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Cost-benefit Analysis of Smart Structures

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Abstract: Smart structure is defined as structure equipped with sensors (especially continuous and composed of fiber optic), so that it is able of transmitting data of interest about its state of health (deformations, cracks, oxidation, etc.). This technology can facilitate the preventive maintenance of buildings and the management of their structural health. Therefore, a necessary aspect of interest to analyze in order to know if the technology is applicable or not, is to evaluate its profitability. Thus, the objective of this paper is to perform a cost-benefit analysis of smart structures, studying on the one hand which is the initial cost increase involved in the implementation of the proposal, and on the other hand to evaluate which is the saving of money to over the time that this application represents, what allows to establish the point of return on investment (ROI), and from which moment it is possible to expect net benefits..

Key words: preventive maintenance, periodic inspections, smart structure, smart city, sensorisation, cost-benefit analysis

1. Introduction

A reinforced concrete constructive element is usually associated with an inanimate being, in the same way that a stone is also associated with an inanimate being. But, if it was possible to implement to this element of reinforced concrete, to this inanimate being, a nervous system that would allow it to transmit data about its health (cracks, deformations, humidity, carbonation, oxidation, etc.)? If this was possible to do with the entire structure of a building?

Clearly it would bring important benefits, through facilitating the maintenance of buildings and the early detection of deteriorations. This that explained in this way sounds to science fiction, it is not at all. In Ref. [1] the technical possibility of providing a nervous system to the structures of buildings is already explained, and how beneficial the application of these technologies could be. The basic explained concept is to provide the structure with some sensors (especially continuous and fiber optic), so that the structure is equipped with a "nervous system" and is able to transmit data of interest about its health (deformations, cracks, oxidations, etc.). Some examples of the use of this technology and of its scientific research in the Department of Civil and Environmental Engineering of the School of Civil Engineering of Barcelona are also explained.

All the aforementioned is clearly framed within the global concept of "Smart city" and "Smart materials". In fact, these types of structures are often referred as "smart structures". The second step of the investigation must go through evaluating the economic viability of the proposal, because if it had a very high implementation cost in the buildings, much higher than any subsequent savings that could produce, it would be clear that the proposal would not be feasible to apply it in a generalized way in the buildings, but only in some specific case for its scientific study. Therefore, the study should be of the cost-benefit type, as it is called in the field of Applied Economics. In this study must be analyzed on the one hand what is the initial cost increase that the implementation of the proposal supposes. And on the other hand it should be evaluated what is the money saving over time that involves the application of the proposal, which allows establishing

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the point of return on investment (ROI), and from which moment it is possible to expect net benefits.

The purpose of this article is precisely to perform the cost-benefit analysis of smart structures, to assess whether their use is feasible from an economic point of view. What is exposed is a summary of the line of research developed in 2015 between Neàpolis (a technological center belonging to the city council of Vilanova i la Geltrú, which has as some of its priorities research, technological innovation, entrepreneurship and collaboration with the university), the School of Engineering of Vilanova i la Geltrú and the School of Civil Engineering of Barcelona (Department of Civil and Environmental Engineering). This research was developed in the framework of an EPS project (European Project Semester), in which four engineering students participated in the final project phase, which were from the following countries: Germany, France and Holland.

In the event that it is consistently proved that the proposal is technically applicable (which, as has been mentioned, has already been demonstrated in research developed in Catalonia), and that it is economically interesting, since the point of return on investment (ROI) is attractive and that the volume of net benefits that can be obtained is important, would imply that it would be interesting to apply these technologies to all the buildings, both existing and new construction. In this way it would contribute to improve the quality and operation of the buildings during their lifetime, saving money, and therefore contributing to improve the quality of life of society and create more sustainable conditions, efficients and respectfuls with the environment.

