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Master's Degree in Civil Engineering

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Structural Health Monitoring through the Building Information Modelling

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Abstract

In the current times there is an increasing number of structures constructed in past decades that present ageing and deterioration. Furthermore, the modern times are requesting new larger infrastructures, subjected to more demanding conditions and heavier loads. The Structural Health Monitoring (SHM) arises as a technology whose goal is the permanent assessment of the asset by the using of sensors, devices that are able to collect a very large quantity of measurements. But this feature brings with it new challenges and becomes vital the using of tools for managing this data and that are helpful for the engineers at the moment of analyzing it.

The Building Information Modelling (BIM) has demonstrated its usefulness when it comes to store and handle all the data related to a project during its designing and construction, and along its service life. The goal of the present work is to study how the SHM systems can be modeled and managed inside the BIM context, and to test the suitability of the current BIM tools for SHM purposes.

This research is carried out through the modeling of two real infrastructures: The Stura Bridge, a very important asset that makes possible the joining of the city of Turin with the Caselle Airport and the Brenner base tunnel, a huge engineering project, currently under construction, that will cross the Alps connecting Austria and Italy. Firstly a model has been created in BIM environment for both cases of study using the software Autodesk Revit and then are modeled new objects that simulate the SHM system elements, i.e. the sensors, for including them inside the two virtual models. Hereafter, by the utilization of Dynamo, which is the visual programming tool incorporated in Revit, are developed a series of scripts with the scope of assisting the installation of the SHM system elements in the models and managing and analyzing the monitoring data in an interactive way through the Revit environment.

The outcome of the study is the simulation of real monitoring activities, such as the sensor placing and data analysis, in the developed programs. Even though until now the monitoring systems have not been officially included in the BIM context by any well-known software, in BIM tools like Revit lies a great potential for SHM purposes due to its natural versatility that is enhanced by Dynamo. It is a matter of time for the incorporation of the SHM in the BIM tools and standards and it is expected that this thesis collaborates to lay the foundation for future researches.

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Introduction

The Structural health monitoring (SHM) has become an important tool for engineers to improve the safety, durability and maintainability of civil infrastructures by means of the permanent assessment of the structural behavior. This constant monitoring of the structure represents the step forward towards the implementation of proactive rather than reactive maintenance plans and makes the SHM a very promising technology in a world with an increasing number of deteriorated structures and larger constructions subjected to more demanding loads.

Along with these benefits also come some new issues and complications that were not present before. The permanent monitoring involves the collection of a huge amount of data which sometimes can represent hundreds or thousands of gigabytes. This means a challenging task due to the fact that this data must be filtered or managed in some way in order to make it suitable for its analysis and interpretation. Therefore becomes essential the using of new tools appropriate for the effective management and analysis of this data that allow a better, less cumbersome and more profitable visualization of it.

An effective approach that can lead to a good solution for these issues is to include the SHM inside the Building information modelling methodology. The Building information modelling (BIM) has appeared over the last few years and has brought with it many changes in how the structures in general are designed, constructed and managed. A BIM model works as a digital repository of the real structure that keeps safe and organized all the project data along its entire life-cycle. The BIM tools have proved their usefulness at the moment of storing, sorting, sharing and visualizing data, features that would make possible the utilization of them for SHM purposes.

The aim of this thesis is to test the inclusion of Structural health monitoring elements in digital BIM models and to evaluate the implementation of BIM for SHM purposes such as the monitoring data management and visualization. More specifically this will be addressed through two different cases of study: 1) The Stura Bridge, structure that takes part of the highway that communicates the city of Turin with its airport and 2) A part of the Brenner base Tunnel, infrastructure that is currently under construction beneath the Brenner Pass that will be part of the railway through the base of the Eastern Alps, in the border between Italy and Austria.

This thesis is subdivided in four sections. The First one is dedicated to the theoretical framework of the two base topics of the work: the Structural health monitoring and the Building information modelling. The second section is separated in two parts: In the first is stated the problem that is treated in the thesis and is explained what is the potential of the BIM methodology for solving it by listing the previous studies carried out by other researchers; the second part is dedicated to describe the two cases of study developed and is established the methodology and the steps that will be followed along the work.

In the third section the study is developed. Firstly is explained how the digital models of the two infrastructures were created in the BIM software, being in this case used Autodesk Revit. Then are presented and explained the different programs developed in this work to address the problem established, all of them by using Dynamo, the visual programming tool built in Revit.

Finally in the fourth section are discussed the results obtained from the developed experiences and are also presented the conclusions of the thesis. Moreover are established the recommendations for the further steps that must be addressed for future researchers in this interesting topic.

Section 1: Theoretical framework

1. Structural Health Monitoring

1.1. Background

Since the last century a huge number of civil infrastructures have been constructed in order to contain the industrialization of the world and the explosive increment in the population.

Particularly bridges and tunnels are critical infrastructures. Their existence is of a paramount importance for the today's world social and economic development, because they make possible to overcome natural barriers communicating cities and countries and allowing the easy, safe and quick transit of goods and people. Due to this relevance, failures in them can mean human and economic losses of importance, and long-lasting closures in the road network can have an impact in the economy of an entire region.

In the case of bridges, just in Europe there are more of 1234 kilometers of road bridges of at least 100 meters long and the number increases significantly if the smaller ones are taken into account. Most of these bridges were designed and constructed after the World War II, with a design life of 50 to 100 years. That means that a great quantity of them is arriving to the finish of their life time and has been deteriorated for decades. According to the European Union BRIME project in 2001 in three European countries such as France, Germany and the United Kingdom were present deficiencies in the 39, 30 and 37 percent of their bridges respectively. Also most recently, the quality of the bridges around Europe and especially in Italy has been questioned after the collapse of the Morandi's Bridge in Genova.

All structures are subjected in a greater or lesser extent to destructive effects such as corrosion of the steel reinforcement or the structural steel, aging of the materials, increasing volume in traffic, fatigue loads and overloading. All these factors alongside defects of design or construction and accidental damage promote their deterioration and can cause the loss of load capacity.

The way to limit this process of deterioration and avoid the extension of damage consist in the periodically inspection and monitoring of the health of the structure. For several years visual periodic inspections together with Non – destructive Testing or NDT have been implemented as a methodology of bridge maintenance programs.

Normal maintenance and inspection routines in structures such as bridges and tunnels are carried out on site by inspectors with considerably experience following a pre-established schedule. This inspection is done from time to time. For example the Swedish Road Administration (SRA) establishes that all road bridges in that country must be inspected at least every six years. The SRA uses a management system that contains a database for deficiencies observed in inspections in all the bridges of the country. The institution *codes for inspection of structures* tell the professional responsible of the inspection the parts of the structure that must be examined. If there are no deficiencies the bridge can continue to operate normally, but if there are and is not possible to assure the traffic safety after an evaluation of it, the traffic must be limited (Hejll, 2007).

On the other hand an inspection can be carried out outside the established date if there are or there will be changes in the performance level, such as variations in the structural system or abnormal loads.

This kind of visual inspections are relevant but sometimes are restricted to the external part of the structure. Because of this, cracks, corrosion and unanticipated deformations can be observed just when they are visible to the human eye (Hejll, 2007). This subjectivity in the observations and the periodic nature of the inspections has led to develop continuous monitoring systems that can be able to give an objective evaluation of the structure condition, with a quantitative and not qualitative methodology. In this way was born the current Structural Health Monitoring.

The Structural Health Monitoring or SHM has its roots in the aviation and aerospace industry. The conception is the use of specialized sensor devices such as accelerometers, inclinometers, strain gauges, among others, to permanently monitor the behavior of the structure, especially the critical parts of it. This is done in order to get timely warnings that can be treated immediately or, depending on the severity, in a scheduled maintenance occasion in the future.

Although it is still a "new" technology in the civil engineering applications, because is not yet globally implemented, progress and advances in the sensors have brought with them a decreasing in their cost, making the SHM systems more attractive for the civil engineering industry.

1.2. State of art

1.2.1. Definition of SHM

A very precise definition of the SHM is given by *Radulescu et al*:

"The Structural Health Monitoring is a non – destructive in-situ sensing and evaluation method that uses a variety of sensors attached to or embedded in a structure to monitor the structural response, to analyze the structural characteristics for the purpose of estimating the severity of damage or deterioration and evaluating the consequences, thereof on the structure in terms of response, capacity, and service-life."

Although SHM uses a lot of devices that are considered as a non – destructive testing (NDT) and non – destructive evaluation (NDE) it presents many differences with the traditional approach of the regular inspections methodology. The former one focuses in a one-time checking of the structure in order to observe the condition at that specific moment and in a specific location. In contrast, the SHM involves the permanent assessment of the structure behavior as a whole and its response to different types of loads through time.

In addition SHM not only involves the acquisition of data through sensors but also comprises the extraction of features of these measurements and the analysis of those features to know the present state of health of the structure. The importance of SHM is that it is essentially the basis of condition-based, rather than time-based monitoring of a structure (Dong et al, 2010).

1.2.2. Components of a SHM system

SHM is constantly changing in time due to the new and more advanced technologies that appear year after year and new details can be added. However every SHM system is basically constituted by:

- <u>Sensors</u>

The first step for the construction of a good SHM system is the selection of the appropriate sensors. In order to measure the phenomena some parameters need to be monitored such as strains, accelerations, deformations, temperature, load, etc. and there are commercially available sensors depending of which of those parameters have to be measured. In addition, other factors must be included in the selection criteria: accuracy, power requirements, durability, reliability, installation and signal transmission limitations and cost.

Nowadays in the market of SHM there is a very wide variety of sensors. It will be discussed later.

- <u>Data acquisition system (DAS)</u>

The data acquisition system (DAS) is the element of the SHM system that tells the sensors when and how to carry out the measurements, i.e. the duration of the data collection and the frequency of the sampling. All the sensors must be connected to the data acquisition central that is located inside or in the vicinity of the structure because is here where the analog output signals coming from sensors are converted into an engineering language. The system can acquire the data of the sensors by wired or wireless connection:

- *Wired connection*

The wired connection is a more traditional type of connection. It has been always the most economical one but the improvements in wireless technologies have done that the cost of wiring become an important economical factor that must be taken into account in the selection, especially in very big or long structures such as tunnels. It is subjected sometimes to electromagnetic interference, but the use of shielded cables or fiber optic sensing (FOS) can mitigate or eliminate this effect, but also the costs increase (Dong, 2010). It is important to consider that there is always the possibility to accidentally damage or cut off the wires.

- *Wireless connection*

It is a newer technology that is used when applying a wired connection becomes impractical due to the extension of the structure, what happens in large structures. It is also used when the signals transmitted through wires could be contaminated with noise. In wireless systems the data is normally transferred slowly and they are currently more expensive than the wired solution.

Even though this it is anticipated that in a near future this technology will be more used due to advancements.

- <u>Communication system (CS)</u>

This is the route that communicates the DAS to the place where the data is going to be processed. This system allows that the data processing and subsequent activities can be done in a different location, taking out the need of having a monitoring office near to the structure. The communication system (CS) also permits to control remotely the DAS and sensors through monitoring software. At present in SHM applications the data can be transferred physically, i.e. telephone lines, optic fibers, etc., or wireless such as radio or cellular transmission technologies, like 3G.

- Data processing

After the data arrives from the field it must be processed because it can contain noise and strange information due to errors and uncertainties coming from the measurements of the sensors. In other words the data must be cleaned before it is stored and analyzed by the structural engineers. This process is done automatically by a computer that applies some algorithms.

- Data storage

Storing the data is a very important activity inside the SHM methodology. That is because it could be consulted in the future for the diagnostic of the structural health conditions. This implies that the way to store it must be conducted in an organized and understandable manner, because it is possible that different people access it, not only the professional that decided how it was stored in the beginning. Must be also taken into account that depending how the SHM system collects the data (continuously, periodic, etc.) the amount of it can increase considerable, so a storage system with larger capacity must be chosen. Currently the storing technology is very developed with new advancements like the cloud storage and with memory capacities unimaginable not long ago.

- Data analysis, prognosis and decision making

This is the most important activity inside the SHM methodology, because its aim is to give a useful meaning to all the data collected, transmitted, processed and stored in previous steps. Here the scope is to interpret the measurements carried out and in order to do this job an expert structural knowledge is required. Normally, analytical models and/or numerical FEM models of the structure are created for simulating the phenomena measured by the monitoring system and consequently understand how the structure is behaving, and how the behavior may be affected by damage, deterioration or other changes in its current state. A simple example of this can be to transform measured strains into stress through an analytical or numerical model in order to observe if certain thresholds are being exceeded or not, but the complexity of the analysis can increase considerably depending on the level of sophistication that is wanted to be achieved (will be explained in a later point).

The last product of the analysis, diagnostics and prognostics activities is to make decisions and give solutions to the encountered problems and emit warnings if it is necessary, because always the safety of the people is the most important good.

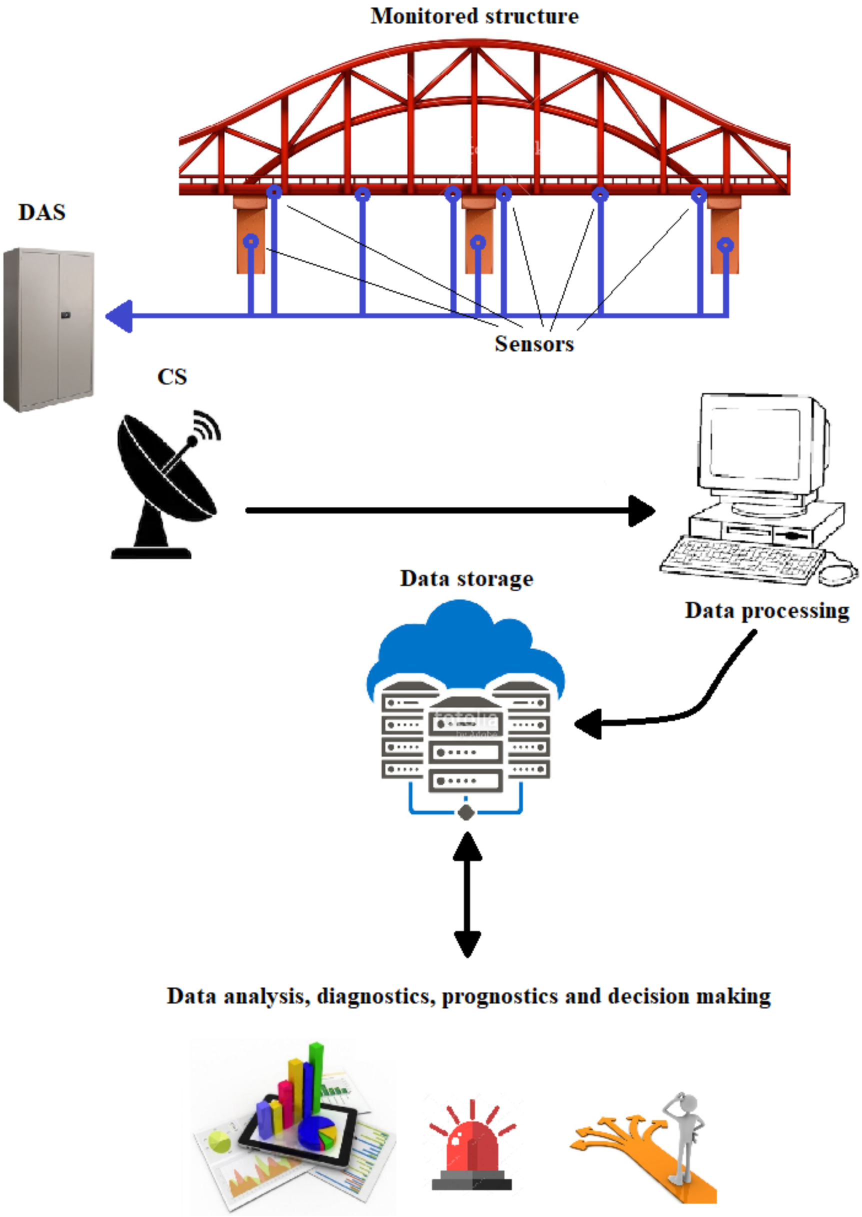


Figure 1: SHM methodology.

1.2.3. Sensing devices

The sensors used depend on the type of data that must be collected. There are plenty of effects that can be monitored in a structure but the most usual parameters that are measured in a SHM program are strains, displacements, rotations, accelerations and temperature.

- Strains

The strain measurements can be performed using different technologies. In the following paragraphs these are explained briefly:

- *Foil strain gauges*

These devices consist in a sheet that is attached to the surface of the structure and when the structural element suffers deformations the sheet deforms too. The device is able to read the change in length of the sheet that is equal to the strain experienced by the element in the direction in which the sheet is oriented. Then this lecture is sent to the readout unit through wires. These sensors can be attached to the structure through adhesive or welded to it. Also in some cases are embedded inside the structure, for example inside the casted concrete.

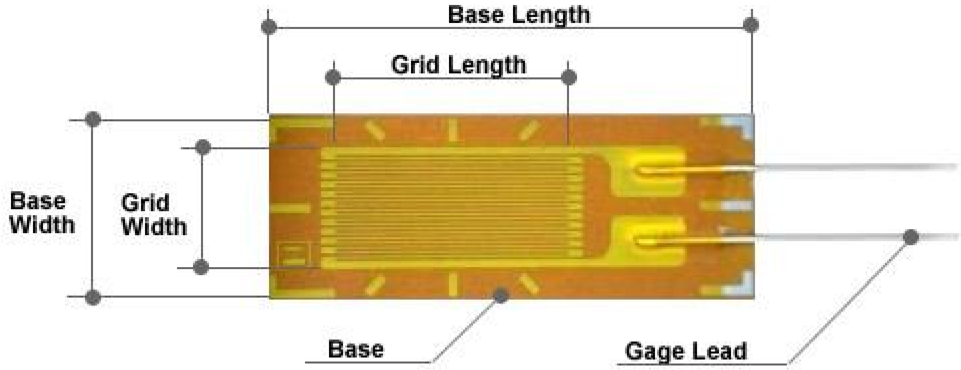


Figure 2: Foil strain gauge. Sensing sheet.

Source: http://www.showa-sokki.co.jp

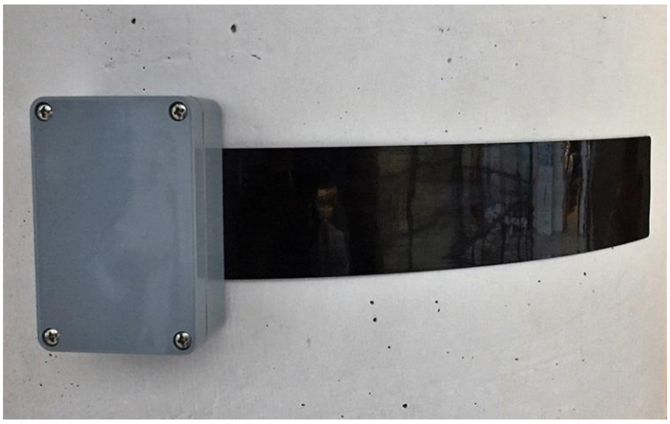


Figure 3: Foil strain gauge included in a multisensory device. SH BOX.

Source: https://www.sysdev.eu

- *Vibrating wire strain gauges*

In the Vibrating wires sensors (VW) a thin steel wire encased in a sealed steel tube is kept in tension between two end blocks attached to the structure (to the surface if it or embedded). The wire is excited by a short pulse of an electromagnet with surrounded coil in the midpoint of the wire. The principle is that if there is any variation in the force that maintain the wire tensed, caused by the displacement of the end blocks, this variation can be measured through the change in the vibrating frequency of the wire, and then the strain can be calculated.

For a proper measuring of the strain a correction must be applied due to the effect of the temperature. That is because the steel wire and the structure can have different thermal expansion coefficients as it happens for example in reinforced concrete structures. Because of this, these devices are able to measure temperature too.

Figure 4: VW strain sensor.

Source: https://www.sisgeo.com

- <u>Displacements</u>

The displacement measurements can be done using *Linear Variable differential Transducers (LVDT)*. This device consists in a hollow metallic tube with a shaft inside surrounded by a coil assembly. This shaft is made of a magnetically conductive material and is free to move linearly along the axis of the measurement and is called *core*. When it is equally distant from the edges no voltage is created, but just it moves a differential voltage is created. As the magnitude of the voltage variates linearly with the core displacement from the center, the displacement of the structure that causes this core movement can be estimated.

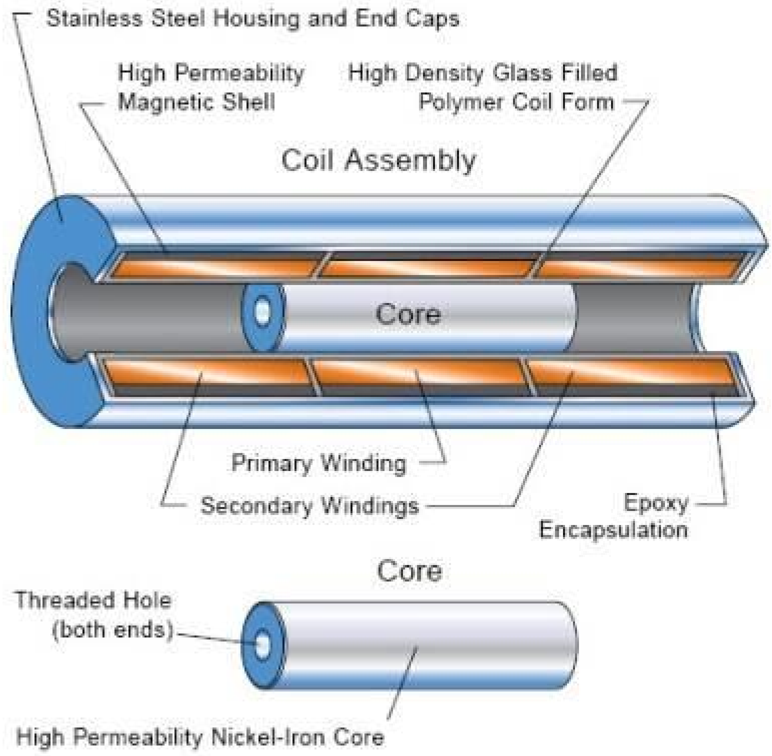


Figure 5: LVDT sensor. Scheme.

Source: https://www.te.com.

- <u>Acceleration</u>

The acceleration in a SHM system can be measured using an *accelerometer.* These can be piezoelectric accelerometers or spring-mass accelerometers.

- *Piezoelectric accelerometer*

A piezoelectric crystal is attached to a supporting base together with a mass. When the supporting base moves the mass apply an inertial force on the crystal. This action causes an electric charge on the crystal that is proportional to the inertial force. Knowing the force and the mass the acceleration can be calculated, just applying the second law of Newton.

They are very light and are able to operate in a limited range of acceleration and frequencies.

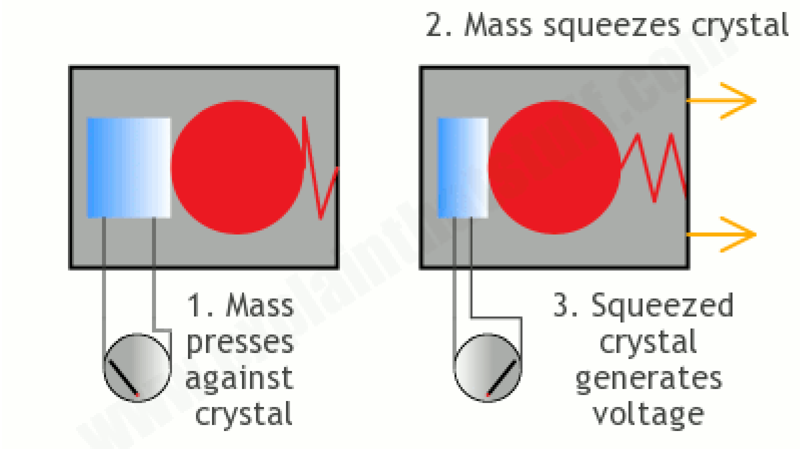


Figure 6: Piezoelectric accelerometer. Functioning.

Source: https://www.explainthatstuff.com

- *Spring-mass accelerometer*

Its functioning is simpler. It basically consists in a damped oscillator. Are heavier than the piezoelectric accelerometers but are more sensitive to little changes in acceleration variations and provide better resolution.

- <u>Temperature</u>

Two of the most commonly used temperature sensors in civil engineering are: *Resistive temperature sensors and Vibrating wire temperature sensors*.

- *Resistive temperature sensors*

They are based on the principle that the electrical resistance of a material changes and depends on the temperature. These can be metallic sensors or thermistors. The first ones depend on the measuring of the resistance of a platinum wire, and the second ones in the resistance variation of a ceramic semiconductor.

The difference between both is that thermistors work in a smaller range of temperature but on the other hand they are able to provide higher accuracy. Theses sensors must be used knowing that produce a certain amount of heat during its operation that can affect the temperature measure.

- *Vibrating wire temperature sensors*

They work with the same principle of the Vibrating wire strain gauges. The tension force in the wire changes due to the shortening or elongation of the wire, produced by the change in the temperature. This affects the frequency of the wire that is measured and consequently the temperature can be estimated.

- <u>Fiber optic sensors</u>

The state-of-the-art in the SHM, especially for large structures, is the using fiber optic sensors (FOS). Their functioning lies in the transmission of light waves through optical cables and how these waves change depending on the condition of the cable. They are most used in civil infrastructure to measure strains and temperature but their field of application can be much wider.

They imply many advantages compared with the traditional electrical sensors. The first one is the stability, because the light signals can travel very long distances without significant transmission loss, which make these kinds of sensors suitable for remote sensing.

Other advantages rely simply in the material of which they are made. Firstly, the glass fiber does not present the problem of corrosion and it allows having very stable continuous monitoring in long term applications. Also they are free from electromagnetic and radio frequency noise, giving a more reliable measurements. In addition the fiber optic cables are very light and thin, fact that facilitate they permanent incorporation in the structure. One important thing is that the fiber optic sensors allow a distributed sensing, because the whole optical fiber is used as sensor itself. These are called Fiber Bragg Grating sensors. In this way measurements can be collected along the whole length of a structure.

Despite of these advantages there are some drawbacks in the utilization of fiber optic sensors, being particularly conditioning their cost and their sensibility to harsh environments.

- <u>MEMS sensors</u>

Micro-Electro-Mechanical Systems, or MEMS, is a technology that can be defined as miniaturized mechanical and electro-mechanical elements that are made using techniques of microfabrication. These are made up of component sizes between 1 and 100 micrometers.

The MEMS sensors are types of these miniaturized devices that can measure different physical parameters. These are used for SHM purposes including accelerometers, inclinometers, and temperature and humidity sensors. Moreover, recently there has been an increase in the presence of low-cost MEMS in the market. Their main advantage is the small size that they have, characteristic that permits its location in places that the traditional type of sensors cannot occupy. This feature makes them so versatile and brings the possibility of installing a large quantity of devices in the same structure or even in the same element. The MEMS are the future for smart-monitoring applications.

1.2.4. Designing a SHM system

It might be thought that for having a good SHM system is only needed to have the more advanced sensors and placing hundreds of them everywhere in the structure, but in reality there are several factors that must be considered in order to have the most effective and optimal system. The true is that the best SHM system is that one that is best suited to the requirements, because of this the following factors must be taken into account:

- The location of the critical parts of the structure (Beams, supports, foundations, etc.)

- The structural phenomena that are required to be studied (Corrosion, cracking, settlements, etc.)

- The loads present in the real condition of the structure (static, dynamic, cyclic, impacts, etc.)

- If the phenomenon that must be evaluated is global or local (e.g.: Is the cracking spread all over the beam or just in the supports?)

