TÉCNICO LISBOA

Extended Abstract

Proposal of a model to manage the wood frame doors and windows from National Palace of Sintra

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Abstract

Asset management is a tool that helps in the decision making process with an integrated system which combines multiples factors such as, performance, costs, sustainability and risk. Applying asset management to building heritage helps to organize a maintenance plan for its components through their life cycle based on the requirements imposed. The main objective in this study is to elaborate a project maintenance plan for the wooden frames doors and windows frames of National Palace of Sintra considering their performance to degradation mechanisms and futures interventions costs. However, wood has several degradation mechanisms turning its forecast degradation very complex. In this study is presented strategies for the wooden frame doors and windows maintenance using the equivalent annual cost technique to compare their profitability through two different approaches: i) deterministic approach; and ii) stochastic approach.

Introduction

The organizations have the perception that an investment in constructed assets can not be considered as an expense but as an opportunity to increase in value their own organization. The asset management is defined by IAM (2008) as a "systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles".

The wood frame doors and windows of the National Palace of Sintra were selected for this study for the implementation of the proposed methodology, continuing works developed in the anomalies rating system (Sousa 2003) and the degradation model (Sousa, Pereira, and Meireles 2015), through integration tool for the decision making for their management considering the life cycle costs.

Literature Review

Degradation Models

According to Edirisinghe, Setunge, and Zhang (2015), various models were developed to predict the deterioration of infrastructure assets including deterministic models and statistical or stochastic models.

Deterministic models describe a mathematical relationship between input and output parameters of an asset system in which a good correlation can be derived from the parameters.

Statistical models are based on statistical theories, such methods are more suitable to model forecasting with data sets that offer a high level of uncertainty. In this model is assumed that parametric density functions are used for measurement errors and certain probabilistic relationships between input data and output data.

Wood frames Degradation

As secondary elements, wood frame doors and windows are frequently forgotten. Given their roles (a barrier between the outer and the inner space, ventilation and illumination), intrinsic characteristics (heterogeneous constitution, small depth, and reduced mechanical strength), and the actions to which they are subjected, they degrade faster than the others building components.

Wood is naturally degraded when exposed to weather agents such as water, radiation, temperature, and wind. In its various forms, water is the most relevant cause of degradation of wood and combined with other environmental factors, in particular radiation, the direct action of water contributes to increase the process of the degradation of the wood. Indirectly, it is an essential requirement for establishing the right conditions for the development of molds and rot fungi (Morrell 2013; Cruz and Nunes 2012; de Brito, Sousa, and Pereira 2006).

The reference service life values of wooden frames can be very different depending on the author. According to Asif (2002) wood frame windows have 39,6 years of reference service life. Citherlet, Di Guglielmo, and Gay (2000) said that reference service life can reach to 45 years. According to Menzies (2013) wood frames can last 65 years in a soft environmental, 59 years in a moderate and 56 years in a harsh environmental, having a maintenance cycle of 5-7 years

Paint System Performance

The main function of the paint system is to protect wood elements from degradation agents. However, the paint is also exposed to degradation agents such as (Asif 2002): i) pollutants; ii) UV; iii) temperature; iV) humidity; and v) oxidation. According to Davies (2013) an alkyd oil paint systems can last 6 years, an acrylic 4-6 years and linseed-oil paint can last 15 years.

In order to maintain the quality of the paint system, maintenance cycles should be considered. The Forest and Wood Products Australia (2012) suggest a maintenance plan between 7 and 10 years. BSI (2013) presented a 4-8 years maintenance cycle depending on the environmental conditions (soft, moderate or harsh).

Methodology

The methodology applied on this study pretend to form an integrated approach for the making decision process in rehabilitation interventions of building heritage elements, considering the life cycle costs. In this methodology the elements are selected on its own, not considering its function in the global system. Also, this methodology only considers a maximum level of degradation but does not considered budgeting limitations. The methodology has four main components: i) context; ii) degradation; iii) costs; and iv) financial analysis. The methodology should be incorporated in a continuously improving system providing an improvement of the relevant aspects optimizing all components (e.g. degradation prevision).

