FINAL REPORT

SMART STRUCTURES

Economic Feasibility Study

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ECONOMIC FEASIBILITY STUDY

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Abstract

Since a few years, the civil engineering world can see a changing about how to preserve and monitor the structures. Thanks to the system of Smart Structures we can notice the early damages on the structure and anticipate the future. This science is already applied on bridges and now different researches work on buildings, such as the company Neàpolis in Vilanova i la Geltrú.

As participators of European Project Semester at the Universitat Politècnica de Catalunya a feasibility study and cost analysis for the implementation of Smart Structure systems had to be done. This has been an assignment of the innovation agency Neàpolis, which was founded in 2007 by the city council of Vilanova I la Geltrú. The outcome of this project should be a cost-benefit-analysis, which compares the costs to the savings and recommendations for the implementation of sensors in the Sant Antoni church and the Neàpolis building.

The research has been done in order to give Neàpolis an indication whether Smart Structures are feasible to put into buildings by lowering maintenance cost and improving the life span of buildings. There is not a known study that is similar to this project, in our knowledge this is the first feasibility study on Smart Structure Systems that has been performed. This is why the research is of importance to the company. Because it has been not possible to gain a great deal of useful information from the internet, the assistance of the supervisors Félix Ruiz Gorrindo and Pau Martí and third parties has been necessary.

In this report you can read on the one hand about the way research has been done. First there are pointed out the most important advantages of Smart Structures. Then there are information about the research of sensors and pathologies that could occur in buildings and how they are related to the project. Our supervisors have been given us lectures about civil engineering to explain the different ways of how a building can be constructed.

On the other hand you can find information about the planning of the implementation of the Smart Structures in the Neàpolis building and the Parroquia Arciprestal Sant Antoni Abat (Sant Antoni church). The buildings are both located in Vilanova i la Geltrú, Spain. After the inspection of both buildings and the transfer of the blueprints we were looking for the best positions for the sensors in the buildings. Therefrom we deduced different concepts for the implementation based on different states of intensities.

Relation to these results formulas has been created to show from which point the implementation of Smart Structure systems in buildings is feasible. There are proposed formulas for the feasibility in time as well as formulas for the break-even-point. Also the different parameters are explained in this report. In the end an example of the Neàpolis building was realised, to prove that the proposed formulas are meaningful.

With the gathering of all the information a conclusion has been drawn on which recommendations have been given.

Keywords: Cost Analysis, Formula, Neàpolis, Sant Antoni Church, Savings, Smart Structures,Sensors

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1 Introduction

As participators of the European Project Semester at the Universitat Politècnica de Catalunya a research for a company had to be done. The research that has been done by the project team is a feasibility study on Smart Structure systems in buildings. This has been an assignment by Neàpolis, an innovation agency, that was founded in 2007 in Vilanova i la Geltrú. As part of the city council of Vilanova i la Geltrú, Neàpolis provides start-up companies a place to work from and gives advice in the way of doing business. The aim of this research should give Neàpolis an indication whether Smart Structures are feasible to put into buildings by lowering maintenance cost and improving the life span of buildings. There is not a known study that is similar to the one in this project and in our knowledge this is the first feasibility study on Smart Structures that has been performed. This is why the research is of importance to the company.

In this report there is a clear structure on how the research has been conducted and about the implementation of the Smart Structure concepts in the Neàpolis building and the Parroquia Arciprestal Sant Antoni Abat (Sant Antoni church), both located in Vilanova i la Geltrú in Spain. Based on these results a formula has been created that shows from which point the implementation of Smart Structures in buildings is feasible. With the gathering of all the information a conclusion has been drawn on which recommendations have been given.

The report starts with chapter 2, the orientation. In this chapter guidance about the project is given and it is the start-up of our project. Here the project is defined and the aims are explained. After this part the research has been conducted in chapter 3, where the research of the pathologies that could occur in buildings, different ways of construction and different types of sensors used for Smart Structures are explained. A greater description of the sensors can be found chapter 4. The impressions we got during the inspections of the Sant Antoni Church and the Neàpolis Building are written in the following part. Then a short overview about the methodologies is given. In chapter 7 and 8 an implementation plan for the Neàpolis building and the Sant Antoni Church is shown, it includes the blueprints and the approximate amount of sensors and the way to connect the entire system. In chapter 9 a way of calculating the feasibility of Smart Structures has been described. There the different parameters are being explained. To explain the proposed formulas more detailed, we created chapter 10 with an example for the Neàpolis building. In chapter 11 the conclusions have been drawn and the recommendations are given. And in the end we want to express our gratitude in chapter 12.

2 Orientation

The origin of the project will be explained in this chapter, here you can read about the definition of the project and how this project fits in the perspective of the company. First a brief summary of the company is given, afterwards the project definition is explained and the aims of the project are being clarified.

2.1 Neàpolis

As an innovation agency Neàpolis is interested in new technologies, designs, and entrepreneurship. The company belongs to the City Council of Vilanova i la Geltrú, and promotes stable relationships with companies and institutions around the world, which helps to place the town in emerging strategic sectors. It connects intensive entrepreneurial and technological initiatives in territory knowledge to the international innovative platforms network. Also Neàpolis collaborates with universities in different issues, for example it directs the Campus Universitari de la Mediterrània.

One of the precisely innovative projects of Neàpolis is researching on the economic feasibility of Smart Structures. That's why we are working together to find a solution for the costs of a Smart Structure system.

Neàpolis has also collaborated on previous projects with students in the EPS program.

2.2 Definition of the Project

In our project for the European Project Semester we are working together with Neàpolis on a cost-benefit-analysis for Smart Structures.

Our mission is an economic feasibility study for the implementation of Smart Structure systems in existing and planned buildings. This analysis needs to include the initial costs involved in the implementation of the Smart Structure system in a building. It should also consider potential cost savings over a determined period to calculate the return on investment and the time to expect net profits.

The goals of this project are to create a formula to calculate the initial costs and savings of smart systems in structures. During the project this proposed formula will be applied to one building to proof the sense of the work.

2.3 Aims

The main aim of the project is to create useful formulas in the context of cost-benefit analysis of Smart Structures, which can be applied on different buildings throughout the world. Therefore concepts for the implementation of Smart Structure systems should be developed for the Neàpolis building and the Sant Antoni church, both located in Vilanova i la Geltrú.

2.4 Definition of Smart Strucutres

A Smart Structure system is a system in a building consisting of sensors that are integrated in the structure of a building to detect pathologies that can occur in this structure in the early stages. By the use of different sensors a wide range of pathologies can be detected such as: cracking, deformation humidity and corrosion.

2.5 Objectives

After consultations with Neàpolis several aims of the project have been established. The main objectives are listed below:

- To carry out a cost analysis for the implementation of Smart Structure technology in existing and planned buildings
- To create a formula that can be applied to other buildings
- To calculate the potential savings for the implementation of a Smart Structure system and identify the potential return on invest
- To develop a concept for the implementation of a Smart Structure system the Neàpolis Building and the Sant Antoni Church to find a result for the initial costs
- To achieve all objectives within the time frame

2.6 Innovative Aspect

There is not a research known about the feasibility of Smart Structure systems in buildings, which makes this research very innovative. The technology of Smart Structure systems is not very widely known yet, and especially the feasibility of these Smart Structure systems is unknown to the industry. By doing this feasibility study and underlining the possible saving that might occur by the implementation of Smart Structures a big leap can be made in the development of Smart Structure systems.

3 Summary of the Research

3.1 Advantages of Smart Structures

The main point to apply a Smart Structure system in a building is the early damage detection. You also obtain the assurances of structures health, strength and serviceability.

The implementation of sensors should also reduce the downtime because if it is possible to detect small damage earlier, the duration of maintenance is shorter than for a larger damage. Reducing the potential for disasters from previously undetectable structure problems ensure also the quality and performance of the building structure.

The direct data about the current status of a structure helps the user or customer in defining and improving the maintenance strategies.

3.2 Sensors

The result of our first research was that there do exist several kinds of sensors and we enclose four different types of sensors.

Sensor	Measurements
Fiber Optic	Deformation, Cracks, Integrity, Stiffness, Temperature, Moisture, Oxygen, Hydrogen, Toxicological substances, pH values, Vibrations Acoustic Emission, Stress & Pressure
Piezoelectric	Mechanical deformation of piezo crystal lattice.
Acoustic Emission	Cracks and Corrosion
Electrochemical Fatigue	Fatigue

Table 1: Different types of sensors

In chapter 4 you can find the selection and description for the sensors used in our project.

3.3 Companies

During our project we tried to contact a lot of companies about the cost of smart structures. To contact them was a really difficult part because they did not answer to our emails. That is why we had problems to move on with our project because the part about costs was missing. Only a few weeks before the final deadline we got the necessary information about Fiber Optic sensors from a German company, the FOS4X GmbH.

Fos4X GmbH was founded in 2010 and is based in Munich. This company works with sensors, in particularly Fiber optic measurement technology applied on wind turbines. They manufacture Fiber optic measurement equipment for monitoring lightweight. The equipment measures wind turbines rotor blade efficiency and wind cogeneration in wind power plants. For some small projects they also applied sensors to bridges. Thanks to them we got cost information about different measuring devices, industrial computer, control box, cooling system and the most important is about the price per sensors.

For the Acoustic Emission sensor the company Bangos from Croatia was found. This company sells different kinds of Acoustic Emission sensors and accorded us also very helpful information about the cost, function and implementation of Acoustic Emission sensors.

3.4 Pathologies

After the research about the different types of sensors we decided what pathologies we want to measure in the buildings. In the region of Catalonia we found six types of pathologies that can have an influence on structural integrity. There has been a score added to the importance of the data. The score of 1 is the most important. The result of this part of the research can be seen in the table below.

Pathologies	Data	Sensors	Importance
Deformation	Force, Stress, Pressure, Stiffness	Fiber Optic Sensors	1
Cracks	Vibrations, Acoustic	Fiber Optic Sensors Acoustic Emission Sensors	1
Corrosion	Oxygen, Hydrogen, Temperature, Toxilogical Substances, Tension, Vibrations, Moisture, Acoustic	Fiber Optic Sensors Acoustic Emission Sensors	1
Humidity	Moisture, ph-value	Fiber Optic Sensors	2
Thermal	Temperature	Fiber Optic Sensors	3
Mold	Moisture, Temperature	Fiber Optic Sensors	3

Table 2: Pathologies with matching sensors

In this project we will only focus on data with the importance 1, because that are the most useful data and most occuring damages of buildings. Data with the importance 2 or 3 are damages which also occur in buildings but we will not consider that in our study.

3.5 Lectures about Civil Engineering

Because the project team was lacked by knowledge related to civil engineering, meetings with civil engineers have been arranged. First we met Miriam Sorriano, a civil engineer with knowledge about Smart Structures, who created a master thesis about the implementation of Smart Structures in bridges.

This lecture demonstrated that the best way to place the sensors would be between the pillars, on bearing walls and the ceiling. The sensors are applied on the surface, which makes it easier to implement the Smart Structures system on existing buildings. For the Neàpolis building this will not be a problem, the sensor might be in view and could be an addition to an already modern and innovative building. In the Sant Antoni church however, we want to be discrete about the placement of the sensors in a historic building. The sensors may not visually damage the building and therefore the placement of the sensors is essential.

3.5.1 Capacity

The capacity of a buliding falls within its lifetime. On a special point of time it is necessary to invest capital for maintenance to extend the lifetime of the building. After the investment the capacity raises back to the initial height. And past some time the capacity drops down again to the point the owner has to invest to ensure that the lifetime will continue.

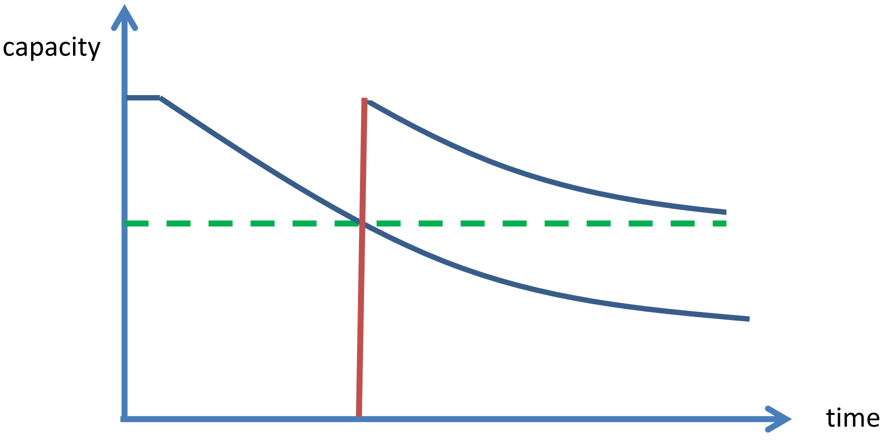


Figure 1: Capacity over time

The broken line in Figure 1 above shows the point of capicity at which the owner has to invest.

