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Do we need a buildings' inspection, diagnosis and service life prediction software?

A. Silva*, J. de Brito

CERIS/ICIST, Department of Civil Engineering, Architecture and Georresources, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, P-1049-001 Lisbon, Portugal

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ABSTRACT

During decades, the maintenance of buildings has been mainly reactive, based on subjective criteria, thus compromising the users' safety and leading to a built park highly deteriorated. The effective planning of maintenance strategies requires the development of accurate tools to aid stakeholders' decisions about when and how to intervene. This study analyses the utility of two computational tools to aid the adoption of condition-based maintenance policies, developed for the buildings' envelope elements. The first tool is as an expert diagnosis and inspection system, which allows understanding how to intervene, based on the pathological characterization of the element analysed. The second tool provides information related with the element's service life (when to intervene), according to their characteristics. However, before the definition of these tools, a question must be raised: "Do users need a buildings' inspection, diagnosis and service life prediction software?" Therefore, this study performs a market survey involving 57 varied stakeholders working on the maintenance sector, evaluating the usefulness of the proposed computational tools, identifying the characteristics that the software must have to ensure its use by the sector.

1. Introduction

The stakeholders and managers of assets, regardless of their type, share a common challenge: how to keep the operational capacity of the assets for as long as possible and as economically as possible without compromising their reliability or safety. According to Faiz & Edirisinghe [25], the answer to this challenge is simple: the only solution is appropriate maintenance. Traditionally, maintenance activities have been considered as a necessary nuisance and as an inevitable and difficult-to-manage process by the different stakeholders [52,76].

In recent decades, stakeholders recognise that maintenance activities create additional value [40] and nowadays, maintenance activities are considered as a strategic issue for the continuous operation of ageing buildings without incidents, while ensuring the fulfilment of their intended functions, the increasing regulatory demands and the users' expectations [50].

The adoption of cost-effective and appropriate maintenance strategies allows optimizing the use of resources, while improving the performance of buildings and components over their life cycle [15]. The selection of optimal maintenance plans should be based on the comparison of different maintenance policies, in terms of their effectiveness and costs. For that purpose, two key elements are required: i) the knowledge of the buildings' performance over time and according to their characteristics, through the implementation of inspection and diagnosis systems and tools; and ii) the prediction of the instant after which it is necessary to intervene, adopting accurate and reliable service life prediction (SLP) methodologies [17].

Over the last years, the authors of this study proposed various inspection and diagnosis systems, as well as several SLP methodologies, applied to the buildings' envelope elements. The knowledge acquired in this field of expertise led to a research project funded by the Portuguese Foundation for Science and Technology, in which SLP methods are used for the definition of a risk-based building management system (SLPforBMS). This project intends to create a reliable building pathology system (BPS), developing a computer tool with [9]: i) an inspection module, allowing the standardization of inspections and the resulting reports; and ii) a decision-making module on the action to be carried out after inspection and diagnosis of any defect, dedicated to building maintenance operations. The project also intends to develop a computational tool, based on an artificial intelligence algorithm, for service life prediction (SLP) of the buildings' envelope elements, learning from the behavior patterns provided by the data acquired in the BPS tool. The SLP tool provides information (with deterministic and stochastic natures) regarding the instant after which it is necessary to

* Corresponding author.
E-mail addresses: anasilva931@msn.com (A. Silva), jb@civil.ist.utl.pt (J. de Brito).

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intervene, according to the element's characteristics (e.g. quality of materials, design, execution and environmental exposure conditions), the users' demands and the building context.

These two computational tools intend to respond to a need of the construction industry, providing a systematic source of information to aid the adoption of effective plans and strategies for condition-based maintenance, adapted to the specificities of the element under analysis. However, before the definition and implementation of these tools, a question must be raised: "Do users need a buildings' inspection, diagnosis and service life prediction software?" Moreover, which characteristics must the software have to ensure their use by the different stakeholders? In this sense, this study performs a survey involving varied stakeholders and managers, working on the maintenance and rehabilitation sector, carrying out a market research with the aim of adapting the computational tools that will be developed to the needs of the market and of the potential users. With this market survey, the authors intended to obtain valid and relevant answers to the questions addressed, and the additional comments provided by the respondents allowed drawing very relevant conclusions regarding the problem under analysis. The different answers to the questionnaire are thoroughly discussed in this study and a statistical analysis is performed in order to identify possible correlations between the different questions. Nevertheless, the analyses performed in this study are fundamentally cognitive, evaluating the practical implications for the maintenance sector, rather than purely statistical analyses.

2. Existing software and research projects for maintenance optimization of buildings and infrastructure

A study performed by Bloch & Geitner [7] reveals that 99% of all the failures of machinery in the mechanical engineering field are preceded by signs or indications that a failure is going to occur. Similarly, the failure of buildings and components are preceded by clear signs of degradation, which become visible through symptoms/defects, which announce the occurrence of a sequence of degradation mechanisms.

The buildings' components appraisal, evaluation and inspection is a decisive element for the success of a given intervention or maintenance action [78]. Likewise, the effectiveness of a maintenance policy strongly depends on the accurate knowledge of the building's service life [63], which allow comparing different strategies during the buildings life cycle. Mann et al. [43] refer that, even though failure detection and prediction of the components' service life are essential tools for the adoption of maintenance strategies, the automation of this information is equally essential for reducing maintenance costs. The authors refer that the lack of standardized tools for inspection and diagnosis often leads to a time-consuming process, often requiring additional travels to collect additional information (that is missing in the first inspection). Moreover, in many cases, a poor survey can lead to misdiagnosis, which implies the adoption of unnecessary or inappropriate works, thus compromising the future performance of the buildings' components [78].

In the last decades, different software packages for maintenance optimization were developed. The later packages are mainly suitable for strategic questions regarding the maintenance concept (Dekker, 1996) and not so much for the use of analytical models for the rational and technically informed management of assets. Currently, different web-based tools and apps can be used by stakeholders for property management. Most of these tools are easy-to-use, functioning more as an administrative and operational tool (for financial management, e.g. tenant, rent and lease management) and not as a technical and scientific recourse for the optimization of the maintenance activities. Moreover, the existing software are not focused in a condition-based maintenance, i.e. the maintenance activities suggested by the existing software are usually programmatic and standardized, not contemplating the knowledge regarding the pathological condition of the element under analysis or its expected service life. Furthermore, most of the existing tools are not easily customizable and are usually developed for stakeholders managing multiple properties and cannot be applied to the analysis of a single case study or a specific construction element.

Recently, in the construction sector, new tools and research projects are proposed for the effective management of the built environment, namely: i) the MicroROOFER computer tool, developed by the U.S. Army for the definition of procedures for surveying and evaluating the condition of bituminous built-up roofs, and determining their maintenance and repair needs [6]; ii) the Belcam project, which intended to aid asset managers to predict the service life of building envelope components and thus adopting cost-effective maintenance strategies [41,77]; iii) the EPIQR [8] and INVESTIMMO [12] projects, for the management of long-term investments in the maintenance and refurbishment of apartment buildings; iv) the TOBUS tool for the management of the refurbishment strategies in office buildings [5]; v) the XENIOS tool [19], for the analysis of refurbishment scenarios in hotels; vi) the Building Life Plans project [46], which presents key failure modes and durability data from over 900 building components; and vii) the software BuildingsLife [51], to aid the implementation of maintenance strategies, considering a database of building defects and the most adequate repair technique (and the costs involved in each operation).

The existing tools and research projects present some limitations, namely: i) the majority of the tools address only one building component, usually the buildings' roofs, do not contemplating the evaluation of the maintenance needs of other building's envelope elements; ii) as mentioned previously, the existing tools are usually focus on administrative and financial questions related with the buildings' maintenance, neglecting technical analysis of the degradation condition of the buildings components. As described by the researchers working in this field of knowledge [37], new studies are demanded to overcome some of the limitations of the existing tools, identifying: i) what data should be collected for the understanding of the degradation phenomena and for SLP; ii) which maintenance actions are urgent and which can be deferred; iii) the risk associated with the estimations, the risk of failures and the related consequences; and iv) how to feed these data into a practical tool to be applied by stakeholders.