- Despite of the SHM market is increasing every year and more economic sensors are appearing, the financial resources and the available technology in the area are limitations that must be also considered.

Taking in account these aspects more correct selections and decisions can be done during the designing of a SHM system. According to Hejll (2007) to design a SHM system the following activities must be carried out:

- <u>Characterization of the structural phenomena</u>

Different types of structural phenomena are measured in different ways, depending on what is causing them. Firstly, the probable cause of these phenomena needs to be identified in order to establish which parameters must be measured. Some examples of these parameters are stresses, displacements, forces, rotations, strains and vibrations. Another kind of parameters such as the temperature, humidity can also influence in a certain level the phenomena, so could be considered too inside a SHM system. For example in bridges, the gradients of temperature might be an important factor in its behavior.

- <u>Selection of the time strategy</u>

This states the duration and frequency of the measurements. The different strategies can be:

- *Short – term monitoring*

This time strategy is selected when the structural phenomenon must be evaluated at a specific moment in time and it not necessary to have a permanent monitoring of the structure. Examples of this can be: passing of an abnormal load through a bridge, change in the static system of a structure, after reparation or a strengthening work, etc. An important aspect to take into account is that a short – term monitoring requires a lower level of data management since it is done over a short period of time.

The short term monitoring is appropriate for the evaluation of instantaneous phenomena, such as instant deformations, vibration of elements, etc. but there is no point in using it for phenomena like crack opening and foundation settlements that develop in a long interval of time.

- *Long – term monitoring*

This kind of time strategy is adopted when is required a constant and continuous monitoring of the structure. The conception is that the structure must be monitored during years or even during its entire life service.

As mentioned before phenomena such as crack opening, settlements, or for example even environmental phenomena like corrosion must be evaluated with this philosophy, due to their slow development. This make the long – term monitoring the correct choice in the case of ancient or heritage structures monitoring, or in order to evaluate the behavior over time of a structure after a repair or strengthening intervention in order to see if this is really durable.

To make this possible is required a more advanced system of data acquisition, management and computer power, since the amount of data is considerable much bigger in comparison with the short – term monitoring. Therefore if this time strategy is selected must be also established the frequency in which the sensors have to collect the measurements. Depending of this, the data acquisition can be in different ways:

Continuous: The data is collected permanently. In this strategy the amount of data is the largest and is only used to evaluate phenomena that changes rapidly in time because of the randomness of its nature.

Periodic: The measurements are collected in a regularly spaced time intervals. With this philosophy the volume of data is considerably reduced and is ideal for the evaluation of phenomena without abrupt changes in the behavior or with a smoothly variations in time. An example of this can be the measurement of temperature.

Triggered: The data collection is activated with the occurrence of certain events or the exceeding of a pre-established threshold. This is also a useful strategy to reduce the quantity of measurements and is suitable when the attention is only focused in some interesting samples. A situation in which this can be used is to evaluate the behavior of a bridge only when heavy loads are passing.

Even though some strategies make possible to collect a more moderated amount of data the data stream should be always processed in order to reduce and make it more manageable.

- Selection of the condition strategy

The selection of the condition means to do choice if the SHM must monitor local or global phenomena. According to this can be defined two strategies:

- *Local monitoring*

Local monitoring is applied in the observation of local phenomena. This statement can sound superfluous but in order to observe and measure the development of a local phenomenon such as the propagation of cracks, their location must be found in the first instance. This implies that a local monitoring strategy is realized after another kind of monitoring has detected the existence of a phenomenon. The local monitoring can be defined as a NDE and is sometimes considered as a not true SHM method because it cannot determine the health of the structure, since is impossible to do it on local level (Hejll, 2007)

- *Global monitoring*

Using a global monitoring strategy the structure can be evaluated altogether. This allows tracking global phenomena such as deformations and vibrations. The state of the art in the SHM consists in the use of global monitoring strategies in order to detect damage in the structure, but it isn't an easy task. In this case the job of the system is not only to carry out the measurements but also to interpret them and even apply decision making algorithms in order determine if there is damage, where it is located and how severe is it. According to Dong (2010) citing Bisby (2006) SHM monitoring, depending on how much sophisticated it is can offer different levels of detail:

Level I: the SHM system is able to detect the damage of the structure.

Level II: the SHM system is able to detect if there is damage and also give some information of its location.

Level III: the SHM system can detect the damage, locate it and even inform its extension and severity.

Level IV: the SHM system is capable to spot, locate and measure the extension and severity of the damage and after that, predicts the remaining service life of the structure and emits alerts. This is the most sophisticated level of a SHM and would make possible a very quick response that can be critical for the safeguarding of the users of the structure.

- Selection of the load effect strategy

This selection depends on how are the loads that produce the phenomenon that is to be measured. Basically there are two types of loads: statics and dynamics.

- *Static monitoring*

Here is included the monitoring of the phenomena produced by static or quasi-static loads, i.e. loads that vary slowly over time. Normally in these cases is sufficient to measure only the peak values produced. For example a static monitoring is done in the proof loading of bridges where a known load is applied on the bridge and deflections are measured. The measuring off settlements, crack widths and inclinations are activities included inside the static monitoring strategy. Even the collecting of temperature and other environmental data can be considered to be a static monitoring.

- *Dynamic monitoring*

In the dynamic monitoring is needed a much higher sampling rate of the measurements in order to collect the data that is produced by dynamic loads. With dynamic monitoring is possible to get information of the modal parameters of the structure, such as frequencies, mode shapes and damping. The measuring of this kind of parameters is very important because with them can be calculated some physical properties of the whole structure, like the mass, stiffness and damping coefficients. Estimating them and their variations in real time are the keystones needed that allow designing a more sophisticated SHM system, able to detect damage, its location or even more.

- Selection of the evaluation method

The evaluation method is the technique used to interpret and analyze the data collected by the SHM system in order to emit a result. During the evaluation the collected data is used and gathered in order create the model that must simulate the real phenomena that was required to be measured in the beginning. For example, if a global monitoring system based in the use of strain gauges sensors applying a static monitoring strategy with long – term and triggered data collection was designed in order to measure the deflection of the beams in a bridge a model able to simulate this phenomenon with that input must be constructed.

After the model is constructed a methodology to interpret it must be selected. Normally this is done with a probability based evaluation but also more advanced methods are used, such as the finite element model methods:

- *Probability based evaluation*

The load effect, represented by the data interpreted by the model, is compared with the structural capacity of the monitored structure or element. It is called probability based because the most of the design codes are sustained on probabilistic models in order to estimate the capacity of the structural members. For having a satisfactory verification the resistance R must be higher than measured the load effect E:

$$R \geq E$$

- *Finite element model evaluation*

Finite element models of the structure can be created in order to emulate the results of the monitoring. In this way the monitored changes can be interpreted by the model in order to predict its future response. This leads to the possibility of the prognosis of damage before it has started to occur and even its future development through the structure.

Finite element methods in combination with optimizing tools are also being developed for the identification of material and structural parameters from the structural response. These so called reversed modelling approaches in combination with long-term monitoring prove to be an important tool in SHM operations in the future (Hejll, 2007).

The final objective of the previously enumerated activities is the selection of the most adequate strategies and sensors for the phenomena that is required to monitor and which level of sophistication is the desired.

1.2.5. Smart-monitoring of RC structures

The monitoring of Reinforced concrete (RC) structures can be carried out by focusing in the concrete matrix or in the steel bars. In the case of a monitoring system focused in the concrete matrix it is required that the used sensors have the enough size to avoid the errors induced by the micro-mechanical properties of the concrete, such as the micro-cracking and the rheological phenomena. Due to this fact, this approach results to be not suitable for the installation of a Smart-monitoring system, which would require the utilization of MEMS that are smaller devices. For this reason is more convenient to focus the attention in the installation of sensors in the reinforcement steel bars, which homogeneity provides the possibility of collecting measurements that are representative of the average behavior of the steel and concrete.

Currently, in existing applications, electric strain gages and FOS sensors are used for the monitoring RC structures. These devices are commonly installed by gluing them in the surface of the steel bars, or are incorporated in a longitudinal groove machined along the bar. The reality is that these technologies and their application methods present many problems and drawbacks. Firstly, both types of sensors can result damaged during the installation or during the concrete pouring and in addition they are subjected to a harsh environment along the service-life. Moreover, other issues are encountered among which can be included the loss of the adhesion of the sensor with the bar, money and time costs of the installation and requirement of specialized labour.

However, an interesting application of this technology is being developed by Tondolo et al. (2018), which involves the utilization of low-cost MEMS sensors installed inside steel bars for the measuring of axial strains. More specifically a transducer is embedded in a small cavity drilled in the core of the rebar, feature that gives a good solution for the problems previously exposed. Excepting the required places for the connection, that are required for the transmission of data and power, the system is totally sealed, characteristic that is very important for its functioning. The sensors are able to measure the pressure inside the cavity. Then if the steel bar suffers any change in its longitude, through the laws of the structural mechanics, the volume of the cavity can be calculated and will be recorded by the device. In addition it is necessary to measure the temperature inside the cavity in order to estimate the variation in the volume by using the laws of thermodynamics applied to the ideal gases, being the fluid in this case the air inside the cavity.

This smart-monitoring system has many advantages over the traditional strain sensor devices, being more durable, economic and able to provide a more accurate, reliable and robust monitoring of the structure, due to the homogeneity of the steel where they are placed and due great quantity of sensors that can be installed. In addition these sensors represent a very important improvement in the case of fire emergencies, because they offer the possibility of monitoring the temperature of the steel, which is the most critical part of a RC structure in this kind of situations.

2. Building Information Modelling

2.1. Background

Whatever the construction project that is being developed, in order to carry out it there are tens to hundreds of documents, blueprints and details that must be followed and interpreted. This number can easily arrive to thousands in the case of major infrastructure projects, such as bridges and tunnels. This job of interpreting the documents is not easy and also must be added the fact that the construction industry is multidisciplinary by nature. In every project, no matter its size, are involved several different disciplines that have their own tasks inside the same project.

This huge amount of information needed for the construction, combined with deficiencies or the lack of communication among the different disciplines, foster the existence of errors and omissions in paper documents that can lead to unexpected field costs, delays and legal problems.

These issues have made the construction one of the least efficient industries in the current days. According to McKinsey, a management consulting firm, since the last century the construction industry productivity has increased in a very slow rate in comparison with others industries such as agriculture and manufacturing. Based on the study, in the case of The United States the productivity in 2010 was even lower than it was in the 1960's.

Figure 7: Productivity of construction industry.

Source: https://www.economist.com

Many efforts have been done in order to solve these problems. The implementation of technologies such as 3D CAD tools (computer aided design) has improved the velocity of the design. Also the development of the internet has made more efficient the timely exchange of information. This contribution has been important but has done little to reduce the severity and frequency of conflicts among disciplines in paper documents (Eastman, et al, 2008).

Because of this need of modernization, Building Information Modelling (BIM) was born. BIM is a methodology that employs digital modelling software in order to carry out a more efficient design and management of a project. Instead of having a great amount of separated drawings, schedules and specification details, all the information needed can be found inside a single digital model, that can be accessed, consulted or even changed by all the disciplines involved in the construction project. This means that the communication among the disciplines is more efficient, not only during the design phase, but along the entire life-cycle of the project. This leads to improve the productivity in the construction, to shorten the completion time and to manage the project in a better way during its service life.

2.2. State of art

2.2.1. What is BIM?

As it was defined by Autodesk in 2019 one of the leading firms in the BIM software industry:

"Building Information Modeling is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure".

BIM is closely related to the using of computer programs but is a common misconception to think that BIM is only software. In reality it is a methodology that integrates all the professionals that play a role in the construction process, such as engineers, architects, constructors, facility managers, etc. and create a transversal communication flow among them. This is done through the elaboration of a virtual model that contains all the information related with the structure during its entire life-cycle.

BIM offers several advantages in comparison with the traditional methodology:

- The BIM tools are able to update the information automatically. If an element is modified in a specific visualization it is updated automatically in all the other plans, sections, details and 3D views. This takes away the possibility of the human error and there is no place for incoherencies, which is a very common problem in the traditional methodology.

- All the stakeholders work in the same model. This makes impossible the loss of information due to lack of coordination among the versions of the project that the different professionals use.

- The project is developed since the beginning in a collaborative environment. The professionals of each discipline can pose different alternatives that they consider convenient for the project, and this will be known for everyone.

- The operation and the facility management tasks of the structure become much more efficient. That is because the information of everything, including the manufactures, service life, and even the performance of the elements can be added to the BIM model.

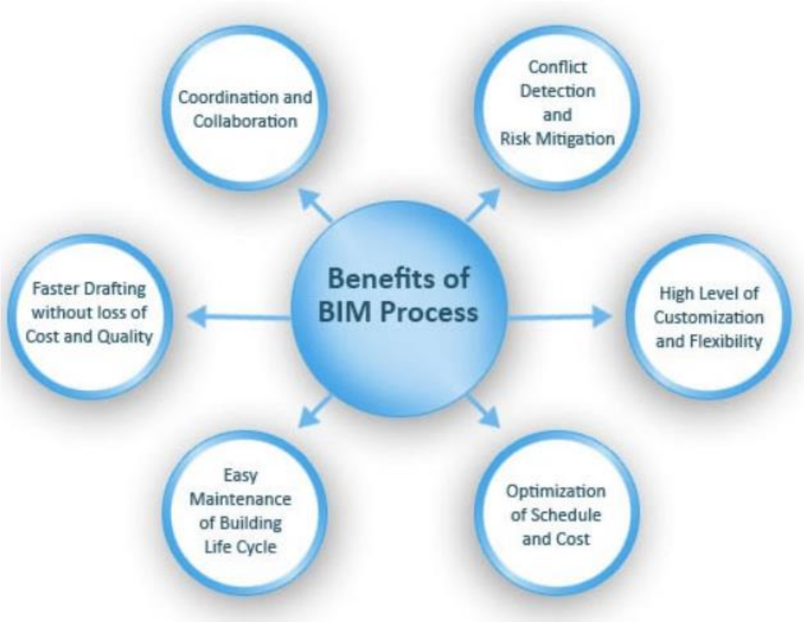


Figure 8: Benefits of BIM process.

Source: https://www.aproplan.com

2.2.2. BIM dimensions

As was said before, the life-cycle of buildings and infrastructures covers many phases. It starts with its idealization and design, passing through its construction and operation, until the structure concludes its lifetime and it is dismantled in order to give place for a new project. The BIM methodology is able to handle this process treating it with different *dimensions:*

- *1st dimension – The idea*

Every project starts from an initial idea. Here the location is defined together with the tentative geometry and the first estimations of the costs and volumes.

- *2nd dimension – The sketch*

In this dimension are determined the generic characteristics of the project. Greater or lesser amount of information is compiled, such as materials, possible structural schemes, structural loads applied, the sustainability level that is required, among other useful data for the project.

- *3rd dimension – The 3D model*

The information collected in the previous dimensions is gathered and then a 3D digital model is elaborated. This model is not static; it evolves along the development of the project because stage by stage more details are added to the elements. The final model is the As-built one that recreates faithfully the real delivered product.

- *4th dimension – The time schedules*

Here the BIM methodology brings the possibility of considering also a temporal dimension. In this way it is possible to carry out an exhaustive temporal scheduling of all the project phases. Information about completion dates, installation and construction time, the order in which components must be installed and dependencies with other project disciplines is the data that can be included inside this plan.

BIM also allows to create different visualizations of these construction stages, enabling a more efficient and error-free execution of the project. Schedules can variate according to the project stage and the BIM tools allow controlling it efficiently.

- *5th dimension – The costs*

BIM brings the dynamism to the next level making possible the estimation and cost analysis as well as the possibility of controlling it during different phases. Higher levels of productivity can be reached thanks to this feature, and staying within the budget becomes a more achievable task.

- *6th dimension – The simulation*

One of the most valuable characteristic that BIM offers is the possibility to simulate the different alternatives of the project, thanks to its intelligent environment. This makes possible to select better techniques and technologies that optimize the time, costs and energy consumption besides the reduction in the environmental impact.

- *7th dimension – The operation*

There is the common mistake of thinking that after a project is delivered the work is done because everything is already executed, but nothing could be further from the truth. The maintenance and operation of a building or an infrastructure can significate a very important percentage of the total accumulated cost at the end of its lifespan. In the following chart (El-Fatah, 2009) can be observed the cost impact of each stage in the total cost of a construction. It is very remarkable that operation and maintenance works can represent a considerable part.

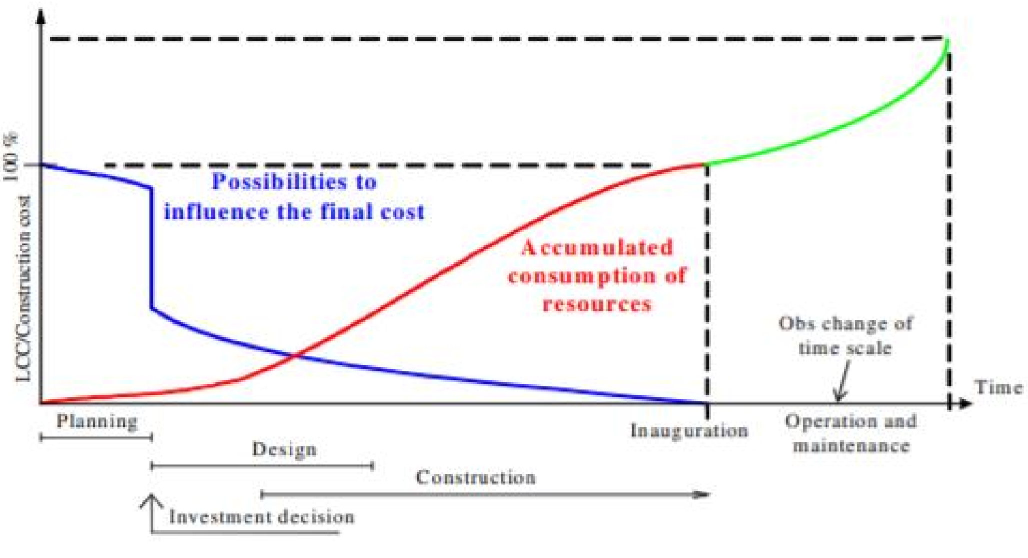


Figure 9: Impact of stages in the final construction cost.

The infrastructures are characterized by large investments (construction cost) and a long service life of 50 to 100 years. Although the annual maintenance cost is relatively small compared to the investment cost (less than 1%), the sum of the maintenance cost over the service lifetime is of the same order of magnitude as the investment cost (Klatter and van Noortwijk, 2003). The bridges or any infrastructure maintenance costs depend on the structural type that is used. Due to this fact the decisions made during the planning and designing stage affects directly the operation and maintenance expenses.

The BIM methodology has demonstrated its usefulness in the operating and maintenance of a structure.

In order to carry out these tasks effectively is very important to have information of how the structure was finally constructed. In the traditional methodology, because of the lack of dynamism in the project development, design and construction documents rarely (if ever) match real world conditions after the fact. This issue is solved with the use of BIM. Firstly if the BIM methodology is followed along all its dimensions the difference between the planed and the delivered product is minimized. If something must be changed unexpectedly, with BIM is easy to modify and the correspondence between the model and the actual result is assured. That means that the digital model created along the previous stages can works as an As-Built model.

Secondly, but not less important, this model is very rich in information and it stores the characteristics of all elements used in the project, such as their costs, manufactures, lifespan and why not, maintenance plans. The BIM model can be used to retrieve and analyze maintenance data.

2.2.3. Interoperability

A project can be carried out by several work teams that belong to different organizations and disciplines in order to complete the different stages of the project. It is desirable that the tools used by each discipline are able to share information with the others and also the data generated is usable for the next phases without re-entry or loss of information.

The multidisciplinary environment of BIM brings with it the challenge of how to make possible that professionals in the different fields can work together efficiently in a unique digital model. Nowadays the market is plenty of technology companies that offer different software for the various disciplines involved in a project. For instance, this issue can be especially challenging along the operation and maintenance phase, because being this the longer one, it is very likely that the professionals in charge be changed or the software used doesn't be always the same. The data must be kept intact after any transfer.

Because of this the interoperability among tools is one of the most relevant features that must be developed for the BIM environment. But what does interoperability really means? AFUL interoperability working group gives the following definition:

"Interoperability is a characteristic of a product or system, whose interfaces are completely understood. With respect to software, the term interoperability is used to describe the capability of different programs to exchange data via a common set of exchange formats, to read and write the same file formats, and to use the same protocols".

For BIM tools is needed not only the ability to transfer information but also to transfer meaning. This is called *semantic interoperability*. Often, software with different purposes but owned by the same vendor can offer tools that allow the data transfer among them, or even with programs made by other companies. But this is not genuine interoperability, is just only compatibility. In order to achieve real interoperability the programs must rely on a common information exchange reference model based in open standards

- <u>Building Smart and the Open standards</u>

Building Smart is an international, open and neutral not-profit-making organization whose commitment is the creation and dissemination of open and international standards for the improvement of the collaborative design, realization, and operation of buildings and infrastructure. It is constituted by several members around the world, such as the leading software developers, building and infrastructure companies, government bodies and educational institutions.

Figure 10: Some of the Building Smart members.

Source: www.buildingsmart.com

Building Smart is constituted by five basic standards. The following are those important for the developing of this work:

- *Industry Foundation Classes (IFC)*

This is the communication protocol in which is based the data exchange. In other words, it is the data schema or format that is in charge of reading the information located in the model in one program and translating it in a common language. It is currently translated in an ISO standard (ISO 16739)

- *Building Smart Data Dictionary (BSDD)*

Each program even though it can do the same things of another, and similar elements can be created they are not structured exactly the same. Maybe in a program a raft foundation is established in the category of slabs, but in the other software it belongs to the category of foundations. This leads to a communication problem. The Building Smart data Dictionary (BSDD) is a shared library of objects and their attributes that is used to identify objects in the built environment and their specific properties regardless of language. In other words, is the language that the IFC format recognizes. As the IFC, the BSDD is currently translated in the ISO standard 12006-3

- *Model View Definitions (MVD)*

Model view definitions are subsets of the general IFC schema that are focused in the data exchange of a specific using or workflow. For example when is needed the transference of a model that was created in an architecture software into a structural analysis one. In this case, there is a lot of information inside the architecture model that is useful for structural analysis purposes, such as the cross sections and lengths of the members or the materials, but many other features maybe are no necessary. A Model View Definition MVD is basically a filtered view of the IFC that allows users to export specific packages of model information to meet a particular use.

So depending on the task for which is going to be used a model after it is transferred different options of MVD are available:

Architecture and building systems → MVD Coordination View

Structural planning → MVD Structural Analysis View

Facilities management → MVD Handover View

2.2.4. Implementation of BIM nowadays

The BIM usage around the world is increasing strongly. According with a market study made by McGraw Hill Construction in 2013, BIM adoption has been experiencing a huge expansion worldwide through the current decade.

Despite of this, the level of BIM adoption in the infrastructure sector is lower than the one in buildings construction, but there are many experiences that shown that this kind of projects are well-suitable to benefit from the BIM methodology. The factor that can increase the implementation level of BIM in major projects, and in fact is exactly what is already being doing since few years ago, is the adoption of government policies.

Percentage of Contractors That Are Using BIM on Specific Project Types
(By Country)

Source: McGraw Hill Construction, 2013

Over 40% | 30% to 40% | 15% to 29% | Under 15%

Building Projects

	UK	France	Germany	US	Canada	Brazil	Japan	South Korea	Aus/NZ
Commercial (Offices, Retail, Hotels)	69%	68%	59%	66%	54%	53%	63%	48%	70%
Institutional (Education, Healthcare, Religious)	61%	32%	31%	77%	41%	31%	23%	35%	39%
Government/Publicly Owned (Courthouses, Embassies, Civic/Sports and Convention)	54%	10%	22%	68%	44%	12%	0%	51%	37%
Multifamily Residential	33%	35%	44%	18%	26%	19%	23%	20%	26%
Single Family Residential	17%	19%	22%	1%	10%	16%	0%	1%	4%

Non-Building Projects

	UK	France	Germany	US	Canada	Brazil	Japan	South Korea	Aus/NZ
Infrastructure (Roads, Bridges, Tunnels, Dam, Water/Wastewater)	33%	19%	16%	14%	31%	28%	13%	24%	25%
Industrial/Manufacturing	26%	23%	19%	35%	36%	31%	47%	24%	34%
Industrial/Energy (Primary Power Generation, Oil/Gas Facilities)	20%	13%	3%	18%	28%	12%	0%	21%	16%
Mining/Natural Resources	6%	0%	0%	4%	18%	6%	0%	1%	11%

Figure 11: Implementation of BIM depending on the type of project.

Source: SmartMarket Report 2013. McGraw Hill.

Around the world the United Kingdom has one of the most ambitious BIM implementation programs. The British Standard Institute (BSI) has produced a series of standards (BS 1192) to support the industry in the adoption of BIM in which has been recognized that the process of moving the construction industry to a total collaborative working environment will be progressive. This process must be carried out by steps or levels that are called the *Levels of Maturity*.

These are established from the level 0 to level 3, as is shown in the following chart:

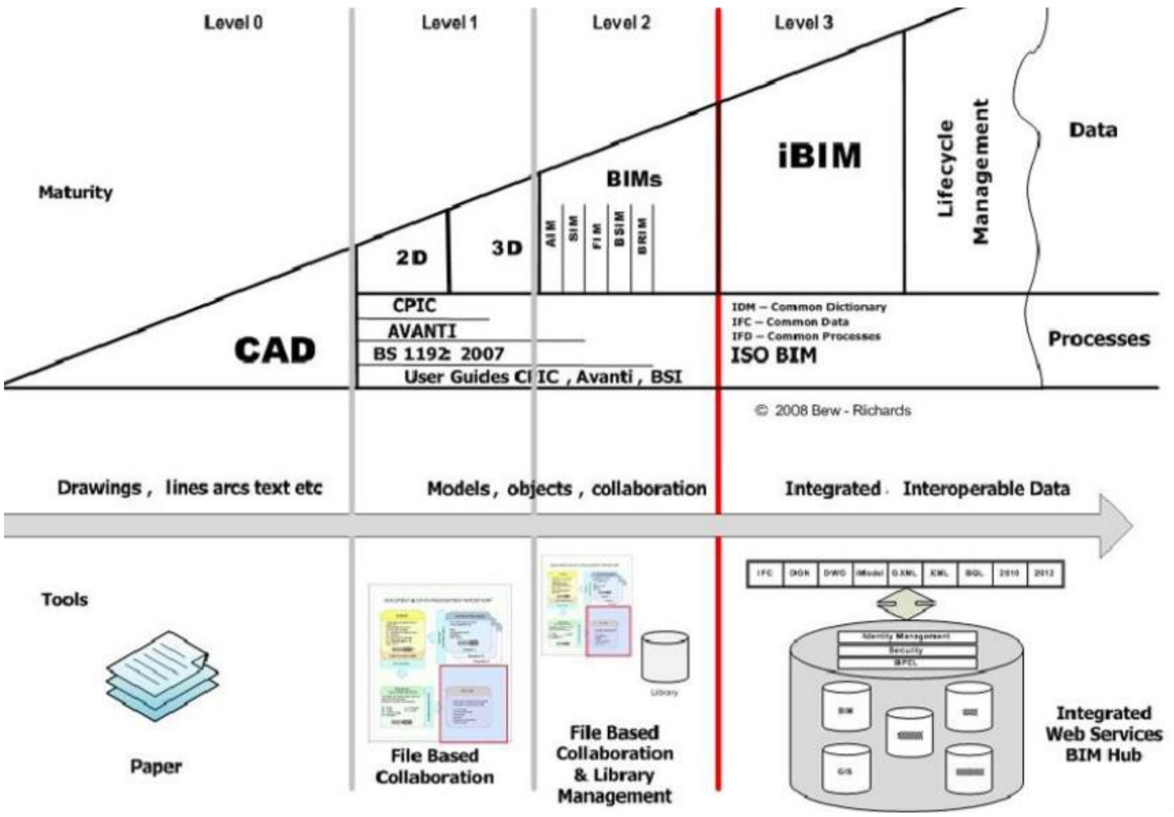


Figure 12: BIM levels of maturity.

