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Bridge Construction. An Economical and Sustainable Approach

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Abstract

This paper presents a methodology that quantifies the life cycle costs of concrete decks of roadway bridges that supports the decision-making regarding the optimal selection between several construction / repair alternatives.

A deterioration model based on the main material and environmental characteristics of bridges is presented. Some of the most up-to-date materials that are used on concrete bridges are also presented and characterized. The quantification of the user costs is presented. These calculations are made considering the vehicle operating costs, the cost of time and accident costs. The user costs are determined by comparing the traffic costs under free flow conditions with those that arise from disrupting the free traffic flow.

The created model is applied to an existing bridge, where the determination and comparison of the costs of the application of different repair alternatives are analysed. At the end, the main conclusions and recommendations are presented.

Key words: *Bridges, deterioration, life cycle costs, sustainability*

Introduction

Bridges, as they are structures designed to have a lifespan of over 100 years, captivate a huge amount of money from the public purse. The costs are associated with much more than just the direct construction costs. Maintenance, rehabilitation, and repair costs are very significant. Associated with direct costs of the promoters, are also the user costs. As the costs, and the environmental effects of their use are deferred for more than a century, there is a great difficulty in choosing the most sustainable solution.

In developed countries, investment in new structures is declining and investments are redirected to the maintenance of existing structures. For example, only a small amount (12%) of the total bridge investment in the US is caused by the construction of new structures (IPCC, 2014). The road transport network is a fundamental asset at both an economic and social level. It has a fundamental role in the daily life of citizens, providing people and goods with quick, easy, and safe means of transport. Historically, it has been, and continues to be a crucial factor in the growth of the economy and prosperity of countries. According to Rodrigue (2020), transport systems face huge requirements to increase their capacity and to reduce the costs of mobility.

The significant increase in the volume of road traffic in the last 50 years has forced, in western Europe, including Portugal, a large investment in roadways. The investment in road networks is massive, with bridges being the most vulnerable elements and, at the same time, the ones that require the largest budget in their management. In most developed countries, major projects for roads construction are coming to the end. Now the focus is on network maintenance operations.

The average lifespan of bridges ranges from 50 to 100 years. Differently to what could be expected from the set of bridges built over these years, many of them already show, after a few decades of use, worrying signs of degradation. These values are continually extended using different management strategies that include different combinations of preservation, rehabilitation, and reinforcement strategies (Lounis and Daigle, 2010).

Bridges are fundamental elements of the road network. Their complete, or partial failure, may cause the disruption of the free flow circulation, leading to costs, both in the public and private

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sectors. In the document prepared by FHWA (2021), it appears that of the approximately 620 thousand existing bridges in the USA about 25% have some type of anomaly.

According to Cheng and Frangopol (2022), structural systems are subjected to a variety of stressors, such as deterioration and natural hazards. The induced structural failure may have a significant impact on the society. Proper life-cycle management (e.g., design and maintenance) should be applied to ensure acceptable levels of safety and serviceability of structures. Nevertheless, over these actions may incur additional costs, which are undesirable for decision-makers. For this reason, life-cycle optimization considering uncertainty can be employed to balance conflicting budgetary and safety constraints Frangopol *et al*. (2017).

Both world population and economy are growing, which put larger pressure on the aging and deteriorating infrastructure. The aging transportation system needs to be upgraded to support the increase in demand. As a result, bridge owners and bridge engineers are looking for efficient and economical methods to repair their bridges and increase their live load capacity. These methods need to be cost effective and constructible, requiring yielding solutions that will lengthen the service life of the structure Chajes *et al*. (2019).

The three pillars of sustainability are the social equity, the environmental protection, and the economic viability. Road bridges, by their unique nature, are fundamental elements of the road network. Bridges are structures that make it possible to overcome natural barriers, bringing people together, making trips shorter, increasing the quality of life of the users who cross them and of the society to which they belong. The reduction of circulation time, in addition to economic savings, provides a clear environmental benefit.

In this article, an economic analysis is made of the utilization of different construction materials of reinforced concrete bridge decks, presenting a methodology that allows the support to the decision-making by the owners, which allows, supported in the economic and environmental criteria, choosing the best sustainable solution.