Therefore, stakeholders still need simple integrated decision-making tools, as the tools proposed by the authors to aid the evaluation of buildings' degradation, and, consequently, the selection of optimal refurbishment strategies, and the improvement of the buildings' durability and environmental performance.

3. New computational tools for the inspection and service life prediction of the buildings' envelope elements

The authors intend to develop two innovative computational tools. As mentioned in the previous section, the existing software concerning the management of maintenance operations, usually suggest standardized measures and policies, neglecting the degradation phenomena of the element or building under analysis. Moreover, none of the existing software address an integrated tool for a building management system of various buildings' envelope elements; on the opposite, the existing research projects and software only analysed one element of the buildings' envelope. Therefore, the two proposed tools comprise the creation of a building management system of building envelope's elements, including inspection and diagnosis, service life prediction procedures and support decision-making processes in the maintenance/rehabilitation area. In the next sections, the two computational tools are described in detail.

3.1. Evaluation of buildings' performance through an expert inspection system

Inspection is one of the most effective ways to analyze the buildings' in-use performance, detecting, at a premature stage, the presence of

defects, which is crucial for the calibration and optimization of preventive maintenance plans [26]. Expert systems systematize the logical steps for the diagnosis of defects in buildings' components [33]. The adoption of an expert inspection system allows optimizing the efficiency of each inspection, minimizing the subjectivity associated with the judgements or expertise of the inspector [72].

Nowadays, building management systems are commonly used; however, existing systems are focused on asset value management or scheduling management. Consequently, the maintenance records section only offers brief details on repair relative to parameters such as time, cost and location. However, building defects may compromise the building in several ways, and require expensive interventions to return the building to its original state. In this sense, not using inspection and diagnosis systems or building pathology systems may compromise the expected long-term performance of the most recent buildings. Existing methods for building pathology assessment [11,13,14,27] present a similar structure, comprising three main groups: i) Description/identification of the defects; ii) Causes' description; and iii) Diagnosis and repair. All the building pathology assessment methods found have a similar structure, but none is entirely devoted to on-site intervention, which enhances the importance of research on this expertise field. Furthermore, no statistical data have been found, specifically in what concerns correlations between defects and maintenance, diagnostic and repair techniques.

To face some of the challenges related, in the last decade, several inspection and diagnosis systems were developed by researchers from IST (University of Lisbon), for the pathological characterization and repair/rehabilitation of the elements of the buildings' envelope, namely: current flat roof bituminous membranes waterproofing systems [79]; ceramic tiling systems [73,74]; natural stone claddings [48]; gypsum plasterboard walls [28]; external claddings of pitched roofs [30]; wood flooring [20]; ETICS [2]; wall renderings [56]; painted rendered façades [54]; door and window frames [57]; and architectural concrete surfaces [72].

The first computational tool, discussed in the survey performed in this study, intends to systematize all these expert systems in one functional tool to aid the technical inspection of the buildings' envelope elements. This software will present a simple and universal classification system (with a standardized terminology) for the defects observed in the elements of the buildings' envelope.

The computer tool includes: i) A database where relevant building information is stored; ii) An inspection module, allowing the standardization of inspections and the resulting reports; and iii) A decision-making module on the action to be carried out after inspection and diagnosis of any defect, dedicated to building maintenance operations.

This tool allows organizing the data collected during inspections, providing a structured report with the statistical analysis of the data gathered, and it is expected that the proposed computerized inspection system has a range set of practical applications: i) Planning of proactive maintenance of buildings; ii) Decision-support in rehabilitation projects; iii) Preparation of devaluation reports of buildings; iv) Official surveys (pre-intervention, effects of insurance policies; sale/rental); v) Preparation of final diagnosis report with a standardized structure; and vi) Pre-normative basis of standardized inspections for buildings to be subjected to an officially recognized methodology.

3.2. Service life prediction as auxiliary tool for decision-making in the management of buildings' maintenance

The use of methodologies supported by service life prediction data is still incipient both at the design/execution and service stages of the buildings. The existing methods address the service life of construction elements in a deterministic way, not considering the uncertainty and variability associated with the degradation agents and their synergy. Therefore, the authors propose the creation of a new user-friendly software capable of estimating the service life of a wide range of building envelope's elements. The expert inspection system developed in the first computational tool can be used on its own or to acquire relevant knowledge regarding the degradation mechanisms and phenomena that may occur during the buildings' components service life. This information is crucial for the definition and implementation of SLP methodologies. Consequently, the knowledge concerning the elements' service life allows defining a decision-making module on the action to be carried out after inspection and diagnosis of any defect, dedicated to building maintenance operations and their scheduling.

This software will enable the practical implementation by different stakeholders (planner, designer, constructor, engineer, architect, manager, insurance company) of various SLP models developed by this research team in the last decade, especially dedicated to the buildings' envelope elements [70,71]. These models can be divided in four categories: i) deterministic models (regression analysis: simple nonlinear regression; multiple linear regression; and multiple nonlinear regression) [32,64,81,61]; ii) stochastic models (logistic regression and Markov chains) [66,67]; iii) computational methods (artificial neural networks and fuzzy systems) [65,68]; and iv) factorial methods (classical and probabilistic approach) [29,31,69].

The degradation phenomenon is extremely complex, involving the interaction between the buildings' intrinsic characteristics and a large set of degradation agents that act simultaneously. Moreover, each building and component is a unique prototype, with unrepeatable conditions. The proposed computational tools intend to provide a realistic estimation of the durability and service life of a specific building component, subjected to a specific set of conditions, i.e. the user introduces the data related with the case study under analysis, obtaining an estimation adjusted to its characteristics and degradation condition (evaluated through the first computational tool proposed). The proposed computational tools are permanently fed by new data related with the degradation of buildings' envelope elements, functioning as a learning machine, acquiring knowledge related with the degradation of the various elem]ents, constantly adapted over the years, thus adjusting the estimations to the evolution of the buildings' characteristics and environmental context. In the proposed software, the estimated service life obtained for a given case study depends on the level of demand established by the user; thus, over the years and according to a specific social and economic context, new levels of demand can be defined, achieving different estimations for the service life of a given component. This capability of adaptation of the proposed software also improves its capability to provide accurate service life estimations adjusted to the specificity of the case studies under analysis.

4. Research design

Market research surveys are essential when a new product is to be developed, aiding the adoption of better and more informed decisions. The survey presented in this study intends to obtain some answers that allow defining a market-oriented software, reducing the uncertainty regarding the expectations of the maintenance and rehabilitation of the built heritage market, related with computational tools to aid the inspection and diagnosis and the SLP of the elements of the buildings' envelope.

The first step of the market research is the definition of the questionnaire. This step is crucial to ensure the validity of the survey, both in terms of the number of participants in the survey and the relevance of the opinions articulated. In this study, the survey is performed using a free online platform (Google Forms), contacting the respondents through electronic mail. This type of survey has some advantages, namely it does not have any cost (unlike traditional methods) and a large number of respondents (in different countries) can be easily reached [59]. Additionally, in the online platforms used for conducting the surveys, the data collected is instantly treated and organized [18]. However, although it is possible to contact almost an unlimited number of respondents, the impersonal nature of the Internet contact can lead to low response rates.

The survey form is shown in Appendix A, presenting a simple form, with uniform color, without images. Various authors [21,22] mentioned that simpler surveys (less sophisticated) have higher response rates and that the structure and language of the questionnaire are fundamental to guarantee the validity of the answers obtained. In this sense, the questionnaire is designed to present the following characteristics: i) should be as succinct as possible, ensuring that the essential questions are answered to characterize the problem under analysis; ii) the questions must be clear and in plain language, without ambiguous or imprecise terms; iii) none of the questions should condition the answers of the respondents; iv) closed questions were adopted, allowing the respondent, whenever he/she wished, to add relevant opinions on each of the topics; and v) the answers to multiple-choice questions appear randomly when a new respondent accesses the questionnaire, intending to reducing or redistributing the bias of the results [42].