2. Methodology

In order to develop this research work, two buildings have been selected in order to make proposals to sensorise their structures (mainly through the use of fiber optic), calculate the cost of implementing and maintaining this technology, and calculate the saving of money involved in the application of this technology when performing preventive maintenance of the structure. Or in other words, estimate the saving of money involved in performing preventive maintenance of the structure using sensors, compared with doing preventive maintenance of the structure without sensors (i.e., as it is currently done, through periodic inspections, etc.). In order the approach is as wide as possible, the two chosen buildings for the study are very different between them, in terms of construction typology, type of structure, age, materials, etc. Thus, one of the chosen buildings is the Neàpolis building (see Fig. 1), built in 2007 (with reinforced concrete structure, grid floors, etc.). The other is the Sant Antoni Abat church (see Fig. 2), built in 1693, (with structure of stone load walls, buttresses, arches and vaults, etc.). Both buildings are located in Vilanova i la Geltrú (Barcelona).

2.1 Types of Sensors

One of the first steps of the research was to study the different types of existing sensors, in order to choose those that are suitable for this research. As a first general approximation, the sensors can be classified as shown in Table 1, where the measured data by each type of sensor is also displayed [2].

According to the spatial distribution of the measured values of fiber optic sensors (FOS), the sensor can be classified into different types.

2.1.1 Point Sensor

The measurement with point sensors is performed only at a single point of the fiber.

2.1.2 Integrated Sensor

Measurement with integrated sensors averages a physical parameter along a certain fiber section and provides a unique value.

2.1.3 Multiplexed Sensor

The measurement with multiplexed sensors is defined by a certain number of fixed and discrete points along a single fiber optic cable. The most common example are multiplexed Fiber Bragg Gratings (FBG).

Fig. 1 Image of the Neàpolis building.

Fig. 2 Image of Sant Antoni Abat church.

Table 1 Different types of sensors.

Sensor	What does it measure
Fiber optic	Deformation, cracks, humidity, temperature, pH, vibrations, oxygen, hydrogen
Piezoelectric	Deformation
Acoustic emission	Oxidation, cracks

2.1.4 Distributed Sensor

The measurement with distributed sensors can be done at any point along an optical fiber with the measurement system based on the scattering (of light or any other electromagnetic radiation) of Rayleigh, Raman or Brillouin.

For this investigation only the third and the fourth sensor are useful. In comparison with the multiplexed sensor, an advantage of the distributed sensor is the fact that a previous definition of the location of the sensors is not necessary. However, in this study the appropriate positions where the sensors should be placed in each of the two buildings have been determined, in order to obtain representative data. The greater cost of the distributed sensors motivated that in this study the multiplexed sensors were selected.

The called Fiber Bragg Gratings (FBG) are similar to very small mirrors forming a kind of grid, created in an fiber optic through a laser. Therefore, small fiber parts are transformed into fiber optic sensors capable of detecting local environment data around those areas. For detection, white light is sent through the fiber and the grids are arranged to reflect certain wavelengths and transmit the rest along the fiber. A data of interest such as deformation, can be determined from the wavelength reflected from each grid. This means that each sensor is related to a certain color of white light and reflects it. If there are small changes, the color will be different and the device can convert this information into analyzable data. Fig. 3 shows this phenomenon.

In this research work, the sensor called "fos4strain" is selected as FBG (see Fig. 4). This sensor is immune to light and electromagnetic interference.

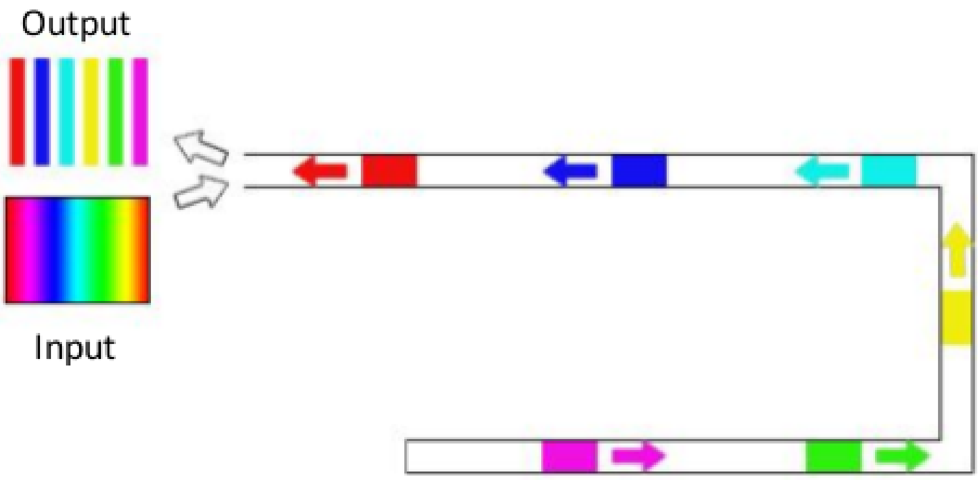

Fig. 3 Operation of the Fiber Bragg Gratings (FBG).