Case Study

National Palace of Sintra

The National Palace of Sintra is part of the built heritage of the Sintra cultural landscape that is included in UNESCO´s world heritage list. It is also the only medieval royal palace in Portugal that still retains its original configuration since the sixteenth century. However, given the importance of the National Palace of Sintra, its dimension, architecture and use and the harsh environment to which it is exposed, its maintenance is an important and complex task.

Wooden frames of the National Palace of Sintra

The wood frame doors and windows of the National Palace of Sintra present a wide range of sizes (from less than 0,2 m^2 to more than 10 m^2) and configurations. Most of the doors and windows are made of *casquinha* or *pinho-de-riga*, a type of wood from a variety of pine tree (pinus sylvestris L.) coated by traditional linseed-based paint with iron oxide pigment which gives a red coloration. The palace has 135 wood frames doors and 164 windows requiring a constant and expensive maintenance.

Sousa (2003) identified and analyzed the main causes of degradation of the wooden frames of the National Palace of Sintra and proposed a scale for quantifying their condition. The main anomalies identified were: degradation of paint systems; degradation of timber elements; broken glasses and cracked putty; and defects and corrosion of ironwork. The scale classifies the condition into five levels based on visual inspection. It is also a representation of the usual degradation stages of the wood frame doors and windows, which starts by the degradation of the paint and then extends to the wood. The levels established are directly related to the typical required intervention as follows: i)level 0: door or window is in a good conservation state and simple maintenance and/or cleaning works are enough, namely, in ironwork at the locations of most intense circulation; ii) level 1: door or window is in a good conservation state (mildew signs may be visible) even though there is a need to clean and prepare the surface to be partially or totally repainted for aesthetical reasons; iii) level 2: door or window is in a reasonable conservation state, however the painting system is already substantially degraded and needs to be scraped before the application of new paint coating; frequently it is necessary to locally fill some joints with putty, namely, those within the lower bars and cushions; iv) level 3: identical to the previous one, however the wooden surface looks irregular demanding a generalized putting of the framing before proceeding with the final painting; and v) level 4: the condition of the door or window is bad, showing degraded elements, usually the lower bars and cushions, therefore, it is necessary to replace the degraded elements before scraping, puttying, and painting. In extreme cases, it may be necessary to reconstruct the whole panel due to the extent of the degradation

Model to manage the wood frame doors and windows

Inspection results

In 2015, 257 wood frame doors and windows were inspected however, 62 of them showed signs of recent intervention. This was confirmed by the National Palace of Sintra management team. Figure 1 presents the distribution of wood frame doors and windows for each degradation level.

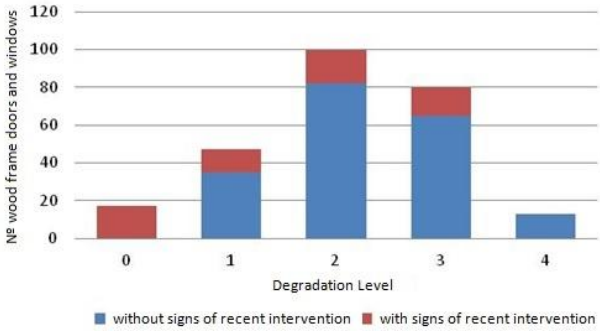

Figure 1 - Distribution of the condition level of the wood frames depending on: a) shelter; b) orientation

Because the exact dates and the nature of the interventions could not be obtained and there was no information on how it was done, the doors and windows with signs of recent intervention should be excluded from the sample.

Regarding the magnitude of weathering effect due to the exposure to environmental agents, two factors were evaluated: i) shelter; and ii) orientation. The doors and windows at sheltered locations (e.g., balconies) presented substantially better condition levels when compared with the not sheltered ones, independently of the orientation (Fig. 2 a)). Considering four orientations (east, north, south, and west), it is possible to observe differences in the condition level of the doors and windows as a function of the exposure to the weather agents (wind-driven rain and solar radiation), in particular when comparing the north and west quadrants (Fig. 2 b)).