The respondents of the survey performed in this study are experts and professionals related with the maintenance and rehabilitation of buildings during their life cycle. These experts were carefully selected, ensuring that all the respondents have a valid opinion on the subject under analysis. 205 experts were contacted via e-mail and through other online forums (e.g. Linkedin and ResearchGate). The respondents are from different countries, trying to ensure a geographic representativeness (some of the countries are Portugal, Spain, Italy, Nordic countries, United Kingdom and other European countries, Japan, Singapore, New Zealand, Australia, USA, Brazil, among others). The survey was available for a period of 5 months and 57 valid responses was obtained (no compensation was granted for the participation of the respondents).

The response rate seems relatively low, especially when considering the number of specialists contacted. However, it is important to notice that online surveys are usually associated with very low response rates [18,24]. A study performed by Schonlau et al. [60] indicates that the response rates for online surveys vary between 7% and 44%, while for e-mail surveys, response rates varies between 6% and 68%. Regardless of the size of the sample, there will always be a sampling error, since it is impossible to investigate the entire target population [18]. Therefore, a low response rate does not imply, by itself, a bias of the sample [35]. In this study, the response rate (27.8%) is within the limits described in the literature, considering the difficulties of obtaining valid responses, as mentioned in this section. Moreover, in survey research, the response representativeness is more important than the response rate [16], and the 57 respondents are representative of the target audience of the study, providing an expert opinion about the phenomena under analysis. Consequently, the results of the survey performed in this study seem valid and will allow obtaining relevant information to aid the creation and implementation of the computational tools proposed.

5. Results and discussion

The results obtained with the survey are presented and discussed in the next sections. They are presented in charts and the additional comments provided by the stakeholders are also provided, which provide an additional insight concerning the respondents' answers. These comments correspond to the expert judgment of the respondents, and are thus subjective, reflecting in some cases current practice rather than true fundamental engineering practice.

5.1. Respondents' profile

The first question is related with the role of the stakeholder in the decision-making process in the maintenance area. Dillman [23] refers that the first question is crucial, defining whether the respondent answers to the survey or simply ignores it. Contrary to what the author suggests, referring that the first question should be comprehensive and should not exclude any respondent, in this case, since the purpose of the survey is to gather the opinion of experts in the field of building maintenance, the participation of respondents who, though having a valid opinion, do not play a relevant or decisive role in this area is restricted. Therefore, the first question is *"What is your current role in the decision-making process in the maintenance area?"* Fig. 1 shows the results obtained, revealing that the sample is distributed almost uniformly between two groups, the researchers (50%) and the pathologists (41.4%), which are mostly professionals working in buildings' rehabilitation and maintenance companies.

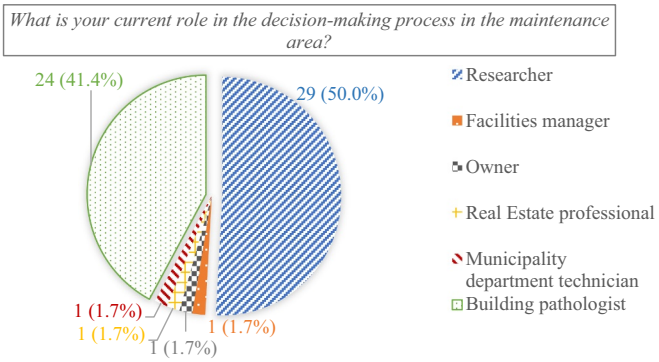

Fig. 1. Profile of respondents in the maintenance area.

5.2. Factors affecting the decision to intervene

The second question intends to understand the reasons that leads a stakeholder to intervene in the building or in their envelope elements. The buildings' components tend to deteriorate in different ways and rates over their service life, suffering various types of depreciation and obsolescence, namely [58]: i) physical deterioration; ii) economic obsolescence; iii) functional obsolescence; iv) technological obsolescence; v) changes in the social context; vi) obsolescence due to the surrounding building; vii) legal obsolescence; viii) aesthetic obsolescence; ix) environmental obsolescence. Thus, there are several reasons that may condition the decision to intervene. A study by Aikivuori [1] reveals that the decision to intervene is mostly conditioned by subjective and programmatic criteria (corresponding to around 44% of the decisions) and that in only 17% of the situations the decision of intervene is based on the building's deterioration or due to technical reasons.

Fig. 2 shows the results obtained for each of the response hypotheses provided in the questionnaire. Regarding the risk of failure of the building's envelope elements, 50% of respondents consider that this criterion always determines the decision to intervene, none of the respondents considers that this factor can be ignored and only 8% consider that this factor rarely leads to a maintenance action.

Naturally, when the buildings and components present an imminent risk of failure, jeopardizing the users' safety, an urgent intervention is required. However, when the maintenance action is only performed after the failure of the buildings' components, it is a purely reactive strategy, and it is necessary to consider the costs of this maintenance policy, as well as the risk and consequences of secondary damage to goods and users [53]. The respondents of the survey reveal that, according to their professional experience, maintenance is almost always reactive. A study by Levitt [38] reveals that 70% of organizations that own or manage real estate have very undeveloped or even non-existent proactive maintenance policies. Reactive maintenance policies invariably lead to higher costs, and actions usually only take place at the level of the element that need an urgent repair, neglecting other necessary but less urgent maintenance works, which could be performed simultaneously, optimizing the use of resources [26].

Concerning the physical degradation of the building's elements, 38% of respondents consider that this criterion always influences the decision of intervene and 40% consider that this factor frequently leads