Methodology

This new reality further emphasizes the importance of approaches, regarding the operation of bridges, to be made, not only based on the safety and functionality of the structure, but also considering economical and environmental approaches. Generally, economic studies are carried out comparing, at current prices, the different costs, and benefits of the various maintenance alternatives.

The cost-benefit analysis of the different maintenance solutions highlights the need to quantify the different factors involved, such as: the costs of traffic disruption; the rate of deterioration of the different structural and non-structural elements of the bridges; the lifetime of the different maintenance and repair alternatives; and the opportunity cost influence into the decision-making process.

With the aim of minimizing the life cycle costs of concrete roadway bridges a deterioration model is defined. Therefore, a probabilistic approach is used, in order to predict the behaviour of reinforced concrete structures, in exposure classes XC and XS, according to EN 1992-1-1 (2004). The model measures the time before corrosion initiation and the propagation time.

Various construction techniques are presented. The service life of each alternative is defined using the deterioration model. The life cycle costs were quantified considering values from international literature.

The cost definition is made considering successive stages: i) determination of the service life of each material; ii) determination of the direct costs of each alternative considering their unit costs; iii) determination of the user costs.

Reinforcement corrosion is basically an electrochemical phenomenon, in which iron is transformed into iron oxide, a material that is much bulkier than the iron from which it originates. Concrete, mainly due to the hydration reactions of the calcium silicate present in the cement paste, is a highly alkaline composite with a pH around 13. The alkaline environment of concrete produces an iron oxide film, which provides protection to the reinforcement through its passivation. This effect, for the carbonation, can be observed in Figure 1.

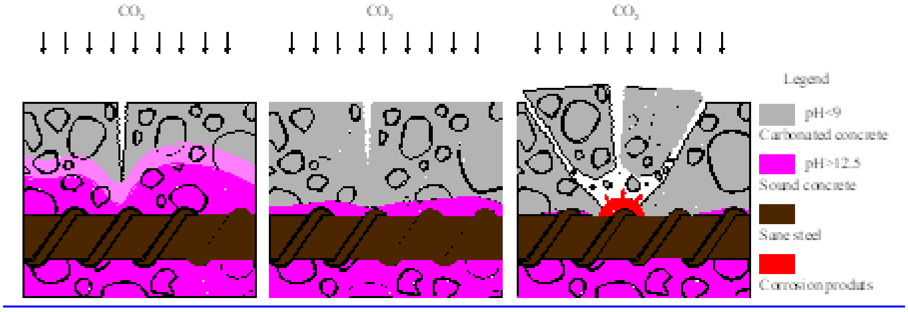

Fig. 1. *Development of the carbonation front (Masy, 1996)*

The main causes of deterioration, of the protective film of the reinforcement in reinforced concrete, are the carbonation of the concrete and the high concentrations of chlorides. These factors depend, among others, on the environmental conditions where the structure is implanted and on the quality of the concrete.

In literature we can find a large diversity of deterioration models. In this investigation the methodology showed in Fig. 1 was used. It comprises two different stages: the initiation stage, while the concrete still protects the reinforcement; and the propagation stage, when the corrosion of the reinforcement occurs, which results in a resistant capacity loss (Tuutti, 1982).

The duration of the initiation period depends on the penetration rate of carbonation and / or chlorides into the concrete. The penetration rate depends on the environment where the structure is inserted as well as on the intrinsic properties of the concrete. The approach to quantify the initiation, and propagation, period for both agents, carbonation, and chlorides, is presented in LNEC E-464 (2007). This formulation is shown in detail in Almeida et al. (2011).