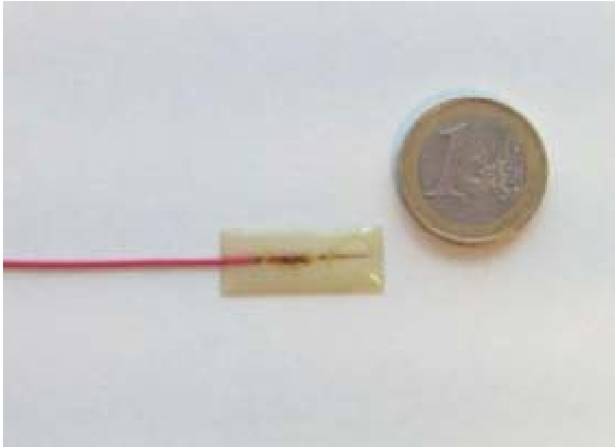

Fig. 4 Sensor "fos4strain".

In addition to the fiber optic, as it has been seen in Table 1, there is the acoustic emission sensor, which is able to detect changes in the structure through capturing the acoustic waves of the vibrations. The causes of these vibrations are structural transformations in the form of cracks, movements and oxidation. This sensor measures high frequency waves in a range from 10 kHz to several MHz and converts them into an electrical signal. The signal is digitized and analyzed through special software. Therefore it is decided to include this type of sensor, due to its capacity to detect oxidation, something that, as it has been seen, can not do the fiber optic sensor. And the early detection of oxidation is considered necessary to performance an adequate preventive maintenance of the buildings. In this research work, it is selected the sensor called "AES150" as the acoustic emission sensor (see Fig. 5).

Fig. 5 Acoustic emission sensor“AES150”.

2.2 Proposal of Different Levels of Intensity

For the implementation of sensors in the buildings structures, as a general principle it is proposed that there may be different levels of intensity in this sensorization or monitoring. It is designated as intensity level in the sensorization the fact of placing more or fewer sensors, and therefore obtain more or less data about the health of the structure, and also spend a greater or lower amount of money on sensorization (both in its implementation as in its subsequent maintenance). It has been considered appropriate to introduce this concept, since depending on the type of building, it may be of interest that the sensorization is more or less intense. For example, it is not the same to consider the structural sensorization of a small detached family house, than a large hospital, or a building of high architectural, historical and artistic value, etc. In the first case, it may be enough to obtain a small amount of data, that is, with a low level of sensorization intensity, while in the second case it may be of interest to have greater control over the structural health and obtain a greater amount of data, that is with a greater sensor intensity level.

In this research work, as a starting point, there have been proposed three levels of sensorisation intensity: low, medium and high. The following figures show the sensorisation proposals in the plant for the Sant Antoni Abat church and for Neàpolis, both with medium intensity level, which is what has been considered appropriate for these two buildings (see Figs. 6-8).