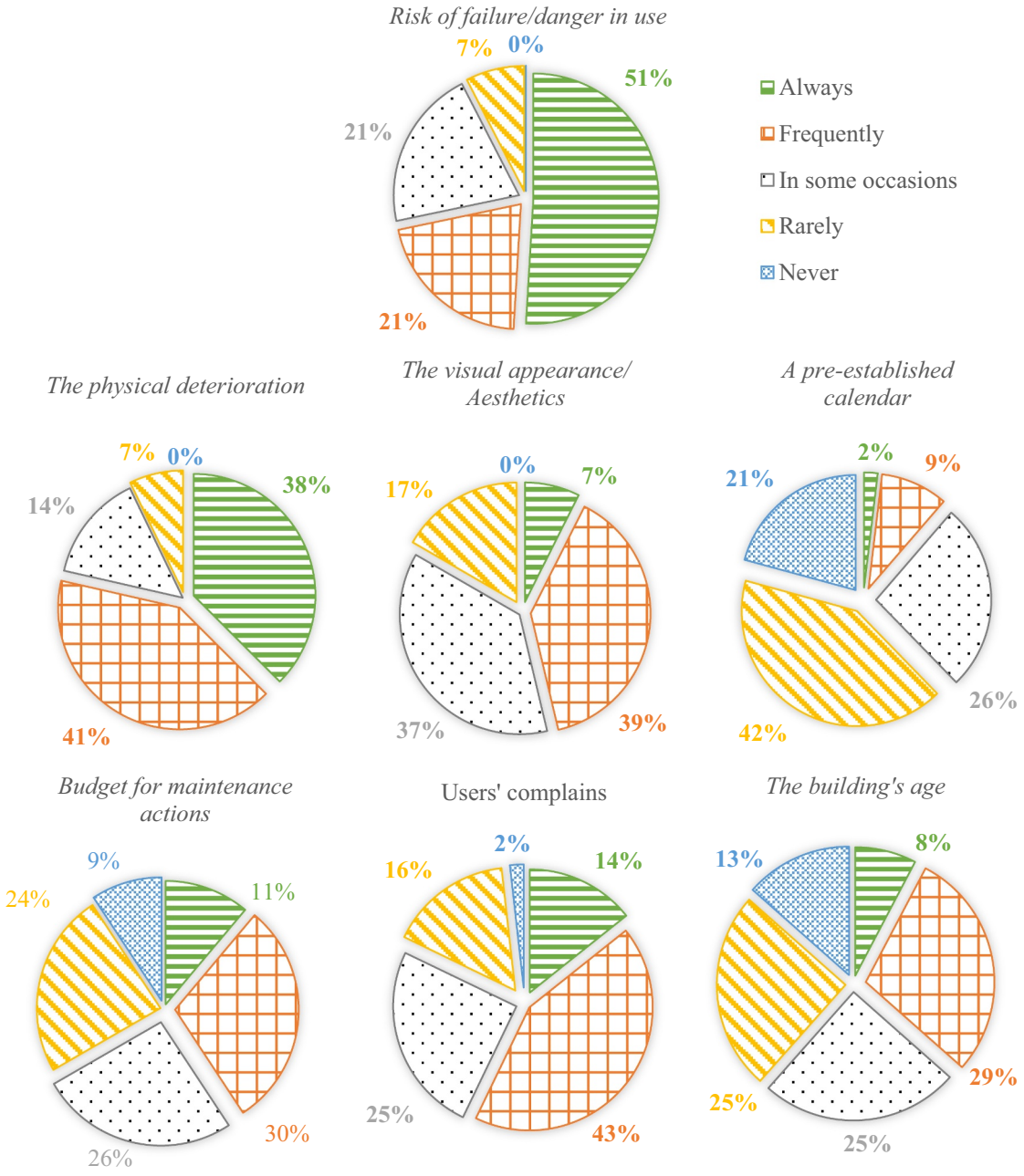

Fig. 2. Most relevant criteria in the decision to intervene.

to maintenance actions. It is consensual between the respondents that physical degradation cannot be simply ignored. According to Shohet [62], the definition of maintenance policies based on the condition of buildings (condition-based maintenance) is a common solution, when applied to large and complex built heritage, under limited economic conditions. There are various manuals and standards [3,49,47] that relate various levels of intervention to different degradation conditions, ranging from inspection and preventive maintenance to less serious degradation conditions, followed by corrective maintenance, general interventions and, finally, reconstruction. The recognition by respondents that the physical degradation is a relevant parameter for the definition of maintenance strategies is an important data for the development of the computational tools, which can provide extremely relevant information for the planning of future maintenance work, indicating the type of action required, and their urgency based on the knowledge on the performance of the elements under analysis, in-use conditions, according to the inspection data.

In the questionnaire carried out, when analysing the relevance of aesthetic reasons for the decision of intervene, most respondents consider that this criterion is not as relevant as the previous two; 40% of the respondents consider that aesthetic reasons frequently condition the decision of intervene and 36% consider that this criterion is only conditioning in some situations. Only 8% of the respondents consider that this factor is always relevant, but that they should not prevail over technical, functional or safety criteria. Non-specialised decision-makers (e.g. private owners) tend to give higher importance to aesthetic reasons in the decision to intervene. However, this criterion is subjective and variable over time, often leading to unnecessary interventions from a technical point of view. The respondents' answers seem consistent with their level of expertise, revealing that maintenance actions required to ensure the performance and safety of the building elements should prevail over maintenance actions based on aesthetics - or sustainability-related reasons.

Concerning the option of a schedule-based maintenance, 40% of

respondents consider that a pre-established calendar is rarely relevant for the decision to intervene, 21% refer that this criterion is not relevant and 27% consider that in some situations this factor may be relevant. Only 2% of respondents consider that this factor is conditioning. The answers to this question reveal that, generally, the maintenance companies do not adopt schedule-based maintenance policies, which imply performing regular maintenance actions, in predefined intervals, regardless of the condition of the element [55]. The perception of the respondents is that the maintenance policies adopted present mostly a reactive nature. However, planning maintenance actions based on the condition of buildings, prioritizing the maintenance works, can be an effective way of optimizing resources and dealing with the scarcity of funds [75].

Regarding the relevance of the availability of funds for the performance of maintenance actions, 30% of the respondents consider that this criterion is often relevant for decision-making, 26% consider that it influences in some situations, and 23% refer that the funds available rarely condition the decision of intervene. In several countries, and particularly, in Portugal, maintenance is usually carried out based on an empirical approach, essentially due to [45]: i) lack of funds for the application of intensive and systematic maintenance policies; ii) lack of knowledge concerning the advantages of preventive maintenance, performed based on technical criteria; and iii) lack of tools and models to support planning these actions. Although the existence of available funds may not lead to performing maintenance actions (when these actions are not justified), the lack of funds always conditions the decision to intervene, regardless of the physical degradation of the building and the risk of its failure. Paulo et al. [51] refer that, usually, maintenance actions are postponed due to lack of funds, thus leading to an increasing number of degraded structures. One of the respondents mentions, in an additional comment that, in his/her company, maintenance works are often performed due to the existence of grants for rehabilitation actions.

About the users' complaints, 15% of respondents consider that this factor is always relevant and should lead, by itself, to the performance of maintenance works, and 42% consider that this is often a conditioning factor. In Portugal, current buildings are often owned by the users, and thus the funds available are more conditioning than the owners' complaints. However, in services and hospital buildings, the rehabilitation actions occur only because of user complaints or for aesthetic reasons, neglecting technical criteria or the analysis of buildings' components degradation. In other countries, decision-makers are aware of the need to ensure that the building meets the users' expectations, recognising that the maintenance programs need to be defined based on the knowledge of the buildings degradation and service life, to ensure an adequate building's performance and without faults throughout their life cycle [39]. Users' satisfaction is intrinsically associated with their perception of the building's condition, so it is not surprising that users' complaints are relevant to buildings' managers [4].

As for age of the buildings, 14% of the respondents consider that this factor, by itself, is never conditioning for the decision of intervene. Nevertheless, over time, a continuous process of degradation of buildings and their components occurs, which is a combination of degradation phenomena with a linear, abrupt and exponential pace, according to the quality of materials, exposure and use conditions [63].

5.3. Relevance of inspection, diagnosis and service life prediction software

The next question of the questionnaire is related with the type of information that the stakeholder intends to obtain with computational tools (Fig. 3), as those proposed in this research project. 69.1% of the respondents considered that the most relevant information to support decision making would be an inspection and diagnostic report. In turn, 10.9% indicate that the most relevant information would be the proposal or suggestion of rehabilitation techniques adequate to the buildings' envelope elements

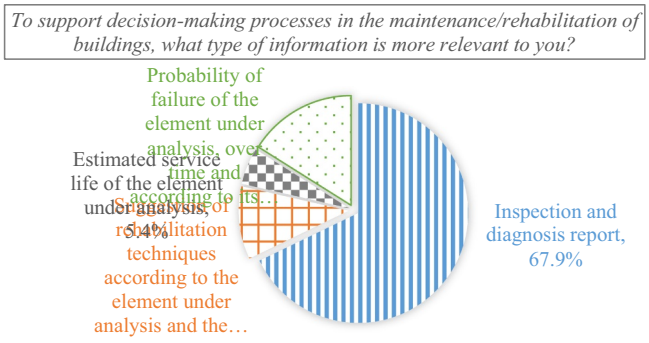

Fig. 3. More relevant information to support decision-making in the maintenance field.

considered, according to the observed defects. It is important to remember that 42.1% of the respondents work in diagnosis, pathology, inspection and rehabilitation of buildings, so this information would be crucial for the development of their professional activity. Only 5.5% stated that the information regarding the service life of the element analysed would be crucial for the decision-making process to intervene and 14.5% considered more relevant the knowledge regarding the probability of failure of the element analysed, over time and according to its characteristics. These results reveal that the respondents who are interested in obtaining the service life of the envelope elements, to decide about a maintenance action, would prefer to gather probabilistic data, instead of purely deterministic information.