3.5.2 Construction

In order to understand how construction is done and pressure is applied to buildings, we had a lecture about construction by our supervisor Félix Ruiz Gorrindo. This has given us insights about the way the vertical and horizontal structures work and how the pressure is divided. This will help with the process of the sensor placement in the different buildings and find the parts which are more likely to have pathologies.

3.5.2.1 Foundation

Started with the foundations we differentiate four types.

The sinlge footing is the most applied foundation and it is used in the Neàpolis building. As it can be seen in Figure 2 and Figure 3 the single footings are slabs of concrete on which the pillars are mounted. The slabs are under the ground and are connected to each other to prevent the movement of the single pillars. This is the most common form of foundation in new constructions.

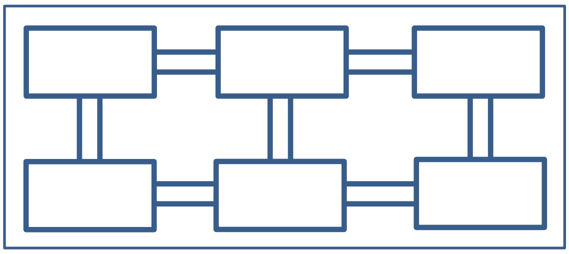


Figure 2: Single Footing – top view

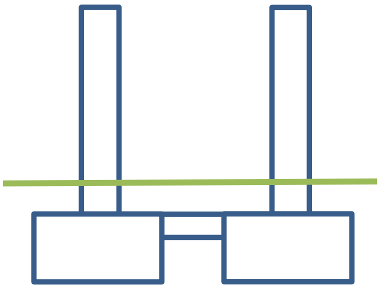


Figure 3: Single Footing – side view

The second type is called continous footing and it is characterized by large feet on which are the main walls based. The slab is placed under the ground with part of the wall as can be seen in Figure 4. The Sant Antoni church has most likely this type of foundation made out of stones.

Figure 4: Continous Footing

The slaps foundation has a ground that fills the whole space of the foundation. It is used for grounds with a low resistance, for example sand grounds.

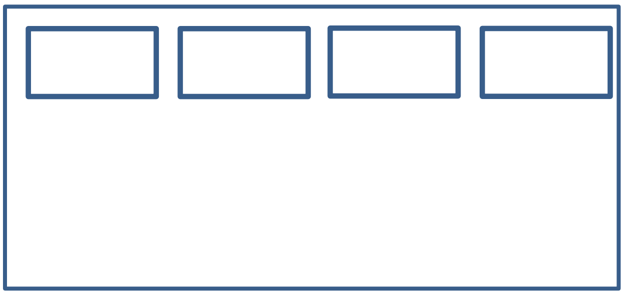


Figure 5: Slaps Foundation - top view

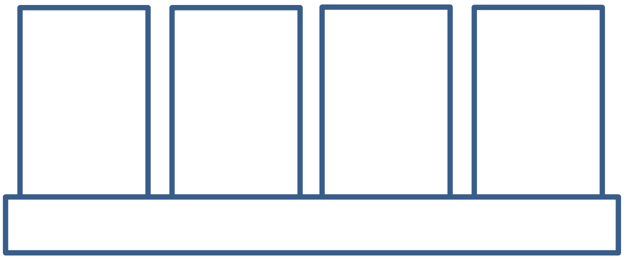


Figure 6: Slaps Foundation - side view

The last type is the pilling foundation. This kind of foundation is used on grounds with different layers. For example, the upper ground of only a few meters has a low resistance and the lower ground has a high resistance. Feet fix the upper ground and in the lower are only pillars for stabilisation. This is visualized in the following figure.

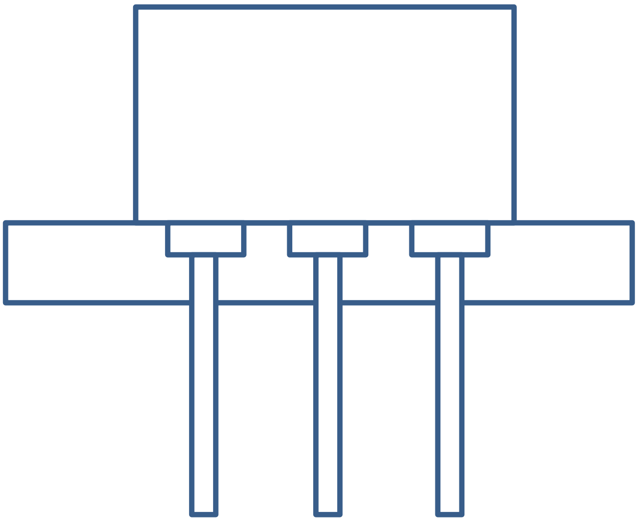


Figure 7: Pilling Foundation - side view

3.5.2.2 Flooring

An important part of the placement is the way of flooring. There are two types explained by Félix Ruiz Gorrindo. The structure of a building can be differentiated between the vertical and the horizontal structure. The vertical structures are the pillars, columns and bearing walls. There are two different kinds of vertical structures.

The one-way floor consist of two beams with several different beams between them, this creates rectangle compartments. These are not likely to be filled with Ferro concrete. The flooring is made out of concrete. This type of concrete is used in the Sant Antoni church.

Figure 8: One-way floor

In the two-way floor there are several beams in two directions between two big beams. As can be seen in Figure 9 there are beams in horizontal and vertical direction and creating square compartments. These compartments can either be hollow or filled with ferro concrete, depending on the necessary strength.

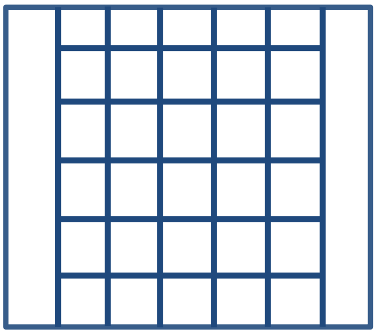


Figure 9: Two-way floor

3.5.2.3 *Arcs*

In the Sant Antoni church you can find many arcs, these have different properties than normal ceilings. In Figure 10 can be seen that the pressure is defied along the entire arc and stones are kept in place just by compression tension.

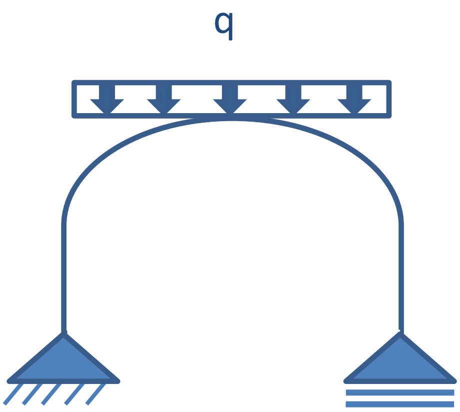


Figure 10: Horizontal load on an arc

3.6 Maintenance

For the maintenance it is important to know how the environment effects on a building. It is only possible to identify exactly what caused the damages if the external influences are known. The condition of a building is connected to those influences. Because of this, it is necessary to analyse all external circumstances relating on the damages.

The main function of the Smart Structures system is the reduction of maintenance costs. To get a clear view of what maintenance is, Miriam Sorriano and Félix Ruiz Gorrindo have shown us two different kinds of maintenance and the comparison between them.

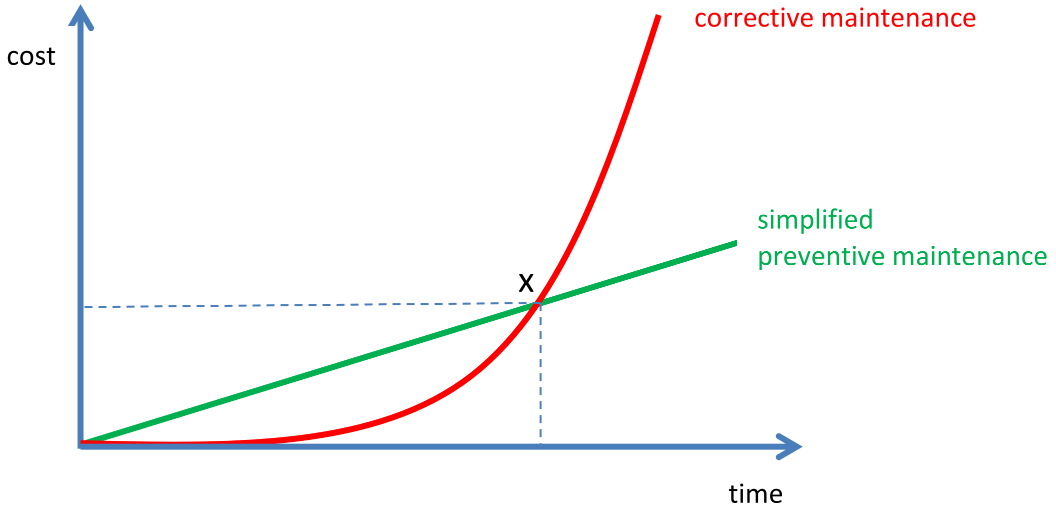


Figure 11: Corrective and preventive maintenance

In Figure 11 you can see the corrective maintenance starts in the beginning as a very cost saving way of maintenance. However after a certain amount of time, when pathologies in the structure are formed at a point that it has to be repaired the costs are jumping. The red line in the graph shows this exponential growth.

On the other side you have the preventive maintenance. The building is maintained on regular basis and is preventing big pathologies. The maintenance is very predictable. In the long run the preventive maintenance will be cheaper than the corrective maintenance.

Point X is the figure is the point that has to be reached for the preventive maintenance to be profitable. In reality preventive maintenance is an investment that has been in certain intervals, that is why the real graph can be compared to stairs and not to a line. The demonstration of this simplification is demonstrated in Figure 12 below.

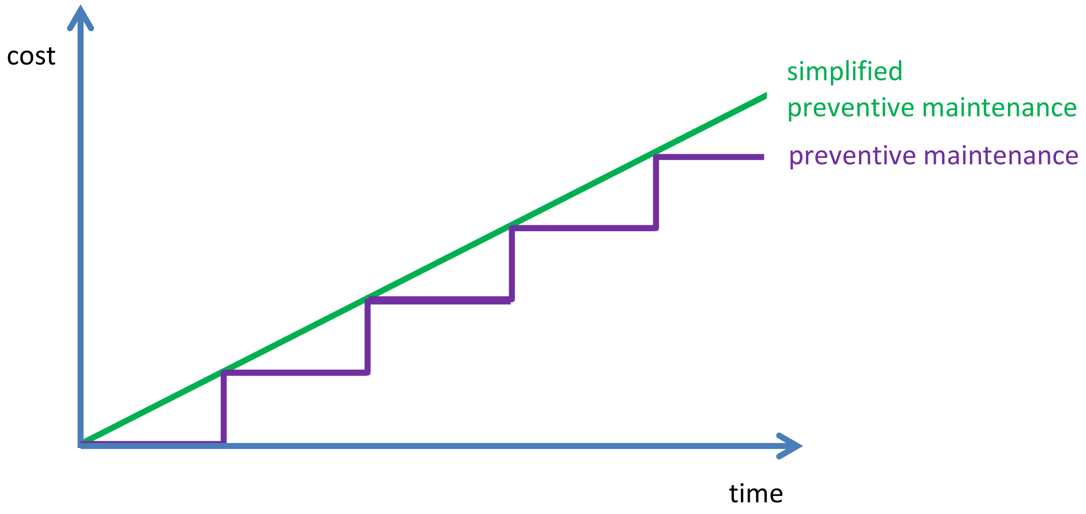


Figure 12: Cummulated costs for preventive maintenance

3.6.1 The Smart Structure hypothesis

Together with the supervisors and civil engineer Miriam Sorriano we came up with our own hypothesis about the influence of Smart Structure systems on preventive maintenance. The idea behind this hypothesis is that, although the installation of the system requires an initial investment, the return will be higher than the costs. The Smart Structure system should be able to detect changes in structures of materials in early stages, making the maintenance on these parts smaller but more effective. Therefore no major maintenance is necessary, which reduces the cost. The Figure 13 below illustrates our hypothesis of saving money with the application of a Smart Strucutre system in addition to preventive maintenance.