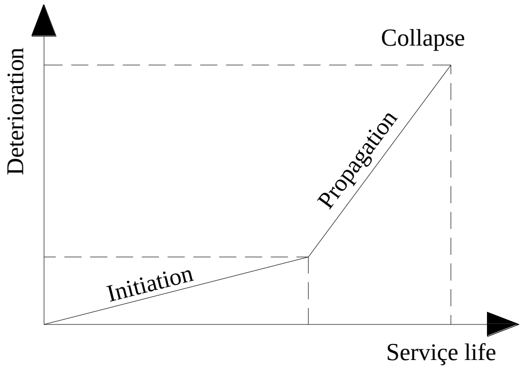

Fig. 2*. Degradation mechanism due to reinforcement corrosion (Tuutti, 1982)*

The lifespan of reinforced concrete structures is expected to be long due to the alkaline environment provided by the concrete, where the reinforcements are located. However, the effect of corrosion is accelerated whenever there is a break in the protective barrier provided by the concrete, reducing its pH, caused by the penetration of chlorides or due to the carbonation of the concrete components through contact with atmospheric carbon dioxide. Reinforcement corrosion is undoubtedly one of the biggest problems of reinforced concrete bridges due to the internal stresses created by the expansion of the corrosion products and the loss of reinforcement section. The existence of these tensions causes cracking and delamination of the concrete accentuating the degradation mechanism.

According to various researchers as Yunovich et al. (2001), and Branco and Brito (2004), the user costs can be 10 to 15 times the direct costs. With the objective of expanding the service live of concrete bridges, various alternatives were tested.

Several construction techniques are presented. The service life of each alternative is defined using the deterioration model. The life cycle costs were quantified considering values from international literature.

The behaviour of the different alternatives was defined relatively to the basic scenario (A0 – common reinforcement). The six alternatives tested can be classified in three groups: coated rebars or change of the chemical composition of steel (A1 – epoxy coated reinforcement, A2 – galvanized steel reinforcement A3 – solid stainless-steel reinforcement, and A4 – coated stain-less steel reinforcement); change of the properties of concrete (A5 – use of corrosion inhibitors); and electric field change (A6 – protection/cathodic prevention).

For all the alternatives it was defined the costs considering successive stages: i) determination of the service life of each material; ii) determination of the user costs.

The user costs quantification considered in the model is performed according to equation (1).

$$C = VOC + TC + AC + ToC \tag{1}$$

here: VOC – vehicle operating costs; TC – time costs; AC – accident costs; ToC – toll costs (when appropriate).

The vehicle operating costs, for different vehicle classes, are quantified after consulting, at the national level, some of the major operators such as car rental, transport, and insurance companies.

The time costs are quantified considering the total distance travelled as well as the possibility of queuing. The time costs are defined, for each vehicle class, considering two references: wages and per capita Gross Domestic Product (GPD).

The accident costs are quantified considering a crash prediction model for highways. Considering the data of road crashes, the model is adapted to other types of roads. This analysis is performed predicting the number and type of victims.

All the costs were computed for different traffic situations: traffic on the road without works; circulation and crossing the work zone; circulation by an alternative route.

In the created model to compute the vehicle operating costs the following costs were estimated: fuel, tires, maintenance, engine, oil, depreciation, and slow marching. This quantification was performed taking into consideration the various vehicle classes. The fuel, tires and maintenance costs were defined based on a survey of manufacturers and carriers and considering market prices of the different components.

Regarding the depreciation costs of the vehicles, it was assumed that the travel time was not representative, and so all the devaluation is focused on the distance travelled, since the travel time considered individually is very small compared to the lifetime of the vehicles.

Determining the cost of travel time is one of the main tools used in defining transport projects. In this research the modal definition of transport is made considering, among other parameters, the costs related to the journey time. The reason why some models do not use these costs in user costs modelling is the complexity of their quantification. However, these costs are in most cases the most important component of the user costs, and for that reason they are quantified in this model.

These costs were computed considering: the percentage distribution of the purpose of travel during the week; the average monthly wage of workers in general and workers in the transportation sector in particular; a preestablished time cost of traveling to work; and the percentage of the costs of non-work trips relative to the costs of traveling to work, based on the values presented in international literature of the distribution of the various purposes of a journey, according to the day of the week.

The realization of construction works is a factor that increases the number of road accidents. The accident costs were computed comparing the accident rate before and after the realization of the maintenance/repair works. The number of accidents was estimated using the formulation proposed by Lopes and Cardoso (2007), presented in equation (2).

$$AC = 9.42 \cdot 10^{-4} \cdot AADT^{0.9} \cdot L^{0.931} \tag{2}$$

here: AC – number of accidents involving personal injuries in a 6-year period; AADT – annual average daily traffic [vpd]; L – length [km].

Since the presented formulation only quantifies accidents in Portuguese highways, supported by the Portuguese accidents database, correction factors were introduced to consider the type of road and its location.