The following two questions, which results are shown in Figs. 4 and 5, intend to acquire information concerning perception of the usefulness of the two computational tools to be developed. The respondents must evaluate the usefulness of each tool between 0 (nothing useful) and 10 (indispensable). Concerning the usefulness of the inspection and diagnosis software (Fig. 4), the results obtained reveal that 74.5% of the respondents assign a rating equal or higher than six, and the majority of the respondents (50.9%) attribute a classification between eight and nine to the usefulness of the proposed tool. Respondents thus seem to recognise the need for a standardized diagnostic system tool. For decades, the evaluation of the condition of buildings degradation was subjective due to the personal perception of the inspectors [75]. With the application of the proposed tool, the inspector will be able to provide objective and reliable information regarding the loss of performance of the buildings' components.

Various respondents provided several interesting suggestions, which will not only allow improving some aspects of the tool but also making it more user-friendly and marketable. The following comments were thus collected:

- Several respondents, one of them with 44 years of experience as Building Regulation Surveyor in the UK, reveal that they "have never used such practical and useful tools as the computational tools proposed in this research project";
- The respondents reveal that it is essential to standardised and automate the nomenclature of anomalies and causes, thus improving the work procedures and business performance in the maintenance area;
- The respondents indicate that each element must be analysed individually, as proposed in the present project, simulating the quality of the materials applied, the conditions of design and execution, as well as the use and environmental conditions;
- The respondents stated that even though the information provided by the computational tool could be extremely relevant, it cannot replace the expertise and common sense of a professional; therefore, due to the complexity of the degradation phenomena, it is suggested that the visual inspections in situ must be performed by an expert that must carefully collect the information required;

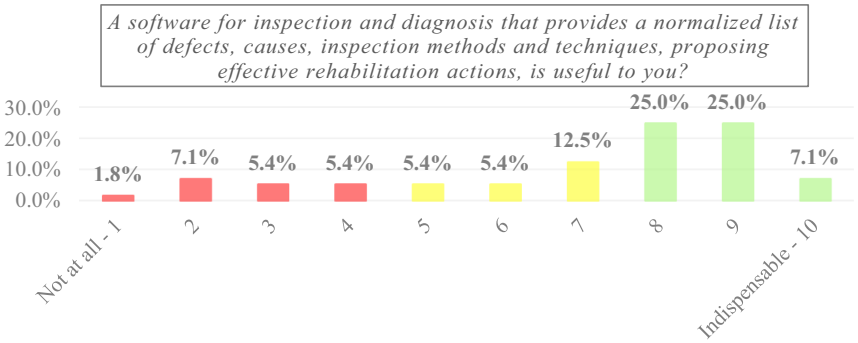

Fig. 4. Usefulness of the inspection and diagnostic software.

- Various respondents recognise that, if reliable and accurate, this tool allows supporting the decision to carry out a given maintenance action, saving time and money; however, to be applicable, IT tools must to be easy to understand and apply; thus, the respondents suggest the adoption of a trial period, which allow understanding the applicability of the tool for the respondents' context of action.

The next question addresses the usefulness of the software for SLP of the buildings' envelope elements. A survey conducted by Brisch & Englund [10] to a group of researchers, standardization committees, universities, manufacturers, associations and consultants in the field of construction reveals that 63% of the experts surveyed consider extremely relevant the information related with the SLP of buildings' components, and that only 6% of respondents consider that this information is not relevant. A similar result is obtained in this survey (Fig. 5), revealing that 82.1% of respondents considered that these tools are relevant in the decision-making process regarding the maintenance actions, assigning a rating equal or higher than six (53.6% assign a classification between eight and ten to the usefulness of this tool). The respondents refer that, once the reliability of the proposed tool is ensured, its application could be extremely useful for the implementation of adequate maintenance policies, thereby meeting a market need, concerning the acquisition of reliable data about when and how to intervene [36].

5.4. Computational features of the software

The next questions address more specific issues related with the computational features of the software. Fig. 6 presents the results obtained for the question "*how would you prefer to access these software tools?*" Most of the respondents would prefer applying an online software, available on any machine, including laptops, tablets or cellphones. This type of application is usually more efficient, since it does not overload the user's machine, thus not compromising the performance of other applications installed that are working simultaneously. Various respondents refer that, preferably, the proposed tools should be available in the various types of applications. Moreover, the respondents refer the need of an experienced technical support, providing relevant information to the users' doubts during the application of the proposed computational tools. The respondents also point out that some precaution must be taken concerning the operating system used in the case of mobile applications, ensuring the compatibility between different operating systems.

In the following question, the respondents must identify, in their opinion, the most relevant characteristics of these tools, and which naturally will condition the decision whether to use them (Fig. 7). In the respondents' opinion, the accuracy of the tools is the most relevant parameter, followed by the ease of use of the proposed tools. Very complex tools, requiring a lengthy learning process, with intricate tutorials, will be doomed to failure, since they will not be used by the construction industry. Therefore, there is a need for tools easily implemented, that provide results that are easy to understand and apply to real situations. The respondents also refer the relevance of the tools' compatibility with the user's hardware. In general, the user wants to apply the software in platforms or application that are already known; although this reason is extremely wrong to choose a particular software, it is still very common in practice. For the respondents, the efficiency of the tools (i.e. the software does not cause the machine to run slowly or fails regularly) and the existence of technical support are less relevant features. One of the experts reveals that the software currently available on the market for inspection and diagnosis is only semi-operational, since the tools' programmer usually defines them in a personalised way, neglecting the perspective of the end user, who will be the one who will ultimately have to use the tool.

Respondents are also questioned concerning the type of licence that they prefer (Fig. 8). In the current market, it is essential to have a trial period before the user buys the licence of the tools. The respondents do not show a clear preference among the options provided in the survey.

Concerning the cost of the proposed tools, the respondents are questioned about how much they would be willing to spend to acquire an annual licence of these tools (Fig. 9). The cost is a sensitive issue, and can also compromise the marketing hypothesis, if the price of the tools

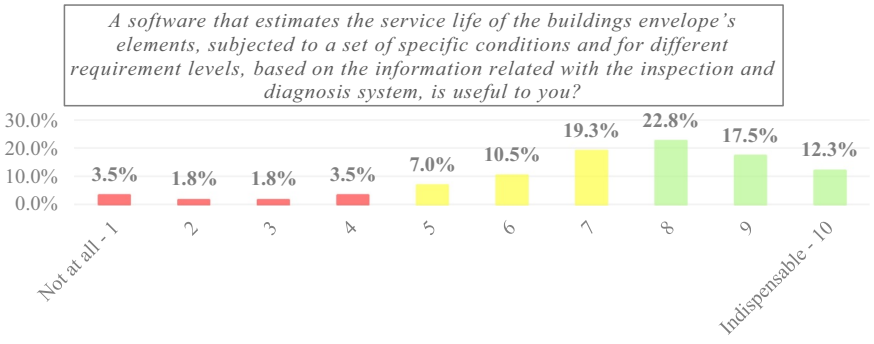

Fig. 5. Usefulness of the service life prediction software.