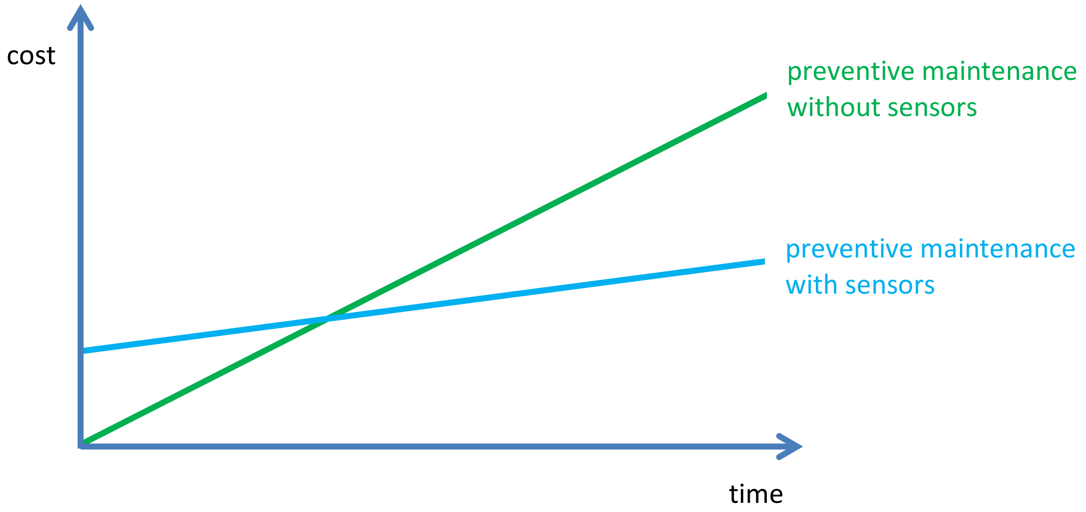


Figure 13: Preventive maintenance with and without sensors

In summary it is supposed that it is superior to perform preventive maintenance than corrective maintenance and with the implementation of a Smart Structure system the maintenance can get more effective and economic.

4 Sensors

A sensor is a device that detects and responds to some type of input from the physical environment. The specific input could be light, heat, motion, moisture, pressure or anything of a great number of other environmental phenomena. The output is a signal that is converted to a human-readable form.

It is possible to embed the sensors inside the structure or on the surface. Moreover it is not necessary to implement sensors in each part of a building. To know the state of the structure the sensors must be applied on the main parts such as supporting pillars or main walls.

4.1 Fiber Optic Sensors

4.1.1 Types of Fiber optical sensors

According to the spatial distribution of the measured value the Fiber Optic Sensors (FOS) can be classified in different types.

1. *Point sensors*

   The measurement in point sensors is carried out only at one single point in the wire.

2. *Integrated sensors*

   The measurement in integrated sensors averages a physical parameter over a certain section of the wire and provides a single value. An example is a deformation sensor measuring strain over a long base length.

3. *Multiplexed sensors*

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

4. *Distributed sensor*

   The measurement in distributed sensors can be done at any point along a single Fiber optic wire with the measuring system based on Rayleigh, Raman or Brillouin scattering.

For this project only the third and fourth sensors are useful. In comparison to the multiplexed sensors, a big advantage of the distributed sensor is the fact that a previous definition of the sensors is not necessary. But for the application in the selected buildings we know exactly the positions where the measurement is reasonable. The obvious higher investment for the distributed sensors transmitted the decision to apply the multiplexed sensors in this project.

4.1.2 Fiber Bragg Grating (FBG)

Fiber Bragg Gratings are similar to mirrors created in a Fiber optic wire by a laser. Short parts of the wire are transformed into a Fiber optic sensor to detect the local environment around the Fiber.

For the detection is white light sent through the wire and the gratings are arranged to reflect particular wavelengths back and transmit all others along the Fiber. The measured quantity such as strain or pressure can then be determined from the wavelength reflected from each grating. That means each sensor is related to one certain colour of the white light and reflects this. If there are little changings, the colour will be different and the measuring device can convert this information into analysable data. The following figure illustrates this phenomenon.

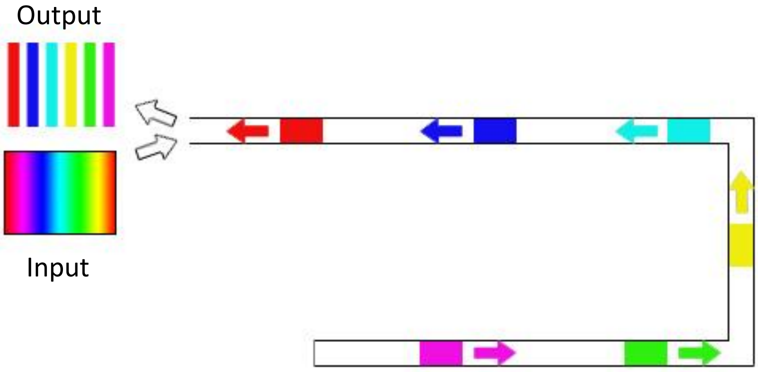


Figure 14: Functionality of Fiber Bragg Gratings

In this project it is necessary to combine different wires to one system. With multichannel measurement devices it is possible to summarize many of those measured sections.

4.1.3 Selection

For this project a FBG-sensor with different measuring points in one wire was needed. And we found the following sensor provided by the German company fos4X.

The fos4strain is a fiber optic strain sensor based on the Fiber Bragg Grating method. It is designed to measure surface strains on a surface and is therefore glued on the selected sector of the structure.

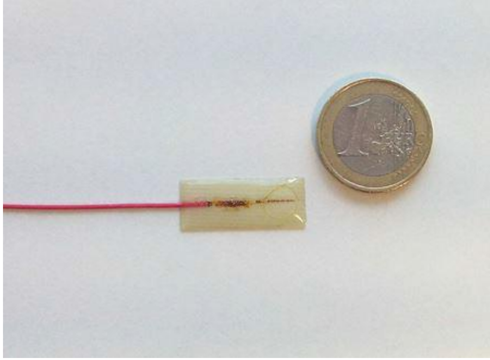


Figure 15: fos4strain sensor

The sensor is made out of glass-fiber reinforced plastics and is immune to lightning and electromagnetic interferences.

4.2 Acoustic Emission Sensors

4.2.1 Definition

The Acoustic Emission sensor is a system for measuring changes in a structure. This system is able to measure all changes by listening vibrations. The causes for these vibrations are structural transformations in form of cracks, movement, phase transformation, the process of corrosion, plastically deformations and material fatigue. The sensor is able to measure the acoustic waves of the vibrations. The vibration of the changes spread from the source in the whole structure. An acoustic noise sensor measures the high frequency waves in a range from 10 kHz up to several MHz and converts them into an electrical signal. The signal will be digitized and analysed by special software.

4.2.2 Selection

It was searched for a sensor which is able to measure corrosion. Buildings can exhibit in some parts evidences of corrosion. This has to be monitored. The Fiber Optic sensors, who will be used for measuring the cracks and deformation, are not able to measure corrosion. Therefore it was necessary to find another solution for this type of damage.

During the research, the company Bangos from Croatia was found. This company sells different kinds of Acoustic Emission sensors and the characteristics of one of these sensors accords with the characteristics that are important for the usage in the buildings.

Figure 16: Acoustic Emission Sensor AES150

The selected sensor, named AE Sensor AES150, is developed for metal structures, but the company insures that it is possible to use the sensors for corrosion monitoring in a building over a longer period. The technical characteristics could be found in the following schedule.

Characteristics	Description
Frequency Range	100 – 200 kHz
Resonance at	150 kHz
Case Material	Stainless steel
Weight	40 gram
Temperature Range	-25 – 700 °C
Dimensions	Diameter = 16 mm, height = 25 mm

Table 3: Characteristics of the AES150

For the installation are several accessories necessary. These are the cables for transfer the data, mechanical holders for the installation on the surface and preamplifiers between the sensor and the output. The price of a sensor including the holders and the preamplifiers constitutes 131 €. The enclosed cables are not sufficient for a long time usage. Therefore it is necessary to purchase suitable cables.

5 Inspection

5.1 Sant Antoni Church

On Wednesday the 15 April 2015 we had the privilege to inspect the Sant Antoni church and find out what pathologies the building has. The building was built in 1771, and this makes it 244 years old. The building is mostly build out of stone and probably has a continued foundation made of stone. The vertical structure consists of bearing walls and pillars that support the horizontal structure. The horizontal structure consists mainly of arcs and domes. Small parts such as the different floors are made of one-way flooring. The main facade of the building has been renovated 10 years ago due to erosion that lead to falling stones.

Cracks, humidity and corrosion are the most common pathologies in the church.


CRACKS **HUMIDITY** **CORROSION**

Figure 17: Pathologies in the Sant Antoni Church

The humidity problems are in 2 stages. The one that can be seen in the middle of Figure 17 is capillarity humidity that seeps in from the bottom. It goes up the wall and might cause mould on the wall and the wood used in the structure. The other form of humidity comes from leaks. This might have an origin in the cracks that can be seen in the church.

5.2 Neàpolis Building

On Friday the 17 April 2015 before our weekly meeting we had an inspection of the Neàpolis building. The building is around 8 years old and was build out of ferro concrete and has single-footing foundation. The vertical structure consists only of pillars and the flooring is two-ways. Where the two-way flooring is mostly hollow, next to the pillars the flooring is filled with ferro concrete for support and strength.

Figure 18: Pillar with two-way flooring

The main facade of the building is made of glass, steel and concrete. These have no structural value and are only for the design. The Neàpolis structure has a parking lot underneath the building. The concrete walls of the parking lot have no bearing function although they need to resist sideways force on the ground applying pressure.

During the inspection of the Neàpolis building no major pathologies were found, however there were some small examples of the capillarity humidity and cracks. The structure of the building is fairly bear, which makes the way the building was constructed easy to spot.

CRACKS **HUMIDITY**

Figure 19: Pathologies in the Neàpolis Building

As shown in Figure 19 there are no major pathologies and the two pathologies that are found can be seen as minor faults in the construction. The capillarity humidity is something that is shown in the outside of the building. However there is no trace of this in the inside of the building. This is something what we have to consider with the placement of the sensors during the creation of the implementation plan.

6 Methodologies

6.1 Comparison of the buildings

Every building is unique because of the location, utilisation and structure. The research focuses on two buildings that both represent a different type of construction. The buildings have been chosen because of these differences. The first building is the Neàpolis building (2007) and the second building is the Sant Antoni church (1693). To compare these two constructions add to the wide approach the research takes, including old and new buildings.

The Neàpolis building is eight years old and modern construction methods and materials characterize the structure of the building. The main part of the building is made out of ferro concrete with columns as the bearing units. Some of the outer walls include great windows and all of the walls are not carrying the construction. For the foundation a single footing was used. This is the most common foundation in modern buildings.

The Sant Antoni church, with an age of 322 years, was built in another way. In the period this building was made, the way of constructing and the selection of materials was different than the methods building and civil engineers apply today. The most common material in the 17th century was stone. The walls, columns and arcs are made out of stone, just in some restored parts as on the surface and in the ceiling was ferro concrete used. The continuous footing is the foundation in the Sant Antoni church, which was the most common foundation in this period.

These facts demonstrate the differentials between the two buildings and with this leads it is feasible to generate a more general outcome of results for the cost analysis.

6.2 Different concepts

To create more savings, for each of the buildings three different intensity concepts of Smart Structure systems have been thought of. These are the low, medium and high intensity. The intensities can be different in each building and even be varied in different floors of the building. The concept will be chosen by contemplate the influences that effects on the building.

Buildings with a healthy structure and less influences that cause great damages need a basic monitoring of the changes. For these buildings, the low intensity concept was developed.

A building with more external influences and some visible damages has a greater risk of changes in the structure. These buildings have a greater requirement of damage detection. The medium intensity concept is the solution for monitoring these structures.

The high intensity concept was developed for buildings with heavy loads. A stressed structure has to be monitored exactly and in different places, to detect the most changes. The type of the building is also necessary. Buildings with a high amount of visitors or residents that have to be safe and resilient need a good health monitoring system to prevent major disasters. In these structures it is a prime importance to realise all changes and damages as fast as possible.

7 Implementation: Sant Antoni Church

In this chapter an implementation proposal of a Smart Structure system in the Sant Antoni church is explained. The explanation includes the reason for all the different choices that are made during the positioning of the sensors. The reasons for the use of certain sensors are explained and the blueprints are included.

7.1 Structure of the Church

The construction of the church started in 1693 and because of a range of interruptions as wars and reconstructions, the building was entirely finished in 1977.