Source: https://bimportal.scottishfuturestrust.org.uk

The UK government has mandate that all publicly-funded construction work must be carried out by using Building Information Modelling to Level 2 of maturity, by 2016. More recently has been released a new international standard for BIM, the ISO 19650 which is based in the BS 1192 series.

A lot of developed and developing countries are also taking seriously the adoption of BIM. In countries, such as Denmark, United Arab Emirates, Australia, US, among others, the government mandates the using of BIM in public projects. Some others like Chile, France and Qatar have fixed deadlines in which the implementing will be mandatory. The fact is that BIM is a current reality and its adoption can make a country rich on the infrastructure side, and also important set an example to others nations.

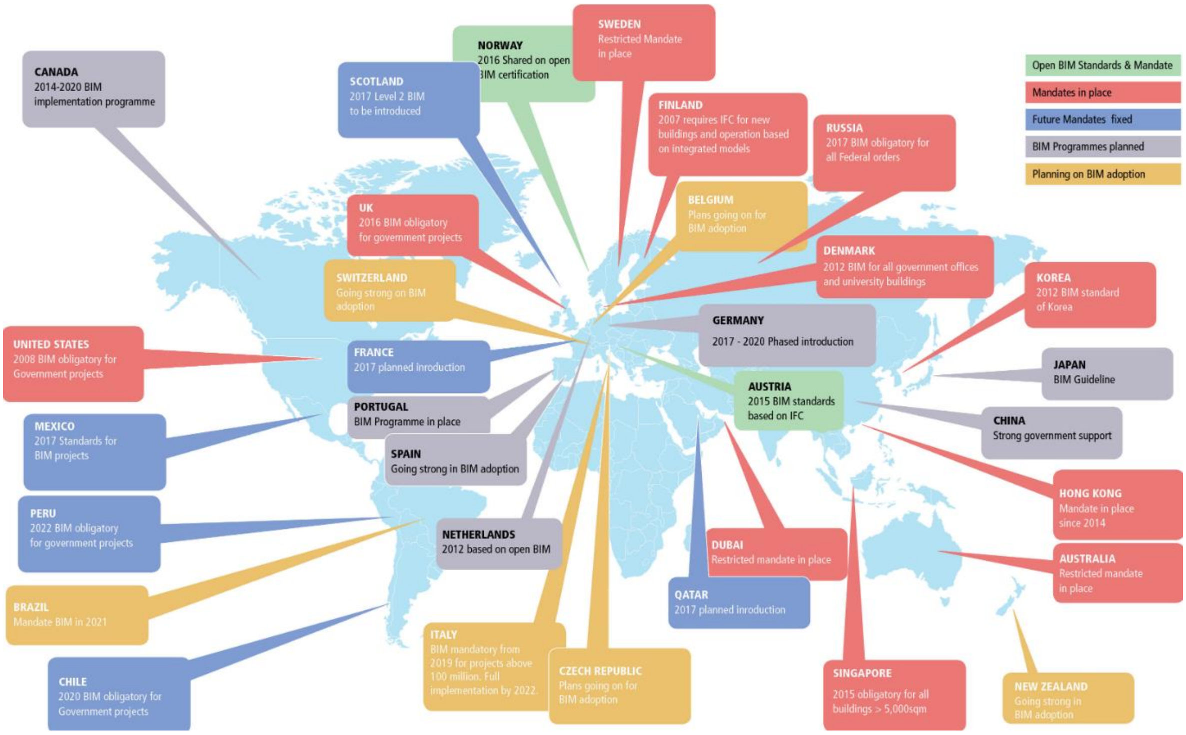


Figure 13: BIM implementation around the world.

Source: https://www.geospatialworld.net

Concluding, these strategies have shown effectiveness not only because of the general increasing of the adoption of BIM but also due to the growing in expertise of the contractors, that are using it at higher levels. According with McGraw Hill SmartMarket report (2013) this increasing is a global trend, as is shown in the following picture:

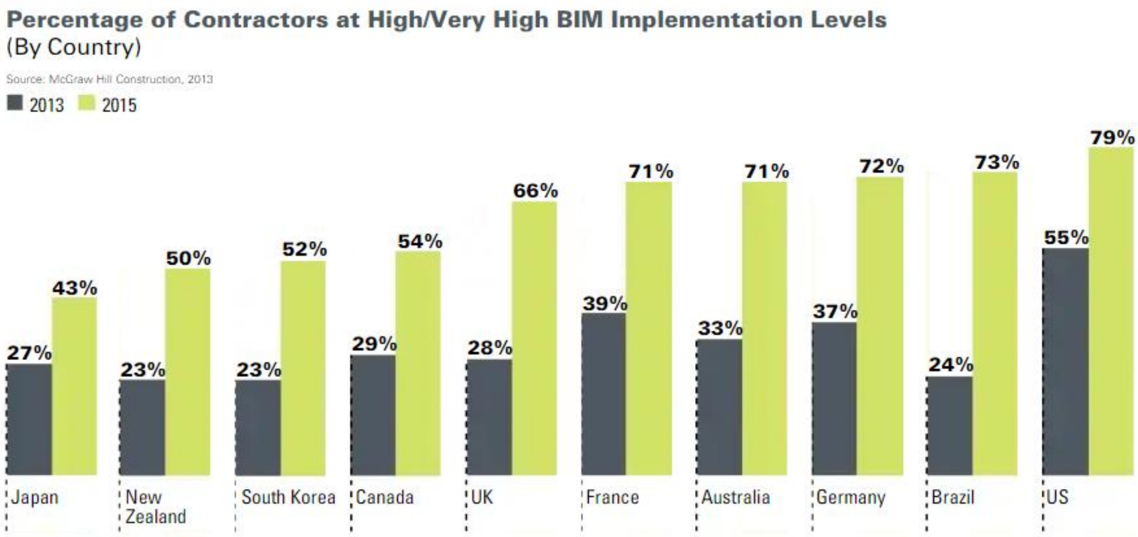


Figure 14: Increasing in BIM expertise.

Source: SmartMarket Report 2013. McGraw Hill.

Section 2: Problem statement and proposed approach

1. Implementation of SHM systems

The using of SHM in infrastructure is a step forward towards the implementation of proactive rather than reactive maintenance systems. Instead of taking action when the damage is already present and visible, SHM allows to prevent it before it occurs and anticipate its future development. That has made the Structural Health Monitoring a very promising technology in a world full of larger structures that can have an advanced age and subjected to heavier loads.

Nevertheless there are many issues that represent a limitation of the SHM implementation. They are basically the following:

- *Cost of SHM Systems*

The must current SHM tools are less economical than the traditional inspection methodologies. This is an important reason that has slowed its spreading around the civil engineering industry.

- *Lack of know-how*

Since SHM is a relatively new technology inside the civil engineering world the general expertise is not so deep. The designing of an efficient SHM system requires some specialized knowledge. Which sensors are more suitable, where those sensors must be placed, when and how often is better to carry out the measurements, etc. are some of the factors that must be taken into account, and for new users this may be confusing.

- *Installation of the systems*

In contrast with the traditional inspections methodology, most current SHM solutions need the installation of wiring in order to collect data measurements. This wire system could become huge in case of larger structures and is true that the installation works may be relatively time consuming, and expensive.

- *Data management*

A very important issue that SHM brings with it is the great amount of data collected in real time. While in periodic inspections the data is collected in a form, the different types of sensors perform a large number of measurements that can possible represent hundreds of gigabytes in the case of continuous monitoring. The management of all original raw data, and all post-processed data, during the entire lifecycle of the structure can become a problem if all the original data are to be kept for future processing (Rio et al. 2012).

- *Interpretation of the results and collaboration*

The most important feature given by the SHM is the possibility to detect and assess damage in real time, but it is impossible to accomplish this task just by looking at the data collected. The data must be interpreted by using different tools, such as analytical and numerical models.

The issue is that most of the times this analyses are only available for the SHM and the structural engineer and the advantages could be not totally exploited. Visualization of data and sensor networks between the parties involved in SHM, i.e., users of SHM (owners, consultants, technology providers, contractors, researchers, etc.) is commonly a “bottleneck” for SHM that can lead to inefficient utilization of SHM or even complete abandonment of the system (Glisic et al, 2010). In order to really take advantage of the SHM benefits the data and the analyses carried out should be available, comprehensible, and transferrable.

2. BIM as a tool for SHM

2.1. BIM potential

Building Information Modeling has considerably changed the way the design, construction and management of buildings and infrastructures is carried out by the construction industry.

BIM is used as a visual model in which can be simulated the real condition of a structure. In addition it can be seen as a digital repository that keeps all the project data safe and organized allowing the management of the project during the life-cycle, not only during design and construction but also along the service-life. Combining BIM with real-time monitoring of structural health with simulation methods will provide a robust and intelligent system for managing modern structures (Seaam et al. 2013). Furthermore, the BIM capability of visualizing the whole structure or its individual elements has shown to be an important tool with regards the decision-making.

The effective manipulation of SHM data collected is obviously a challenging mission. This problem can be addressed by integrating the collected data in a tool like BIM by creating a single digital model that can be effectively used whenever needed (Valinejadshoubi et al. 2017). According to Valinejadshoubi et al (2017), BIM can be beneficial in the SHM process in the following aspects:

- Visualization of sensors with their data in a semantically-rich model
- More effective SHM system planning and design
- Creation of unique digital model available for all the relevant stakeholders
- Better SHM data control and management
- Better interpretation and analysis of the measured data
- Better and more timely emergency reactions
- Can provide a useful database for future projects

2.2. Previous experiences

BIM is currently utilized as a tool in order to plan and design some building facilities such as mechanical HVAC systems, electrical installations and plumbing networks. Another kind of services can be also modelled in the multidimensional BIM environment, being fire protection systems, telephonic networks and data centers some of them. This leads to consider that structural health sensor systems can be seen as one more facility that could be installed in buildings or infrastructures. However, in the case of the operation of these facilities, i.e. facility management, BIM software solutions and standards, are not totally suitable to support this features and to allow decision-making (Gerrish et al. 2015). This can be attributed to the fact that BIM was initially conceived to be implemented in the design and construction phases, whose required data is different of the maintenance phase (Becerik - Gerber et al. 2012).

In the case of infrastructures the bibliography dedicated to the use of BIM in facility management is not so deep. Particularly the research related with the integration of BIM with

SHM, has demonstrated that this topic is in phase of development, due to the fact that these are two relative new tools inside the civil engineering world. This is one of the challenging issues that must be faced by the BIM solutions industry in the near future.

The BIM potential in SHM systems necessarily implies the integration of this type of data inside the BIM solutions. Some researchers have appointed the lack of tools for the simulation of SHM elements in the available palette of BIM software and open standards. For this reason the development of these features has been addressed in the current bibliography because having them, more semantically-rich and interoperable BIM models can be created. Furthermore, another subject of interest found in the available studies has been the developing of different ways of visualization of the monitored data. SHM data is time-dependent, and for this reason the implementation of tools that allow its practical interpretation is very relevant and essential.

The current bibliography related with this topic can be summarized as follows:

- Rio et al (2012) were among of the first in addressing the representation of structural health monitoring sensors inside the BIM environment and also including them in the IFC open standard. Their research was based in the modeling of an existing building with vibrating wire sensors installed during its construction. Neither the authoring software nor the IFC standards includes tools for modelling the sensors, so the alternative solution was the using of proxy elements such as smoke sensors in order to represent them. Custom parameters were assigned by the authors to the sensors, and a user defined property set was created in order to enable the storage of the sensor data in IFC format and allows its consequent exportation into an IFC 2x3 data file. After that, by the using of an independent model viewer can be confirmed that the IFC file is able to store all SHM data.

However, the creation of the new property set is a manual job and the entire process relies in visual inspection. According to the authors more specific modeling rules for SHM purposes have to be established and documented. On the other hand, will be very useful the development of automated methods for BIM quality assessment for SHM.

- This methodology was also developed by Chen et al (2014) but in this case with environmental devices, particularly temperature sensors. The data collected by these sensors was incorporated in a BIM model through an ad hoc method. Again user custom elements were defined in the authoring BIM tool for the representation of the sensors. Then the sensor data, stored in text files, was assigned to the different element instances, creating user defined parameters and property set in order to be suitable for the IFC export. Also in order to allow the visualization of the time dependent data some 2D charts can be generated using the authoring tool accessing to its API (Application Programming Interface) in order to develop macros. The drawback is that these features sometimes are created for specific projects and not developed for general purposes and most of the data resides only inside the model.

- Valinejadshoubi et al (2017 and 2018) likewise the previous researchers have experimented with the inclusion of SHM in building models. As in earlier experiences, some structural sensors were incorporated in the model satisfying the IFC requirements. In this case the model is of a non-constructed building.

Before the simulation of the sensors the interoperability offered by BIM tools allowed to transfer the architectural information model to structural analysis software. Being the analysis carried out, it was used to identify the more adequate locations of various SHM sensors. Mode shapes and floor acceleration were used to determine the locations of accelerometers and maximum bending moment places coincide with the more logic locations for placing the strain sensors. This demonstrated the usefulness of BIM in the planning and design of more effective SHM systems.

According to the researchers some of the virtues of BIM can be applied to the sensor system simulated. The sensors can be sorted, managed and organized in schedule tables, where can be included parameters such as type, description, model, manufacturer, cost, location, among some others. A part of this, the authors also have demonstrated the utility of working directly with the API of the BIM software or alternatively the utilization of already developed tools that work in the same way. These add-ins, as have been called, can be used for example to link the virtual sensors in the model with the data coming from the real sensors, data that can be also included in the schedules if it is desired. Was also demonstrated that is possible to link external tools like Microsoft Excel or MATLAB to de model, utilities that can be helpful in manipulating the SHM data to interpret it better.

- Contemporaneously similar studies were developed by Del Grosso et al (2017) but applied to a bridge. The model was firstly created in structural analysis software, and then transferred to the BIM general tool, demonstrating that this procedure can be also suitable for infrastructural projects.

- Dávila Delgado et al (2016, 2017 and 2018), as the other researchers exposed above, have addressed quite recently this topic. These studies, in agreement with the previous researches done by Rio et al (2012), have appointed the usefulness of defining the sensing elements in a way that make them suitable for open BIM standards. A general method was used to amend various IFC schemas, while trying to use the existing IFC entities as long as possible was the rule. This approach resulted to be useful because has permitted to describe other types of monitoring systems without changing so much the IFC specification.

The authors have also experimented with automated parametric modelling applied in a bridge with a SHM system constituted by fiber optic sensors. In order to do that, virtual sensors were created in the BIM model, taking in account the peculiarity that every sensor may differs in its geometry as these are conceived for distributed sensing. For that reason the FOS had to be simulated as an adaptive component. Also the author assigned graphical parameters to the sensors, feature which allows controlling the visualization of each sensor independently. That is useful to represent the performance of the structure or some interesting behavior by the change in color or texture.

Have been previously appointed by the researchers that until now BIM software solutions lack capabilities to allow dynamic visualization of data and to record and use time-series information, such as the data related to the performance and degradation of the structure. Currently there are two ways to solve this problem. One is the developing of new internal tools using the BIM software API and the other is to create stand-alone external applications from scratch. They finally addressed this issue creating an independent tool, but instead of creating it from the beginning, they used a game engine. Game engines are software frameworks that help the development of video games. Nevertheless they are also suitable for developing other kind of utilities as scientific applications.

2.3. Aims of the present work

As it was studied by the researchers that have worked previously in this topic, BIM has demonstrated its value by improving the management of monitoring data and providing good tools for its visualization. In addition to this, including sensor and monitoring data inside BIM models represents many advantages, due to the fact that their locations can be evaluated in a better way and future errors during its installation can be avoided.

The aim of this thesis is testing the potential of the utilization of BIM for SHM purposes by using different BIM software tools. Particularly will be addressed the following aspects:

- SHM system planning, design and installation.
- SHM data management.
- SHM data visualization.

3. Cases of study

In the present thesis the potential of BIM in SHM purposes is evaluated through two real cases. A bridge and a tunnel:

3.1. Stura Bridge

The studied structure consists in a bridge that crosses the Stura River, being part of the Torino – Caselle highway. This is located in the northern part of the city of Turin and communicates the city center with the airport. The structure is owned and managed by ANAS (Azienda Nazionale Autonoma delle Strade), the public company in charge of the construction and management of part of the road infrastructure around Italy.

In the following figure can be observed its exact location by using Google Maps:

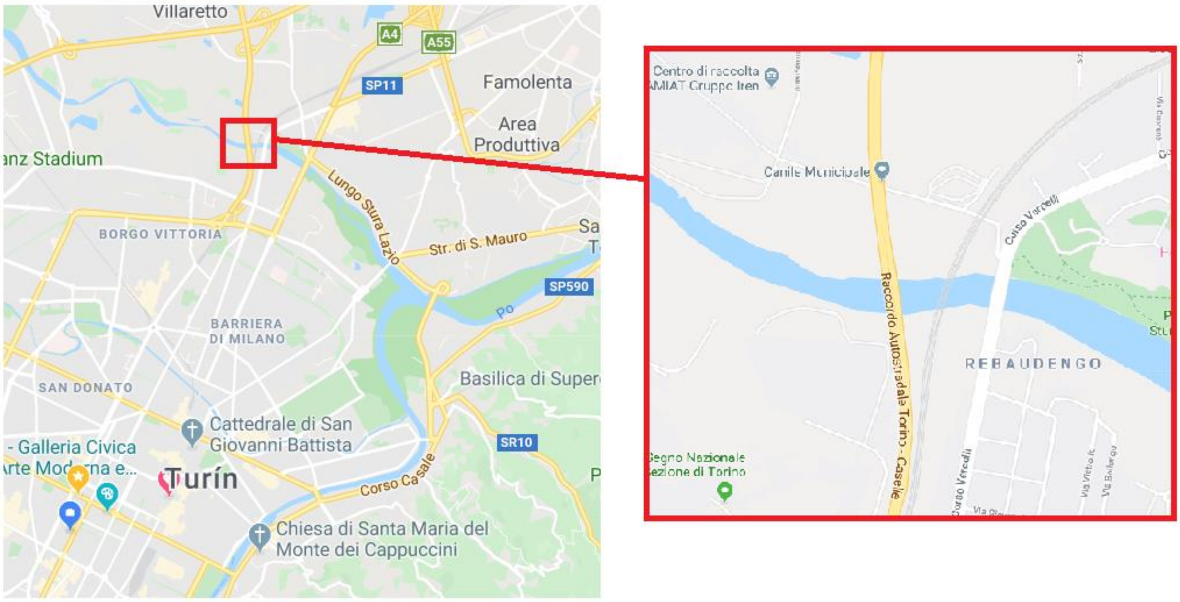


Figure 15: Case of study location

Source: Google Maps

The structure is in reality constituted by 2 independent and equal bridges, one for each traffic direction. The bridges are constituted by 6 simply supported consecutive spans, all of them with the same length of 36.50 m. The deck, with a width of 13 m, consists in a reinforced concrete slab of 25 cm thick, supported by 3 longitudinal prestressed concrete beams of 35.70 m length, with 2.10 m height double T cross-section. The interaxis between the beams is 4.30 m, being the cantilever of the slab of 2.20 m on both sides. In each span the longitudinal beams are joined transversely by 5 equally spaced reinforced concrete beams with rectangular cross-section, being its height equal to web of the longitudinal beam and its width 25 cm.

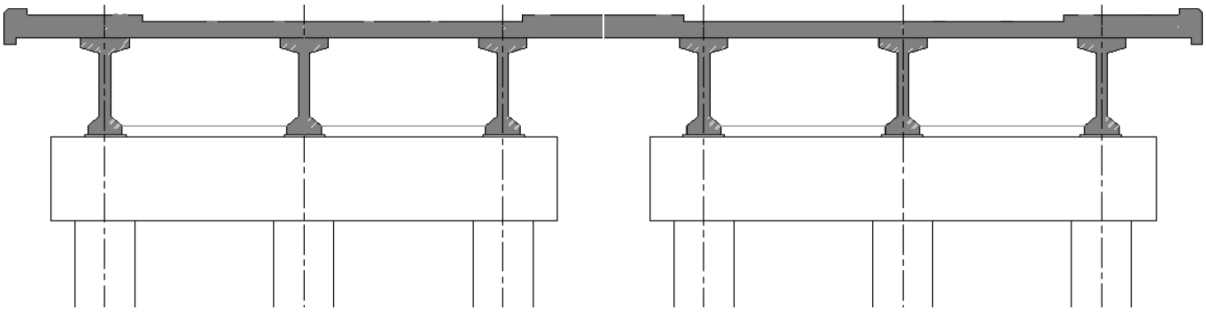


Figure 16: Transversal profile of the bridge.

The longitudinal beams rest over very thin supports that are installed on reinforced concrete caps with 11 m length and rectangular cross-section with 1.80 m height and 2.20 m width. The intermediate pier supports are constituted by 3 reinforced concrete columns with circular cross-section of 1.20 m diameter, joined at the top by the reinforced concrete cap with the previously exposed dimensions. The height of the piers is variable along the bridge, being these starting from the Turin side of 1.50 m, 11.80 m, 11.35 m, 10.50 m and 6.80 m respectively.

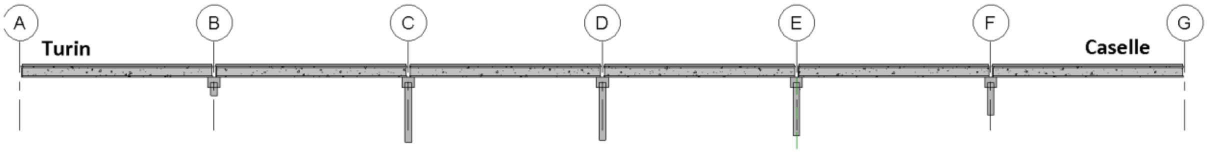


Figure 17: Longitudinal profile of the bridge.

The deck is skewed an amount of approximately 14.60 º.

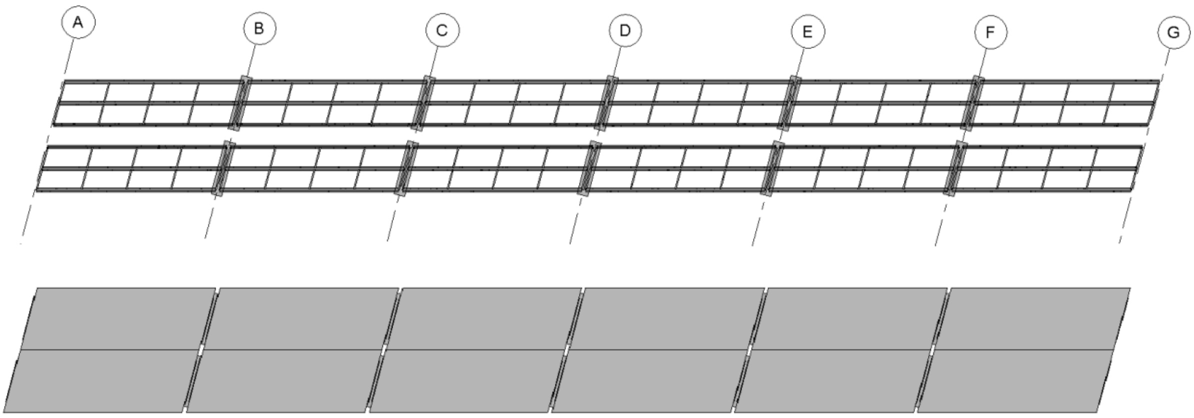


Figure 18: Plant view of the bridge.

The real bridge can be observed in the following pictures:

Figure 19: Stura bridge pictures.

Source: Piano dispiegamento dei Sensori (SYSDEV– Studio AITEC, 2018)

In the structure is installed a SHM system constituted by 49 multi-purpose sensors. The decision of the number and location of the sensors came from the evaluation of the structure with the creation of a finite element model in a structural analysis software, where were identified the most critical locations, or those ones subjected to the most relevant effects. In the bridge are installed 2 types of multi-purpose sensor devices: strain multi-sensors and displacement multi-sensors. The first consist in a flexible part which is a strain foil gauge that is able to measure the deformation of the element along its axis, and a rigid part constituted by a metal box that contains a thermometer and an accelerometer. The second is constituted by a piston that is able to measure the relative displacement of an element respect to another considered fixed, and by a rigid part that as in the previous case contains a thermometer and an accelerometer.

All the information about the sensors is present in the following data sheets:

A) Strain multi-sensor data sheet.

	Il sensore SHM è composto da due parti, inglobate tra loro a formare un unico oggetto: • Una **parte flessibile**, in materiale plastico, che incorpora l'elemento sensibile allo STRAIN e una guida termica per la lettura di TEMPERATURA • Una **parte rigida** (contenitore stagno apribile) contenente l'elettronica del sensore e la batteria intercambiabile			
DIMENSIONI	**PARTE FLESSIBILE**	55x250x0,3 mm.	Dimensioni parte sensibile allo strain: 200 mm.	È totalmente stagna e sigillata e può essere verniciata o ricoperta.
	PARTE RIGIDA	98x64x36 mm.	È totalmente stagna e sigillata e può essere verniciata o ricoperta da materiali non materiali metallici (per non schermare l'emissione radio). È necessario lasciare accessibile il coperchio per la sostituzione della batteria.	
PARAMETRO	**RANGE**	**RISOLUZIONE**	**ACCURATEZZA**	**NOTE**
Deformazione (Strain)	+/- 3%	50 microstrain	+/- 50 microstrain	Misura bidirezionale eseguita lungo l'asse longitudinale del sensore
Temperatura	-40°C / +125°C	+/- 0,5 °C	+/- 0,5 °C	Aiuta a compensare la deformazione indotta dalla dilatazione termica del substrato
Inclinazione	-	0,05 °	+/- 0,05°	Eseguita con accelerometro triassiale
Accelerazione	+/-2g	-	Rumore tipico di 90µg/√Hz.	-
Evento sismico	Il sensore fornisce in output i seguenti parametri: • Durata dell'evento sismico, espressa in secondi • Frequenza media dell'evento sismico, per ogni asse (X-Y-Z), espressa in Hz. • Accelerazione di picco (positiva e negativa) registrata durante l'evento sismico, per ogni asse (X-Y-Z), espressa in mG • Spostamento di picco (positivo e negativo) registrato durante l'evento sismico, per ogni asse (X-Y-Z), espresso n mm Contemporaneamente al campionamento dell'accelerazione sui 3 assi, viene fatto un campionamento ad alta frequenza (125 Hz) dello STRAIN, memorizzando il valore massimo raggiunto, sia positivo che negativo. Inoltre, al termine dell'evento sismico, viene fatta una lettura finale di STRAIN e TEMPERATURA, per verificare gli effetti del sisma sulla struttura monitorata.			
DURATA BATTERIA	3/5 ANNI: sensori su strutture più stabili inviano meno messaggi consumando meno energia			
GRADO DI PROTEZIONE	IP67			
RANGE DI ESERCIZIO	-40°C + 85°C			

Figure 20: Stura bridge strain multi-sensor Data sheet.