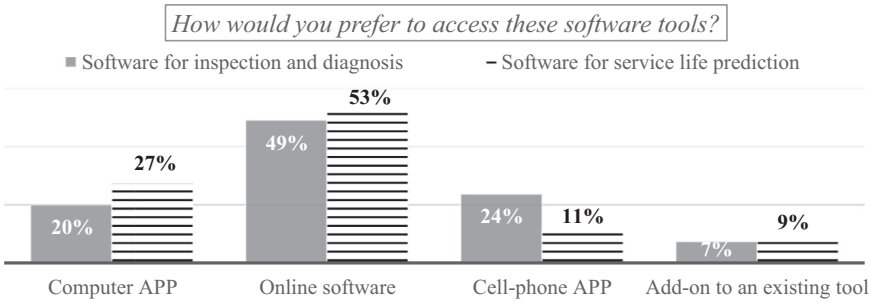

Fig. 6. Preferential method for using the proposed tools.

is too high for the target market. Most respondents indicated that the price of tools should be between 50 and 100 euros. Some respondents also point out that the tools should be free, given their relevance for the industry. Nevertheless, the respondents refer that the price of the tools will depend on their potential: i) if the tools present only an inspection report, a maintenance plan or a statistical analysis, the cost must be low; ii) but if a database is generated, with a systemic analysis of the elements' degradation condition over time, providing an expected service life, then it is another reality and the cost may be higher.

5.5. "Need to have" or "nice to have"

In a business model, it is crucial to distinguish between a "nice to have" tool from a "need to have" tool. In other words, the marketing of the proposed tools will necessarily require the substantiation of the tools' usefulness. Therefore, the potential commercialization of these tools requires a clear proof of their benefits, from the analysis of the potential economic gains obtained with their application.

The tenth question intends to identify possible reasons that may prevent the purchase of these tools and some respondents refer the following reasons: i) if the tools are not easy to use; ii) if the results are too generic and simplistic, and if it is not possible to adapt to the specific case studies that the user intends to model; iii) or if the tools cannot be adapted to the user's geographical and environmental exposure context; iv) if the cost of the tools is too high; the respondents also suggest adapting the cost to other economies, i.e. currency conversion issues must be considered, since a price that is reasonable in euros may not be so in other economies; and v) finally, if the user does not have confidence in the results, he/she will certainly does not apply the proposed tools.

Finally, a crucial question arises, trying to understand whether, from the respondents' point of view, these tools solve a real problem or not, that is, whether these tools are indeed necessary for the maintenance industry (Fig. 10).

About 60% of the respondents answered "maybe", since the information presented in the questionnaire regarding the computational tools is too generic, not presenting a real application that could be tested so that the respondents could have a clear opinion about the advantages, limitations and the field of application of the tools. Approximately 30% of respondents considered that "yes", the tools are relevant and responds to a current market need, and only 10.5% (6 respondents) considered that these tools are not necessary.

5.6. Statistical analysis and correlation research between the different questions addressed in the questionnaire

The answers provided by the respondents in the survey performed, as well as the additional comments, allow obtaining some extremely relevant information concerning the respondents' preferences regarding the two software tools proposed. In previous sections, the results obtained for each question are thoroughly discussed. However, as mentioned by Hollingsworth et al. [34], in the analysis of survey results, sometimes an additional perspective is required, allowing a more meaningful interpretation of the relationship existing between response variables.

In this sense, a statistical analysis is performed to explore the presence of correlation between the survey responses. For that purpose, a multiple linear regression analysis is performed, as well as a partial correlation analysis, evaluating the correlation between the mutually exclusive answers present in the survey. In this analysis, one of the answers is considered a dependent variable, evaluating which answers to the survey present explanatory power for the description of the specific answer under analysis. The same methodology is adopted for the different answers, measuring the correlation magnitude between questions through the Pearson's product-moment coefficient (r). This correlation coefficient varies between $+1$ and -1, indicating the strongest positive and the strongest negative correlation possible, respectively, in which 0 indicates that there is no correlation between variables. To evaluate the correlation between responses to different questions a cross tabulation analysis is also applied, to compare the results obtained for two survey questions. Cross-tabulation tables or bivariate tables allow describing the relationship between two questions with categorical answers, showing the categories of one question as column and the categories of a second question as rows [80]. Both methods intend to obtain some additional relevant conclusions regarding the preferences of the respondents, establishing some conceptual knowledge related with the causal effects between the answers to different questions. Nevertheless, the existence of correlation does

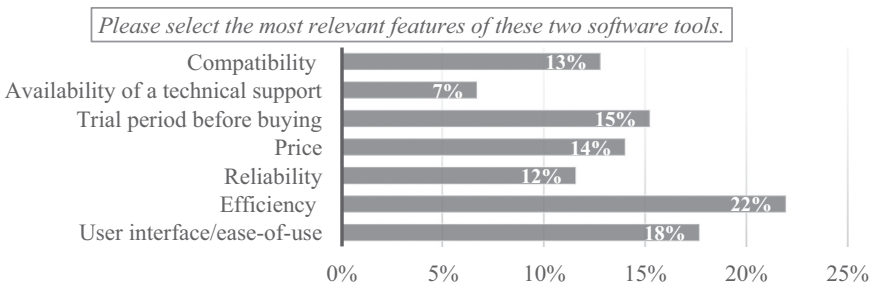

Fig. 7. Most relevant attributes of the proposed software.

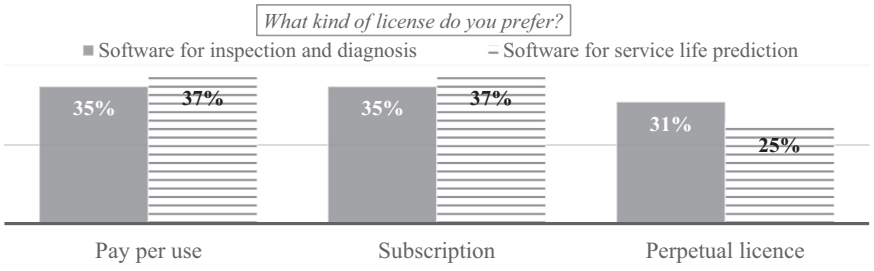

Fig. 8. Type of licence.

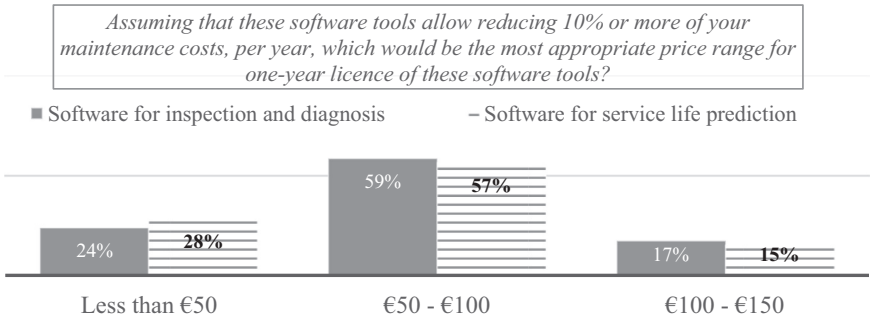

Fig. 9. Price range for one-year licence of these software tools.

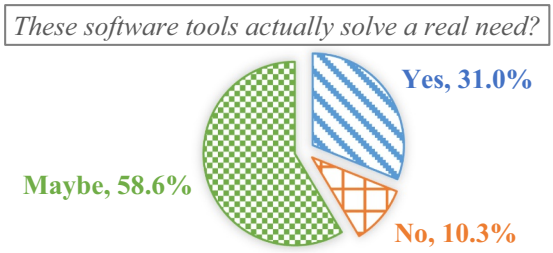

Fig. 10. Analysis of the relevance of proposed tools.

not establish a cause and effect between questions, i.e. the existence of correlation may suggest, but not imply a causal relationship between the survey questions.