The church has three naves with chapels. The roofs are vault to the main nave until the side edges. There are two facades, one on the Plaça de Sant Antoni and the other one the Plaça de les Neus. The facade of the square of Sant Antoni has 4 large columns compound of decorations on the top with entablature and triangular pediment.

The Sant Antoni Church is an old stone building, so it is advantageous to combine the Fiber Optics with Acoustic Emission sensors. Because the acoustic system permits to deliver data between the stones, it has a high sensitivity. This is because of the non-homogenous components of a stone structure. Therefore it is perfect for buildings that are made of stones.

7.2 Position of the Sensors

7.2.1 Deformation

According to the inspection of the church, we saw that the biggest cracks seem to start around the arcs. Therefore, we chose to put sensors on the top of the arcs. The numbers of the sensors in the area depends on the chosen level of intensity, as it will be explained in chapter 7.3.

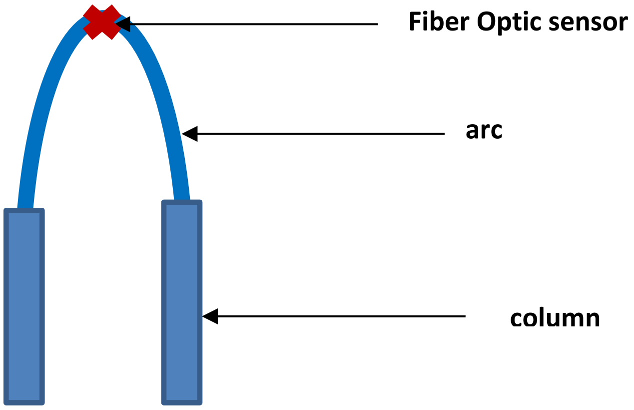


Figure 20: Position of sensors in arcs

7.2.2 Humidity

About the humidity we know that the most important humidity flux comes from the ground consequently, so we decided to put sensors on the bottom of the column. Moreover we know that the humidity can create a range of damages on the paintings and also on the wood, which is in the church used for example for the stairs or furniture. To know how many sensors we need, once again it depends on the wanted intensity level. However, we can put humidity sensors in particularly on the corners of the porches because there is the place where paintings and decorations are.

7.2.3 Corrosion

Weather conditions contribute to the forming of corrosion, especially in the coast regions corrosion is found on buildings and structures. For the Sant Antoni church this can be a major issue for the exterior, due to the high amount of wind next to the coast. In the interior of the church corrosion can also be a major issue, this is mainly due to the salty air which leads to the corrosion of the iron bars in the reinforced concrete used for the renovation. The corrosion can lead to cracks in these parts of the building, therefore the most logical place to put the sensors is on the outside of the building, and in the new front facade, where the ferro concrete was added during renovations.

7.3 Different Concepts

The placement of the sensors has been figured out with the help of the phD civil and building engineer Félix Ruiz Gorrindo. Also the lecture of the civil engineer Miriam Sorriano has given us a great insight of the placement of the sensors. It has been also of great help the drawings of the church made in the School of Building Engineering of Barcelona (García, I. and Alegret, J., 2010).

As we explained in chapter 6, we propose three different levels of intensity of the implementation of sensors.

7.3.1 Low intensity

The low intensity concept is the one that is considered as the basic way of measuring the vital parts of the building. For the low intention there are optical Fibers and acoustic emission sensors. Together they can measure all different pathologies that we defined as necessary to measure in chapter 3.4.

In the Figure 21, the map of Sant Antoni Church is being displayed with the proposed low intensity level of a Smart Structure system. In the Sant Antoni Church there are 28 columns where the sensors should be located in directions from side to side. The sensors will be attached to the columns and to the arcs in the outer rows. The green line is demonstrating the optical Fiber wire. There are two measuring points on the different columns in addition to the optical Fiber, because the structure is fairly symmetric it is easy to place the sensors in an efficient way.

All the cabels together count 149,8 m of Fiber optic wire and 16 sensors in total. The wires and sensors will be placed between the arcs and the roof and there is a crawling space in between. Therefore the visual aspects of the building are not damaged.

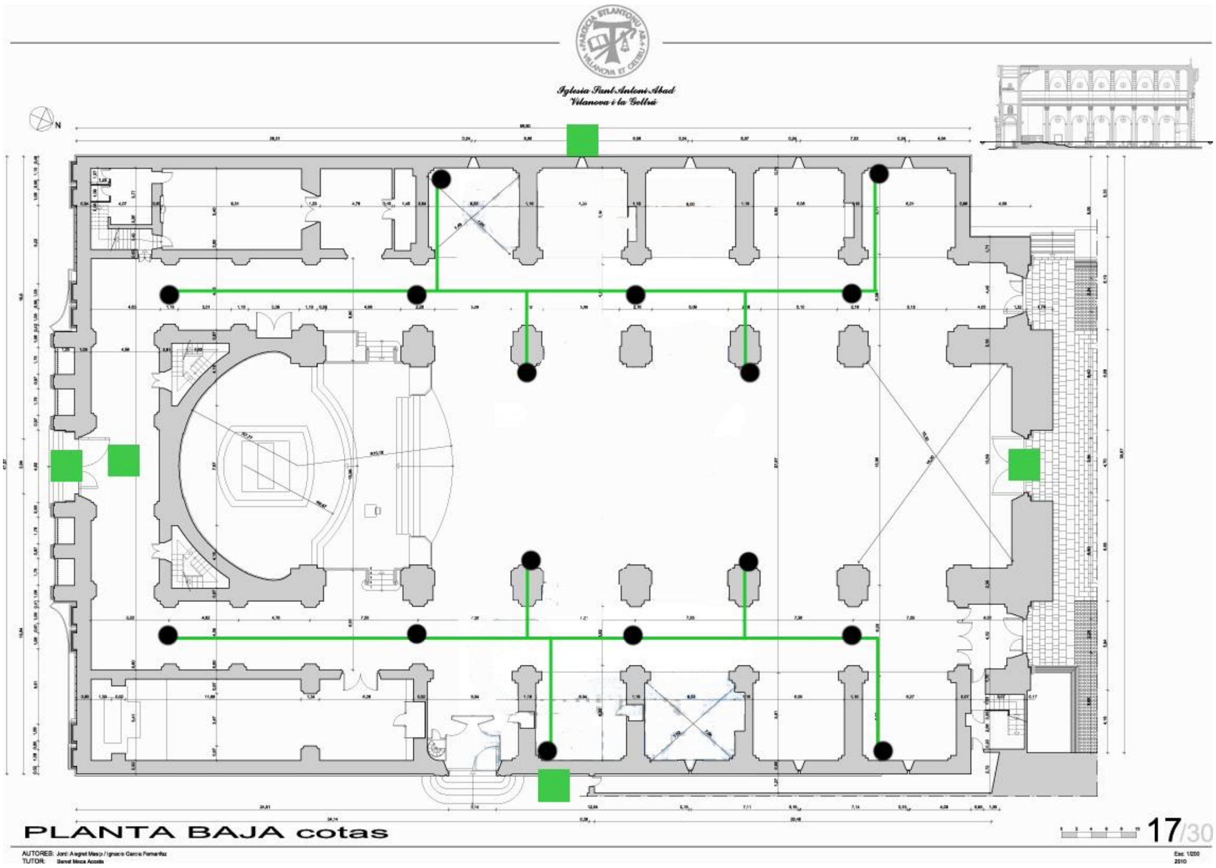


Figure 21: Low-Intensity-Concept for the Sant Antoni Church

To measure the corrosion in the low intensity setting there will also be Acoustic Emission sensors placed in the church: one on each side of the building and one on the ferro concrete structure on the 3rd floor of the front facade. That is to collect the basic data about corrosion on each side of the building.

The church has different forms of humidity problems and the main problem is due to capillarity humidity. Because the humidity comes from the ground, 4 sensors are placed in the bottom of the outer walls. This will be done in the corners and so the visual aspects of the building will not be suffering under the placement of the sensors. By putting these sensors in the corner an additional 26,4 m of optical Fiber is added.

In total the Sant Antoni church will have 16 Fiber optic sensors and 5 acoustic emission sensors with a total amount of 176,6 m Fiber optic cable.

7.3.2 Medium intensity

The second stage of damage detection in the Sant Antoni church is a measuring system with more sensors but also higher costs. Because more sensors are used, the system can measure the current status of the building with higher precision and maintenance can be applied more detailed.

In Figure 22 you can see the proposed medium intensity concept for the Sant Antoni church. This concept is based on the low intensity concept and sensors will be added to the layout.

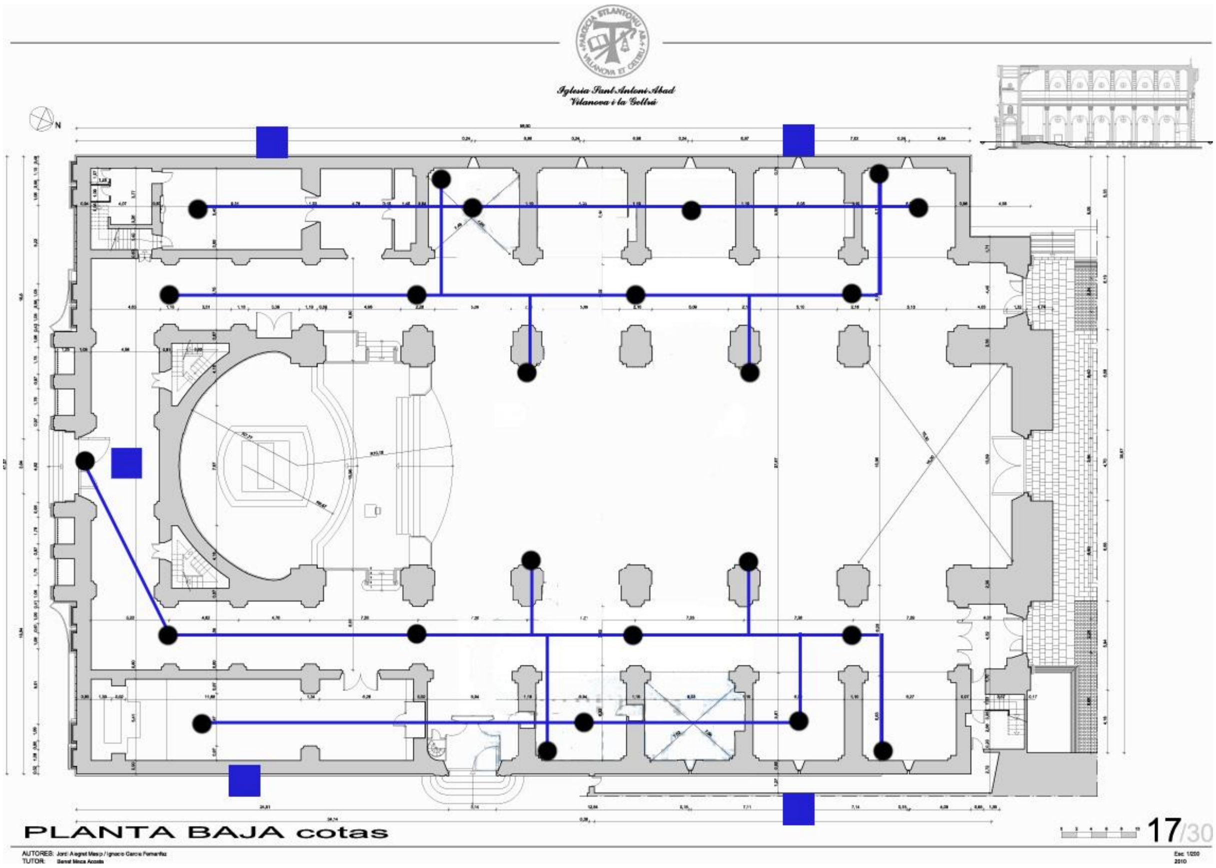


Figure 22: Medium-Intensity-Concept for the Sant Antoni Church

The Fiber optics sensors that are added will be in the bowls on the outside of the building. The stress on these bowls is measured for all pathologies. This will add 8 more sensors to the basic level of protection. A length of 117,3 m optical Fiber will be necessary.

There are no additional capillarity humidity points added, because of the ground moisture is the same over the entire ground floor. This does not add any sensor or meters to the medium intensity circuit.

For the measurement of corrosion there will be 2 additional sensors and the ones that were placed in the previous stage will now be placed not in the centre but on the outer sides of the long walls. This is going to give a more detailed placement of corrosion. The sensor in the ferro concrete will not be changed, so we still have one sensor there.