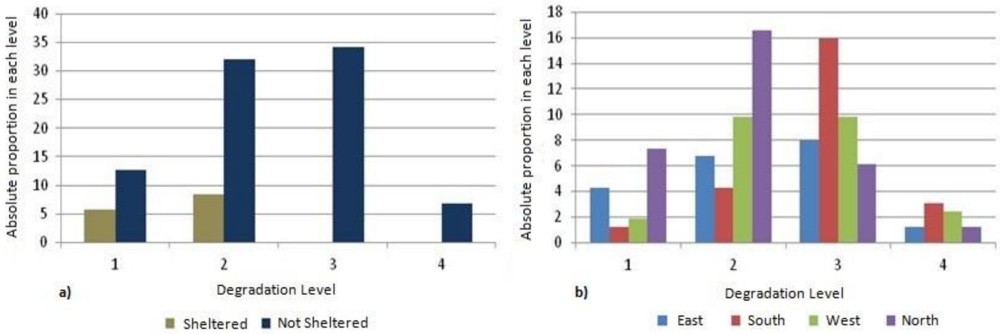

Figure 2 - Distribution of the condition level of the wood frames depending on: a) shelter; b) orientation

Comparison between 2013 and 2015 inspections

In 2013 were inspected 89 wood frame doors and windows which 27 of them had signs of recent intervention. In 2015, 7 wood frames of this sample were registered with recent intervention as well. However, one frame showed signs of recent interventions in both periods and because of that this frame should be excluded for the sample just one time. In this sample 6 wooden frames are located in sheltered places but one of them also has signs of recent intervention. Figure 3 presents the distributions of wood frame doors and windows for each degradation level for 2013 and 2015. These distributions do not have frames with signs of recent intervention or sheltered. Also, 5 exotic wood frame windows coated with varnish were excluded because their performance to degradation agents is different from the others frames.

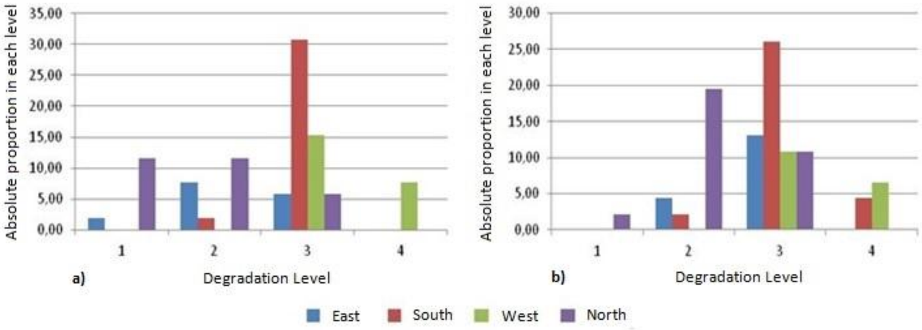

Figure 3 - Distribution of the condition level of the wood frames in: a) 2013; b) 2015

The differences between the graphics (Figure 3) are mainly due to an evolution of degradation level occurred in some elements and the reduction of the sample of 2015.

In 2015 were registered 26 frames (including wooden frames with signs of recent intervention) with an evolution of degradation level distributed by all orientations (7 east, 8 south, 3 west and 8 north) and occurred from level 1 to 2 (10 wood frames), level 2 to 3 (12 wood frames) and level 3 to 4 (4 wood frames).

Degradation Model

The equation of the degradation model presented in this study is based on the model proposed by Sousa, Pereira, and Meireles (2015). The sample of the degradation model is composed of 8 wood framing elements oriented east, 15 oriented south, 8 oriented west, and 15 oriented north and considered three moments in time, 2003 (level 0), 2013 (first inspection) and 2015 (second inspection). The sample does not have wood frame doors and windows with signs of recent intervention or located in sheltered places.