The correlation analysis between some of the questions does not provide additional information relevant to the explanation of the problem under analysis, and thus is not discussed in this study. Nevertheless, the statistical analysis performed allows obtaining the following main conclusions:

- The questions related with the utility of the two proposed software tools present a relatively strong correlation. A Pearson's product-moment coefficient or a correlation coefficient (r) of 0.689 was obtained, revealing a positive correlation between the two questions, which indicate that, generally, the respondents that attribute a low value to the utility of the inspection software also attribute a low value to the utility of the service life prediction software, and in the opposite way, when a high value is attributed to a given software, a high value is also attributed to the other proposed tool;
- The correlation analysis between the questions related with the relevant information to support decision-making in the maintenance field and the preferential method for using the proposed tools (Table 1) reveals that: i) the respondents with a higher interest in the inspection and diagnosis tool, are as well more interested in obtaining an inspection and diagnosis report or suggestions of rehabilitation techniques; these respondents consider more relevant to apply the proposed tool in an online or cell-phone application, which facilitates the practical application of this tool during in situ inspections; ii) the respondents more interested in the SLP software want to obtain an estimated service life or the probability of failure of the element under analysis, and will prefer to obtain these estimations using computational or online applications;
- The statistical analysis also revealed a strong positive correlation between the costs of the two proposed computational tools (r of 0.884), which indicates that the respondents are usually willing to pay a similar amount to acquire both computational tools. Regarding the analysis of the correlation between the costs of the software and the score attributed to their utility, a positive correlation indicates that the respondents are available to pay more when they recognise the utility of the proposed tools. The respondents are from different backgrounds and social contexts, and even when they recognise and are interested in applying the proposed tools, the price they are willing to pay is not so much correlated with the relevance of the tools, but instead with economic and operational reasons;
- The respondents established the price of the software mainly according with the type of licence acquired and with the type of access or application of the proposed tools. Table 2 shows a cross tabulation analysis between the costs of the software, their type of licence and type of application. For both models, the respondents prefer the application of the proposed software through online subscription, followed by the application of these tools by online pay per use. The cell-phone application of these tools, in a pay per use mode, also seems interesting for the respondents, since it allows applying the tools for singular and specific in situ occasions. Due to the subjectivity inherent to attributing a price to a product, it is not possible to identify a linear correlation or pattern between the price and the other variables; either way, two patterns can be identified: i) as expected, the respondents are more available to pay more for

Table 1
Cross-tabulation analysis between the responses related with the type of information obtained and the type of application of the proposed software.

	Add-on	Cell-phone APP	Computer APP	Online
Inspection and diagnosis report	5%	19%	14%	50%
Suggestion of rehabilitation techniques	2%	2%	5%	2%
Estimated service life of the element under analysis	0%	0%	13%	25%
Probability of failure of the element under analysis	13%	13%	25%	38%

Table 2
Cross-tabulation analysis between the responses related with the type of application, type of licence and the costs of the software.

Inspection and diagnosis software				**SLP software**			
Correlation between the type of application and the cost of the software							
	€100–€150	€50–€100	Less than €50		€100–€150	€50–€100	Less than €50
Add-on	2%	2%	0%	Add-on	2%	0%	2%
Cell-phone APP	9%	11%	6%	Cell-phone APP	4%	7%	2%
Computer APP	4%	6%	9%	Computer APP	4%	16%	7%
Online	0%	40%	11%	Online	2%	33%	20%
Correlation between the type of application and the type of licence							
	Pay per use	Perpetual	Subscription		Pay per use	Perpetual	Subscription
Add-on	2%	4%	0%	Add-on	0%	4%	2%
Cell-phone APP	12%	4%	10%	Cell-phone APP	6%	4%	2%
Computer APP	6%	10%	4%	Computer APP	10%	8%	8%
Online	16%	14%	20%	Online	21%	10%	23%
Correlation between the type of licence and the cost of the software							
	€100–€150	€50–€100	Less than €50		€100–€150	€50–€100	Less than €50
Pay per use	2%	23%	6%	Pay per use	2%	23%	13%
Perpetual	11%	21%	2%	Perpetual	9%	15%	4%
Subscription	2%	15%	17%	Subscription	2%	19%	13%

acquiring perpetual licences and the majority recognise that it is not feasible to pay less than €50 for this type of licence of the proposed software; and ii) the respondents are more willing to pay between €100 and €150 for cell-phone or computer applications.

The statistical analysis performed intends to evaluate some trends in the correlation or potential causal effect between two responses. As mentioned by Maroco [44], statistics are rarely a good replacement for logical understanding and knowledge of the scientific bases in the area under analysis. In this sense, the analysis performed in this study, even though using statistical tools, is more focused on the careful examination of the results obtained in the survey, obtaining additional information concerning the influence of the experience and empirical knowledge of the respondents in the meaningfulness of the answers to the questions.

6. Conclusions

The authors of this study intend to create two computational tools, allowing a systematisation of inspection and diagnosis procedures, and predicting the service life of the buildings' envelope elements. These tools are fundamental for the further definition of a decision-making module regarding the implementation of effective maintenance operations. Before the definition and implementation of these tools, in this study, a market survey is performed, which has both strategic and tactical implications, intending to adapt the proposed tools to the real needs of the maintenance industry.

Survey research can be very powerful tool, and in some situations, can be the only way to perform a particular inquiry or ongoing research. The main shortcoming of this kind of studies is the representativeness of the sample, due to a common problem, that is the low response rate to this type of surveys. In this study, 57 relevant answers were obtained, from experts on the maintenance and rehabilitation area. The response rate is relatively low, as expected, but it seems sufficient to enable generalising the results to the target population; in fact, the respondents are from different countries and work actively on the market research context. Therefore, the results obtained allow evaluating the perception of the stakeholders regarding the usefulness of the proposed tools, and the relevance of these tools for the industry. Moreover, the survey avoids that these tools are defined in a purely academic context, which could cause a definition of non-pragmatic tools. Conversely, the survey allows defining user-oriented tools, learning from the experience and useful suggestions of other researchers and practitioners, since the success of these tools will depend on their acceptance by the industry.

The respondents reveal an alarming, but not surprising reality, referring that, in their action scope, maintenance actions are usually performed in extreme situations, when the users' safety is already compromised. Nevertheless, the respondents believe that in a few years, the maintenance actions will be planned rationally and in a technically informed way, preventing the risk of failure rather than repairing the building after it occurs. The respondents acknowledge the relevance and need of the proposed tools, recognising their practical advantages and their applicability to the maintenance and rehabilitation context, aiding the optimization of maintenance strategies.

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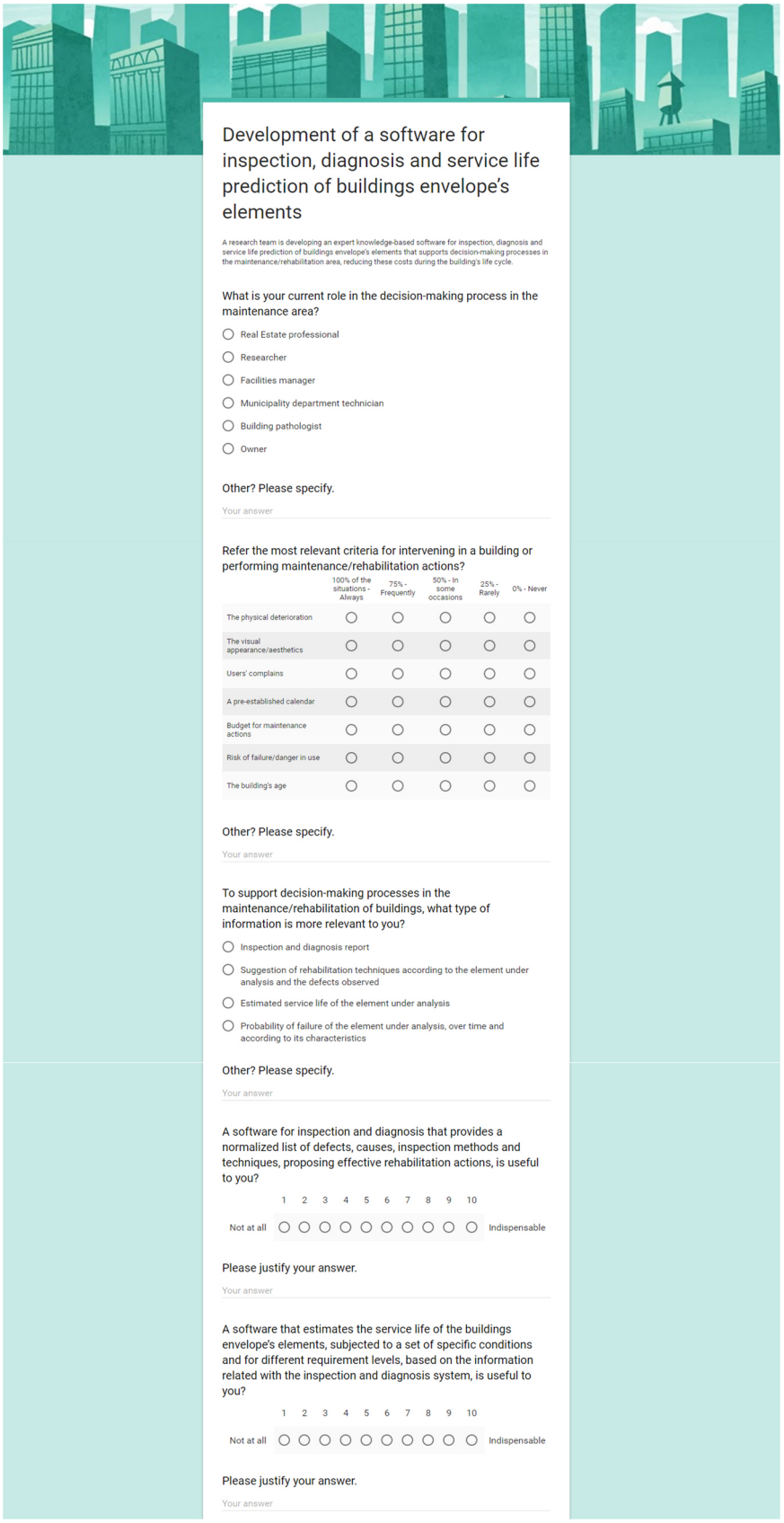
Appendix A