B) Displacement multi-sensor data sheet

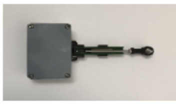
	Il sensore SHM è composto da due parti, inglobate tra loro a formare un unico oggetto: • Un **sensore di spostamento** a pistone • Una **parte rigida** (contenitore stagno apribile) contenente l'elettronica del sensore e la batteria intercambiabile			
DIMENSIONI	**PARTE ESTENSIBILE**	135/185 mm.	È totalmente stagna e sigillata	
	PARTE RIGIDA	98x64x36 mm.	È totalmente stagna e sigillata e può essere verniciata o ricoperta da materiali non materiali metallici (per non schermare l'emissione radio). È necessario lasciare accessibile il coperchio per la sostituzione della batteria.	
PARAMETRO	**RANGE**	**RISOLUZIONE**	**ACCURATEZZA**	**NOTE**
Spostamento	0-50 mm	0,1 mm	+/- 0,1 mm	Misura bidirezionale eseguita lungo l'asse longitudinale del sensore
Temperatura	-40°C / +125°C	+/- 0,5 °C	+/- 0,5 °C	Aiuta a compensare lo spostamento indotto dalla dilatazione termica del substrato
Inclinazione	-	0,05 °	+/- 0,05°	Eseguita con accelerometro triassiale
Accelerazione	+/-2g	-	Rumore tipico di 90µg/√Hz.	-
Evento sismico	Il sensore fornisce in output i seguenti parametri: • Durata dell'evento sismico, espressa in secondi • Frequenza media dell'evento sismico, per ogni asse (X-Y-Z), espressa in Hz. • Accelerazione di picco (positiva e negativa) registrata durante l'evento sismico, per ogni asse (X-Y-Z), espressa in mG • Spostamento di picco (positivo e negativo) registrato durante l'evento sismico, per ogni asse (X-Y-Z), espresso n mm Contemporaneamente al campionamento dell'accelerazione sui 3 assi, viene fatto un campionamento ad alta frequenza (125 Hz) dello STRAIN, memorizzando il valore massimo raggiunto, sia positivo che negativo. Inoltre, al termine dell'evento sismico, viene fatta una lettura finale di STRAIN e TEMPERATURA, per verificare gli effetti del sisma sulla struttura monitorata.			
DURATA BATTERIA	3/5 ANNI: sensori su strutture più stabili inviano meno messaggi consumando meno energia			
GRADO DI PROTEZIONE	IP67			
RANGE DI ESERCIZIO	-40°C + 85°C			

Figure 21: Stura bridge displacement multi-sensor Data sheet.

The installed SHM system was conceived to perform a long-term monitoring of the whole structure (Global monitoring), based on the continuous monitoring of the static or quasi-static loads passing over the bridge (Static monitoring) that produce strains in the elements and relative displacements between them. On the other hand to measure the accelerations and vibrations was planned a triggered monitoring regime, in which the system only records the values above the established threshold. In this thesis was only studied the potential of BIM in SHM for the continuous monitoring of the strains and displacements measurements, therefore the acceleration monitoring is outside the scope of the present work.

3.2. Brenner Base Tunnel

The Brenner Base Tunnel (BBT) is a straight, flat railway tunnel that will cross the eastern Alps under the Brenner Pass. The Brenner Pass is located at the border between Austria and Italy, and is one of the main passes of the eastern Alpine range, being the one with the lowest altitude. Because of this reason it is a very important traffic connection, along which passes the motorway E45 and the Brenner Railway, two vital transport infrastructures that join the northern and the southern part of Europe.

Figure 22: Brenner Pass. Right: Geographical location. Left: Photograph.

Source: https://en.wikipedia.org/wiki/Brenner_Pass.

The current infrastructures are not enough to support all the traffic of goods and people, making the traffic jams very frequent in the motorway. Also the railway service is not so efficient because the trains are limited to slow speeds due to the steepness of the existing tracks. The new tunnel will help to give a solution to this situation, allowing the trains to shorten the travel time between Innsbruck (Austria) and Fortezza (Italy), but it represents an engineering challenge due to the fact that after its completion, expected for 2028, it will be the second longest in the world with 55 kilometers long.

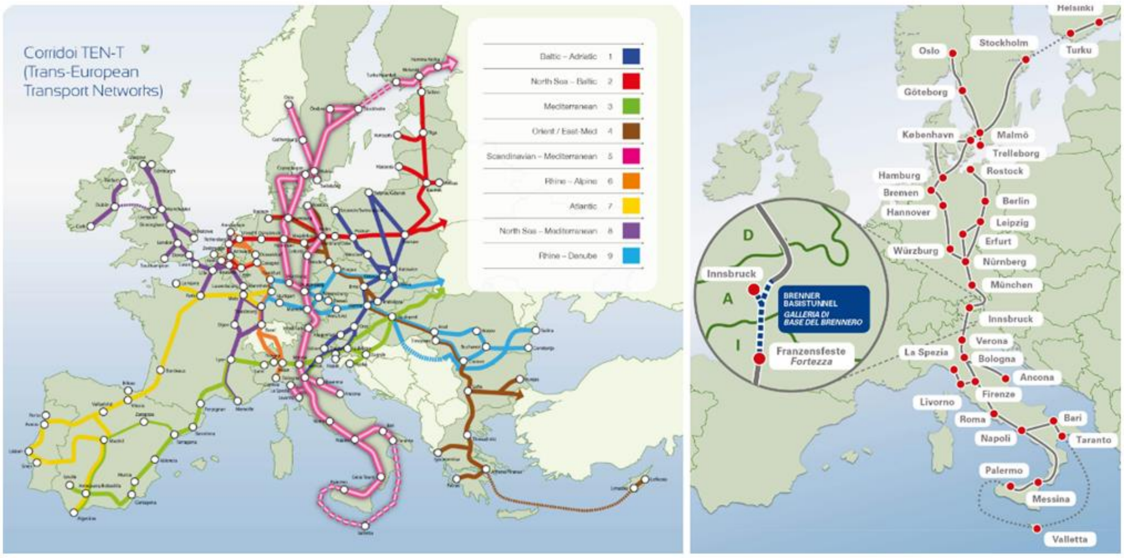


Figure 23: BBT in the context of the European Transport Network.

Source: https://www.bbt-se.com/en/information/media-corner/

The tunnel is in reality a system of 3 separated tubes. The two main ones have a diameter of 8.1 meters and run beneath the terrain with variable gap of 40 to 70 meters apart from each other. The third one consist in an exploratory tube with a smaller diameter that its useful during construction providing information about the rock mass, and will be essential for drainage when the BBT becomes operational. Moreover, the 2 main tubes are connected between them every 333 by side tunnels that work as escape routes in case of emergency.

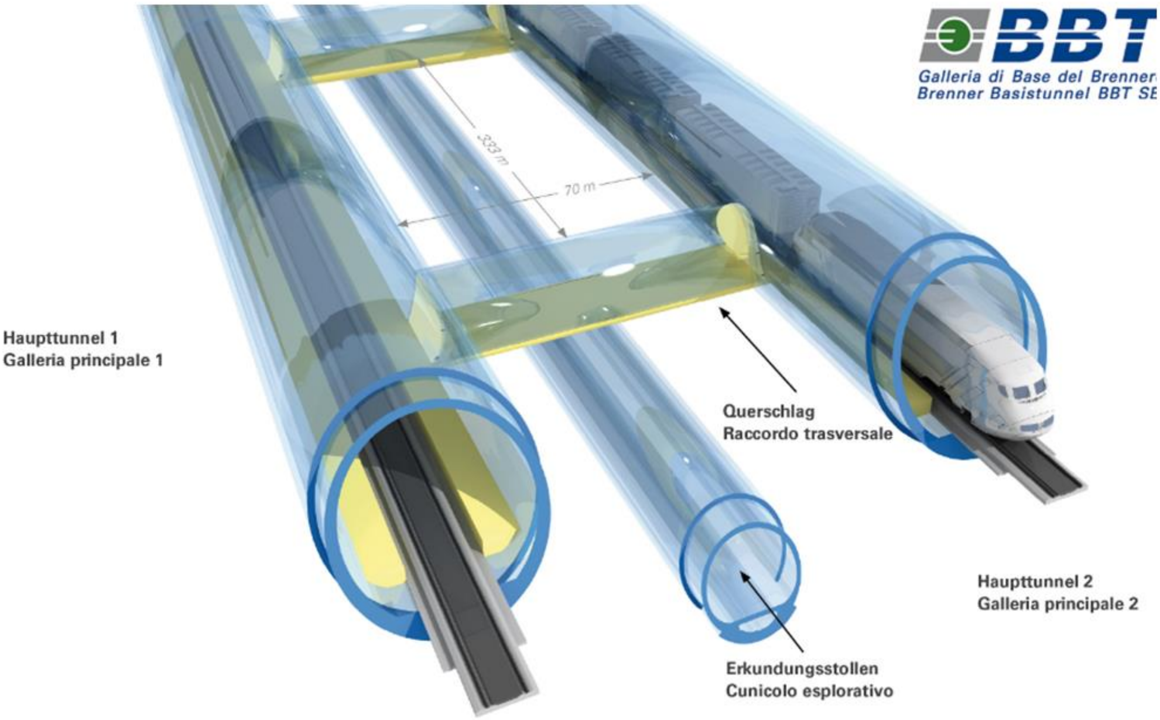


Figure 24: : Brenner Base Tunnel infrastructure virtual scheme.

Source: https://www.bbt-se.com/en/information/media-corner/

The tubes are constituted by a long chain of rounded pieces called rings that are composed at the same time by smaller parts, known as tubing ring segments. The ring´s segments work predominantly in compression with a behavior similar to the pieces of an arc. There are two types of segments: the standard ones, that are 6 for the case of the main tubes and have a shape which is not perfectly rectangular but rather a rounded parallelogram with their longitudinal extremes deformed by an angle. This angle is given by the key segments, which have a trapezoidal rounded shape and are the last pieces that are placed in order to complete each ring. Moreover, each ring is not aligned with the one in the previous progressive since it is rotated in the clockwise direction 51.4 direction, being the ring placed with the same rotation angle every 7 rings. All the segments have a thickness of 20 cm.

Figure 25: Tube pieces. Middle: Ring. Left: Key segment. Right: Standard segment.

Currently a traditional monitoring system is included inside the tunnel designs. This monitoring system consists in embedded sensors inside the reinforced concrete tubing ring segments and integrates different type of devices: a pressure cell located in the center of the extrados of the segments, a pair of extensometers in the radial direction, and another pair of extensometers in the longitudinal direction at the reinforcement depth, one for the intrados and other of the extrados. The system is completed by a lecture box, embedded in the segment but positioned at its extrados. Moreover, the system is installed just in the standard segments and in selected rings, each 50 meters.

Below is shown a scheme that illustrates the sensor system:

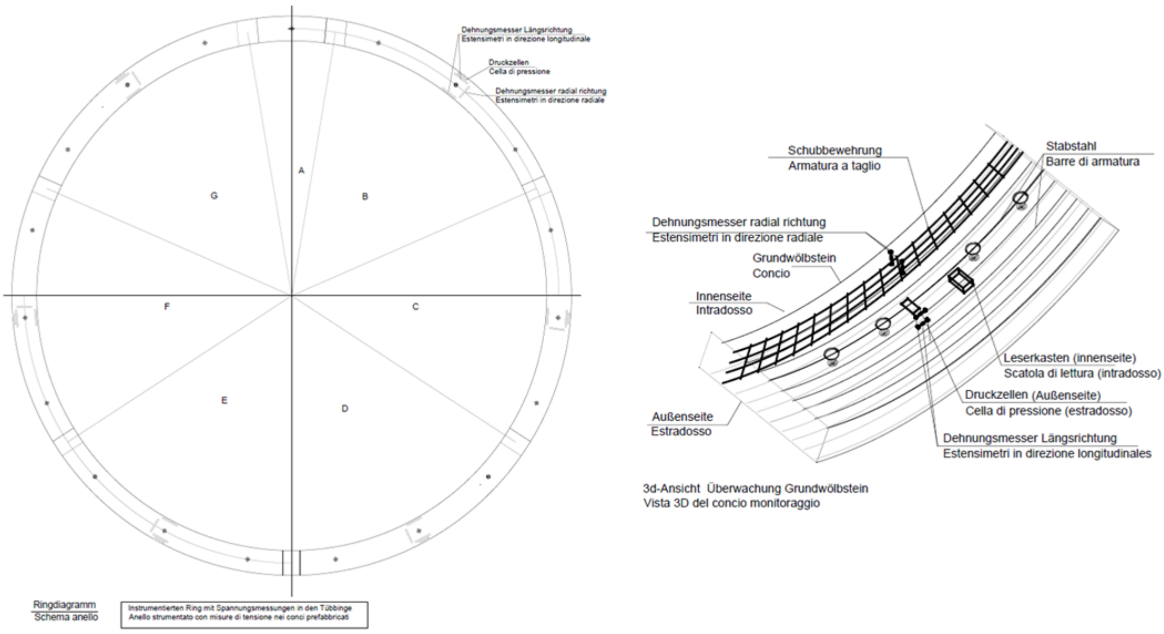


Figure 26: Tunnel monitoring system.

Moreover just as a research scope it is also analyzed the hypothetical case of a Smart-monitoring system constituted by MEMS transducers installed in the reinforcement bars of the tubing ring segments, with the aim of measuring the axial strain of the steel bars and consequently the strain of the segments. More specifically, the smart-sensors are placed equally spaced in selected bars, every 50 cm.

The reinforcement of the tubing ring segments is constituted by transversal, longitudinal and radial reinforcement, with the addition of other reinforcement bars placed in the lateral boundaries of the segment. The reinforcement cage configuration is the following:

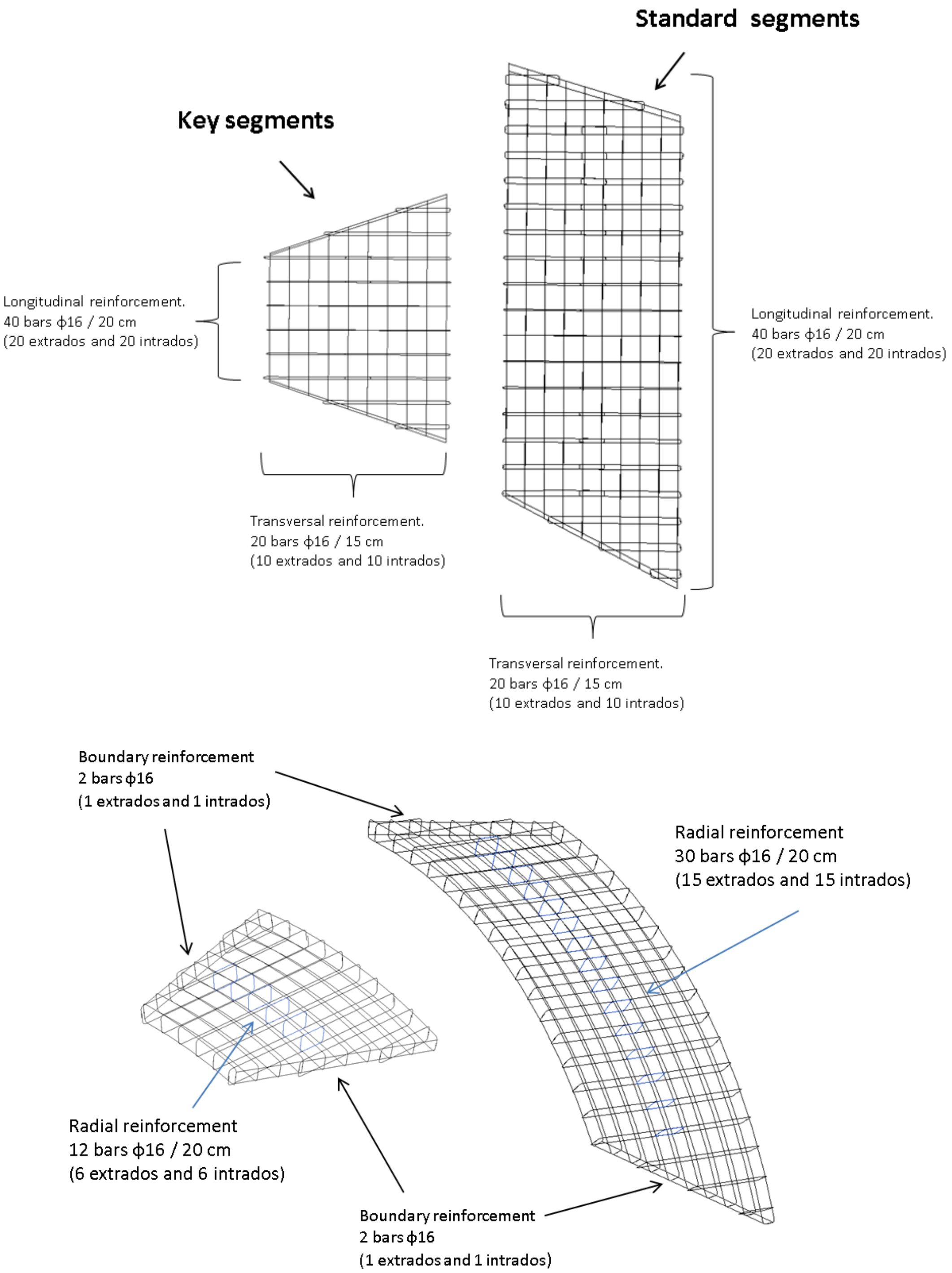


Figure 27: Brenner base tunnel. Reinforcement of the segments.

4. Proposed approach methodology

In this sub-section is discussed the BIM software that will be used for the developing of the work and the methodology that will be followed.

4.1. BIM software used

The BIM software tools that will be used are Autodesk Revit for the elaboration of the semantically – rich model of the bridge, Autodesk Robot Structural Analysis to conduct the structural analysis of the bridge and Autodesk Dynamo Visual Programming for the developing of the SHM tools in the BIM environment. A brief description of each software is done bellow:

4.1.1. Autodesk Revit

Autodesk Revit is a building information modelling software for architects, landscape architects, structural engineers, mechanical, electrical, and plumbing (MEP) engineers, designers and contractors. The software allows users to design buildings, structures and their components in 3D, annotate the model with 2D drafting elements, and access building information from the database of the building model. Revit is a multi-dimensional BIM software provided with tools that allow the planning and tracking of the various stages in the lifecycle of the building or infrastructure, from concept to construction and later maintenance and/or demolition. The software can be also used as a very powerful collaboration tool between different disciplines in the civil engineering industry.

The Revit work environment allows users to manipulate whole buildings or assemblies (in the project environment) or individual 3D shapes (in the family editor environment and in the conceptual mass environment). Revit includes categories of objects, called “families”. The families are the building blocks of a Revit model. They offer reusable parts that can vary from very specific shapes to highly adaptable and configurable parts that can be easily reused and modified. Revit uses a strict hierarchical organization of families. Each family belongs to a category, which determines the functionality and how it can be used in a model. The families are defined into 3 groups:

- *System Families*

System families are families that are built into Revit. Examples of these are basic walls, floors, stairs, among others elements. They are always available in any project and cannot be removed. That means that are totally controlled by the Revit software but despite of this the user is able to access and change some of their parameters, such as the height of a wall or the number of steps in a stair.

- *Loadable Families*

Loadable families are families that can be loaded into the project. These can be created with the help of the family editor as parametric models with dimensions and properties. This lets users to modify a given component by changing predefined parameters such as height, width or other information. In this way a family defines a geometry that is controlled by parameters, each combination of parameters can be saved as a type, and each occurrence (called instance in Revit) of a type can also contain further unique variations.

- *In-Place Families*

In-Place families are families that are created directly inside the project. That means that they are unique items and can't have types or be reused in other projects, as it happens with the loadable families. They can be useful for objects that are needed only once.

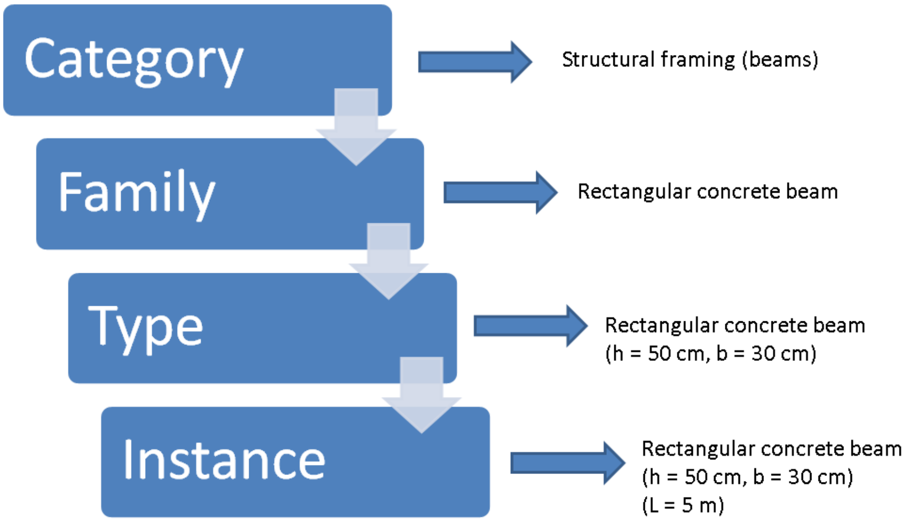


Figure 28: Revit elements hierarchy.

4.1.2. Autodesk Dynamo Visual Programming

Dynamo is an open source graphical programming environment for design. There are two versions of Dynamo: Dynamo Studio that is an independent software and the Dynamo extension for Revit, which comes with Revit and is used in the development of this thesis. Dynamo extends the power of Revit by providing access to the Revit API (Application Programming Interface) in a more accessible manner. Rather than typing code, with Dynamo can be created programs by manipulating graphic elements called "nodes". This is a less complex and friendlier approach to programming, convenient for the professionals involved inside the construction industry, that are often not used to the traditional programming languages.

- <u>Benefits of using Dynamo</u>

Dynamo is a very helpful tool in designing. Its benefits are summarized as follows (Arch smarter, 2018):

- *Automatization of repetitive tasks*

During the designing process with Revit, must be performed numerous repetitive tasks very often, such as creating elements or assigning tags. With the help of a Dynamo program this job can be done much quicker.

- *Accessing and setting the data of the Revit elements*

Through Dynamo it is possible to manipulate all the information present in the Revit model. The parameters and properties of each element can be accessed or set by using a Dynamo script. This data can be also manipulated and analyzed, exported to other software or imported from them, combined with data extracted from different elements, etc.

- *Interoperability with other software*

Dynamo offers the possibility to connect the data inside the BIM model in Revit with other software, by using nodes that allows the user to save time and work in a more efficient manner. For example Dynamo is able to communicate efficiently with Excel, NavisWorks, Robot Structural Analysis, SAP 2000, among other useful tools.

- <u>The basics of Dynamo environment</u>

In Dynamo, each node does a specific task. Nodes have inputs and outputs. The outputs from one node are connected to the inputs of another. The script of the program that in Dynamo is called "graph" flows from node to node. The result is a graphic representation of the steps required to achieve the end objective. The Dynamo interface is very visual. In the main workspace the visual script is created with the nodes, and also it is possible to see the geometry that is being created or called from Revit.

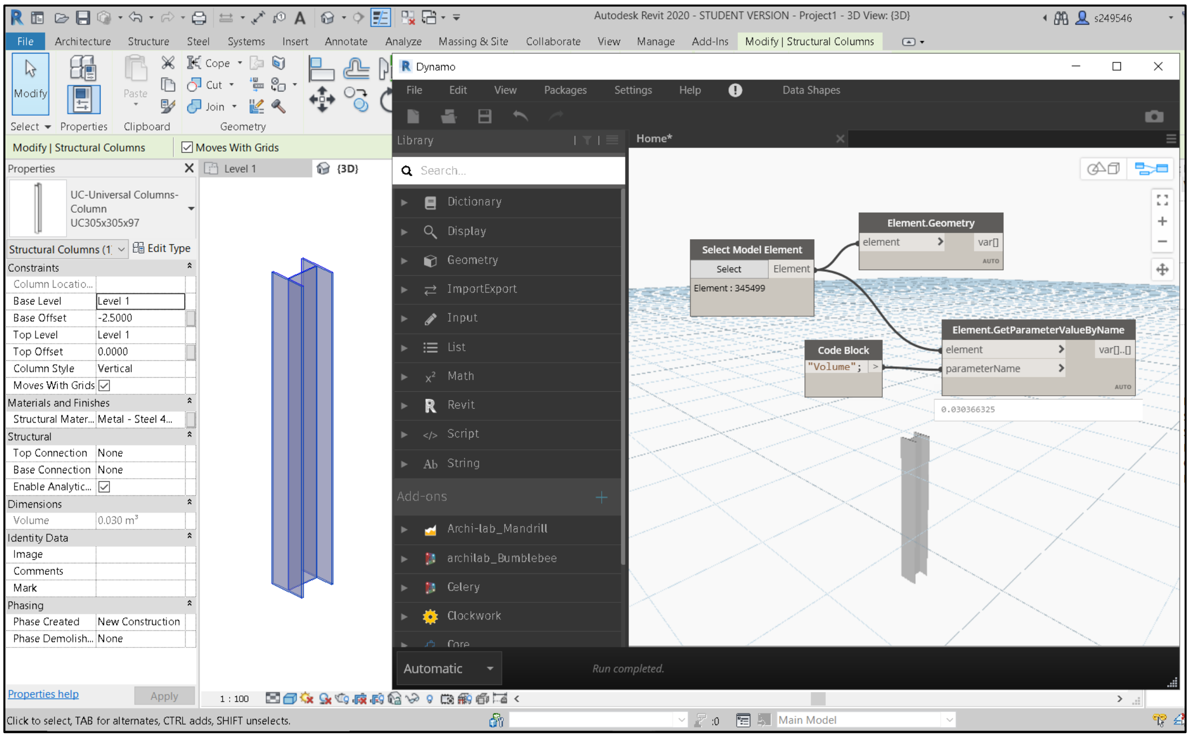


Figure 29: Real example of a Dynamo script.

In the picture above can be observed with a simple example how Dynamo works. The nodes are selected from the library that is located in the left part of the Dynamo interface. There are many built in packages that come with dynamo:

- *Display:* that gathers nodes that permit to set and manipulate colors, and create color ranges, very useful for visual analysis.

- *Geometry*: that allows creating and manipulating objects, as lines, curves, planes, solids, etc.

- *Import/export:* where nodes useful to import and export data are found, for example with AutoCAD, excel or text files.

- *Input:* that includes nodes for any different input, as numbers, integers, Booleans, number sliders, time spans, among others.

- *List:* where are included very useful nodes with which data lists can be created, inspected and manipulated, features very important for BIM software.

- *Math:* that gather nodes for different mathematical and logical tasks

- *Revit:* that provides nodes that allow the communication between Revit and Dynamo and let to manipulate every Revit element and its information through Dynamo.

- *Script:* in which coding nodes are present. This is very useful because allows create custom scripts with which the users can code their own routines in a high level programming language, as it is Python.

- *String*: where very useful nodes are included, very helpful at the moment of manipulating strings variables (text).

In the example case nodes from the *Revit* library are used. The first node selected is the "Select model element" node that allows selecting any element directly from Revit in the background. Then the nodes "Element.Geometry" and "Elemen.GetParameterValueByName" are placed. The first let to visualize the exact geometry of the element in the Dynamo interface and the second permits to obtain any parameter of the element, being in this case the volume.

- <u>Dynamo packages and user community</u>

Any program that users create with Dynamo can be saved as a Custom Node. A Custom node is a node with inputs and outputs but constituted by other different nodes or code written by the user. These custom nodes can be published and be available for free for all the Dynamo users around the world. That means that exist a very large library of pre-coded Dynamo scripts that can help with every imaginable task or feature of Revit.

These pre-coded scripts are called Dynamo Packages, and can be easily downloaded and included inside the Dynamo default library. For the developing of this thesis were used the following packages:

- *Data-Shapes*

Data-Shapes is a custom nodes package that aims to extend the user functionality of Dynamo scripts. Data-shapes provide a large variety of input nodes (text input, list input, slider input, selection inputs, etc.) that combined with input-form nodes add greater functionality to Dynamo player. Dynamo Player is the built in tool in Revit that provides a simple way to execute Dynamo scripts, allowing to playing the program and setting its inputs directly from the Revit environment, without having to open Dynamo.