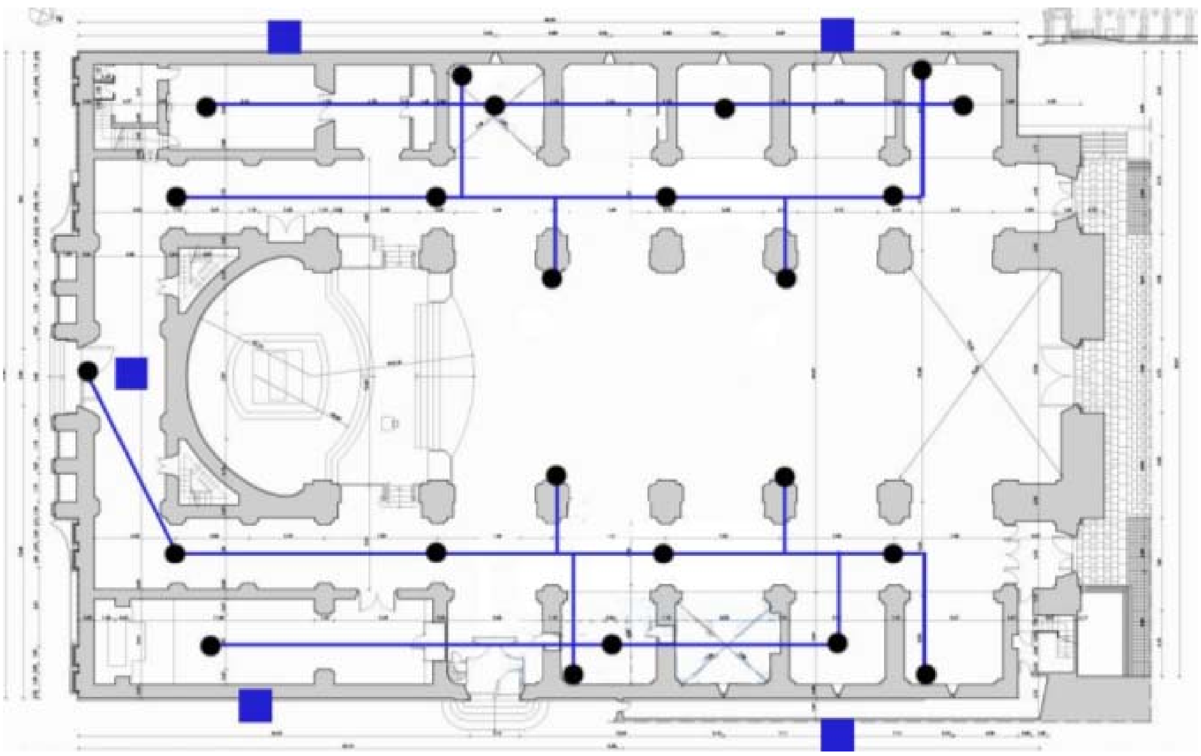

Fig. 6 Example of medium intensity sensorisation in Sant Antoni Abat church.

Fig. 7 Example of medium intensity sensorisation in the Neàpolis building.

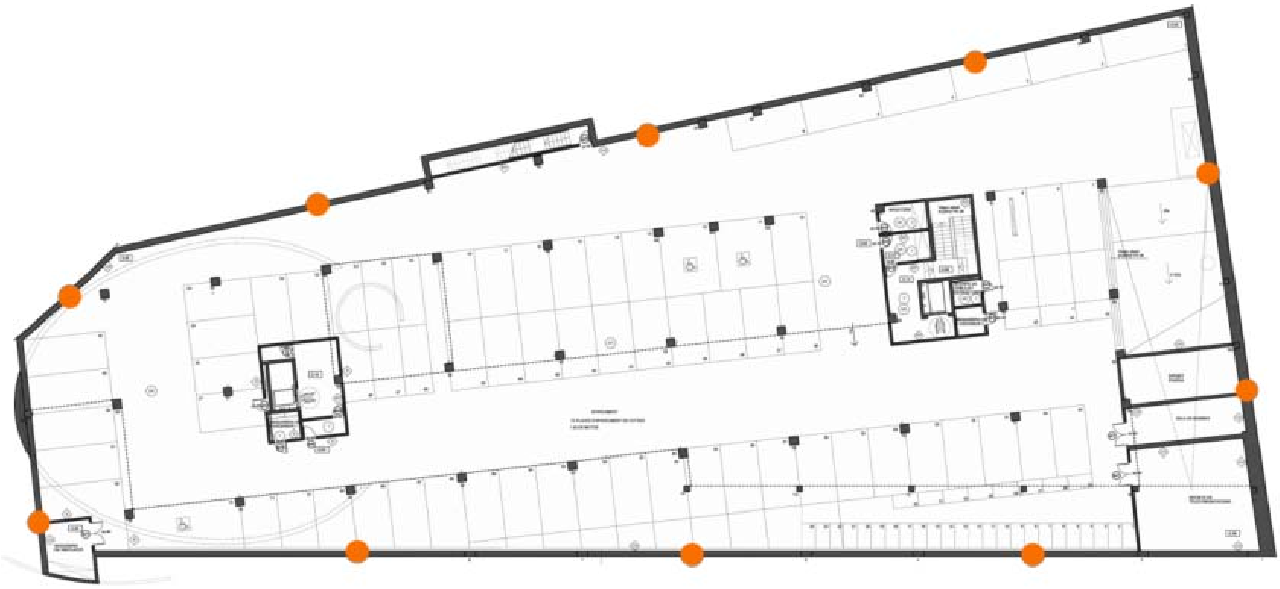

Fig. 8 Proposed situation of acoustic emission sensors in the Neàpolis building.