The average condition level (ACL) of the wood framing elements can be estimated by the equations presented in Figure 4 for each orientation based on age (time period since the last maintenance). Because the data set is composed of points in three moments in time only, it is assumed a linear degradation rate as referred to previously. The corresponding 95% confidence intervals (CI) are also included to allow estimating the uncertainty associated with the estimates provided by the equations.

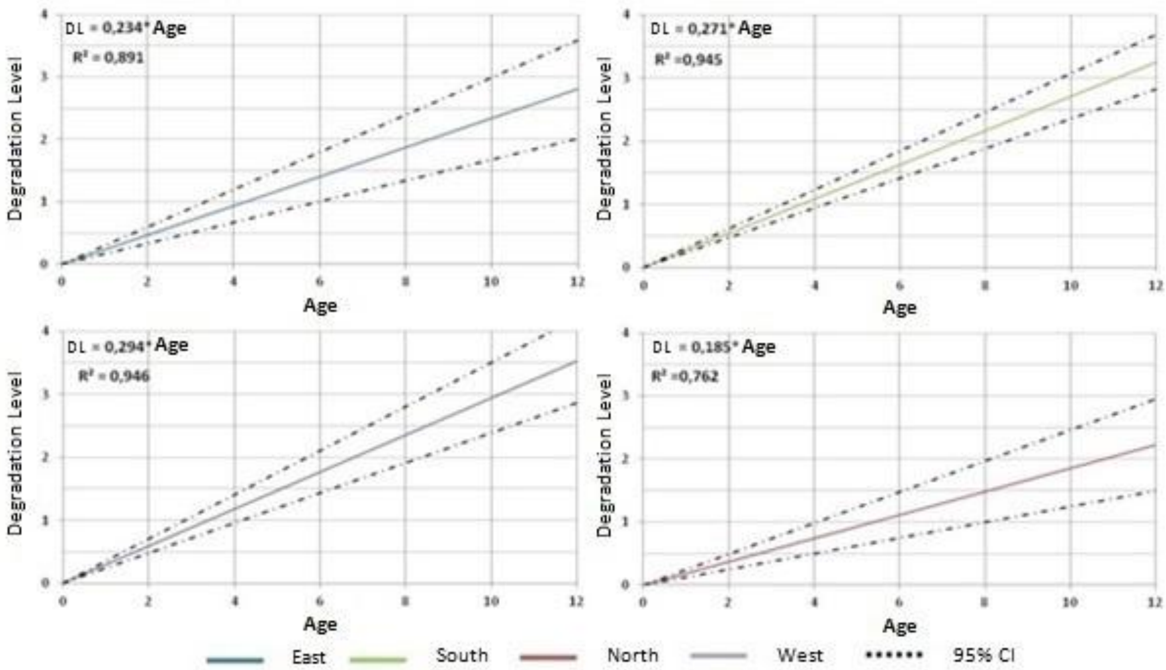

Figure 4 – Degradation rate curves depending on the orientation of the wood frames

Adopting the equations of the ACL for each orientation presented in Figure 4 and the start of condition level 4 as the end of the service life, the reference service life (RSL) of the wood frame doors and windows are presented in Table 1. The definition of the end of the service life adopted is due to the fact that there are very few frames in level 4 and far from total failure. Therefore, it is only possible to estimate the time until the biodeterioration of the wood starts and, in fact, the RSL obtained refer more to paint protection rather than all the wood frames.

Table 1 – RSL of the National Palace of Sintra wood frame doors and windows

Orientation	Mean RSL (Years)	97,5% RSL (Years)	2,5% RSL (Years)	Range (Years)
Global	16,6	19,4	15,3	4,1
East	17,1	23,9	13,4	10,5
South	14,8	17,0	13,0	4,0
West	13,6	16,8	11,4	5,4
North	21,6	32,2	16,3	16,0

The uncertainty represented by the confidence intervals may be regarded as an indication of the influence of other factors affecting the degradation rate that are not taken into account explicitly. These factors may include hidden defects not detected during the rehabilitation, previous rehabilitation interventions, work and curing conditions, labor and material aspects, frame-specific aspects, among many others. By doing so, it was assumed that the environmental factors are the most important agents to explain the degradation rate of the wood frame doors and windows of the National Palace of Sintra

According to Sousa, Pereira, and Meireles (2015), the ACL of wood frame doors and windows could be calculate using the global radiation in a vertical surface (GRv) and the wind-driven rain (WDR) were determined for each orientation (Table 2).