- *Clockwork*

Clockwork is a collection of custom nodes that contains many Revit-related nodes, but also lots of nodes for various other purposes such as list management, mathematical operations, string operations, unit conversions, geometric operations (mainly bounding boxes, meshes, planes, points, surfaces, UVs and vectors, paneling and its more important feature for the developing of this thesis: the script flow control nodes, that allow to have a better organized flow of the code while the program is running.

- *Archi-lab Bumblebee*

In the default Dynamo library are nodes that allow the interoperability between the Dynamo environment (and consequently the Revit environment) with Microsoft Excel, but their usefulness is limited. Bumblebee is an Excel and Dynamo interoperability plugin that vastly improves the capability of Dynamo to read and write Excel files.

- *Celery*

It contains nodes that provide a better way to access data and manipulate outputs. One good example is the Celery slider input that works similarly to the default slider of from the Dynamo library but their limits are inputs established by the user.

- *Archi-lab*

This package is developed by the same author of Archi-lab bumblebee but this is useful in a more general way. It offers a series of nodes which purpose is to help with some frequent tasks that the users encounter. From the manipulation of PDF files to Revit selection nodes, the Archi-lab library is very wide and probably the user will find a node that can be useful in his or her script.

- *DynamoRebar*

Dynamo for Rebar allows the parametric rebar design inside of Dynamo. The library contains a set of nodes that help create bars and containers in Revit. With it, it is possible to create reinforcement from curves modelled in dynamo and assigning to the rebar, type, styles and hooks.

- *BIM4Struc*

BIM for structures is a series of packages dedicated to help the Revit user that deals with the design and modeling of structures. Particularly the package BIM4Struc.rebar helps with the creation and managing of the reinforcement.

4.2. Work methodology

4.2.1. Stura Bridge

For the development of this work a series of steps are carried out, each one of them including many tasks. These steps as summarized in the following list, where the specific activities necessary for the completion of each one are also established:

- Elaboration of the Revit model

This step consists in the elaboration of an As-built model of the bridge in Revit. This task is done by using the Project environment in Revit and in order to be completed it includes many activities:

- *Elaboration of the longitudinal beam family*

The first activity that must be done is the creation of a new family of beams in the family editor. The reason is it does not exist any loadable family by default in Revit that have the same shape of the cross-section of the longitudinal beams used in the Stura Bridge. The longitudinal beams present in the bridge also have some details in their extremes that have a particular importance and structural meaning. For this reason this detail must be also included during the modelling of the family.

- *Elaboration of the model in Revit*

After having created the two new families the Revit model can be completed. The idea is to recreate virtually in the most accurate possible way the condition of the real bridge, i.e. the As-Built model.

- Elaboration of the sensor families

In order to complete the As-Built model of the bridge the SHM system must be created, i.e. the sensors. In order to do this task a new family is created in Revit by using the Family editor. The sensors consist in an adaptive component family under the category of specialty equipment. A specific shape and some parameters are assigned to the family. These parameters are monitoring related information and information about the location of the sensor and are conceived as instance parameters, which means that are unique for each device. In total 3 different types of sensors are modeled:

- *Strain multi-sensor family*

This family is the virtual representation of the strain measuring sensors installed in the real bridge.

- *Displacement multi-sensor family*

This family is the virtual representation of the displacement measuring sensors installed in the real bridge.

- *Strain visualization sensor family*

This family does not represent any real object in the bridge but rather is a tool that will help the graphical visualization of data in forward steps.

- <u>Elaboration of the sensor placing program</u>

    - *Single sensor placing program*

By using the Dynamo extension for Revit is developed a program that allows placing in any Revit element the previously created sensors families (Strain multi-sensor family and Displacement multi-sensor family) one by one but in a more organized and accurate manner. For this scope are utilized the default Dynamo library, custom python nodes developed by the author and other downloaded packages as Clockwork and Data-Shapes.

    - *Multi sensor placing program*

In this case, also by using Dynamo for Revit is developed a program that allows placing the sensor families, in this case only for the beam elements but doing it in a more automatic way. For this scope are again utilized the default Dynamo library, python scripting nodes and other downloaded packages as Clockwork and Data-Shapes.

- <u>Elaboration of the SHM data management program</u>

Again making use of Dynamo for Revit is developed a program, but in this case for the management of the monitoring data. This program is able to retrieve monitoring data (strains or temperatures) from text files, with interaction with the virtual sensors placed in the structure. The program is also capable to manage and analyze this data and export it to an excel file. For this scope are used the default Dynamo library, python routines and other downloaded packages as Clockwork, Data-Shapes and Archi-lab Bumblebee.

In the following figure can be observed schematically the explained methodology and how the different BIM and traditional tools used are related:

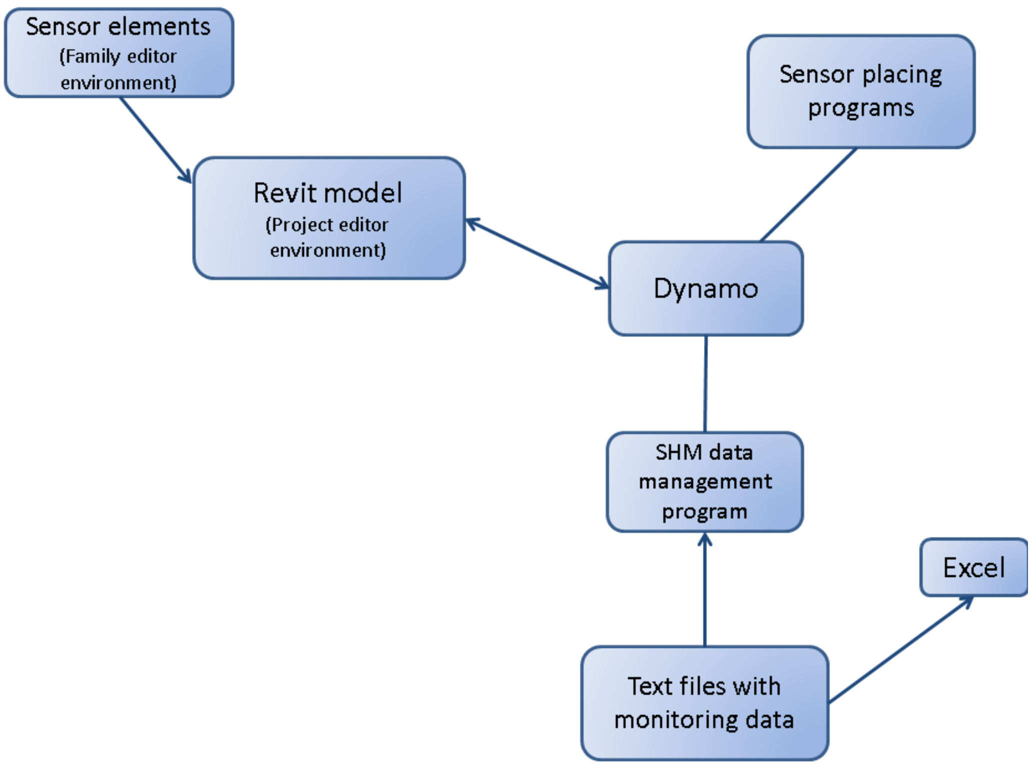


Figure 30: Work methodology scheme. Stura Bridge.

4.2.2. Brenner Base Tunnel

Just like in the case of the Stura Bridge, in order to develop the entire work, several steps must be done sequentially, that at the same time involve many sub tasks. These activities are explained below:

- Elaboration of the Revit model

This stage involves the elaboration of the As-built model of the tunnel in Revit. It is important to say that in contrast with the model that will be created for the bridge, it is going to be considered just a part of the Brenner Base Tunnel, particularly, a limited part of its route (approximately 100 m) and only one of the 2 main tubes. This task is done by using the Project environment in Revit and in order to be completed it includes many activities:

- *Elaboration of the tubing ring segment family*

Firstly a new family of adaptive components must be created. The scope of this object is to emulate the segments that constitute the pieces of the Rings. The reason of creating them as adaptive components is their variability of location along the Tunnel alignment, which forces them to have adaptability and versatility as characteristics.

- *Elaboration of the model in Revit*

Once the tubing ring segments family is created it is possible to start the elaboration of the model. The point during this step is to emulate in the most faithful way all the geometrical features that characterize the tube. The most efficient route is through the using of Dynamo, which is ideal for the creation of structures with special geometries that can be hard to deal with via the traditional Revit project environment methodology. Moreover, are also added the reinforcement bars to the tubing ring segments, task again performed with the help of Dynamo and making use of some self-developed python nodes and downloadable packages as DynamoRebar and BIM4Struc.

- Elaboration of the sensor families

For completing the As-Built model of the bridge the SHM system is also created. This system is basically constituted by the sensors. By making use the family editor these are simulated by adaptive components, under the category of specialty equipment. In the same way that was done for the sensors installed in the Stura Bridge, different shapes are added to the different types of sensors and some parameters are incorporated to them with the aim of storing identity and monitoring data.

- *Pressure cell sensor*

This family is the virtual representation of the pressure cell installed in the center of the extrados of the segments.

- *Radial and longitudinal extensometers sensor*

These are two separated families that represent the radial extensometers and longitudinal extensometers respectively.

- *Lecture Box*

This family does not represent any sensor. It represents the lecture box located in the intrados of the segments.

- *Smart-sensors*

Finally the smart sensors, placed in the reinforcement are also simulated by using the Revit family editor environment.

- Elaboration of the SHM system placing programs

With the aim of automatizing the process of locating and placing the sensors some Dynamo programs are developed. The scope is to facilitate the selection of the desired rings and the location of the sensors in those elements, storing in their parameters the specific coding and coordinates. In order carry out the development of this programs are used the default Dynamo library, python scripting nodes and the downloadable packages Clockwork, Data-Shapes, DynamoRebar and BIM4Struc. Will be developed a program for each type of sensor:

- *Transversal extensometers placing program*
- *Radial extensometers placing program*
- *Pressure cell placing program*
- *Lecture Box placing program*
- *Smart-sensor placing program*

Once the programs are developed, the SHM is installed in the specified tunnel rings.

- Elaboration of the SHM data visualization program

Finally with the help of the Dynamo extension for Revit is developed a program that is able to provide a graphical visualization of the monitoring data, supported in the extensometers placing program created in the last step. In order to perform this task are used the default Dynamo library, python routines and other downloaded packages as Clockwork, Data-Shapes, Celery and Archi-lab Bumblebee.

Then, a program that provides the possibility of creating a graphical visualization of the Smart-sensor monitoring data is also written.

In the following figure can be observed schematically the explained methodology and how the different BIM and traditional tools used are related:

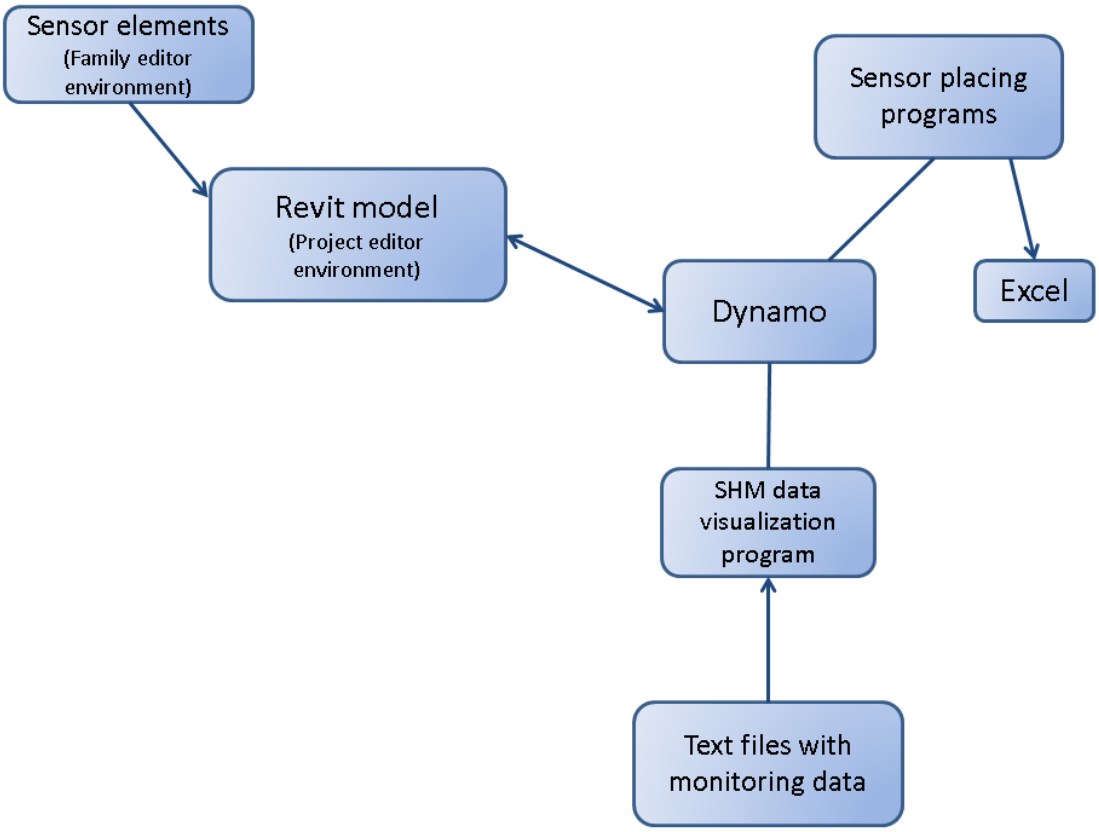


Figure 31: Work methodology scheme. Brenner Base tunnel.

Section 3: Work development

1. Stura Bridge

1.1. Elaboration of the Revit model

The first task developed in this part of the work was the elaboration of the BIM model of the bridge in Revit. As it was explained in the last point of the previous chapter this step gathers many different activities with the final goal of creating the virtual model of the structure, emulating the as-built situation in which the bridge is currently.

1.1.1. Revit model – first part

This Revit model is created by using the *Structural Analysis – Default Metric* template. A template in Revit is the starting point for a new project because depending on the selected template (Architectural, Electrical, Mechanical, Structural, etc.) it includes different loaded families, defined settings (such as units, fill patterns, line styles, line weights, view scales, and more), geometry, etc. For example the *Structural Analysis* template is the best suited for the modelling of infrastructure or models related more with structural engineering purposes. It includes features such as the Analytical model where the analytical representation of the elements are visible, and are those ones that in the case of sending the model to a Structural Analysis software would be exported.

Once started the project with this template, the first step is to draw the axes and levels that are the guide lines that will allow placing the elements in their correct locations. There are 7 inclined axes (from A to G) separated 36.50 m that correspond to the 5 piers and the 2 extremes of the bridge and 5 longitudinal axes for each traffic direction that will allow to locate the longitudinal beams and the slab. Then the levels are drawn respect to the centroid of the longitudinal beams. *Grillage* corresponds to the centroid of these beams; *Slab* is aligned with the centroid of the slab; *Pier Caps* coincides with the centroid of the pier caps; and there were created levels each one corresponding to the base of each pier.

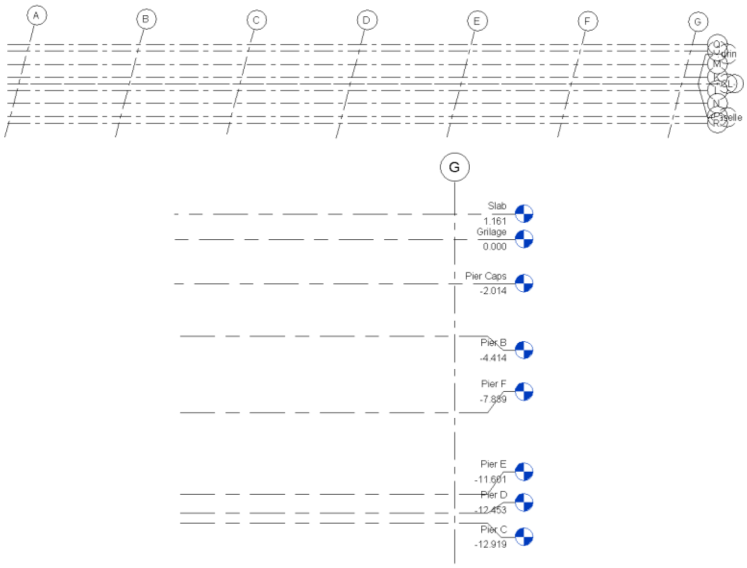


Figure 32: Axes (above) and levels (below) of the model.

The next step is the creation of the piers that are constituted by the reinforced concrete columns and the reinforced concrete pier caps. New family types are created for both elements starting on loadable families that are included in the Revit library. The concrete pier caps are constrained to the *Pier Caps* level and the columns have as top level the *Pier Caps* and as base their corresponding base level created in the previous step. Moreover are also added some slab footing to the piers, being in this case 0.80 m thick slabs.

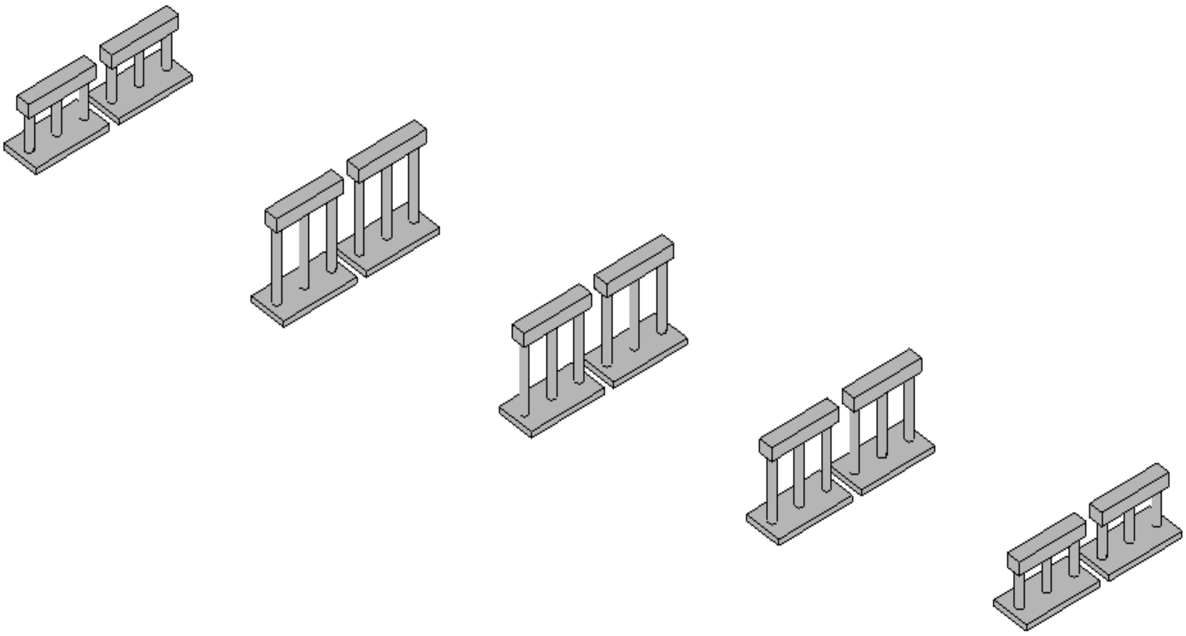


Figure 33: Revit Stura Bridge model. Piers.

1.1.2. Longitudinal beam family

Before continue with the completion of the Revit model, a new family for the longitudinal beams must be created. The issue with the longitudinal beams is that their cross-section is not available in the Revit library as an existing loadable family, because these don't have a common shape used in the building industry. In order to carry out this task is used the Revit family editor in which it is possible to create new loadable families or modify existing ones. For this scope the starting point is selecting the most adequate template, as it was done at the moment of starting the Revit model in the project environment. In this case the template selected is the *Metric – Structural Framing: Beams and Braces* template, being this the most adequate one at the moment of creating new beams or framing in general.

The family is created is parametrically, that means that its shape is flexible and can change depending on the values assigned by the user, but always conserving its double T section. Also is possible to modify the longitude of the extreme structural details.

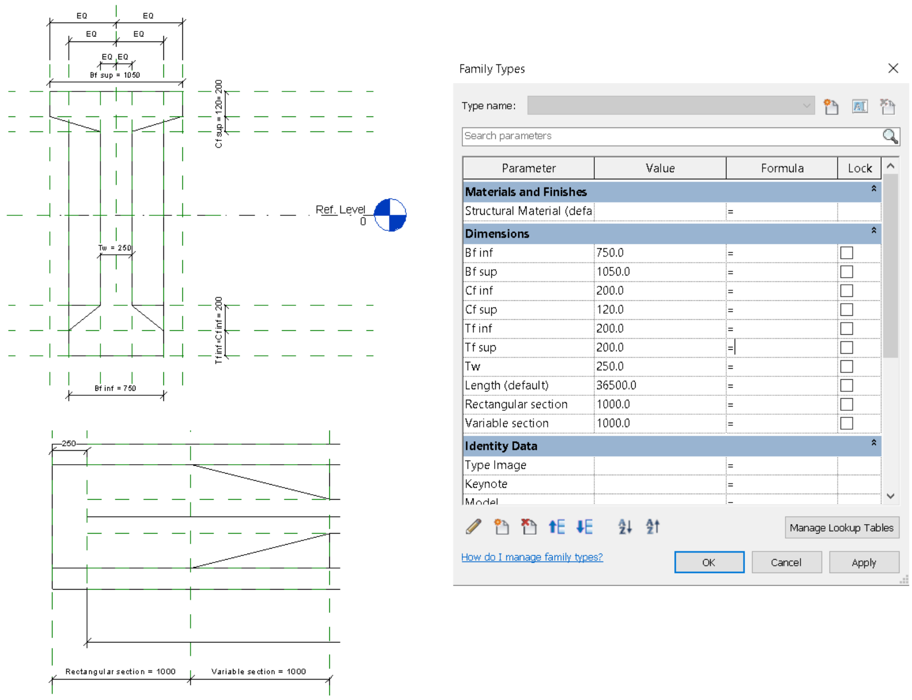


Figure 34: Longitudinal beams family. Stura Bridge.

1.1.3. Revit model – Second part

Then, this new family can be loaded into the project and assigned in the correct places. Also the transversal beams are added but these having rectangular cross-section are available in the default Revit families. After that takes place the creation of the slab. This slab is Revit floor element that is added to the model constrained to the *Slab* level.

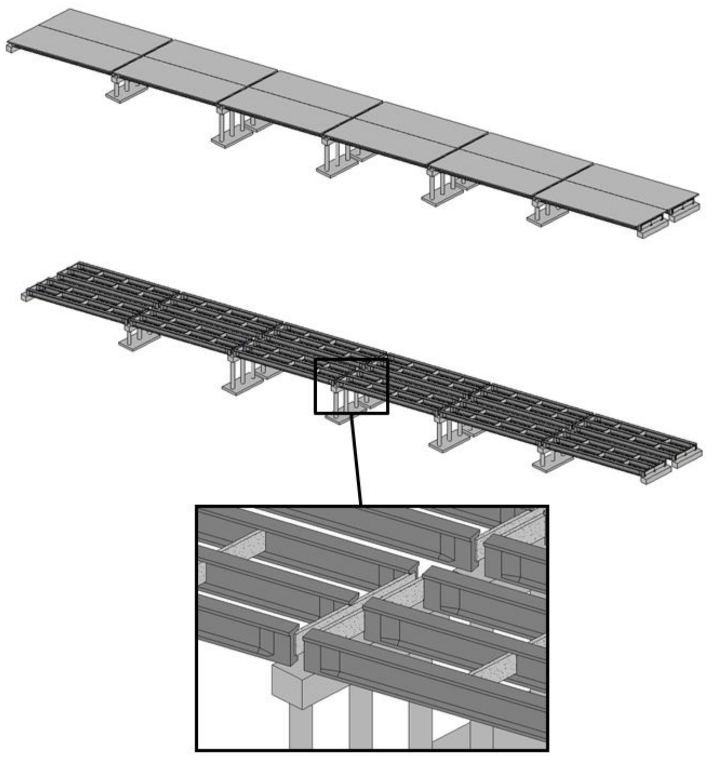


Figure 35: Revit model of the Stura Bridge. Complete (above). Hidden slab (below).

The final step of this task is crucial if for any reason is desired to export the model to Robot Structural Analysis software. As the analytical elements visible in the Analytical model view of Revit are those ones that at the end will be exported to the other structural software is necessary to set their analytical alignments as a *Projection* and coincident with the *center of the element* (the centroid). This must be done because Revit by default places these analytical alignments at the top of the element in the case of beams and at the bottom in the case of floors. If this step is not done the elements will be exported to Robot at wrong levels.

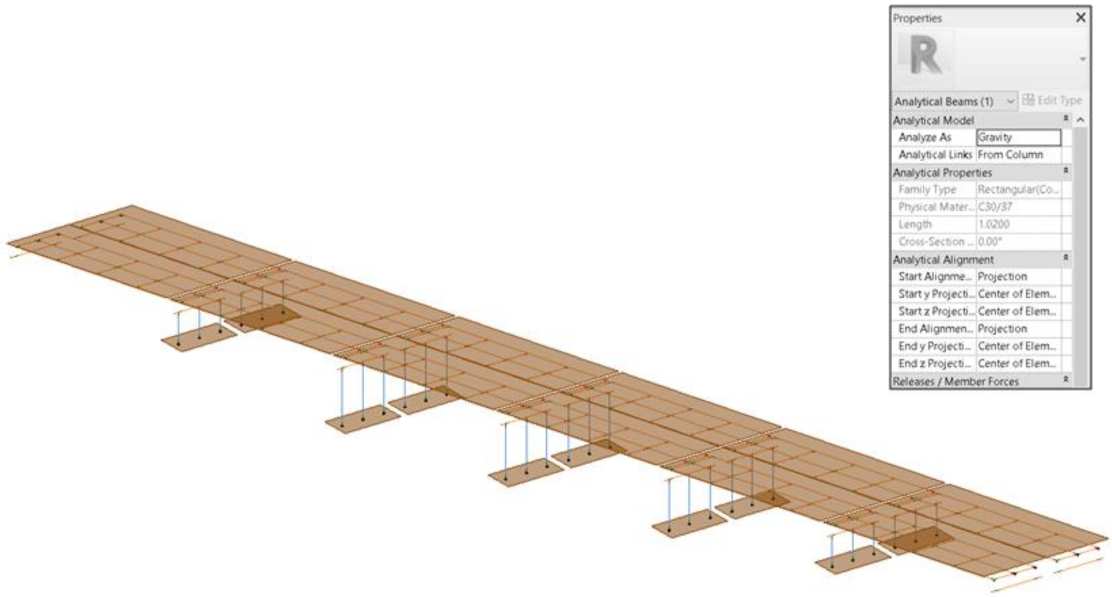


Figure 36: Revit prototype analytical model.

1.2. Elaboration of the sensor families

The scope of this thesis is to find an effective manner to introduce the SHM components into the BIM methodology. This cannot be addressed without creating and including in some way a virtual representation of the sensors inside the BIM model. In order to do this were modeled in the Revit family editor new families:

1.2.1. Strain multi-sensor family

The goal of creating this element is to emulate in a virtual way the real Strain multi-sensors placed in the Stura Bridge. In order to model this family the first step is the selection of the correct template. As sensors are placed in specific points of the structure, i.e. point based elements; the most suitable template is the *Generic Model – Adaptive* template. This allows creating a family that is able to be placed by selecting points in a certain order in the Revit environment, because of this reason it is "adaptive".