The blue lines in Fig. 6 show the situation of the fiber optic (in the arcs, vaults and columns), the black points indicate the location of the sensors in the fiber. The blue squares indicate the location of the acoustic emission sensors.

The blue lines in Fig. 7 show the situation of the fiber optic (in floors and pillars), the violet points indicate the location of the sensors in the fiber.

2.3 Economic Feasibility Assessment

To evaluate the degree of economic viability of the application of sensors in structures, the cost of performing preventive maintenance (without the use of sensors) must be compared with the cost of performing preventive maintenance using sensors. Based on this reasoning, the following Equation is proposed:

$$F = \frac{PMC \cdot T}{IC + (SSC + SPMC) \cdot T} \tag{1}$$

Where:

F = Feasibility

It indicates the degree of economic viability of the investment.

PMC = Preventive Maintenance Cost

It represents the cost (annual average) of performing preventive maintenance of the structure without using sensors (that is, as is currently done, through periodic inspections, etc.).

IC = Initial Cost

It represents the cost of implementing the sensor system of the smart structure. It includes the cost of the sensors and fiber optic that is installed, the cost of its installation and the cost of the software to obtain and manage data.

SSC = Smart System Cost

It represents the cost (annual average) of maintaining the sensor system of the smart structure. It includes the repair or renewal of cables (fiber optic) or sensors that have malfunctions; the maintenance of the software that controls the system; the cost of data management obtained by the system.

SPMC = Smart Preventive Maintenance Cost

It represents the cost (annual average) of performing preventive maintenance of the structure using sensors.

T = Time

It is the time (in years) during which the comparative study is performed.

2.4 Degrees of Economic Feasibility of the Investment

From the obtained results from the Eq. (1) it follows that:

- If $F < 1$; indicates that the investment is not profitable;
- If $1.01 < F < 1.25$; indicates that the investment is slightly profitable, with a small margin for deviations;
- If $1.26 < F < 1.50$; indicates that the investment is profitable, with important margin to absorb possible deviations;
- If $F > 1.51$; indicates that it is a solidly profitable investment, with a high return on investment.

2.5 Period of Investment Recovery

In case the investment is profitable ($F > 1$), it is interesting to know the moment from which it starts to obtain net profit (the benefit exceeds the initial investment). This moment is visualized in Fig. 9, where the point of return of the investment (Point ROI; Break-Even-Point) is observed. The following important aspects are also observed conceptually:

- The two curves are of constant slope (they are lines), considering that the average annual cost of maintenance in both cases is constant.
- The PMC line (red color) starts at the origin of coordinates, since there is no initial cost for T = 0.

The SPMC line (green color) starts on the abscissa axis, due to have initial cost for T = 0.