Table 2 – GRv and WDR of the wood doors and windows for each orientation

Orientation	GRv (kW/m^2)	WDR (mm)
East	10.194,88	50,9
South	12.145,28	172,1
West	10.092,94	204,3
North	4.531,62	135,2

By comparing the degradation rates presented in Figure 4 and the values presented in Table 2, the wood frame doors and windows oriented north are the less degraded, indicating that the paint degradation is controlled by the radiation. Also, despite receiving the largest amount of radiation, the wood elements oriented south are not as degraded as the ones oriented west, indicating a nonlinear combination of radiation and wind-driven rain contributions to the degradation.

In this study, the equation was adjusted to the 2015 inspection with the software IBM SPSS with the due care.

(Eq. 1)

$$ACL = Age \times [0{,}442 \times (\frac{GR_V}{10000})^{3{,}055} + 0.238 \times e^{\left(\frac{WDR}{100}\right)^{0.873}} - 1{,}027 \times \left(\frac{GR_V}{10000} \times \frac{WDR}{100}\right)^{0{,}697}]$$

The ACL values estimated by equations of Figure 5 show an insignificant difference (maximum of 0,03) when compared to the ACL calculated by Eq. 1, so can be concluded that the Eq. 1 is well adjusted to de degradation of wood frames of National Palace of Sintra.

Costs

The intervention costs of wood frames of the National Palace of Sintra were based in 2003 interventions. For this study, the costs sample was analyzed by degradation level and type of work: 4 wood framing elements in level 1(none had metal workshop); 11 in level 2 (2 of them had metal workshop); 25 in level 3 (6 of them had metal workshop); and 6 in level 4 (1 of them had metal workshop). Figure 5 presents the distribution of the cost by the degradation level. However, for this study was considered only the costs without metal workshop to be in accordance with the degradation scale.

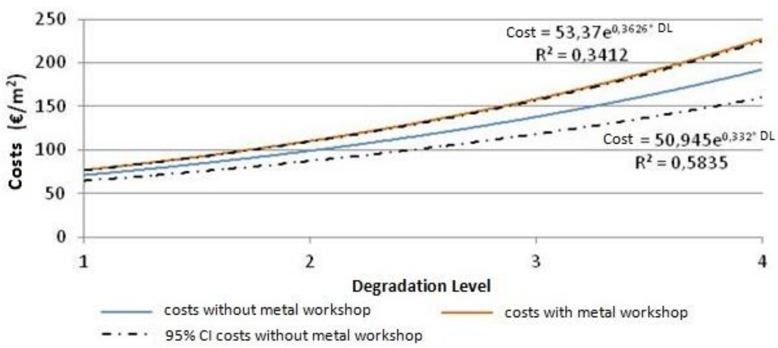

Figure 5 – Cost rate curves depending on the degradation level

Theses intervention costs should be actualized to the present day with inflation occurred during 2003 and 2015.

Annual Cost Equivalent (ACE)

The ACE is used as a decision making tool in capital budgeting, during the planning process for determining long time investments, when comparing investment projects of unequal life spans. By choosing the option with the lowest annual equivalent cost, the option with the lowest total cost is chosen (Langon 2006). This technique was used to compare the maintenance strategies presented in the present study. The following equation was used to calculate the ACE:

(Eq. 2)

$$ACE = \sum_{t=0}^{N} \frac{C_0 \times (1+I)^t}{(1+d)^t} \times \frac{d \times (1+d)^N}{(1+d)^N - 1}$$

Where C_0: Actual cost (€/m^2); I: Inflation; d: discount rate; N: period of analysis (years); t: instant of time (years). For the present study the inflation rate is equivalent to the mean of the inflation rates between 2003 and 2015 (I=1,494%). Also, the period of the analysis should not be too low (e.g. 2 years) or too high (e.g. 50 years) in order to keep the credibility of the analysis, so it was adopted about 30 years for the period of analysis. The discount rate used is 4% taking account the period of analysis and the type of investment.