For the modelling it is required to carry out some steps. First a shape is added to the model, which will be the physical representation of the sensor; in this case a cylindrical shape is chosen. After that, some parameters are added to the new family. These can be divided in two groups:

- Identity data parameters

These parameters are conceived to help at the moment of differentiate one sensor of the others and make it unique. Although in the model will be many Strain multi-sensors each one must have a name or code, because the measurements that they collect are unique. For this reason these parameters are *Instance parameters:*

- *Host element*

This parameter stores the Revit ID code of the element in which is installed the Strain multi-sensor. This Revit ID code is an unique 6 digits number that Revit assigns automatically to every element that is created.

- *Sensor number*

Is very common that more than one sensor are assigned to the same element. For that reason the Revit ID code is not sufficient to give a sensor an unique name, so listing them in some way is necessary. This instance parameter store a number for each sensor installed in the same element.

- *Sensor ID*

Now combining the two previous parameters can be created an unique identification code for each sensor. So this parameter is thought to store a text variable with the format: *Sensor number – Host element.*

- Structural parameters

These parameters are also of instance type and store information useful for the SHM data analysis and visualization. These are the following:

- *Initial strain and Initial temperature parameters*

These two instance parameters are in charge of storing the initial values of these two measured parameters. These must be established by the user with certain values, respect to which the collected measurements will be compared. For example when the sensors are installed in an element, it already has a strain and there is a certain temperature in the environment, so these values could be considered as the initial strain and the initial temperature respectively.

- *Strain and temperature thresholds parameters*

In order to give a sense to the data and analyze it, it is necessary to compare the collected measurements with some established limits or threshold values. These are 4 parameters that are thought to store the positive and negative threshold values for the strain and temperature measurements and must be set by the user.

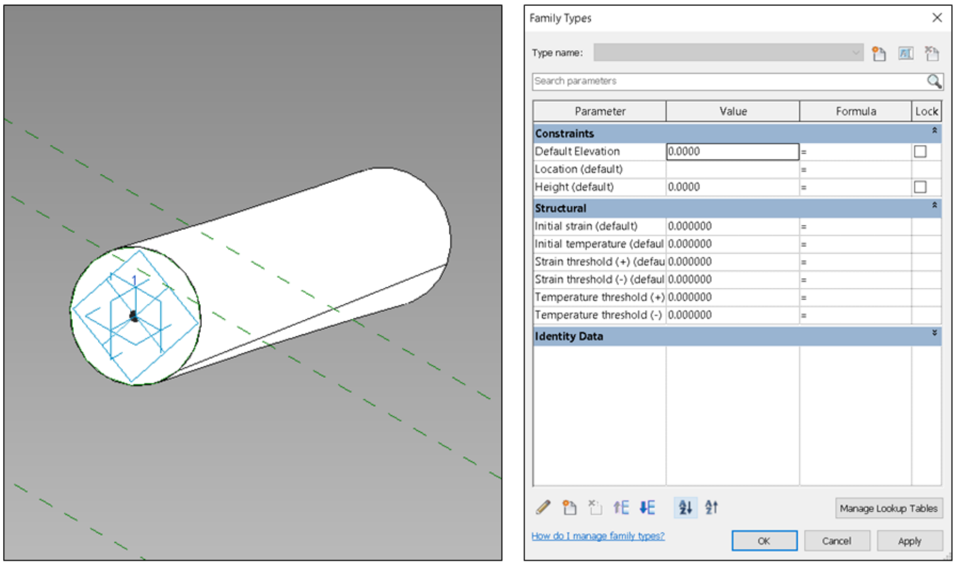


Figure 37: Strain multi-sensor family. Adaptive component and parameters.

1.2.2. Displacement multi-sensor family

This element is created to simulate virtually the real Displacement multi-sensors that are installed in the bridge in study. As in the previous case this family was modeled in the family editor of Revit, starting with the *Generic Model – Adaptive* template. This family is very similar to the Strain multi-sensor family with specific differences.

The main aspect that differentiates this sensor from the previous one is that instead of measuring strains, it is able to carry out the measurement of relative displacements between 2 elements. All the parameters created for the Strain multi-sensor family that are related with strains are changed to displacements. Also important is the creation of an additional parameter that stores the Revit ID code of the base element, i.e. the element considered "fixed" respect which the relative displacements are measured, so in this case the Sensor ID parameter has the format: *Sensor number – Host element – Base element.*

On the other hand, the shape assigned to the family is the same, a cylinder.

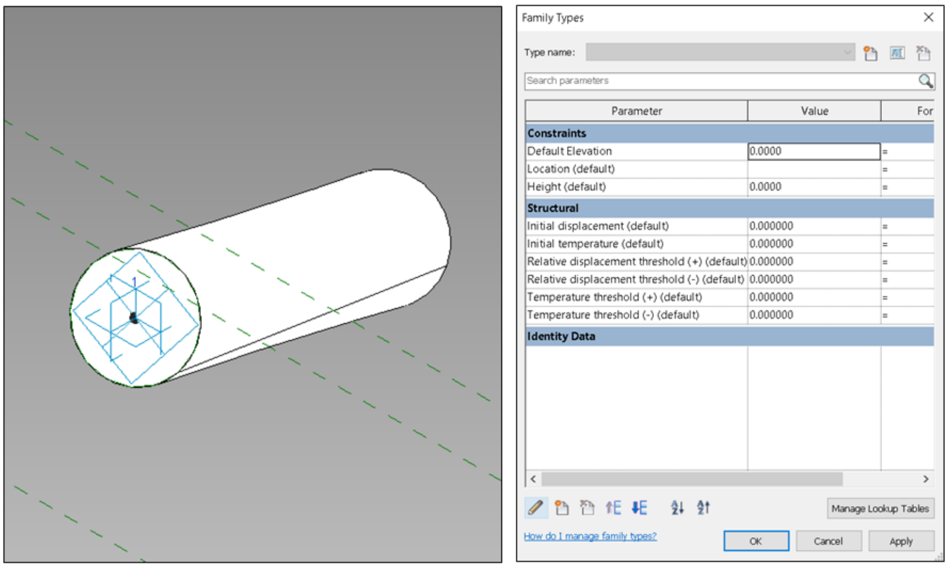


Figure 38: Displacement multi-sensor family. Adaptive comp. shape and parameters.

1.3. Elaboration of the sensor placing programs

Being the sensor families created it is necessary the development of a program that facilitates the placing of the sensors in their respective locations. Using Revit there are two ways of performing this job: one is by the development of a custom add – in that is able to interact with Revit through its API. The issue is that this methodology requires a deeper knowledge in the field of programming as it must be done by using a high level programming language, e.g. C-sharp. The other alternative is by using the Dynamo extension for Revit, option which was finally chosen.

There were developed 3 different programs for the sensor placing. These are thought to provide more accuracy at the moment of placing the SHM system and also to help in the creation of the sensors in a more organized way that will benefit future activities as the data management and data visualization. The programs are now explained:

1.3.1. SHM Strain multi-sensor placing: Planar surface elements.

The Dynamo graph elaborated for this program follows in general a linear sequence, where every step depends on the outputs coming from the previous one. The script works with the following steps:

1. Input form 1: Selection of the monitored element

This first group of nodes of the graph allows the selection of the element where the user wants to place the sensor. This is through the using of a node that creates an input form provided by the Data-Shapes package. The input form can be customized by adding different type of inputs, adding a logotype, a description, changing the texts of the buttons and changing the size of the appearing window. Can be seen that the "code block" nodes are used to set the texts that customize the input. Finally a python script called "Control point" is written and it allows to set the outputs to "empty list" if the output "was canceled" is true.

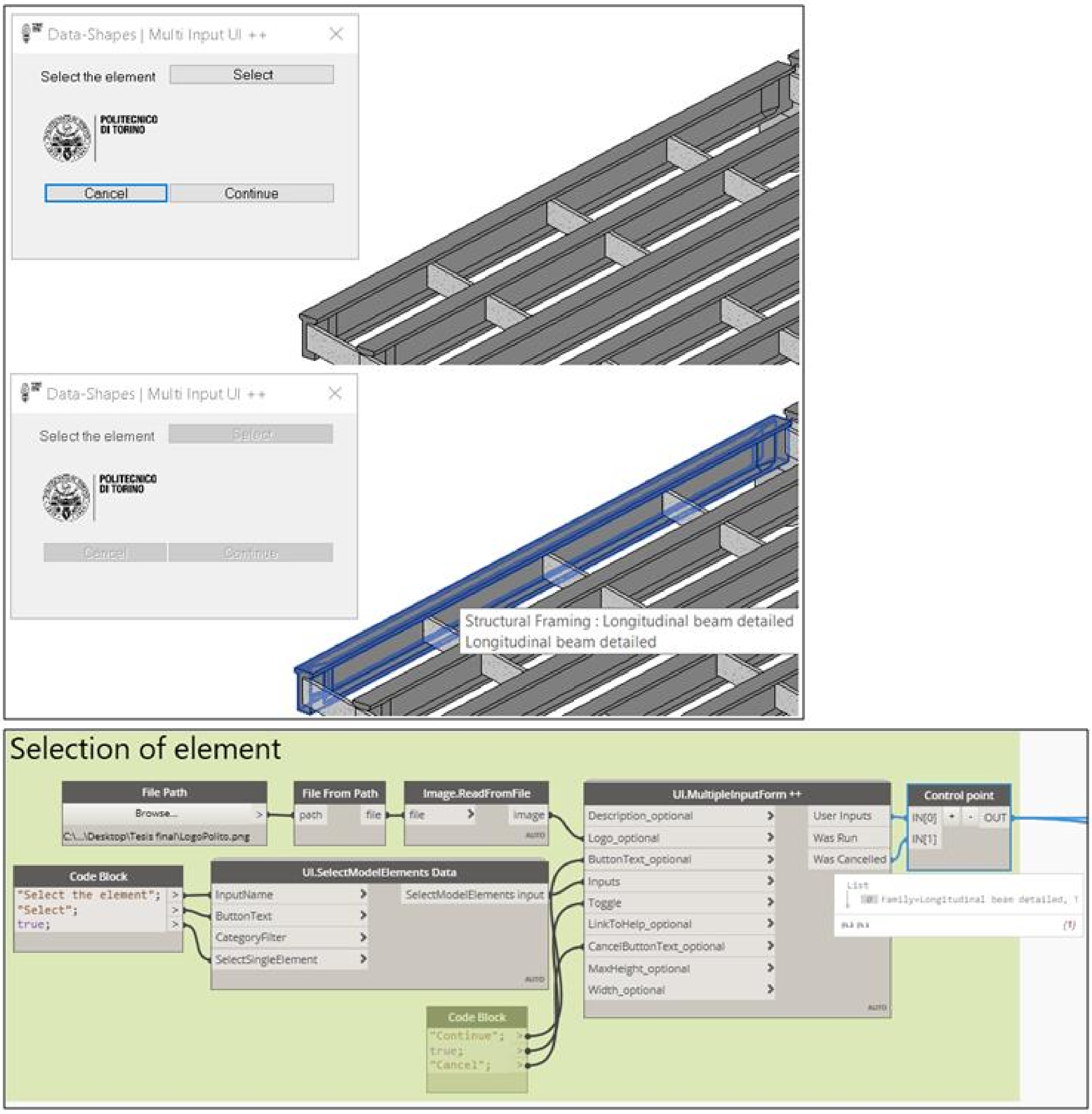


Figure 39: Bridge SHM strain multi-sensor placing. Element selection.

2. <u>Input form 2: Selection of face and edges</u>

Once the element is selected the program asks to select the face of the element on which the sensor must be placed, and two edges of this face. These edges are necessary for the program because it must place a sensor in a certain coordinate plane, and the edges represent the axes of this coordinate system. It is important to take into account that this two edges must intercept mutually. Can be observed that the Dynamo convert these Revit inputs in a surface and two lines. An important node used in this group and always in an input form group is the “Pass-through” node; it allows having a more organized flow of the graph, because it stops the running of the following node until another node has done its calculations.

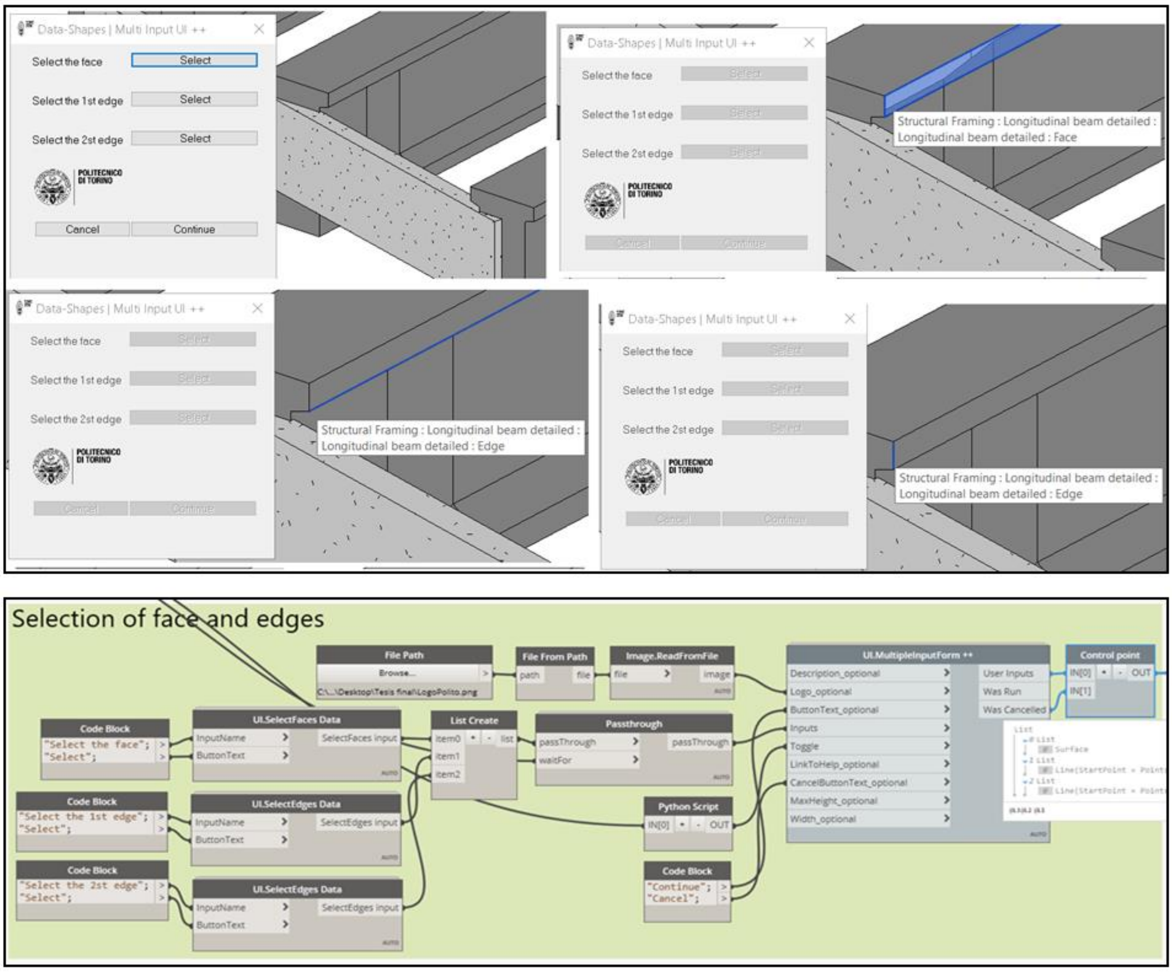


Figure 40: Bridge SHM strain multi-sensor placing. Face and edges selection.

3. Orientation of the edges

The two lines that represent the edges are oriented randomly by Dynamo. That means that not always the start point of these lines is the intersection of both. Because of these reason these must be oriented by the node group shown below. Here is used a python script node that was called “Oriented edges” that consist in a routine that change the direction of the lines if they are oriented wrongly.

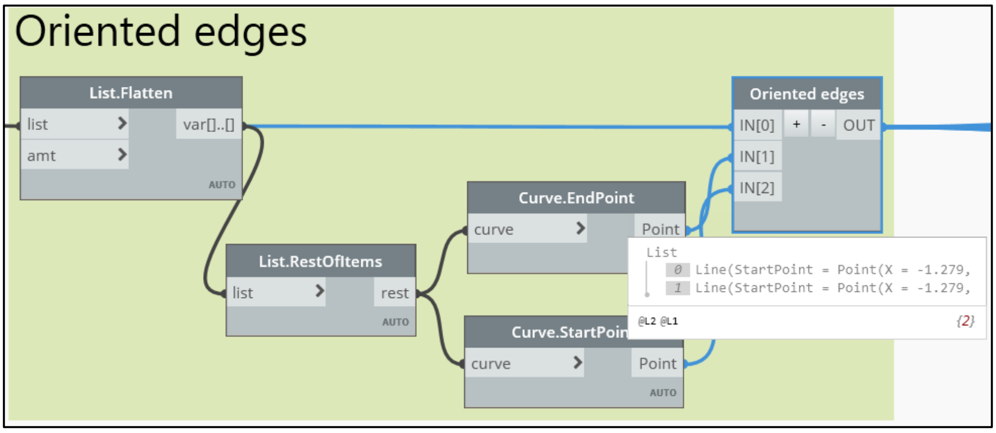


Figure 41: Bridge SHM strain multi-sensor placing. Edges orientation.

4. Sensor location

4.1. Input form 3: Absolute or relative coordinates

Now the program gives to the user the opportunity of choosing which type of coordinates to use to indicate the sensor location:

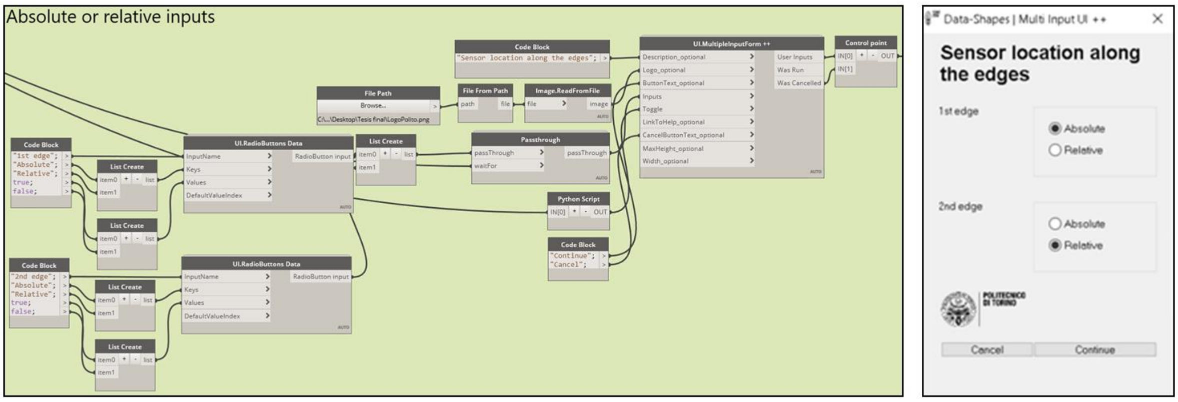


Figure 42: Bridge SHM strain multi-sensor placing. Type of coordinate selection.

4.2. Input form 4 and 5: Sensor location along the edges

If absolute is selected, as it was done for the 1st edge, the location of the sensor along this edge must be introduced in meters. On the other hand, if is chosen relative, the relative position of the sensor (from 0 to 1) must be indicated, as it is in de 2nd edge. The output of this node group is a single point along each edge.

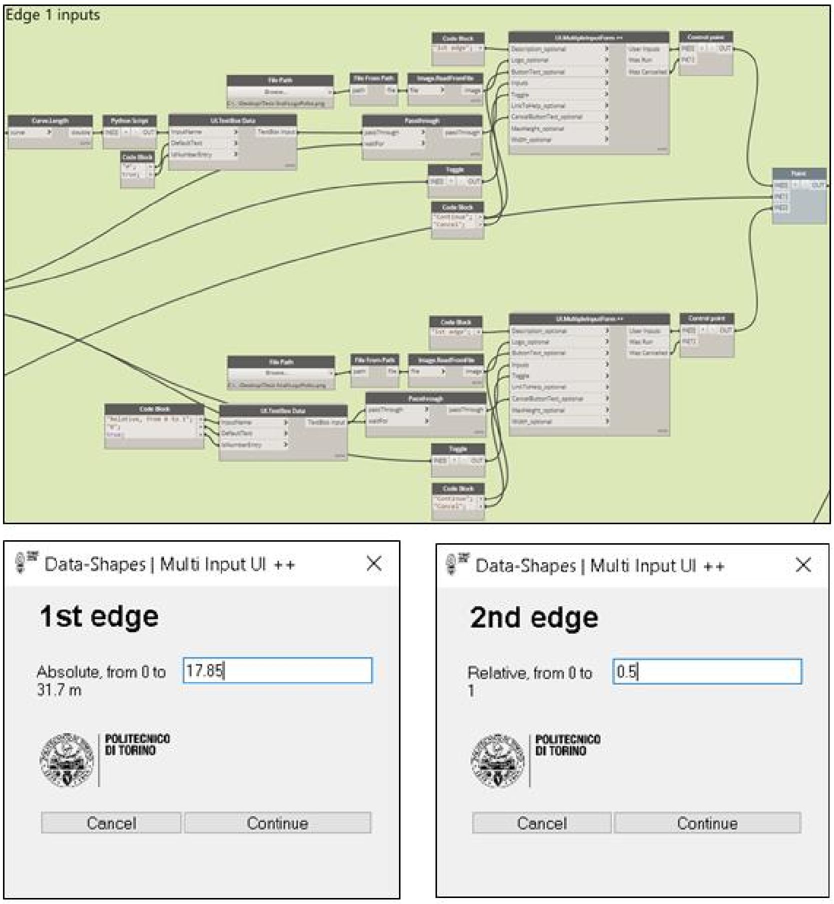


Figure 43: Bridge SHM strain multi-sensor placing. Coordinates introduction.

4.3. Input form 5: Sensor inclination

Once the sensor location is introduced the program asks about the orientation of the sensor. First it asks for a relative or absolute orientation. If absolute is chosen the sensor can be placed horizontally or vertically. If relative is chosen the orientation options are relative to the edges: aligned with the 1st edge, aligned with the 2nd edge or inclined respect to the 1st edge. If there was the case in which the sensor must be placed with an angle respect to the 1st edge another input would appear, that asks the inclination angle of the sensor.

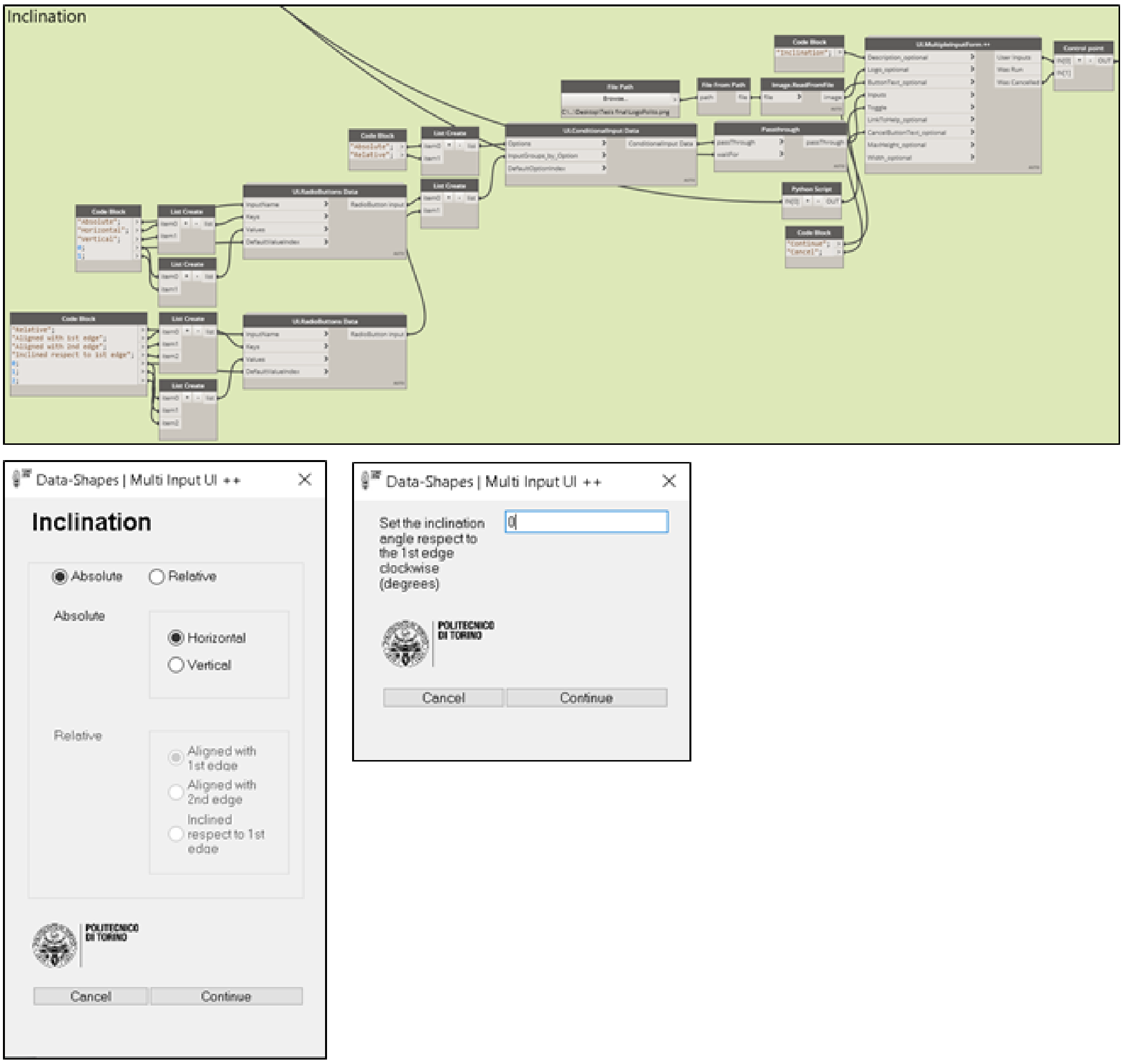


Figure 44: Bridge SHM strain multi-sensor placing. Sensor inclination.

The final output of this series of nodes is the 2 points in which the adaptive component family of sensor is going to be placed. As a remark, if one or both points cannot be created because they are outside the element, the program is capable to warn you about the error and it forces to start the procedure again.