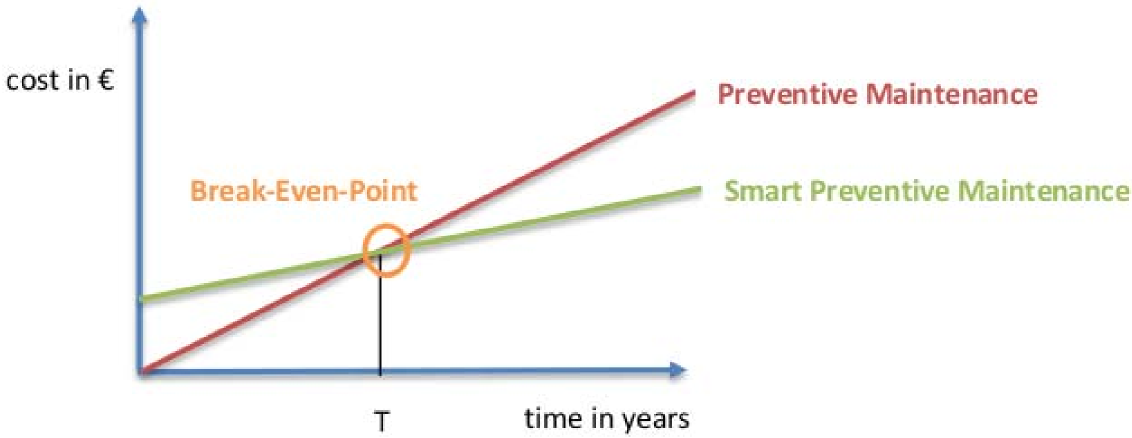

Fig. 9 Point of return on investment (point ROI; Break-Even-Point).

The slope of the SPMC line is lower than the slope of the PMC line (i.e., $\frac{dSPMC(T)}{dT} < \frac{dPMC(T)}{dT}$). This is because it is considered that using sensors (smart structure) the cost of preventive maintenance is lower than performing preventive maintenance without sensors.

To analytically determine the value of T (time, in years, after which net benefits begin to be obtained), it starts with expression (1) and then it equates to 1 (F = 1). Clearing, the Equation (2) is obtained, that allows to calculate the value of T.

$$\frac{IC}{PMC - (SSC + SPMC)} = T \quad (2)$$

2.6 Methodology for the Determination of Parameters

Once explained the general approach and proposed mathematical equations to determine the degree of economic viability of smart structures, it will de explained the methodology to determine the value of the different parameters that affect the explained mathematical equations.

PMC = Preventive Maintenance Cost

It represents the cost (average annual) of doing preventive maintenance of the structure without using sensors (that is, as is currently done, through periodic inspections, etc.).

To determine this value, the following has been done:

1) Ask if in the two buildings object of the study (Neàpolis and Sant Antoni Abat church) there are data on the annual cost of doing preventive maintenance. In none of these two buildings these data exist.
2) Obtain data on various expenses in recent years in these two buildings in terms of repair and maintenance.
3) Study bibliography on preventive maintenance costs in old buildings and recently built buildings.

IC = Initial Cost

It represents the cost of implementing the sensor system of the smart structure. It includes the cost of the sensors and optical fiber that is installed, the cost of its installation and the cost of the software to obtain and manage the data.

To calculate this value, companies in the sector that market and install the proposed sensors and optical fiber have been consulted.

SSC = Smart System Cost

It represents the cost (average annual) of maintaining the sensor system of the smart structure. It includes the repair or renewal of wires (fiber optic) or sensors with deteriorations; the maintenance of the software that controls the system; the cost of data management obtained by the system.

To calculate this value, the following has been done:

- Consider the lifetime of each type of sensor and fiber optic; the cost of extracting and placing new sensors and fiber optic (when they cease to function due to dysfunction or to have exceeded their lifetime); cost of periodic reviews of the system by a computer engineer or similar.
- To estimate these values, companies that install the proposed sensors and fiber optic have been consulted.

SPMC = *S*mart Preventive Maintenance Cost

It represents the cost (average annual) of performing preventive maintenance of the structure using sensors and fiber optic. To determine this value, the following factors that suppose savings with regard to PMC are considered:

- It is needed less time (and therefore less cost) of technician (building engineer, civil engineer, architect, etc.) in building inspection and diagnosis. So, in PMC, the technician must periodically check the building (which involves important amount of time, depending on various building data: size, type of construction, number and characteristics of existing dysfunctions, etc.). However in SMPC, the technician, even from home or office, can obtain on computer or smartphone the data on the state of health of the building, reducing the needed time to permform de diagnosis and teherfore reducing the cost.

- Through SPMC is possible to know before when deterioration appears (the system software can include an application that warns the technician in case deteriorations appear, or when they exceed a certain magnitude). This earlier detection of deterioration in SPMC with respect to PMC allows the therapeutics applied in SPMC to have less cost. For the application of the aforementioned software, it may be useful to use a scale of deterioration severity in buildings, which allows the classification of deteriorations according to their degree of severity [3].
- Derived from the previous point, it is also possible to introduce another type of additional cost. Indeed, if the building has severe deteriorations, on one hand it is necessary to spend money to repair it. But on yhe other hand, it is also necessary to consider that the users of the building will probably have to take some measures that may imply cost in some way. These measures may include the following: temporary evacuation of the building (or part of it), longer trips (for example, if the people who works in the building's offices should temporarily go to a further away location), etc. These losses must be considered and valued economically, in this additional cost.