In Portugal, likewise in most countries, the accident statistics only include the ones with victims (fatalities, serious injuries, or light injuries). For that reason, an additional adjustment was also introduced to consider the damage-only accidents. This adjustment was accomplished with the values proposed Bickel et al. (2006).

Results

Case study – Cortiçô brook bridge. To validate the effectiveness of the methodology, a case study of quantification of the life cycle costs in a real bridge is presented in this section. The bridge chosen for the application of the methodology is integrated in the A25, concessioned by ASCENDI – Autoestradas das Beiras Litoral e Alta, S.A.. The construction of this bridge was carried out between May 2004 and July 2005.

The 122.0 m long bridge is located on the Celorico da Beira/Fornos de Algodres subsection (12.1 km long) and has five spans. Fig. 3 presents the elevation of the bridge over the Cortiçô brook.

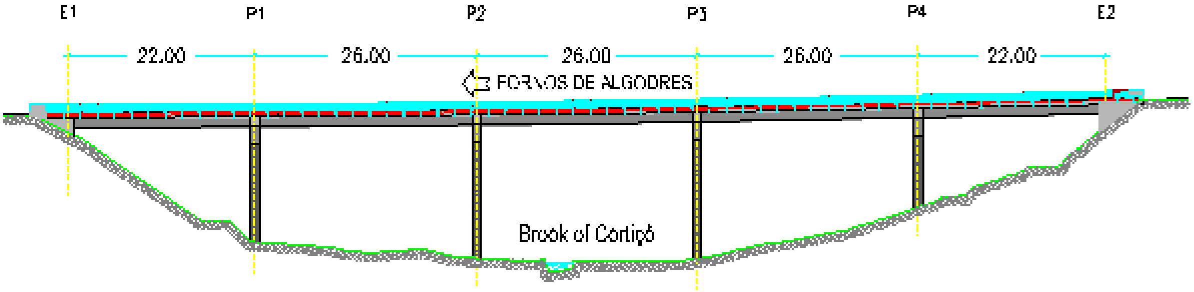

Fig. 3. *Elevation of the bridge over the Cortiçô brook (ASCENDI, 2003)*

Analysing the traffic flow data, it is found that the share of heavy vehicles using the highway is about 25% of the overall traffic. This is a very high value when compared with the average distributions that are usually considered. This distribution reflects the fact that this highway is one of the Portuguese major heavy vehicle connections to Spain and central Europe.

In Fig. 4 it's plotted the average daily traffic for the highway section Celorico da Beira/Fornos de Algodres for the period 2016-2021. It can be observed that annually a peak occurs in August. This can be explained by the huge number of Portuguese emigrants that returns in that month to Portugal for holidays. In the graph the year 2020 is plotted in black. In March of 2020 it can be noted a huge decrease of total number of vehicles crossing the highway. The justification was the

COVID restrictions that the Portuguese population was submitted to. In 2021, plotted in red, we can witness that the traffic numbers have gradually recover to the situation before the COVID.

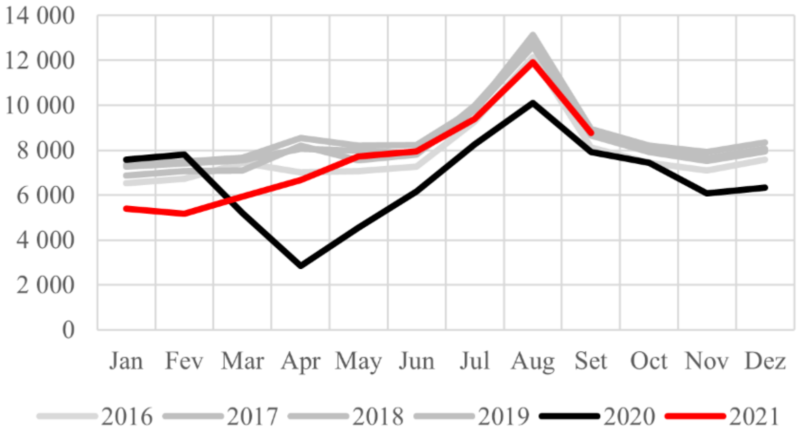

Fig. 4. *Average daily traffic for the section Celorico da Beira/Fornos de Algodres (ASCENDI, 2003)*

Using the deterioration model, the initiation time for the basic alternative A0 was computed. The strategy defined assumes that repairs are implemented at the end of the initiation period, in principle a conservative approach. The initiation time was computed considering that the environmental exposure class was XC3 and 30 mm of reinforcement cover. Under these conditions the expected initiation time is 30 years.