The total system contains 293,5 m of Fiber optic wire and will have 24 Fiber Optic sensors and 5 acoustic emission sensors.

7.3.3 High intensity

The high intensity is the most covering system that is planned for the church. This covers the all the pathologies in all segments of the church. With this system the change of catching pathology in the early stages is the highest.

In Figure 23 the high intensity system is displayed in red. For the high intensity system we made use of the structure of the previous proposals. The new sensors are added to the grid of the previous ones, so it is easy to extend the system supplementary.

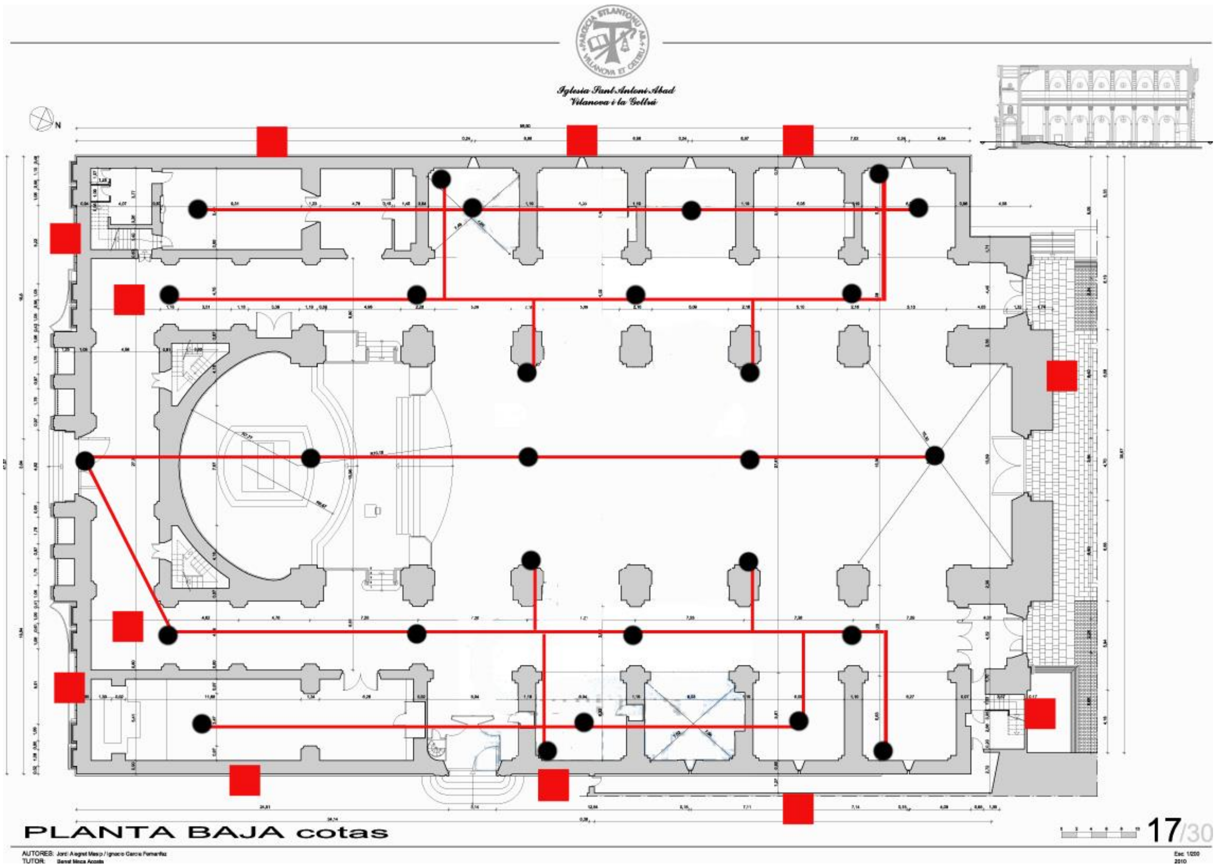


Figure 23: High-Intensity-Concept for the Sant Antoni Church

In the centreline of the building we added another 3 sensors in order to measure the bowls and the arcs of the main hall of the church. Normally the changes of formation in this part of the structure are caused by different parts of structure such as the columns, however the pathologies will be the biggest in the arcs and the bowls that is why in the high intensity system there is chosen to add another row of sensors. For this an extra 44 m of Fiber optic wire is needed and another 5 Fiber optic sensors are added.

Just like the basic and intermediate level, there will only be four sensors to measure humidity on the bottom of the walls. This will give enough information on the capillarity humidity, because of the ground moisture is the same all over the building. So if one part will show deflections, most of the other parts will do the same.

For the corrosion another 4 acoustic emission sensors are added to the system, as can be seen in Figure 23. This leads to 3 sensors on each of the long sidewalls and 2 sensors on the front and back facades. Also in this option there are additional Acoustic Emission sensors chosen to place in the Ferro concrete.

The total system with the high intensity settings will need 337,5 m Fiber optic wire and will have 29 Fiber Optic sensors and 12 Acoustic Emission sensors.

7.4 Recommendation

Based on the different developed concepts, one reasonable concept for the Sant Antoni Church has been selected. By considering the different circumstances that can influence the structural health of the Sant Antoni church, such as the environment, the use of the building and the construction, the following solution is meant to be the most economic.

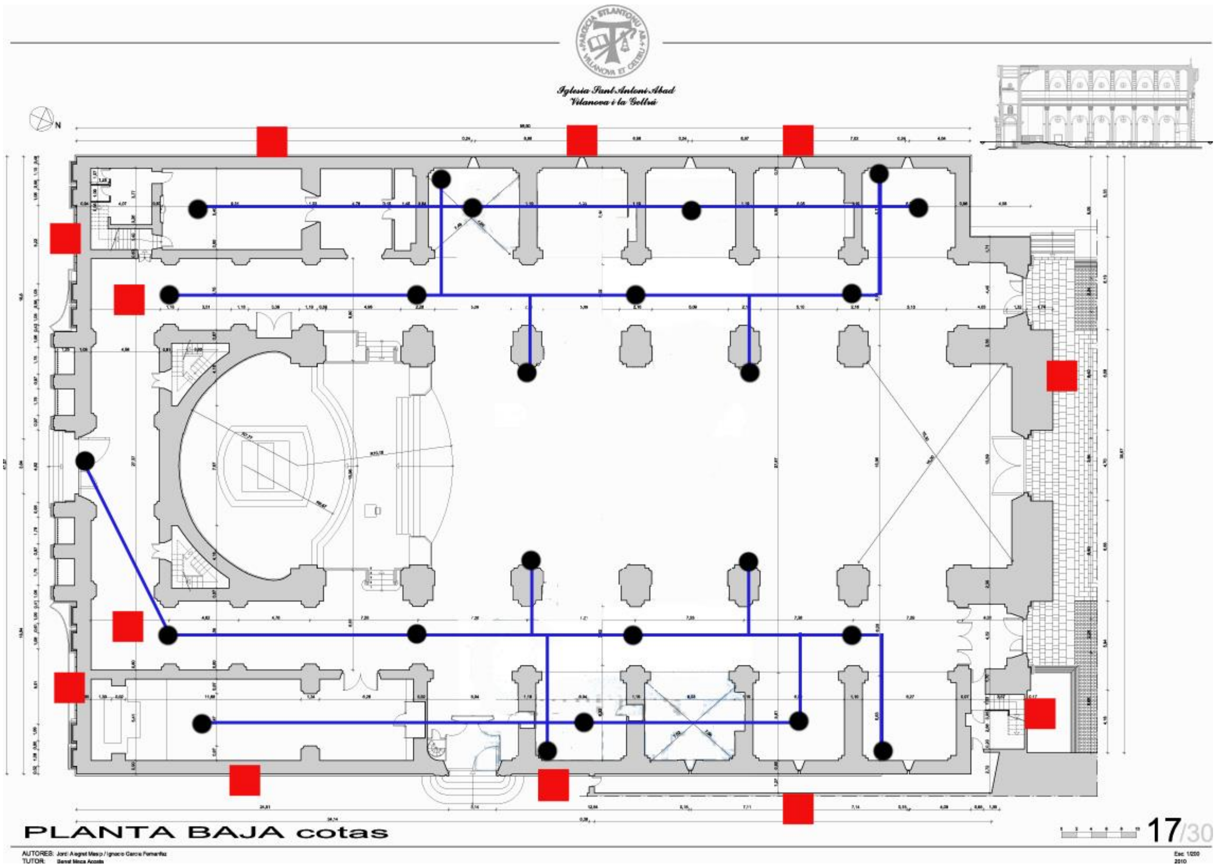


Figure 24: Concept for the Sant Antoni Church

For the Sant Antoni church the best solution concerning the Fiber Optics is the medium intensity concept. This means that the structure will have 29 Fiber Optic sensors to detect cracks, humidity and deformations. These FBG-sensors will be lased into 337,5 m of cable and coming together in the office in the front facade, where the data can be read on a computer.

This suggestion also includes 12 Acoustic Emission sensors from the high intensity Smart Structures concept. These will collect the corrosion on the outside of the building and the state of the ferro concrete in the main facade. The main facade is the only one that contains ferro concrete, due to relatively recent renovations.

The building has different pathologies, such as cracks, humidity and corrosion. We can qualify the general state of deterioration of the building as intermediate. To illustrate this concept, if we take as a reference the scale of gravity of damages in buildings developed in (Ruiz, 2014), the grade of gravity (*G*) for the whole building should be *G* = 5 (in a scale from *G* = 0 (perfect state) to *G* = 10 (extreme gravity).

Most pathology is already seen by eye and therefore it is not useful to install the high intensity concept. However the San Antonio Church is a historical building and there is a great interest in the preservation of the building, on this account the medium intensity was chosen. This will be more useful because it saves costs but is still giving data. The major pathologies are visible so the system only has to give information about the expansion of these damages.

The climate of the region has a high influence on the corrosion of the building. Although the building survives for centuries, however it starts showing some severe cases of corrosion. This is mainly due to the wind in the coastal climate. Therefore we think it is a good option to choose the high intensity level for the Acoustic Emission Sensors.

8 Implementation: Neàpolis

In this chapter an implementation proposal of a Smart Structure system in the Neàpolis building is explained. The explanation includes the reason for all the different choices that are made during the positioning of the sensors. The reasons for the use of certain sensors are explained and the blueprints are included.

8.1 Structure of the Building

The Neàpolis building is around 8 years old and located in the centre of Vilanova I la Geltrú. It contains in total 5 floors with one floor underground. This one is used as a parking garage. The building is composed of ferro concrete except the top floor, which is fitted and made out of a steal construction.

As it is already said in chapter 5.2, the structure of the building contains a single foot foundation and two-way flooring in the vertical direction. The walls of the building are not bearing and the whole load is located on the around 60 columns in each floor. Due to the floor plan there are some columns missing in the ground floor, the first and the second floor. That is because of the size of the auditorium in the first and second floor. A column in the middle of the room would be obstructive. The layout of the smart structure system is not affected by this instance.

Although there are some slight pathologies, such as humidity, the general health of the building is good. If we take as a reference the scale of gravity of damages in buildings developed in (Ruiz, 2014), the grade of gravity (*G*) for the whole building in this case should be *G* = 1 in a scale from *G* = 0 (perfect state) to *G* = 10 (extreme gravity).

8.2 Position of the Sensors

Based on the structure of the building it has been necessary to find the most important points to detect the damages.

8.2.1 Bending (Deformation)

Deformations are one of the most occurring situations in buildings. The following figure shows the bending of a ceiling between two columns:

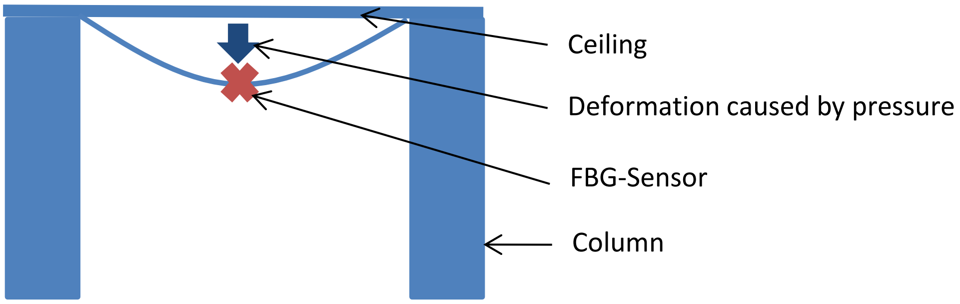


Figure 25: Position of the sensors with bending

From this figure the scheme for the positions of FBG-Sensors in the Neàpolis building is derivable. It is demonstrated in the next figure.