It should be highlighted that from all the studied parameters (PMC, IC, SSC and SPMC), SPMC is the one that presents the greatest difficulty in obtaining results with a high degree of certainty. This is partly due to the fact that, based on the studies explained on this paper, there is not any building in the world with a smart structure, from which it is possible to get experimental data. On the other hand, in the few constructions where the concept of smart structure is used (some bridges, thermal power station, etc.), there is not any economic study focused on the savings that the use of this technology implies compared to not use it. To obtain consistent SPMC values, the most appropriate methodology would be to have several pilot buildings with smart structures, and thus get experimental data from them on the costs of SPMC.

3. Conclusions

After applying the methodology and mathematical expressions proposed to the two studied buildings, it is obtained in both cases that F > 1 (the investment is profitable). In the same way, it is obtained that for the Sant Antoni Abat church, T = 10 years (the period of recovery of the investment is 10 years); and for the Neàpolis building, T = 15 years.

These results indicate that, in addition to the fact that the use of this technology is profitable, that its profitability is higher in old buildings than in recently built buildings. The latter seems reasonable, because in an old building, due to having a greater probability, in principle, of suffering important deteriorations, the fact that through the use of sensors it is possible to detect these dysfunctions earlier, which allows greater savings of money by reducing repair costs, compared to the option of preventive maintenance without the use of sensors.

On the other hand, in a quite new building (which is properly constructed, therefore, without important defects in project, execution, materials, etc.), there is, in principle, a lower probability of suffering relevant malfunctions, what the saving is less significant with respect to the option of preventive maintenance without the use of sensors.

It is recalled here that in the quite new building, it is based on the premise that the building was built without sensors, and afterwards the sensors and optical fiber (attached to the surface, as mentioned) are installed. In the case of a building that is already built with a smart structure, the results may be different, probably with greater profitability. This is so since the initial cost (IC) is likely to be somewhat lower, compared to the initial cost in the case of the existing building in which the sensors are installed afterwards. In addition, in new buildings, other types of technologies can be applied in order to monitor the reinforced concrete structures, such as smart dust, which was already explained in the previous article [1].

It should be noted that the use of sensors and fiber optics in buildings can be used for broader purposes to the referrals of structural monitoring and optimization of the management of the structural health of the building. Therefore, this technology can also be used in the field of home automation and energy efficiency of the building, thus achieving a comprehensive concept of smart building.

The different concepts explained in this paper demonstrate the goodness of the use of smart structures, both from a technical and economical point of view. Thus, perhaps in a few years the existence of smart buildings will begin to be usual, both in terms of smart structures, and in terms of energy efficiency and home automation, and these aspects can even be collected at the level of regulations.

Building engineers, civil engineers, architects, industrial engineers, computer engineers, and other professions are perfectly qualified to work in the field of smart structures, as well as in energy efficiency of the buildings and home automation, and more generally in the field of smart cities. This is an example of hybridization, which in this framework means the cooperation between different professions, in order to achieve maximum efficiency and therefore be very useful to society.

References

[1] F. Ruiz and A. Llorens, Les estructures intel·ligents. Aplicació de les noves tecnologies per la gestió de la salut estructural dels edificis. L'Informatiu. Col·legi d'Aparelladors, *Arquitectes Tècnics i Enginyers d'Edificació de Barcelona* (2012) (333) 98-103.

[2] K. Lau, L. Zhou, P. Tse and L. Yuan, Applications of composites, optical fiber sensors and smart composites for concrete rehabilitation: An overview, *Applied Composite Materials* 9 (2002) 221-247.

[3] F. Ruiz, Escala de gravedad de daños en edificios: de la asignación directa a la constrastación estadística. Tesis doctoral. ETS de Ingeniería de Caminos, Canales y Puertos de Barcelona-UPC, 2014.