The increase in service life for each of the alternative solutions was defined using data from international literature. The service life and the intervention periods of each of the alternatives are shown in Table 1.

Table 1. *Service life and intervention dates*

Alternative	Construction year	Service life	1st intervention	2nd intervention	3rd intervention
A0	2005	30	2035	2065	2095
A1		50	2055	2105	-
A2		35	2040	2075	-
A3		110	-	-	-
A4		80	2085	-	-
A5		50	2055	2105	-
A6		65	2070	-	-

The analysis period considered was 100 years. It can be observed that, for the considered period, the alternative A0 (common reinforcement) will have 3 interventions. On the other side we have the alterative A3 (stainless steel) with a service life of 110 years.

The user costs are quantified through a comparative study of the user costs between the scenario of traffic flow without any disruption due to the existence of works and the scenario resulting from the traffic flow that occurs with construction works. The difference equals the costs attributed to each intervention. This study is performed considering the highway length between the A25 highway nodes next to the bridge, in this situation nodes 24 and 25. In this study, the costs were quantified in two circulation scenarios: the basic scenario which results in a bypass implemented in the A25 Highway detouring the whole traffic to the South Bridge over the Cortiçô brook; and the diversion of the whole traffic to the alternative road.

Fig. 5 presents the cost analysis for the A0 alternative. It shows that in the unrestricted traffic flow scenario the main user costs result from vehicle operating costs. The second largest component of the costs results from toll costs, followed by time costs and, to a much lesser extent, accident costs, much lower than the other user costs.

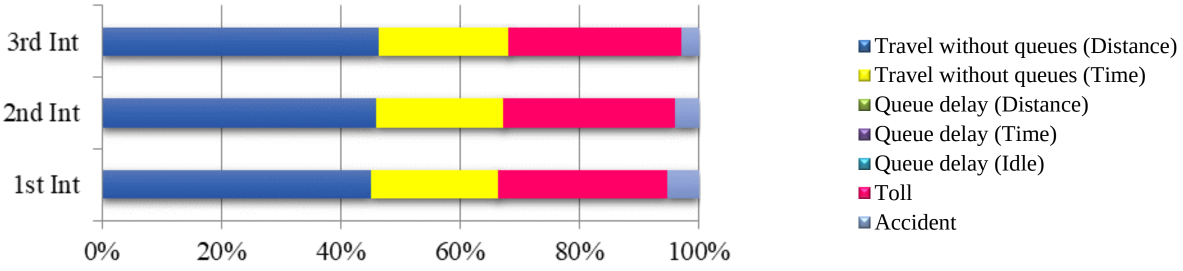

Fig. 5. *Cost distribution - circulation without construction works - Alternative A0*

In the forced flow scenario, shown in Fig. 6, there is a costs' weight redistribution. In this scenario the main cost component is time costs due to the formation of queues. It is also noted that the costs arising from unrestricted traffic flow become residual.

There is a considerable costs' increase from the first to the third intervention that results from the increased traffic in the detour road. The reason is that, in this scenario, it was imposed that the limit number of queued vehicles was 500.