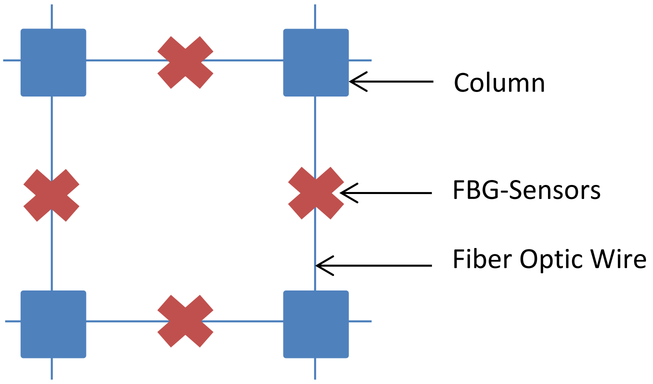
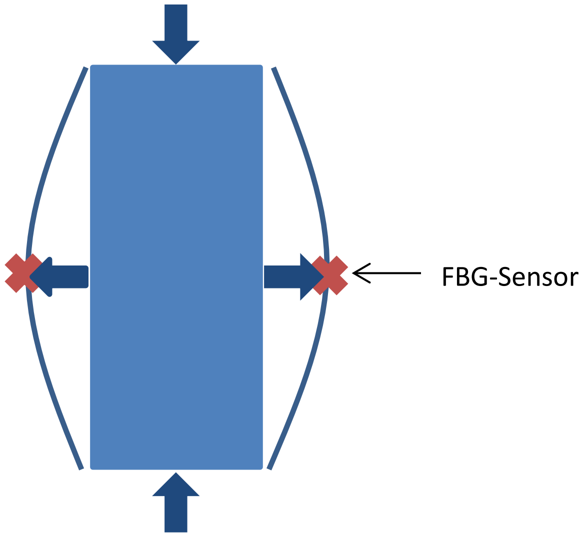


Figure 26: Scheme for sensors with bending

8.2.2 Compressing

The columns are the bearing units in the building and here is the most emerging stress in the structure. The sensor is placed in the middle of the column and connected to the wires on the ceiling. On this point the compression affects the most to the structure.



8.2.3 Corrosion

To detect corrosion on the building the sensors have to be placed on walls which are directly and for a long term in contact with water. The expansion of corrosion is also in other walls possible but the appearance is more unlikely.

Due to this information the Acoustic Emission sensors for the detection of corrosion in the Neàpolis building are installed on the exterior walls in the basement and ground floor. During the inspection of the building were already small damages detected, caused by the capillarity of the underground water. This is confirming the need of corrosion monitoring in these exterior walls.

8.3 Different Concepts

For the Neàpolis building we decided to create also three different concepts for the implementation of the Smart Structure system. We wanted to generate several layouts for the different loads in the building, which can be selected for the certain demand of each floor. The concepts differ in the characteristics of numbers of sensors, placement of the sensors and in the cost aspect.

8.3.1 Low Intensity

The first concept is made for parts of buildings with low strain and fewer changes in the structure. The low intensity concept includes an arrangement of 3 Fiber Optic wires in the ceiling. The wires are placed, with the same distance, on the beginning, in the middle and in the end of the floor to measure the structure on different parts with different forces by using fewer sensors. In the Neàpolis building are altogether 14 Sensors planned for the low intensity concept, as you can find below.

Figure 27: Low-Intensity-Concept for the Neàpolis Building

The first line of Fiber Optic sensors will be installed in the first row of columns on the right side. Here are 5 columns, this results that there are 5 Sensors and 14,5 m of wire in the beginning of the floor.

In the middle of the floor, in the fifth row of columns is the second wire with a length of 11,7 m and also 5 sensors between 5 columns. The distance between the first and the second wire and the second and the third, should be as equal as possible. Therefore the third wire is placed in the ninth row of columns. Here are only 3 columns and 4 sensors and only 9 m of wire needed. Altogether are 14 Sensors and, with including the connections between the rows, are 59,5 m of wire necessary.

It is also necessary to measure the compressions, caused on the forces, in some of the columns. As it was said in Chapter 8.2.2, the sensors will be placed in the middle of the column with a connection to the ceiling. Therefore the chosen columns are in the second, fifth and tenth row in the middle of the ceiling. Selected are the second and the fourth column, respectively in the eighth row in the first and third column. Their distances to the middle and the outer walls are nearly the same and with their positions in the middle of the floor are the circumstances and influences of the environment similar to most of the other columns. The system for compression monitoring requires a length of wires of 10,5 m and 6 sensors in addition.

8.3.2 Medium Intensity

The second concept is named middle intensity and it is, in the points of placement and number of sensors, different than the low intensity concept as you can see in Figure 28.

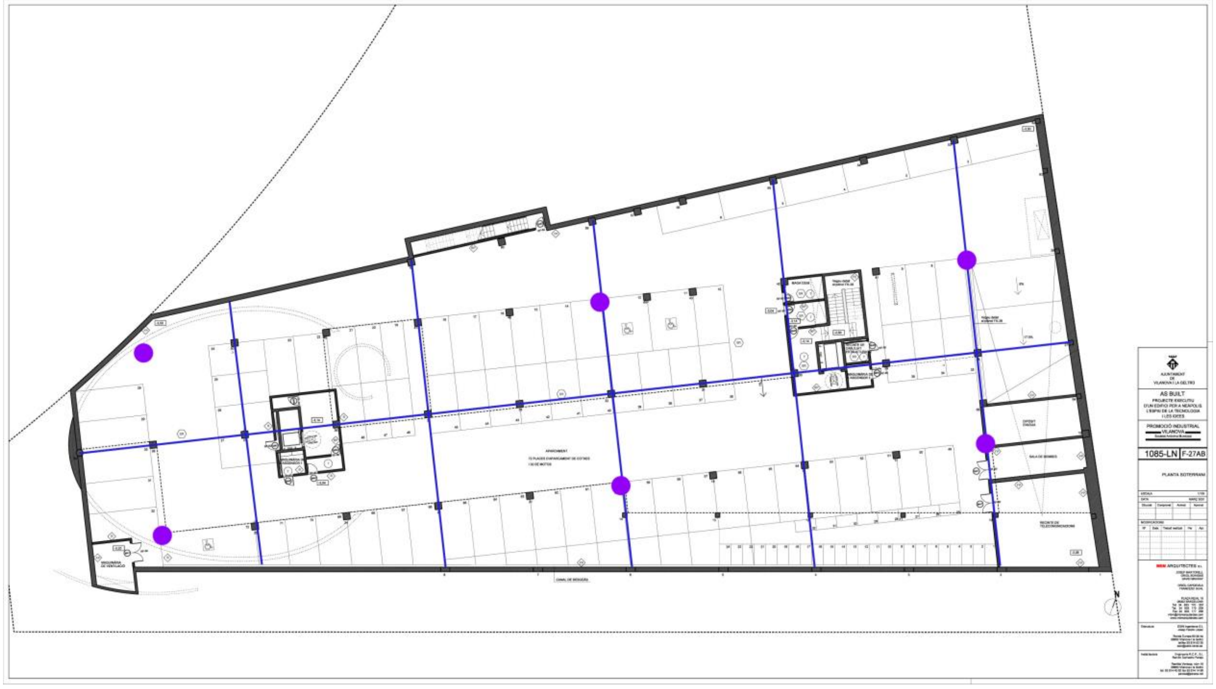


Figure 28: Medium-Intensity-Concept for the Neàpolis Building

The number of used sensors and wires is more than twice as much. In this concept it starts also in the first row of columns on the right side. Beginning from this point every second row is equipped with Fiber Optic sensors. This kind of placement reduces the distances of sensors, accordingly the area of measuring is much greater than in the low intensity concept.

Additionally one wire with sensors is placed in vertical direction, in the middle row of the columns. This arrangement also enlarges the area of measuring and it enables a measurement on the outer walls, on the right and left side, of the building.

The arrangement in horizontal direction includes, in total, 23 Sensors and 58,8m of wire. In vertical direction are 11 sensors and 34,5 m of wire used.

In this concept are also Fiber Optic sensors in some of the columns. The positions are the same as in the low intensity concept. For every column are 1,75 m of wire and one sensor needed. The sum of all required wires is 10,5 m and 6 Sensors will be used.

8.3.3 High Intensity

The last concept is the high intensity and it is able to measure the changes in a great area of the ceiling. The placement of Fiber Optic sensors starts in the first row of columns on the right side. From this point every second row is provided with wires and sensors, as well as in the medium intensity concept. The concept is pictured in Figure 29.

Figure 29: High-Intensity-Concept for the Neàpolis Building

It is not necessary to place sensors in every row. The differences of environmental influences between these distances are very low. According to the number of sensors and the length of required wires are the same as in the medium intensity concept. A length of 58,8 m wire and 23 sensors are planned.

The difference between the medium and the high intensity concept consists in the Fiber Optic sensors in vertical direction. Instead of one wire in the middle of the ceiling, two wires in the first and the third vertical row of columns will be used.

This arrangement enlarges the area of measuring once again because of the smaller parts of the grid. This method permits a better measurement of the outer walls on the left and right side. Furthermore the sensors are closer to the longer outer walls, nevertheless near enough to the middle to measure also the inner part of the ceiling. In the first wire with a length of 34 m are 11 Sensors included. In the third, because of one extra column, are 12 Sensors used and 32 m of wire.

The compression in the columns will be monitored as well. The selection of columns is the same as in the low and medium intensity concept. In the first, fifth and tenth row are altogether 6 Sensors and a length of 10,5 m of wire used.

8.3.4 Concept for Corrosion Measurement

The Fiber Optic sensors are not able to measure corrosion. On this account it is necessary to choose another kind of sensor. Selected was the Acoustic Emission sensor as the best solution. The sensors will be placed on the outer walls of the building as it is pointed out in Figure 30.

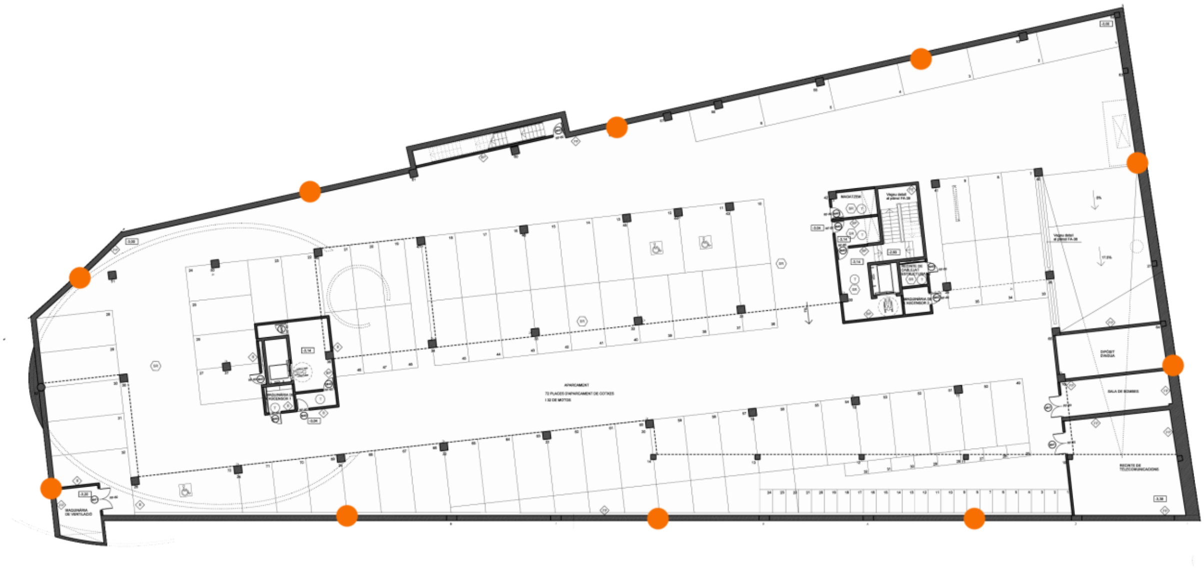


Figure 30: Concept for Acoustic Emission Sensors in Neàpolis Building

The arrangement of the sensors is regardless of the intensity concept constant. It can be added to every concept.

The sensors are placed on the surface of longer walls of both ends of the second, fifth and eights row of columns. On the shorter walls, the left and the right one are also sensors placed. On both ends of the first and the third row of columns the sensors are installed on the surface of the walls.