See Fig. A1



Development of a software for inspection, diagnosis and service life prediction of buildings envelope's elements

A research team is developing an expert knowledge-based software for inspection, diagnosis and service life prediction of buildings envelope's elements that supports decision-making processes in the maintenance/rehabilitation area, reducing these costs during the building's life cycle.

What is your current role in the decision-making process in the maintenance area?

- Real Estate professional
- Researcher
- Facilities manager
- Municipality department technician
- Building pathologist
- Owner

Other? Please specify.

Your answer

Refer the most relevant criteria for intervening in a building or performing maintenance/rehabilitation actions?

	100% of the situations - Always	75% - Frequently	50% - In some occasions	25% - Rarely	0% - Never
The physical deterioration	○	○	○	○	○
The visual appearance/aesthetics	○	○	○	○	○
Users' complains	○	○	○	○	○
A pre-established calendar	○	○	○	○	○
Budget for maintenance actions	○	○	○	○	○
Risk of failure/danger in use	○	○	○	○	○
The building's age	○	○	○	○	○

Other? Please specify.

Your answer

To support decision-making processes in the maintenance/rehabilitation of buildings, what type of information is more relevant to you?

- Inspection and diagnosis report
- Suggestion of rehabilitation techniques according to the element under analysis and the defects observed
- Estimated service life of the element under analysis
- Probability of failure of the element under analysis, over time and according to its characteristics

Other? Please specify.

Your answer

A software for inspection and diagnosis that provides a normalized list of defects, causes, inspection methods and techniques, proposing effective rehabilitation actions, is useful to you?

	1	2	3	4	5	6	7	8	9	10	
Not at all	○	○	○	○	○	○	○	○	○	○	Indispensable

Please justify your answer.

Your answer

A software that estimates the service life of the buildings envelope's elements, subjected to a set of specific conditions and for different requirement levels, based on the information related with the inspection and diagnosis system, is useful to you?

	1	2	3	4	5	6	7	8	9	10	
Not at all	○	○	○	○	○	○	○	○	○	○	Indispensable

Please justify your answer.

Your answer

Fig. A1. Questionnaire used in the market survey.

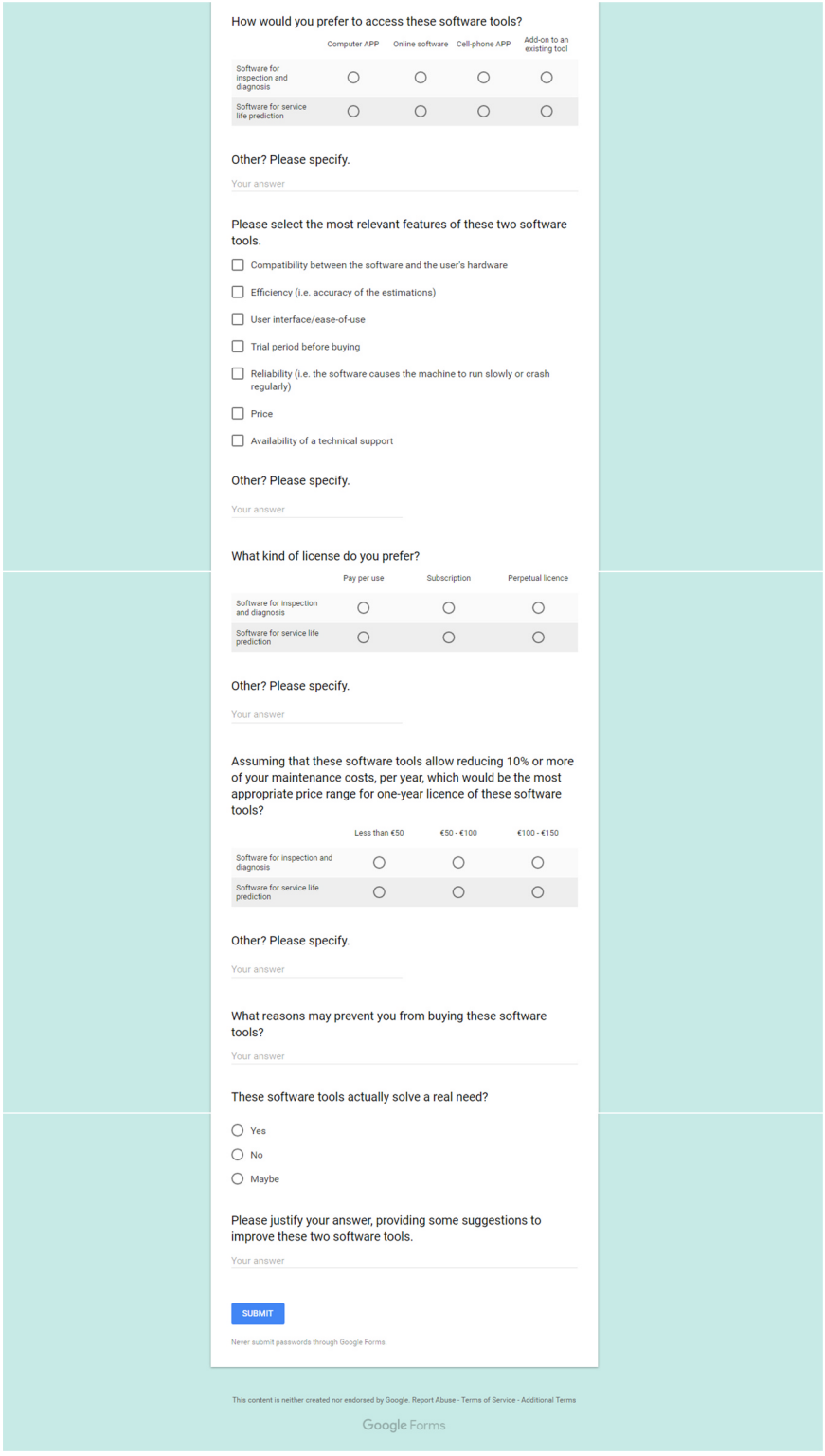


Fig. A1. (*continued*)

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