Maintenance Strategies

The minimum requirements were gathered during the 2015 inspection in tandem with the management team of the National Palace of Sintra for the maintenance model that should be used in order to keep the image and well running of the palace. With that, the palace can be divided in two degradation levels:

- degradation level ≤ 3,15, for the tourist course, including the gift shop, the VIP area and wooden frames belonging to the south façade (entrance of the palace) (Area1);
- 3,5 ≤degradation level< 4, for the others wooden frames (Area 2).

Figure 6 presents a schematic graph that demonstrates the limits of the Area 1 and Area 2.Also, due to the present degradation of the wood frame doors and windows, rehabilitation should be performed in a near future and by that, for the strategies presented in this study, 2017 is considered the year 0.

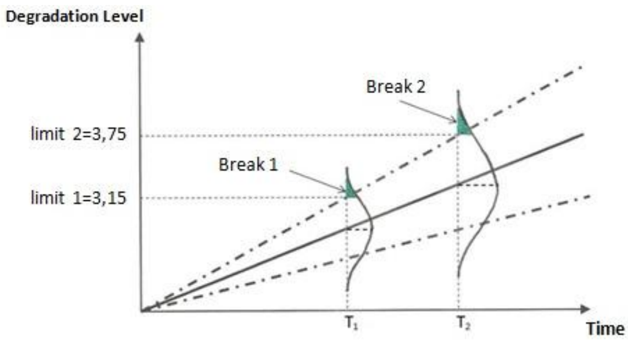

Figure 6 – Imposed limits for each Area

The strategies suggested for the management plan of the wood frame doors and windows of the National Palace of Sintra were:

- **Strategy 1**: the wood frames oriented west have highest degradation rate, so the degradation limits are controlled by this orientation. For the west orientation, the wood frames reach the limits at the 9 years of age for Area 1 and at 11 years for Area 2. Due to that, the interventions plan has the following cycles: each 9 years for wood frames in Area 1; and each 11 for Area 2;

- **Strategy 2**: the palace has two distinctive sectors (Manuelino and Joanino sectors) enabling to organize the maintenance plan combining these two parts of the palace. Due to that, the interventions plan has the following cycles: each 9 years for wood frames in Area 1 of Manuelino sector; and each 11 for Area 2 of Manuelino sector and all Joanino sector;
- **Strategy 3**: this strategy analyses a preventive maintenance plan, i.e., evaluates the costs for a plan with more cycles of interventions. Due to that, the interventions plan has the following cycles: each 5 years for all wood frames oriented east, south and west; and each 10 years for wood frames oriented north (degradation level at age of 5 is 0);
- **Strategy 4**: on the contrary, this strategy evaluates the costs for higher levels of degradation. So this maintenance plan has cycles of 11 years (limit year for west orientation not reach the level 4).

For each strategy was calculated the ACE in deterministic approach, i.e., was used the mean values of level of degradation and the mean values the maintenance costs. Table 4 shows the results of ACE for each strategy.

Table 3 – ACE results for each strategy

	Present Value Cost (€/m^2)												ACE (€/m^2)
Instant (years)	5	9	10	11	15	18	20	22	25	27	30	33	
Strategy 1	-	11867	-	18069	-	9528	-	13817	-	7650	-	10566	3940
Strategy 2	-	10140	-	19768	-	8141	-	15116	-	6537	-	11559	3927
Strategy 3	17711	-	20741	-	13878	-	16252	-	10874	-	12735	-	5331
Strategy 4	-	-	-	30664	-	-	-	23448	-	-	-	17852	3965

However, as presented before, the degradation level and maintenance costs have a distribution associated. So, it is important to analyze how these parameters change over time. Due to that, it was used a stochastic approach to evaluated the fluctuations of degradation level and costs by using the software Oracle Crystal Ball. This approach analyzes the minimum, mean and maximum value of costs corresponding to the respective level of degradation in the year of analysis. Consequently, the result of ACE will be presented with a distribution as well.