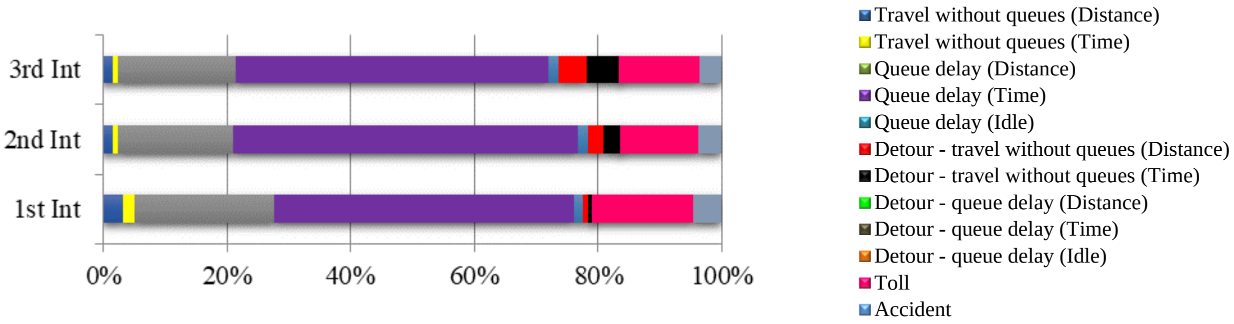

Fig. 6. *Costs distribution - circulation with construction works - A0*

For the seven alternatives, the users, and total costs were computed. All these discounted values were calculated for the reference year of 2022. The user costs are plotted in Table 2. We can see that the alternative A3 doesn't have any costs, because the lifetime (110 years) of that solution is higher than the study period. In the opposite side the alternative A0 is the most expensive because it will be necessary to perform 3 interventions.

Table 2. *User costs*

Alternative	A0	A1	A2	A3	A4	A5	A6
Total	7.729.536 €	4.443.790 €	5.591.359 €	0 €	1.532.029 €	4.443.790 €	2.250.760 €
Ranking	7	4	6	1	2	4	3

The overall costs of each alternative are presented in Table 3. These costs were computed by adding the direct costs and the user costs. The solution that uses common steel is about 19 times more expensive than the optimum solution.

Table 3. *Global costs*

Alternative	A0	A1	A2	A3	A4	A5	A6
Total	8.013.345 €	4.671.162 €	5.903.597 €	396.638 €	1.777.612 €	4.667.079 €	2.911.148 €
Ranking	7	5	6	1	2	4	3
Incremental cost relative to the most economical solution	1920%	1078%	1388%	0%	348%	1077%	634%

Conclusions

The main conclusion drawn from the presented combined analysis of user costs and direct costs is that investment options should not be made considering only direct costs.

Direct costs vary fundamentally with the materials used. It was found that the materials used are the main cost-generating factor, because the shorter its useful life, the greater the number of interventions that the bridge will have to undergo, attributing very important costs to users. It has been proven that small changes to the value of the cover, which are associated with reduced costs, can lead to significant savings, as this increases the protection of the reinforcement and, therefore, the useful life of the structure.

It is observed that, when only considering the direct costs and the immediate costs, the solution of application of current steel reinforcement is the most economical. However, with the discounted values of direct costs, this solution is not even the most economical when considering the number of interventions in the period of analysis.

Introducing user costs, and given their magnitude, it appears that the economic performance of alternatives can undergo a significant change depending on the total number of interventions. The solution that foresees the use of stainless-steel reinforcement is, in the bridge under study, clearly the most economical solution due to the non-existence of user costs

As user costs are a significant part of the total costs, from the analysis of the traffic for this route, user costs for the summer months (July, August, and September) can suffer a strong increase, since for this route seasonal traffic is very significant. Therefore, it is imperative that the planning of the works tries, whenever possible, not to affect the months with the highest volume of traffic. It has been proven that the effective control of the intervention time produces savings that can be directly proportional to the time of execution of the works.

From the analysis of user costs, it is proven, for this scenario, that the crossing costs, when there are no construction works, result mainly from the cost of operating the vehicles and, to a lesser extent, from the cost related to the crossing time.

Regarding the cost of time, it is demonstrated that the cost related to the time spent by the occupants of light passenger vehicles represents 37% of the total cost. The time cost of heavy goods vehicles represents 26% of the total.

When traffic disturbances are introduced, there is a transfer of the weight of costs from the scenario in which queues are not formed to the scenario in which traffic circulates with queue formation.

In conclusion it can be stated that considering the disaggregated analysis of the results, it is established that the disturbance of the normal flow of traffic is the main factor. This disturbance makes the environmental component assume a very significant importance, as the travel time increases greatly causing the vehicles pollution to increase as well. A sustainable approach, in the construction of reinforced and pre-stressed concrete bridges, allows the optimization of the promoter's investment, the reduction of user costs, the reduction of gas emission resulting from combustion, providing a cleaner environment and also reducing social inequalities.

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