC’s in table 5 with the same input parameters. The conclusion is the same in all the cases, SMA is the most economical alternative.

Table 2: NPV of only agency costs.

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

Table 3: EUAC of only agency costs.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>ALT. 1 (x 1000)</th>
<th>ALT. 2 (x 1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$518</td>
<td>$463</td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td>$47</td>
<td>$43</td>
</tr>
<tr>
<td>Minimum</td>
<td>$374</td>
<td>$389</td>
</tr>
<tr>
<td>Maximum</td>
<td>$661</td>
<td>$551</td>
</tr>
<tr>
<td>Perc. 1 (5%)</td>
<td>$460</td>
<td>$406</td>
</tr>
<tr>
<td>Perc. 2 (50%)</td>
<td>$499</td>
<td>$444</td>
</tr>
<tr>
<td>Perc. 3 (75%)</td>
<td>$560</td>
<td>$507</td>
</tr>
<tr>
<td>Perc. 4 (95%)</td>
<td>$582</td>
<td>$521</td>
</tr>
</tbody>
</table>
By doing the analysis for the runway of the Lisbon airport the conclusion is clear. The results of the deterministic approach with all the costs included show that the SMA pavement 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.

After analysing the result, it was also clear 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.

The most influential factor is definitely 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 into consideration, the SMA-option becomes more interesting than the AC-option. This because AC needs two rehabilitations and SMA only one.

For its proper application of LCCA and reliable results, it is necessary to have relevant data. 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 self.

Another remark is that the value 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.

4. Conclusion and recommendations

After analysing the result, it was also clear 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.

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References