Altogether are 10 sensors projected.

8.4 Recommendation

Based on the developed concepts, the intensities were transferred to the floors in the Neàpolis building. It was looked for the forces of weight, environmental influences and the basic structure of the individual floors.

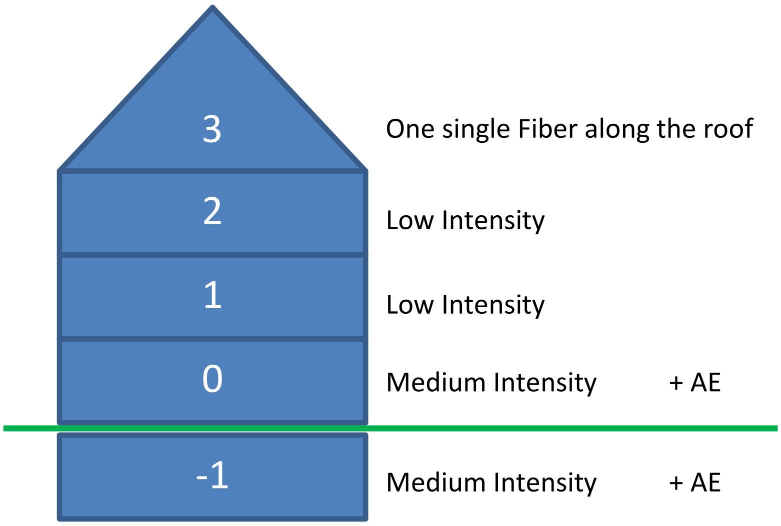


Figure 31: Recommended concept for the Neàpolis building

In the basement floor are the highest forces of weight and the bearing units are emerging the most stress. Therefore the medium intensity was chosen. The building is around 8 years old and the occurrence of damages does nearly not exist. Based on the strain in this floor it is necessary to monitor the changes. The only found damage in this floor was humidity in some parts on the outer walls. It is a useful solution to install the Acoustic Emission sensors on the surface, where the damage was seen. By using the medium intensity in combination with the concept of corrosion measurement, a number of 34 Fiber Optic sensors and 6 Acoustic Emission sensors will be required.

For the ground floor the same solution is recommended. In this level is the stress nearly the same as in the basement floor. The force, caused by the weight of the higher floors, affects to the structure and the bearing columns. Therefore the medium intensity is reasonable.

Monitoring of corrosion is in this floor useful as well. The ground floor has also contact to earth, where a great occurrence of humidity appears. The humidity causes corrosion and some parts of the ground floor are already affected. It is a practical solution to detect corrosion with Acoustic Emission sensors in the ground floor. The number of sensors is the same as in the basement floor, 34 Fiber Optic sensors and 6 Acoustic Emission sensors.

The first and the second floor are, contemplating the structure, similar. Therefore it was the same concept for both floors chosen. The force of weight in these floors is less pronounced than in the basement and ground floor. On this account it is not necessary to measure the structure in so many locations. That is why in the first and second floor the low intensity concept is recommended. The result is, that in every floor are 14 Fiber Optic sensors are needed.

It is the same for the formation of corrosion detection. In these two floors is a much lesser occurrence of parts with corrosion. The humidity does not move from the ground to the higher floors and rain has not that much influence to cause corrosion. The consequence of this knowledge is that it is not necessary to use Acoustic Emission sensors in the first and second floor.

The third floor has a different structure than the others. It is only a drafted construction on the top of the second floor. The floor has no bearing columns, but outer walls. There are no important loads, because it is the top floor, which has not to bear other constructions. Because of the low influence forces and also to save money, no one of the described concepts will be applied here. The only part that will be monitored is the great steel beam in the celling. This is the unit that bears the most loads on the top floor. It is also needless to detect corrosion, for the same reason as in the first and second floor. That is why only 6 Fiber Optic sensors in the length of the steel beam are recommended.

9 The Cost-Benefit-Analysis

In this chapter the proposed formulas, which have been created for the calculation of the feasibility of Smart Structure systems in buildings, are explained. With the creation of the formulas, an easy way to calculate the feasibility Smart Structure systems is obtained. There are two main formulas that are made out of the same components. The first formula is to calculate the feasibility at a certain amount of time and the other formula is to calculate the break-even-point (BEP).

9.1 Parameters of the formulas

This formula is expressed in cost (c) and each part is expressed in cost per time $(\frac{c}{t})$.

Legend of symbols:

c	cost
t	time
m	meter
m²	square meter

9.1.1 Initial Costs (IC)

The Initial Costs define the introduction cost which is needed for the beginning, to set up the system of Smart Structures. For that, it needs to be figured out how many sensors and which lengths of wires for the entire system are required to deliver the data from the sensors to the central system.

$$\mathit{Sensors\ number} * \mathit{sensors\ cost}(\mathbf{c}) + \mathit{wires\ length}(\boldsymbol{m}) * \mathit{wires\ cost\ per\ meters}(\frac{\boldsymbol{c}}{\boldsymbol{m}}) + \mathit{installation\ cost}(\boldsymbol{c}) + \mathit{system\ to\ collect\ data\ cost}(\mathbf{c})$$

9.1.2 Smart System Cost (SSC)

The Smart System Costs define the cost to maintain the system of Smart Structures, all about the components of the Smart Structures system. For example, to renewal of some wires or sensors, which are defect and also the system control checking by a computer engineer.

Renewal System cost

$$\left\{ \begin{aligned} &\frac{\mathit{New\ sensors\ cost}\ (\boldsymbol{c}) * \mathit{new\ sensors\ number}}{\mathit{Lifespan\ sensors}(\boldsymbol{t\ in\ years})} \\ &+ \frac{\mathit{Wires\ cost\ per\ meters}\ \left(\frac{\boldsymbol{c}}{\boldsymbol{m}}\right) * \mathit{wire\ length}(\boldsymbol{m})}{\mathit{Lifespan\ wires}\ (\boldsymbol{t\ in\ years})} \\ &+ \mathit{Installation\ cost\ per\ hours}\left(\frac{\boldsymbol{c}}{\boldsymbol{t}}\right) \end{aligned} \right.$$

$$+ \mathit{Inspection\ Cost\ of\ the\ system\ per\ hours}\ (\mathit{computer\ engineer})(\frac{\boldsymbol{c}}{\boldsymbol{t}})$$

System Control cost

9.1.3 Smart Preventive Maintenance Costs (SPMC)

The Smart Preventive Maintenance Costs defines the costs for maintenance, which appear during the year, although a Smart Structure system is used. In this case it is precisely known where the problem is and the damage can be repaired accurate and prompt. With this system money can be saved in the reparations by detecting pathologies in early stages and it will also save time and money about the work of diagnostics, made by a civil or building engineer because the system shows easily and fast where the pathologies are located.

To be the most realistic as possible, this formula of the SPMC depends on the surface in particularly. Is the surface that we have to repair expanded, more time and consequently more money is needed to fix it. Moreover a factor α is added to the formula, which represents the evolution of the crack during the time.

$$\begin{aligned} & Surface\,(\boldsymbol{m}^{\boldsymbol{2}}) * \boldsymbol{\alpha} \\ \text{Repairing cost} \rightarrow\ & * \Big[(materials + tools)cost\ \left(\frac{\boldsymbol{c}}{\boldsymbol{t.m}^2}\right) \\ & + Qualified\ workforce\ cost\ (civil\ engineer + civil\ worker)\ per\ hours \left(\frac{\boldsymbol{c}}{\boldsymbol{t.m}^2}\right) \\ & + Downtime\ cost\ per\ hours\ \left(\frac{\boldsymbol{c}}{\boldsymbol{t.m}^2}\right)\Big] \leftarrow \text{Financial loss} \end{aligned}$$

9.1.4 Preventive Maintenance Cost (PMC)

The Preventive Maintenance Costs defines the maintenance cost during the year without the sensors. In this case we do not use the Smart Structure system consequently it is complicated to localise the problem precisely. Therefore more money and time will be lost than with a Smart Structure system because a larger area has to be covered. The cost will increase also due to the fact that the civil engineer or building engineer needs more time to diagnosticate the building regularly. The factor α is more important for the PMC than the SPMC because without sensors the crack evolution during the time is faster and more important.

$$\begin{aligned} & Surface\,(\boldsymbol{m}^{\boldsymbol{2}}) * \boldsymbol{\alpha} \\ \text{Repairing cost} \rightarrow\ & * \Big[(materials + tools)cost\ \left(\frac{\boldsymbol{c}}{\boldsymbol{t.m}^2}\right) \\ & + Qualified\ workforce\ cost\ (civil\ engineer + civil\ worker)\ per\ hours \left(\frac{\boldsymbol{c}}{\boldsymbol{t.m}^2}\right) \\ & + Downtime\ cost\ per\ hours\ \left(\frac{\boldsymbol{c}}{\boldsymbol{t.m}^2}\right) \leftarrow \text{Financial loss} \\ & + Inspection\ cost\ of\ the\ building\ (civil\ engineer)\ per\ hours \left(\frac{\boldsymbol{c}}{\boldsymbol{t}}\right)\Big] \end{aligned}$$

9.2 Feasibility

The use of this proposed formula can be a great asset in the determination of feasibility over time. For the use of this formula we apply some parameters, which will be explained in Chapter 9.19.1.

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

F = Feasibility
PMC = Preventive Maintenance Costs
IC = Initial Costs
SSC = Smart System Costs
SPMC = Smart Preventive Maintenance Costs
T = Time

The formula works by dividing the costs for regular preventive maintenance (PM) by the costs for preventive maintenance with Smart Structures (PMSS). When you fill in the blanks, you will get a certain number, which can tell you the margin you save or loose in comparison with regular preventive maintenance at a certain amount of time. The number can also be used to determine a safety rate to the investment in Smart Structures. The outcome of the formula is very important. The grades given are determined by the time the sensors have to be replaced. The following can be said about the investment and the feasibility of the investment:

Grade	Status of investment
<1	It is not profitable
1,01 – 1,25	It is profitable but there is a small margin for errors or deviations
1,26 – 1,50	It is profitable, there is room for errors and deviations because of a good margin gap
> 1,51	It is a solid investment and there is a high return on investment

Table 4: Feasibility Grades

When the grades out of Table 4Table 4 are multiplied by 100% you will get the percentage that will be made in comparison to the traditional preventive maintenance. The percentage is a nice indicator of the profits that can be made with the implementation of the preventive maintenance with Smart Structure systems.

9.3 Break-Even-Point

The break-even-point permits to create graphs to compare the cost of the preventive maintenance without sensors with the preventive maintenance with sensors. We can see the evolution over the time and can find out the time when there are benefits of the PMSS.

With the two main parts of this formula we get two straight lines and we can deduce the break-even-point. Therefore we need to calculate the time when the Smart Structures begins to save money to compare with the common preventive maintenance.

To calculate this time, we have to consider that the result of the Benefits Evolution is 1, means that this particular year, the costs of the preventive maintenance with and without sensors are the same.

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

$$IC + (SSC + SPMC) \cdot T = PMC \cdot T$$

$$IC = PMC \cdot T - (SSC + SPMC) \cdot T$$

$$IC = (PMC - (SSC + SPMC) \cdot T$$

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

With this formula the following graph of the break-even-point and the associated cost schedules can be found out.

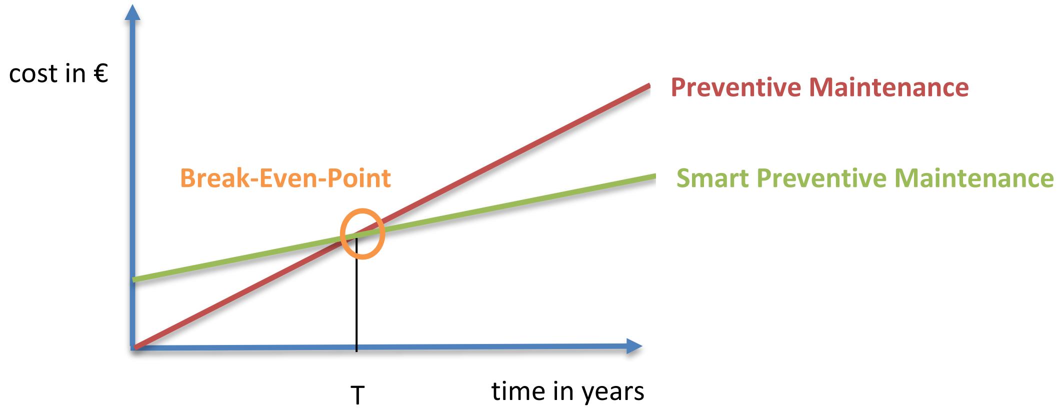


Figure 32: Graph of the benefit evolution

Moreover, the way of thinking for this formula is that we are in the prevention of the building, we would like to prevent damages therefore we do not consider a failure**.**

9.4 The Reasoning

In the formula we assume that $\frac{PMC}{Smart\ Structure\ Costs} > 1$, this means that the hypotheses is that preventive maintenance with Smart Structures system will be cheaper than the regular preventive maintenance. The reason why this hypothesis has been drawn is that we expect that maintenance can be applied in earlier stages and will lead to smaller fixes. These smaller renovating jobs will be less costly and can be translated in factors such as: lower down time, lower manual labour costs, lower machine hour costs and lower material costs.