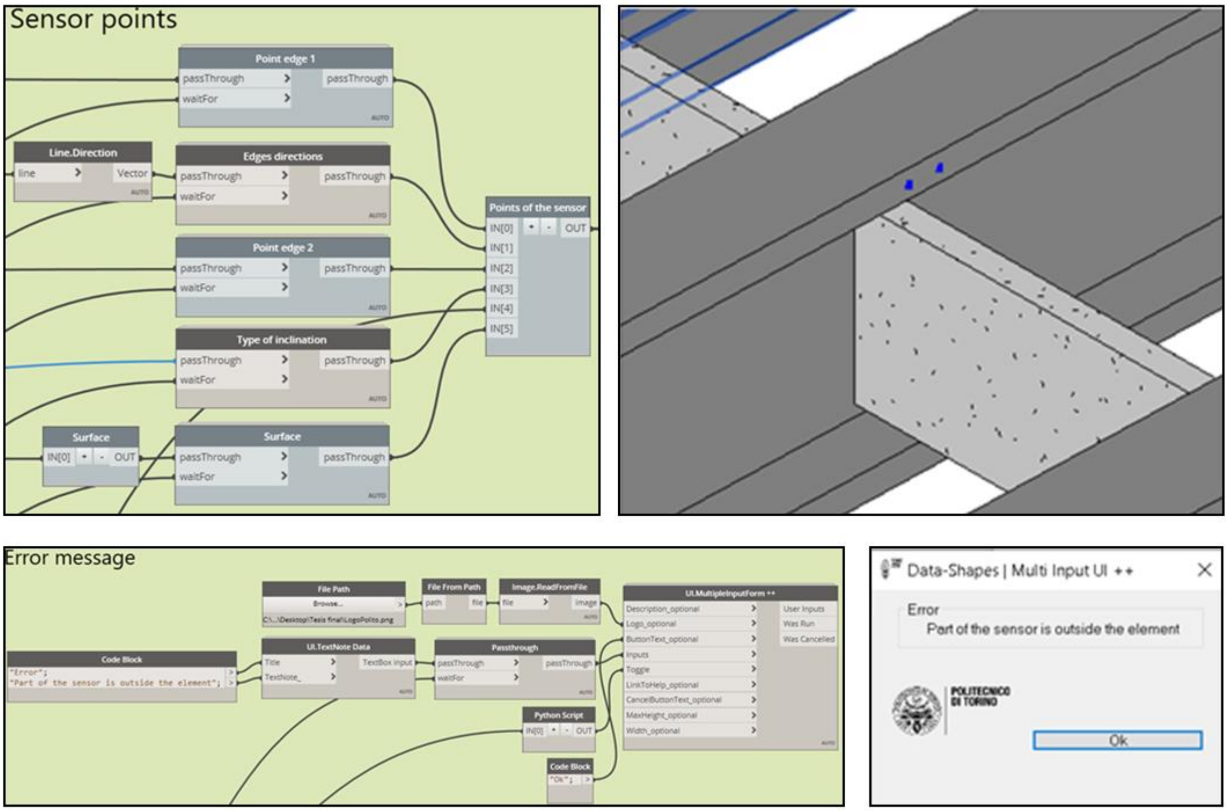


Figure 45: Bridge SHM strain multi-sensor placing. Points and error controlling.

5. Sensor creation

Being defined the position where the sensor will be placed, the program automatically adapts the Strain multi-sensor family to the 2 points. This is done through the node that is able to create an adaptive component family by points called “Adaptive.Component.ByPoints”. As a remark each point in the list must be given to the creation node in sub-list, if not the program is not able to create the element. Can be seen that the desired family is just selected, the placing points are provided and then the new element is created in the Revit environment. After that the color of the sensor is changed in the view in order to differentiate theses from the Displacement sensors that will be added later.

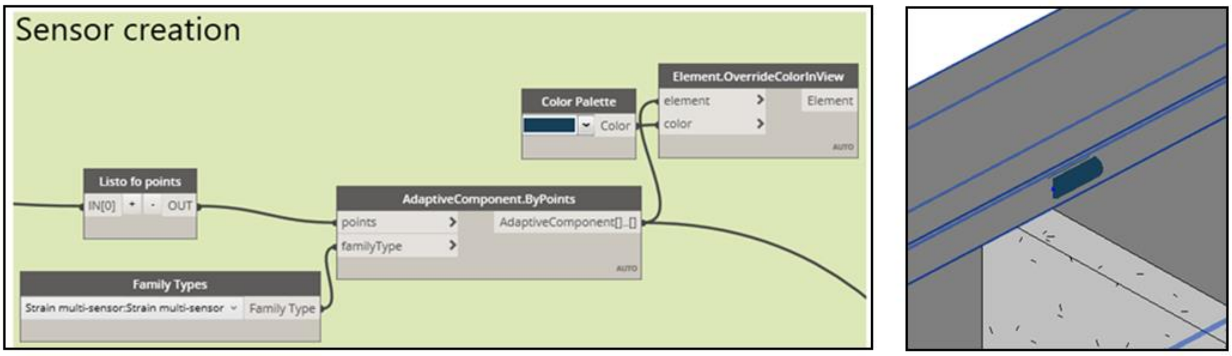


Figure 46: Bridge SHM strain multi-sensor placing. Sensors creation.

6. Sensor identification

After the sensor is created in the Revit environment it must be named and enumerated according to where it is placed. The next part of the program is dedicated to this issue.

6.1. Host element assignment

Firstly is assigned the value to the Host element parameter. The node Element ID obtains the unique Revit code from the selected element, while the ID python script routine transforms this item into a string (text). Then the node "Element.SetParameterByName" overrides the parameter value.

6.2. Sensor number assignment

Then the number of the sensor must be assigned. First the existing number of sensors that are installed in the element must be obtained, so, a python scripting node counts all the Strain multi-sensors that have the same host element, and then it assigns to the new one the following number in that list.

6.3. Sensor ID assignment

Finally the last two parameters are used to set the Sensor ID parameter. This is done through a python script again that is able to combine the Host element and the number of each sensor as a continuous string with the format Host element – Sensor number.

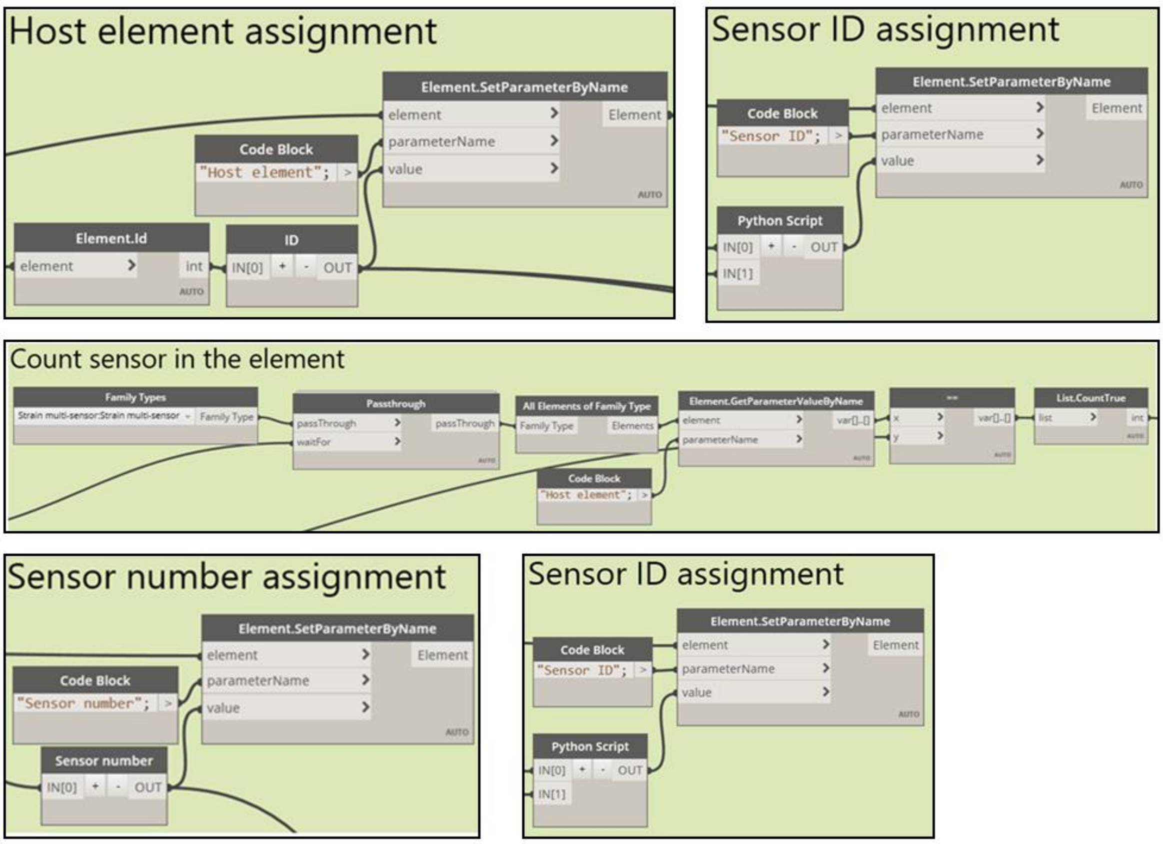


Figure 47: Bridge SHM strain multi-sensor placing. Parameters setting.

The final result can be seen in the properties palette in the Revit environment, every time that a sensor is selected.

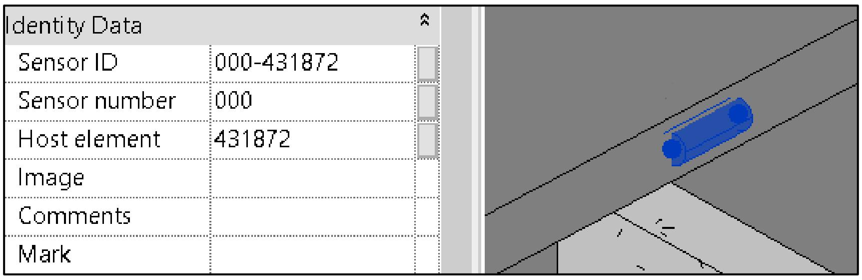


Figure 48: Bridge SHM strain multi-sensor placing. Sensors family parameters.

1.3.2. SHM Strain multi-sensor placing: Rounded columns.

In contrast with the explained previously, in this case the program is intended for rounded shape columns, or in general, columns without planar surfaces. It is developed only for columns because these elements are those ones that usually have these types of cross-sections, being the circular one very common in buildings as well as in infrastructures such as bridges.

All the steps carried out while the graph is running are explained as follows:

1. <u>Input form 1: Selection of the element</u>

This graph group works in a similar way as in the previous program excepting that the selection is filtered only for the Revit Structural Columns category by specifying this feature to the input node, given by the downloadable package *data-shapes*.

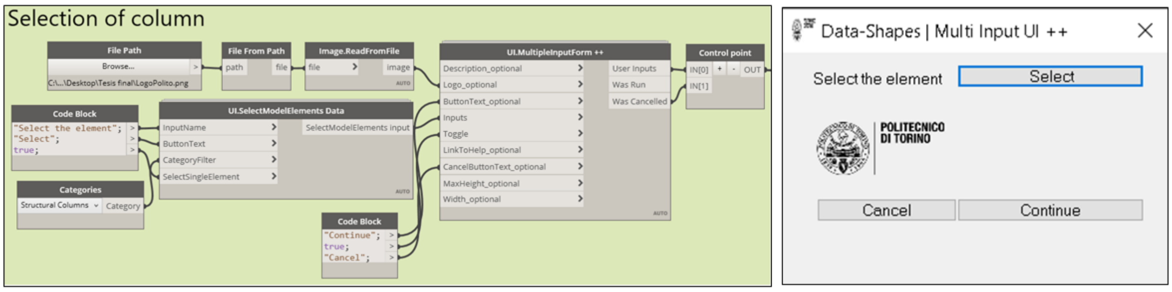


Figure 49: Bridge SHM strain multi-sensor placing. Selection of the rounded column.

2. <u>Column geometry</u>

Once the column is selected some useful information of its geometry is obtained by the following part of the graph. First the element faces are obtained with the “Element.Faces” node. After that, 3 python scripting nodes are written: the first called “Extreme faces” is able to filter only the surfaces at the base and the top of the column. The second called “Rounded surface” creates the lateral surface of the column from the perimeter curves of the base and top surfaces. The third called “Axis line” creates a line that goes from the center point of the bottom surface to the center point of the top surface.

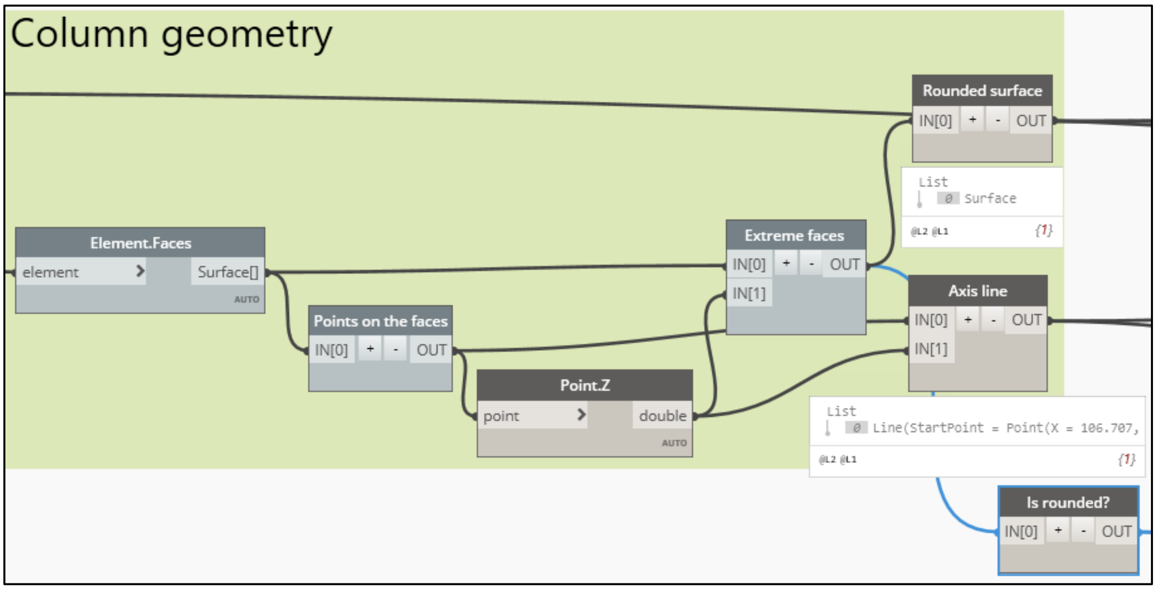


Figure 50: Bridge SHM strain multi-sensor placing. Column extraction.

One last python node named "Is rounded" checks if it is true that the column id rounded or not. If it is not rounded a warning message appears, asking to use the program intended for elements with planar surfaces.

Figure 51: Bridge SHM strain multi-sensor placing. Error message "not round".

3. Sensor location

3.1. Input form 2: Sensor coordinates

This next input form allows introducing the coordinates of the sensor in the column surface, specifically: the height of the cross-section of the column in which the sensor must be placed and the angle from 0 to 360º measured clockwise from the rightest point of the column cross-section.

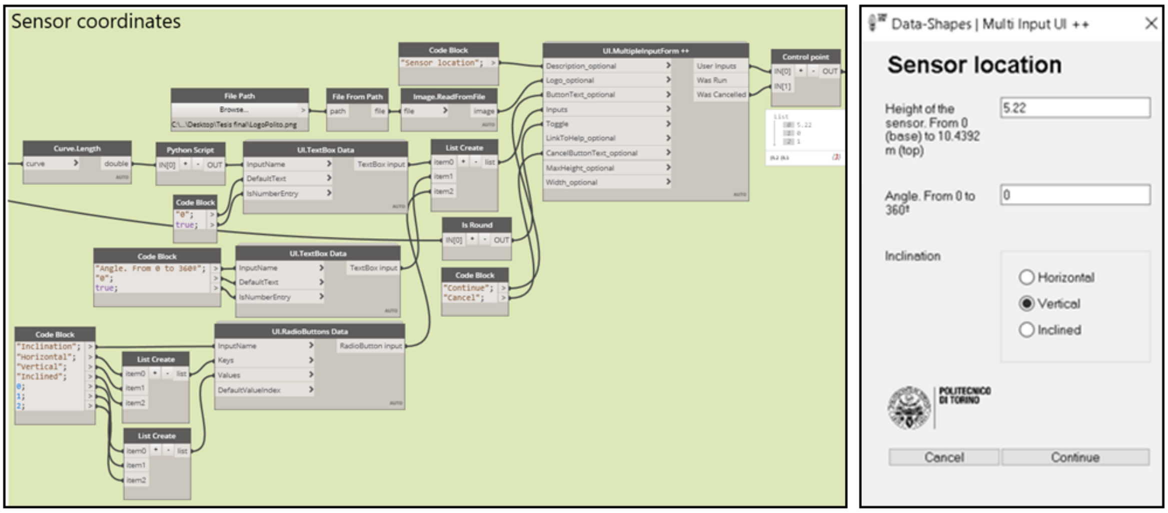


Figure 52: Bridge SHM strain multi-sensor placing. Sensor coordinates.

3.2. Placing points

With the inputs introduced in the last step the location of the sensor is calculated by the program by the implementation of a python routine, located inside the node “Points in section curve”. First it finds the section curve at the indicated height and creates some points along this curve. This is done with the goal of creating a new poly-curve with this points but establishing its starting point in the leftmost one, or that one with the lower X coordinate value. In that way can be controlled that the angular coordinate starts in the correct place.

After that, another python routine called “Sensor location” is able to take the previously introduced inputs and calculate the final output of this graph group that is the 2 points where the adaptive component will be placed.

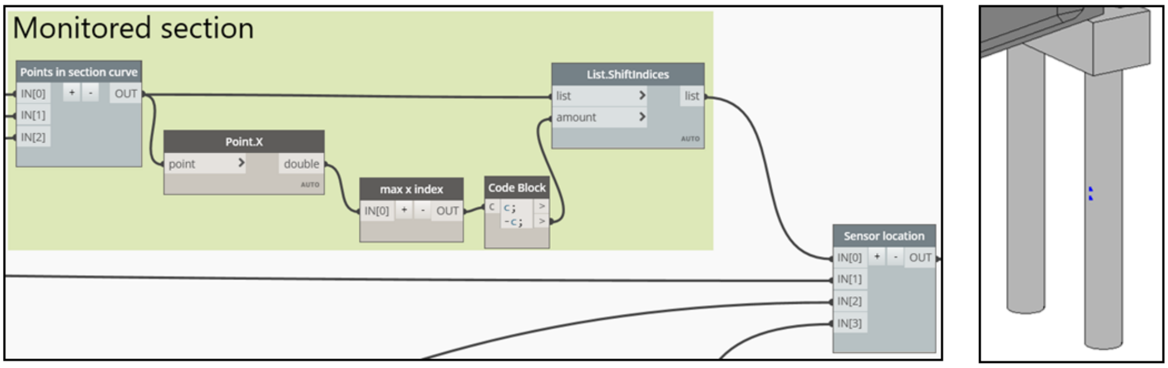


Figure 53: Bridge SHM strain multi-sensor placing. Creation of the placing points.

3.3.Sensor creation

This task is done in the same way as it was done for the case of elements with planar surfaces. The sensor is created with the settings introduced in the inputs again by using the “AdaptiveComponent.ByPoints” node.

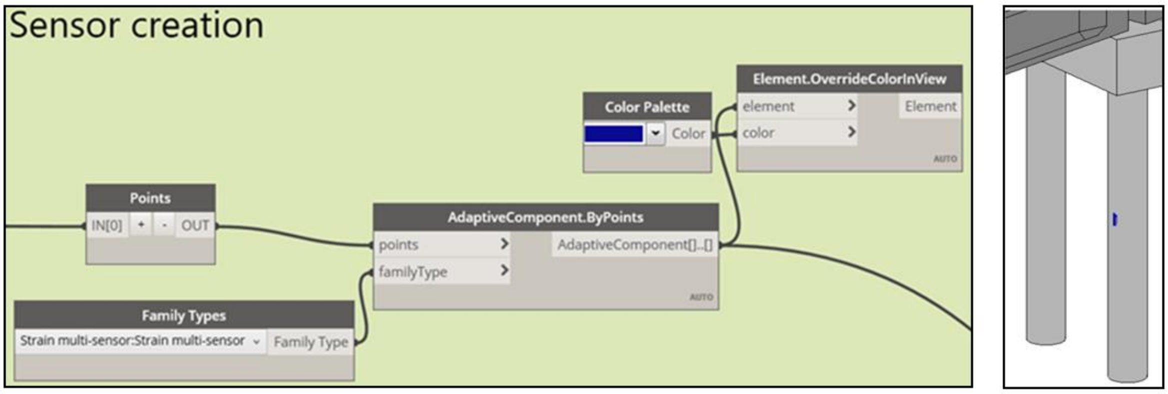


Figure 54: Bridge SHM strain multi-sensor placing. Sensor creation.

4. <u>Sensor identification</u>

Finally, the Host element, the number and the Sensor ID parameter are assigned and are visible in the properties palette that appears just selecting the created sensor.

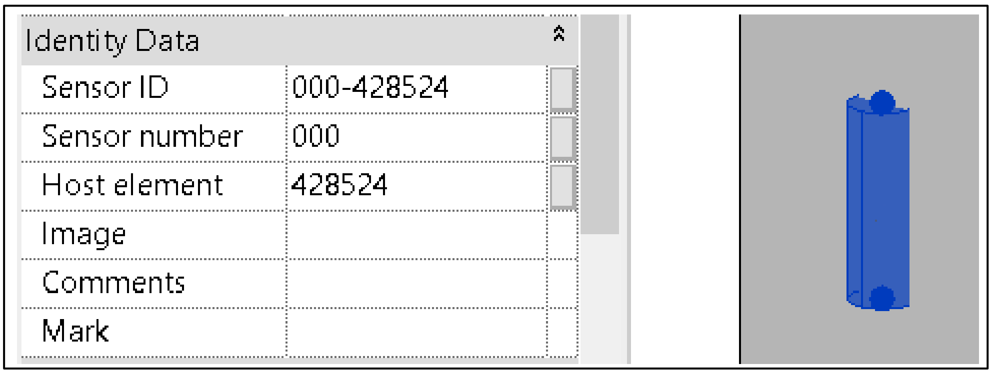


Figure 55: Bridge SHM strain multi-sensor placing. Sensor identification.

1.3.3. SHM Displacement multi-sensor placing

This program works basically in the same way as the Strain multi-sensor placing program. In fact the graphs used are the same, excepting for two details.

The first detail can be found in the 1st input form. While in the Strain multi-sensor program was asked to select the element in which the sensor will be placed, in this case the inputs are two. First must be selected the element to measure, but then is requested the element that is considered fixed for the measurements, or in other words, the element respect to which will be measured the relative displacements of the first element. In this case the measured element is the longitudinal beam and the base element is pier cap.

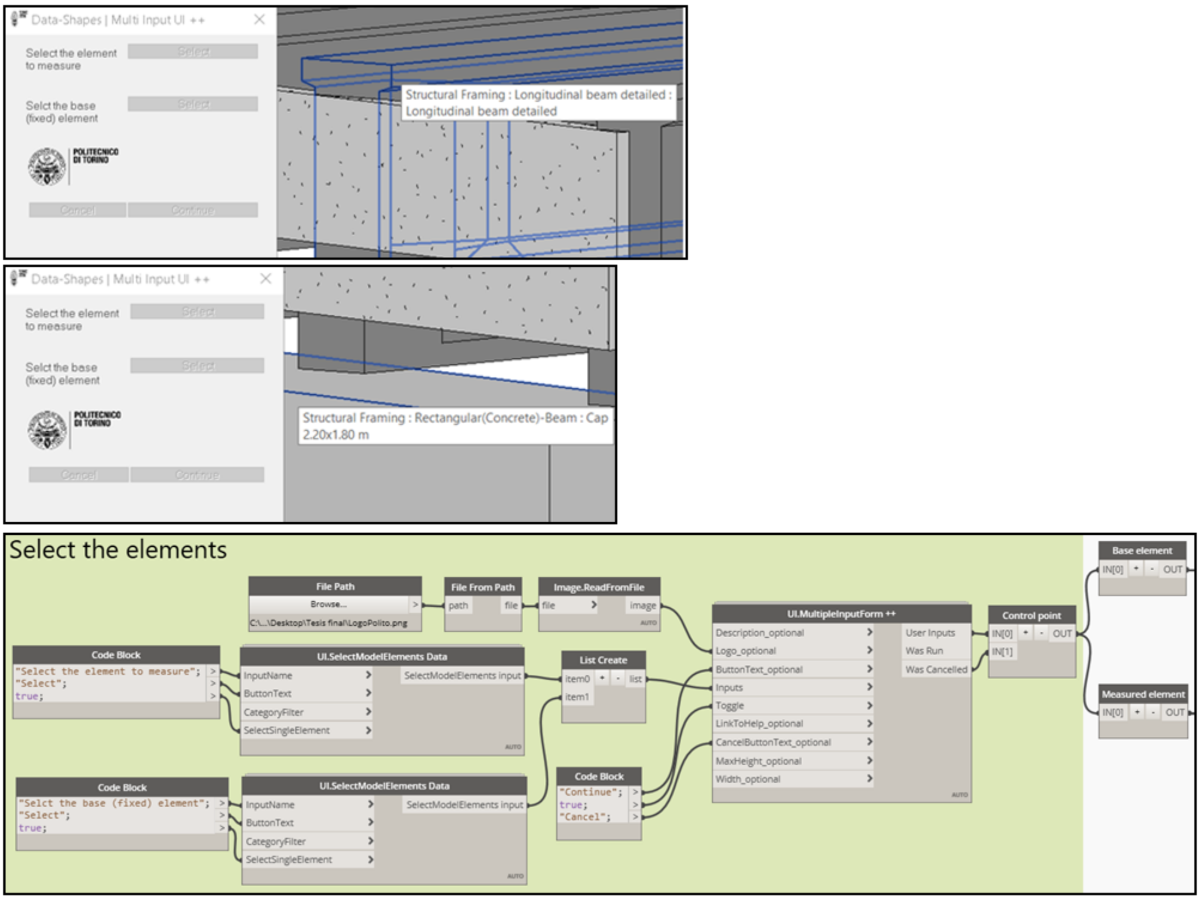


Figure 56: Bridge SHM displacement multi-sensor placing. Selection of the elements.

After that the program flows with the same sequence as in the Strain multi-sensor program. The second difference is found at the end of the graph, at the moment of the sensor identification. A part of the Host element, the sensor also has a Base element, so this parameter must be also assigned.

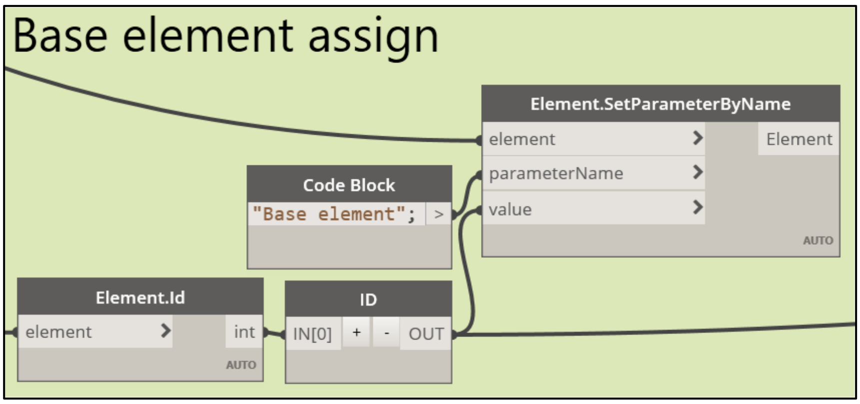


Figure 57: Bridge SHM displacement multi-sensor placing. Base element parameter.

Finally the assigned parameters can be seen in the properties palette of the sensor

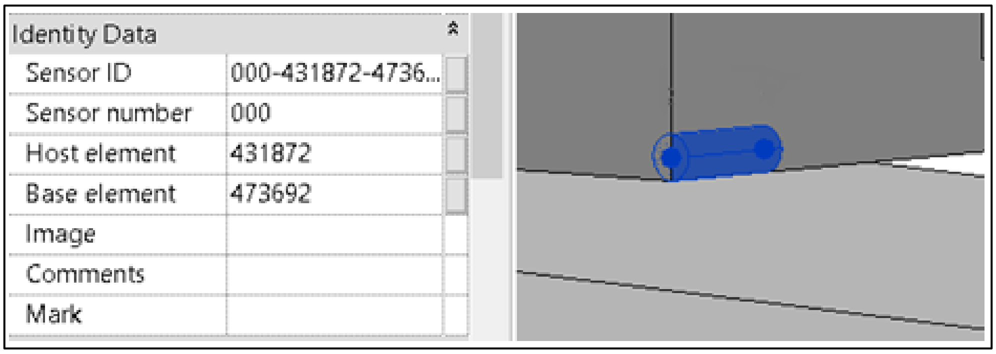


Figure 58: Bridge SHM displacement multi-sensor placing. Parameters setting.