With this approach, it was found that at the age 10 the ACE have an optimize value. ACE was calculated with the deterministic approach of 3 cycles of interventions for all wooden frames at every 10 years of age (**strategy 5**). The result was an ACE = 3732 €/m^2, less than the ACE of the best solution presented before (strategy 2). However, when calculated the ACE of the strategy 2 and strategy 5 with Oracle Crystal Ball, the conclusion was different. The strategy 2 presented an optimize ACE = 3795€/m^2 and the strategy 5 an optimize

ACE = 3919€/m^2. This difference of values between the two approaches is related to the combination of the distributions of the costs using in the stochastic approach with its value over the period of analysis.

It was concluded that the stochastic approach presents more rigor than the deterministic approach and the strategy 2 is the optimal maintenance plan for the wood frame doors and windows of the National Palace of Sintra.

Figure 5 presents the ACE cumulative distribution of strategy 2 with 85% certainty. With that, the decision making can be made based on risk and uncertainty.

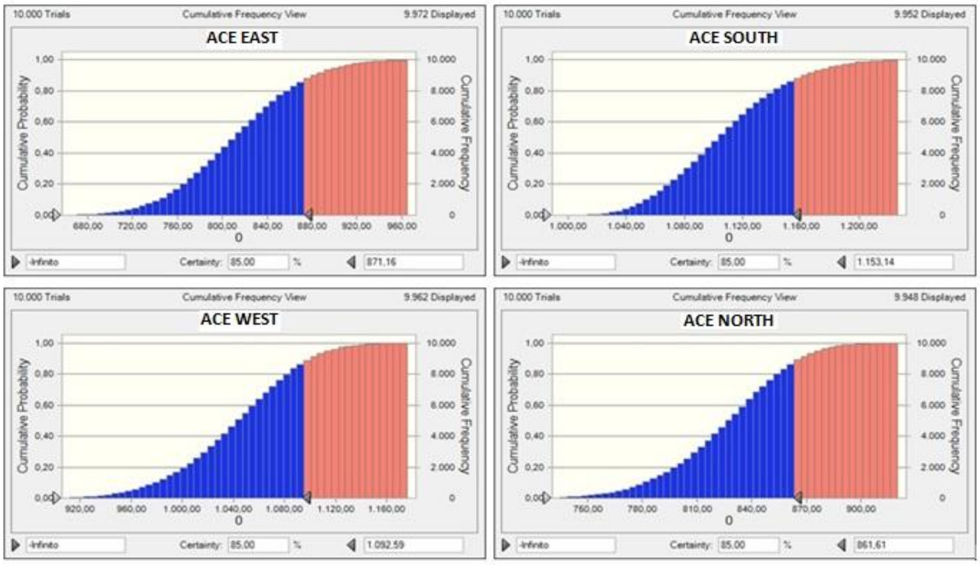

Figure 5 – Cumulative distribution of ACE for each orientation

Yet, the interventions life cycle plan should be integrated in a continuously improve system. At each future intervention should be adding to the data base the information that has influence in the financial analysis such as: i) costs; ii) materials; and iii) proceedings and techniques.

Final Considerations

This communication pretends to contribute for the asset management implementation in building heritage through a methodology that helps in decision making for interventions in building materials and components. In this study was presented a management model for the exteriors wood frame doors or windows of the National Palace of Sintra integrating their degradation and the interventions costs.

During the elaboration of this study was identified some contents that should be analyzed in futures works in order to complement the present study. A few subjects should be developed in the future such as: i) analyze the degradation of the wood frame doors and windows between the age 0 and 10 allowing to understand if the degradation model has a linear or non-linear behavior; ii) study the many components of construction costs to adjust the interventions plan; and iii) compare the rehabilitation cost to the cost of a new wooden frame.

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