10 Example of use

To conclude our project, we decided to apply the proposed formula on both buildings to get a comparison. This example permits to make our reasoning about the formula more concrete and to prove that the system of Smart Structures enables to save money.

10.1 The parameters

During our investigation according to the companies to get information about the cost of sensors, one of the companies that we contacted transmitted us several figures about the cost of sensors and also about industrial computer cost or measuring devices costs. After a telephone call with Mr. Eichhorn from the German company fos4X GmbH from Munich, we were able to work on the example with a real idea of the cost of the preventive maintenance.

Components	Costs
Measuring devices	
For 18 sensors	20.000 €
For 72 sensors	25.000 €
For 576 sensors	58.000 €
Industrial computer	1.500 €
Control box	1.000 €
Cooling system	300 €
Sensor (incl. wire)	190 € (per sensors)

Table 5: Information about costs of a Smart Structure system

The fos4x GmbH offers 3 different measuring devices. Relating to the amount of sensors the device must be chosen. In the case of the recommendation for the Neàpolis building we have around 130 Fiber Optic sensors, that is why the measuring device for 576 sensors must be taken. For the Sant Antoni church the second solution for 72 sensors could be taken because in total are less sensors needed.

The price for all of the sensors, which are already including the wires, can be calculated by the amount of the sensors multiplied by the price of 190 €/sensor.

To get the price of the whole components without installation, there have to be added the cost of an industrial computer, a control box, a cooling system for the computer and the software. The software is custom-built, that is why a uniform pricing was not possible.

10.2 Demonstration of the feasibility

Some data are still missing to complete the calculation consequently. That is why we assumed some other costs to demonstrate the formula.

10.2.1 Feasibility of the Sant Antoni church

The following parameters were for the Sant Antoni church chosen.

Preventive Maintenance Costs = 40.000 €
Initial Costs = 100.000 €
Smart System Costs = 5.000 €
Smart Preventive Maintenance Costs = 15.000 €
Time = 20 years

$$Feasibility = \frac{40.000\ € \cdot 20\ y}{100.000\ € + (5.000\ € + 15.000\ €) \cdot 20\ y} = 1{,}6$$

In the case of the Sant Antoni church a Smart Structure system would be very profitable. It also has a high return-on-investment.

10.2.2 Feasibility of the Neàpolis building

The following parameters were for the Neàpolis building chosen.

Preventive Maintenance Costs = 30.000 €
Initial Costs = 150.000 €
Smart System Costs = 5.000 €
Smart Preventive Maintenance Costs = 10.000 €
Time = 20 years

$$Feasibility = \frac{30.000\ € \cdot 20\ y}{150.000\ € + (5.000\ € + 10.000\ €) \cdot 20\ y} = 1{,}33$$

For the Neàpolis building a Smart Structure system would be reasonable.

10.3 Demonstration of the Break-Even-Point

If the assumed costs from the example before are set into the proposed formula for the break-even-point we can get the year after the implementation, when the whole system gets profits.

10.3.1 Break-Even-Point of the Sant Antoni Church

By using the data from the example in chapter 10.2.1 the following break-even-point can be calculated:

$$\frac{100.000\ €}{40.000\ € - (5.000\ € + 15.000\ €)} = 5\ years$$

The following graph verifies the calculation from getting a benefit after using a Smart Structure system for 5 years.

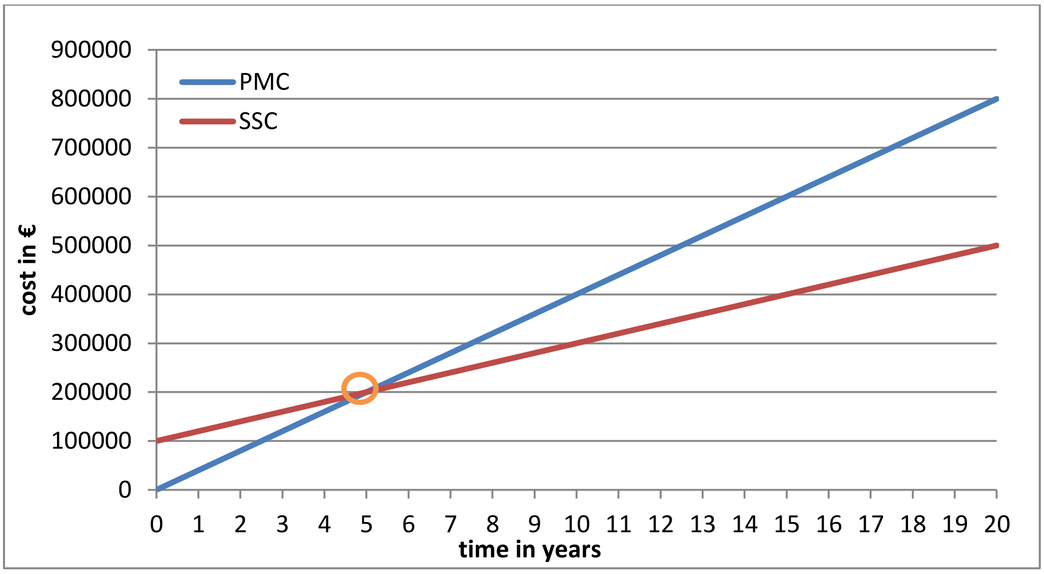


Figure 33: Break-Even-Point of the Sant Antoni Church

According to the graphs in Figure 33, we can see that the preventive maintenance with a Smart Structure system is less expensive that the preventive maintenance without Smart Structure system. The break-even-point is around 5 years.

10.3.2 Break-Even-Point of the Neàpolis building

For this example the data from the previous demonstration in chapter 10.2.2 are used.

$$\frac{150.000\ €}{30.000\ € - (5.000\ € + 10.000\ €)} = 10\ years$$

The Figure 34 is demonstrating the graphs of the Smart Structure costs and the preventive maintenance cost without sensors. They cross at about 10 years and that is the point where the investor gets benefits.

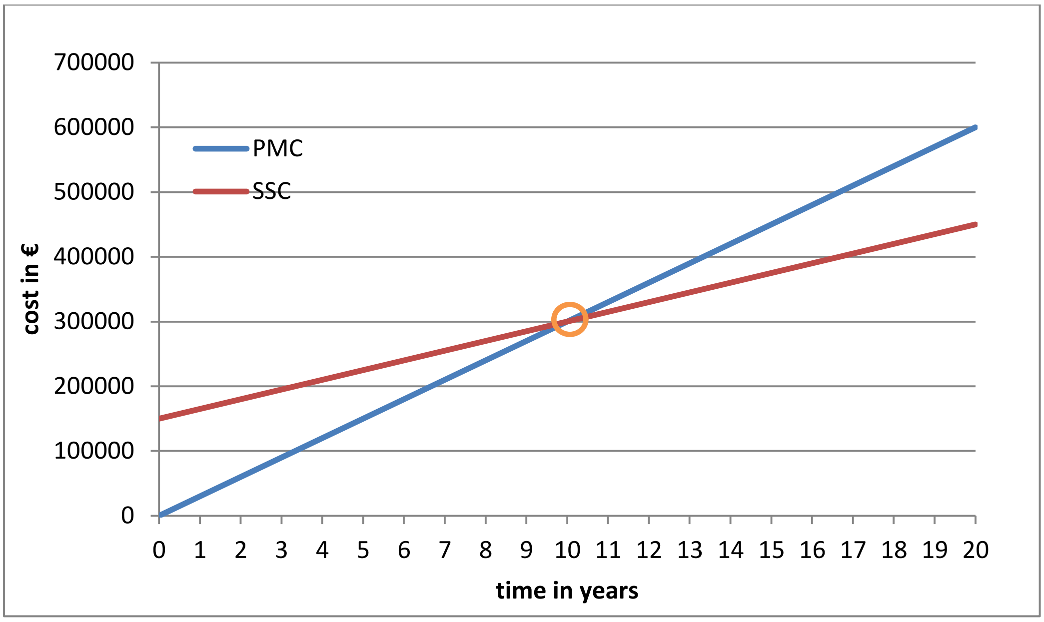


Figure 34: Break-Even-Point of the Neàpolis building

In comparison to the Sant Antoni church the Neàpolis building needs a longer time to get the investment of the Smart Structure system back. That is because the building is by contrast to the church much younger and has not a lot of pathologies. The whole system gets really interesting, if a building needs a lot of maintenance like the Sant Antoni church. Because only if money is invested in the preservation of a bulding, it is possible to get benefits. And the more it has to be invested in the health of a structure, the more can the Smart Structure system save and the faster the invest will be returned.

11 Conclusion

In this chapter the conclusion of the project is drawn, this will be done in 3 different sectors. First we start with the implementation plans for the Neàpolis building and the Sant Antoni church, after that the cost analysis with the proposed formula will be summarized and the project in total will be deduced.

11.1 The Buildings

11.1.1 Neàpolis building

The Neàpolis building (2007) is a relatively new building and can be described as healthy building (G=1; Ruiz, 2014). This means that pathologies are rarely found. The pathologies found in the building were just humidity and one very small crack. So we can conclude that the building is in great shape and therefore the high intensity monitoring system is not necessary. We recommended for the different floors different intensities. This is reasonable because the forces on the different floors of the building are not the same. The lower floors bear more weight than the upper floors and the top floor has a totally different structure with a not important load. The corrosion monitoring will be established in the basement and the first floor because the humidity will contribute to the corrosion in the buildings.

11.1.2 Sant Antoni church

The Sant Antoni church (1693) is a building that is in an intermediate state (G=5; Ruiz, 2014). This means that the building is in relatively good shape, but does show some harms. These pathologies are cracks, humidity, corrosion and deformation. Because these pathologies are found, the conclusion can be drawn that the building can make use of the Smart Structure technology. The implementation plan based on this conclusion is the medium intensity concept for the FBG-sensors and the high intensity concept for Acoustic Emission sensors. This solution was chosen because the medium information can give enough data about the existing pathologies in the specific parts of the building. For the high intensity Acoustic Emission sensor the reasoning lies in the environmental conditions of location of the church. Vilanova i la Geltrú lies in a coastal region where the air is salty and the wind is strong. This leads to corrosion of the outer walls and the ferro concrete.

11.2 Cost-Benefit-Analysis

After performing the cost-benefit-analysis, the conclusion can be drawn that Smart Structure systems will be profitable in the future. Even though not all necessary data were gathered, a formula proposition could be created and proved in this report that the formula shows potential. But after everything there can be said that the formula and the cost analysis need a lot of work, the parameters will need some details and for that companies have to be approach to retrieve the necessary data.

11.3 The Project

The project can be seen as successful. We have to conclude that even though not all aims set in the project scope are met progress has been made in a field where none of us had any knowledge of. The research is in our knowledge the first time a feasibility study about Smart Structures is applied. Therefore these are the first steps in the direction of feasibility calculations for Smart Structures.

The team was very happy to get involved in that very interesting topic during the European Project Semester. We learned plenty of new interesting things related to different parts of the project, such as sensors and electronic devices, creating a formula and economic topics as well as topics from the civil engineering and building concepts. We gained a great deal of experience in international teamwork and due to the fact that we had problems in the beginning, we also learned how to solve problems.

In summary we can look back on a successful project with new experiences and interesting contents.

11.4 Further Research

The aim of the Project was reached, however there are some topics they could be prepared. During the work there were some lacks about the information for technical aspects. For a detailed analysis it is necessary to develop solutions for the installation and connection of the sensors.

A concrete software or a system how to analyse the collected data is also missing and it could be interesting to work on this topic.

Directly to work further on the project of a feasibility study and cost analysis, there has to be a detailed research about the several parts of the initial costs. For example the cost of maintenance could be, if a team has the time to concentrate on this part, more exactly. The part of collecting information about prices and costs is really time-consuming and it is difficult to find useful sources or companies who agree to provide information.

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