1.3.4. SHM system of the Stura Bridge

By using the placing sensor programs explained in the previous points was created the SHM system installed in the Stura Bridge. This system consists in 42 Strain multi-sensors (black) and 7 Displacement multi-sensors.

This work is done by using the Dynamo player platform, where the desired program can be ran without open the Dynamo interface.

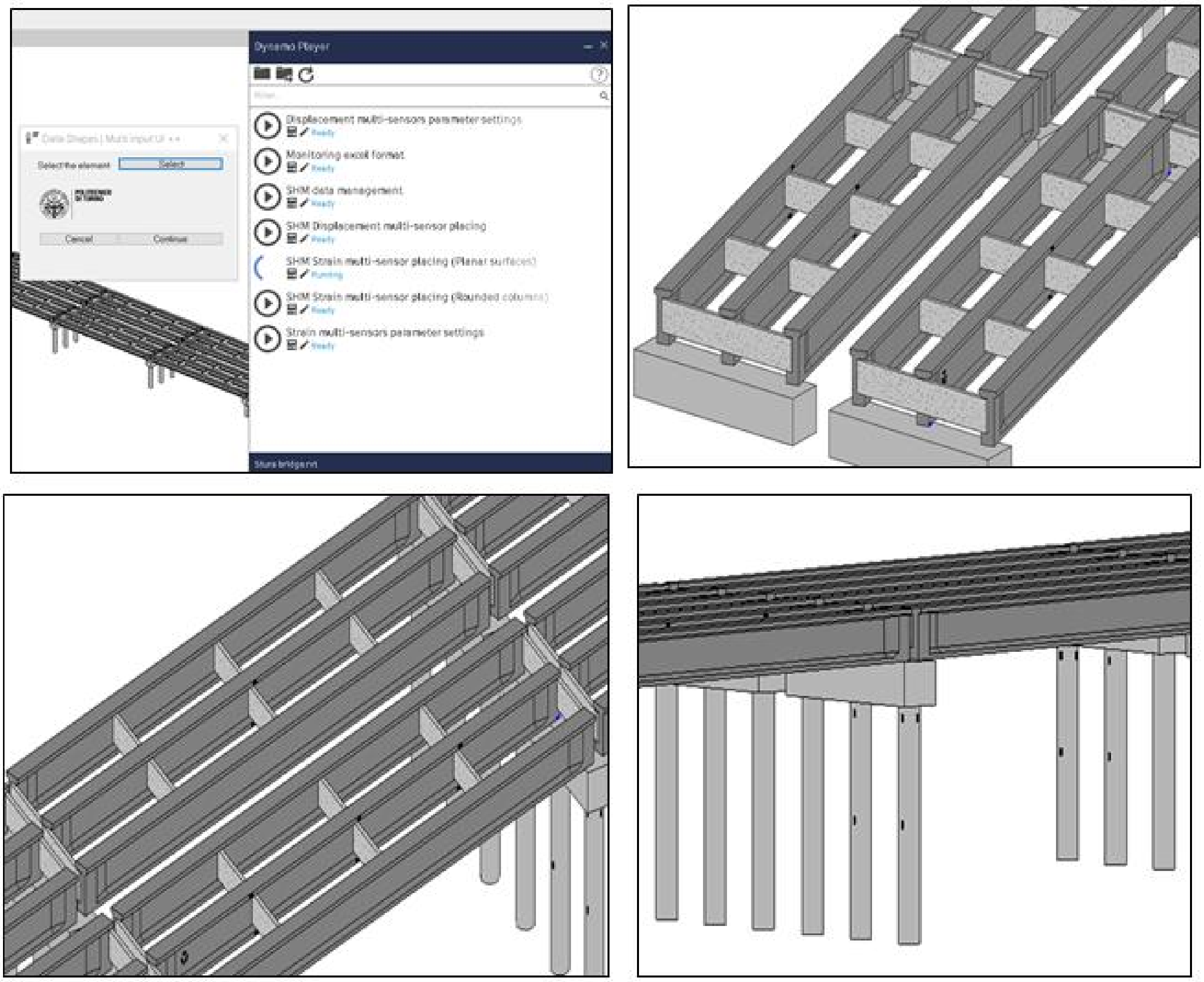


Figure 59: Bridge SHM system installation.

1.4. Elaboration of the SHM data management program

One of the challenges of the SHM is the management of the collected data. In the case of a continuous monitoring system, the sensors collect and send packs of data with the measurements uninterruptedly. This data on its own is meaningless, because it must be processed and analyzed in some way in order really identify and characterize the possible phenomena that could be happening at specific moment in the structure. The issue is that the amount of data may be huge and its size depends on the number of installed devices, the sampling rate with which the sensors measure and the time interval analyzed.

Dynamo has demonstrated to be very useful when it comes to gather and manipulate the data that constitutes the BIM model and offers the possibility to import and export it from external files, such as excel and text files. Due to these features that Dynamo provides was developed a program with the goal of retrieving, manipulating and analyzing monitoring interactively through the Revit model interface.

1.4.1. Modeling of the monitoring data

It is important to point out that due to the fact that real monitoring data from the installed sensors in the Stura Bridge was not available the strain, displacement and temperature data was modelled by the author. By using excel and with the help of the Dynamo script explained below was created the format with which the SHM will send the monitoring data:

1. <u>Input form1: Setting of the sampling rate and the file path to save the excel file</u>

This input form allows setting the time gap between the measurements that the sensor performs and where the final excel file will be saved in the computer.

2. <u>Creation of the time span</u>

Now that the time gap is known a python scripting node is written in order to create the list with the times. For doing that firstly is created a range from 0 to 86400 seconds, adding a number of seconds equal to the selected time gap in each step. This range represents the entire day expressed in seconds. Then after doing many operations this times expressed in decimals are transformed into sexagesimal numbers, i.e, hours, minutes and seconds in three separated lists.

Then the remaining part of his graph group get this lists and through the node "TimeSpan.Create" can be created the time span from the 00:00:00 (0 hours, 0 minutes and 0 seconds) to the 24:00:00 (24 hours, 0 minutes and 0 seconds) of the day.

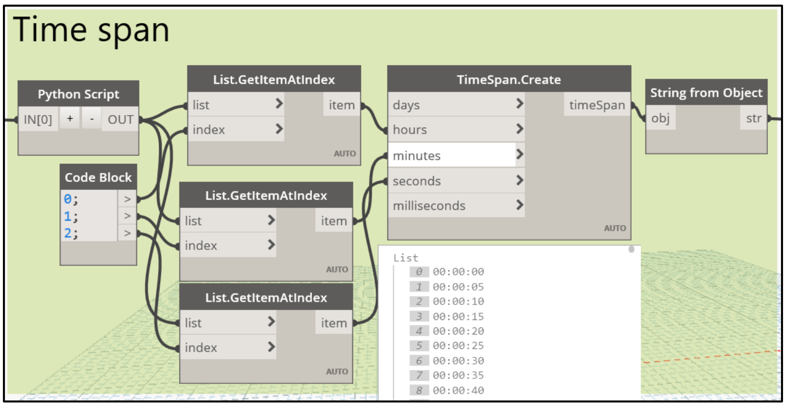


Figure 60: Bridge SHM data modelling. Time span creation.

3. Selection of the type of sensor

The strain multi-sensors and the displacement multi-sensors measure different types of parameters and because of that the program asks to define which type of sensor will be included in the monitoring format. This graph group creates a list with all the sensors that belong to a certain type present in the project which can mean a large number in certain cases.

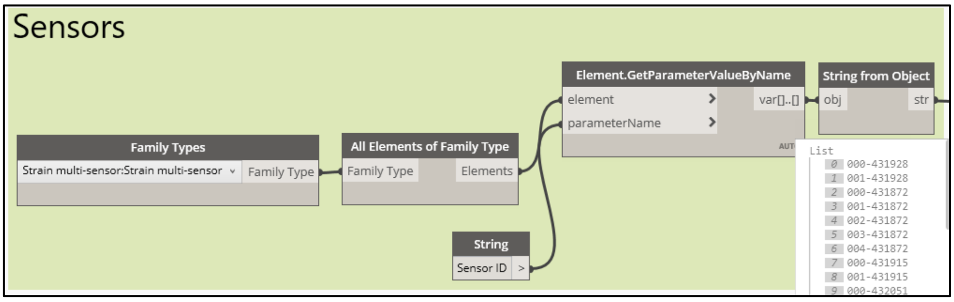
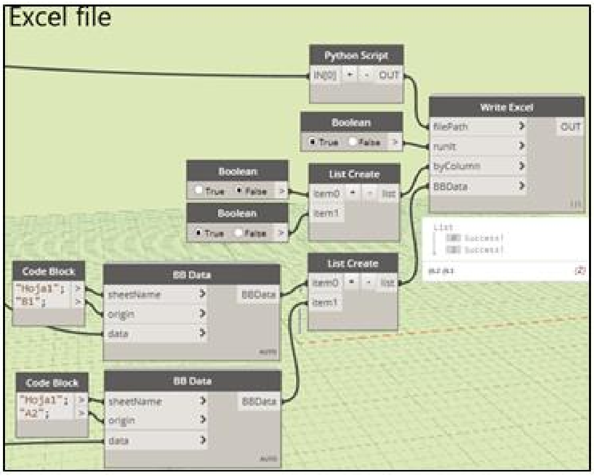


Figure 61: Bridge SHM data modelling. Sensors selection.

4. Writing of the excel file

By making use the Dynamo Package Archi-lab Bumblebee, the list with the sensors ID and the list time span are exported to an excel file. It writes the first in the first row, and the second in the first column.



	A	B	C	D	E	F	G	H	I	J
1		000-431928	001-431928	000-431872	001-431872	002-431872	003-431872	004-431872	000-431915	001-431915
2	00_00_00									
3	00_00_05									
4	00_00_10									
5	00_00_15									
6	00_00_20									
7	00_00_25									
8	00_00_30									
9	00_00_35									
10	00_00_40									
11	00_00_45									
12	00_00_50									

Figure 62: Bridge SHM data modelling. Excel file writing.

The same process can be done for the Displacement multi-sensors and another format is created.

After that, the different measurements can be created following a normal distribution. The excel built-in function that allows to create numbers that follow the normal distribution of probability is the *NORM.INV ( )* function. It requires 3 inputs: a probability, the mean and the standard deviation. The probability value is given by a random number (excel function *RAND ( )*) and the mean and the standard deviation are chosen arbitrarily.

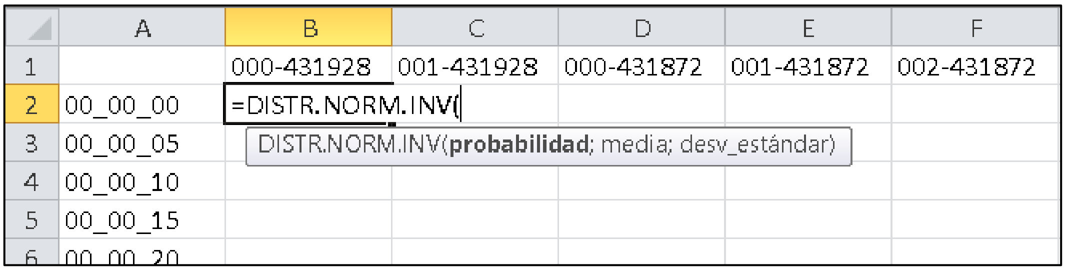


Figure 63: Bridge SHM data modelling. Data modelling.

- The strain multi-sensors measure the data in microstrain (με) with a resolution of 50 with and accuracy of +/- 50. For this reason in order to present the data in an easier way to handle, this is expressed in terms of με x 10^3.

- The displacement multi-sensors measure the data in millimeters (mm) with a resolution of 0.1 and accuracy of +/- 0.1. In this case the data is expressed in mm.

- The temperature values for both the strain and displacement multi-sensors are measured with a resolution and accuracy of +/- ºC. The data is also modelled in Celsius degrees.

Then, after all the fields in the format are filled with the created data, the file is saved as a txt file (.txt) where every measurement is separated from the other with "," and the rows are separated with "/".In that way were created some files, each one representing one day of monitoring data, for each type of measured parameter. For example, was simulated the data of 7 days (from the 1st to October 7th) for strains.

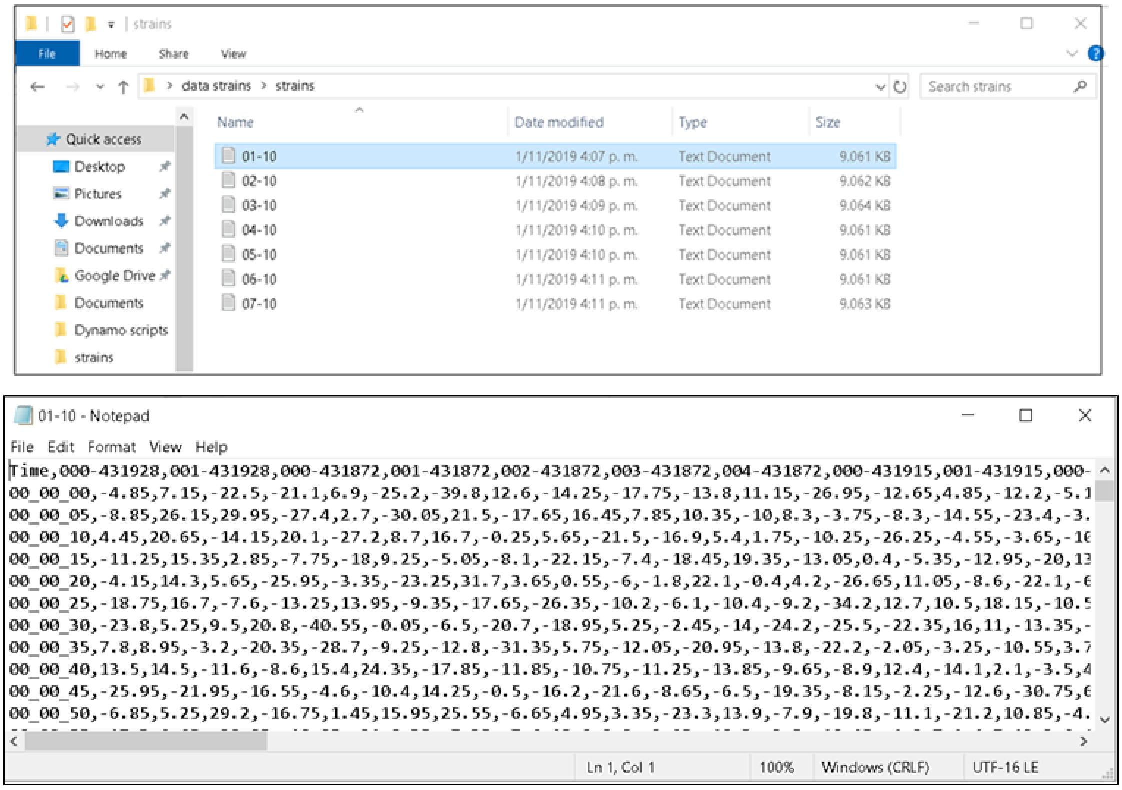


Figure 64: Bridge SHM data modelling. TXT files generation.

1.4.2. Assignment of the initial values and thresholds of the sensors

In order to perform the data analysis, the measurements collected by the sensors must be manipulated in some way. First of all, this data are not absolute measurements, it corresponds to variations of these parameters respect to an initial value, for example strains due to the permanent load, already present in the beams before the installation of the sensors. On the other hand, in order to analyze the data collected, this must be compared with the defined thresholds. So, the initial and thresholds values have to be established for each sensor. This task can be done in Revit manually, but in the case of a large number of sensors (47 in the case of the Stura Bridge) a Dynamo script can be created for a quicker completion of this repetitive task.

1. Input form 1: selection of the sensors and the parameters to set

This graph group allows selecting through an input form all the sensors that is desired to set, and the parameters that is wanted to define. This leads to the possibility to assign the parameters to multiple elements expeditiously.

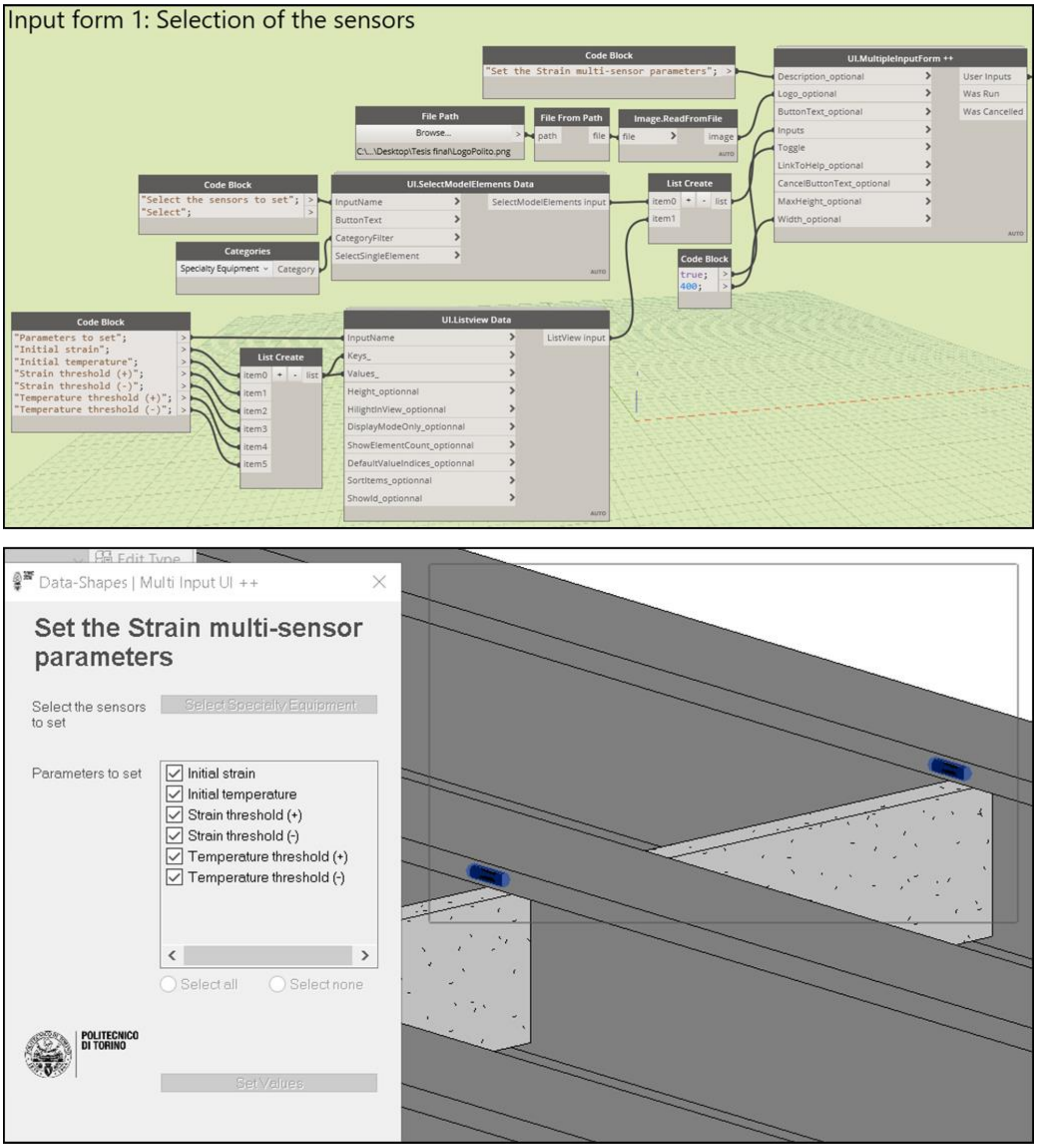


Figure 65: Bridge SHM initial values setting. Selection of the sensors.

2. <u>Input form 2</u>: Introduction of the parameters values

After the sensors and the parameters to introduce are known, the values must be assigned. The following graph group creates a second input form that allows the introduction of these numbers.

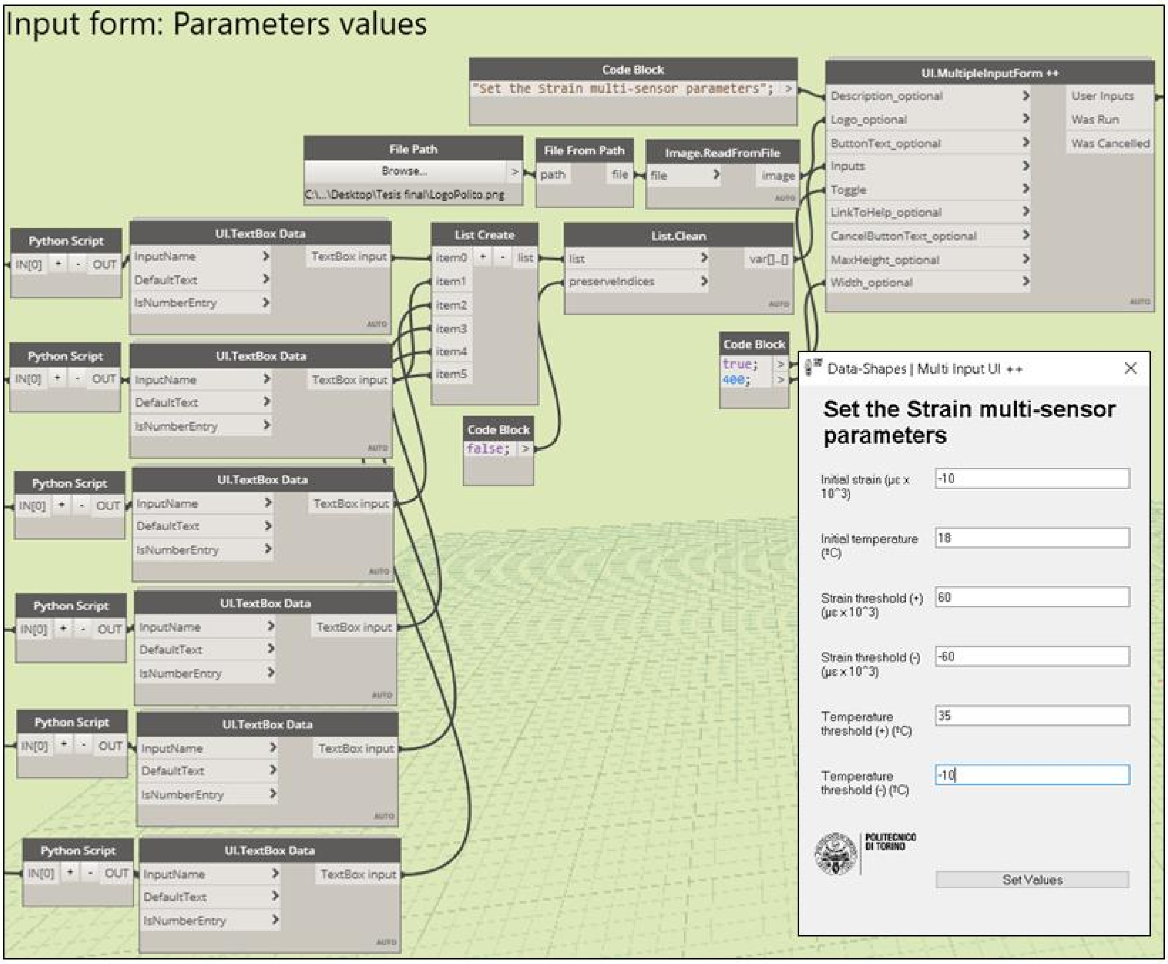


Figure 66: Bridge SHM initial values setting. Introduction of the values.

3. <u>Assignment of the parameters</u>

By the following group of nodes the introduced values are assigned to the sensor elements. All the python scripting nodes used are useful for getting the different value introduced in the previous input and in the case where no value are written it returns an empty list. This is important because in that way the programs doesn't show any warning.

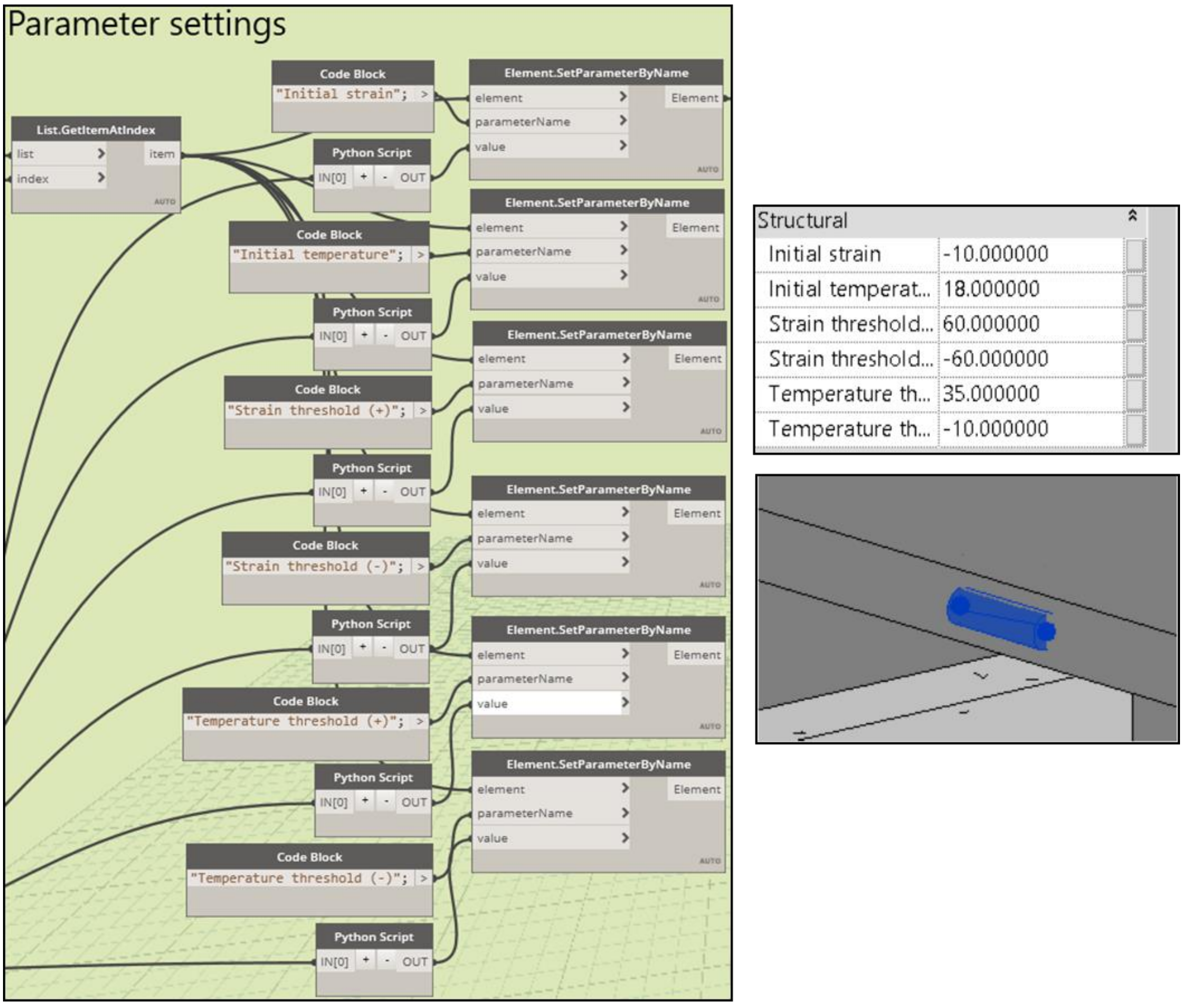
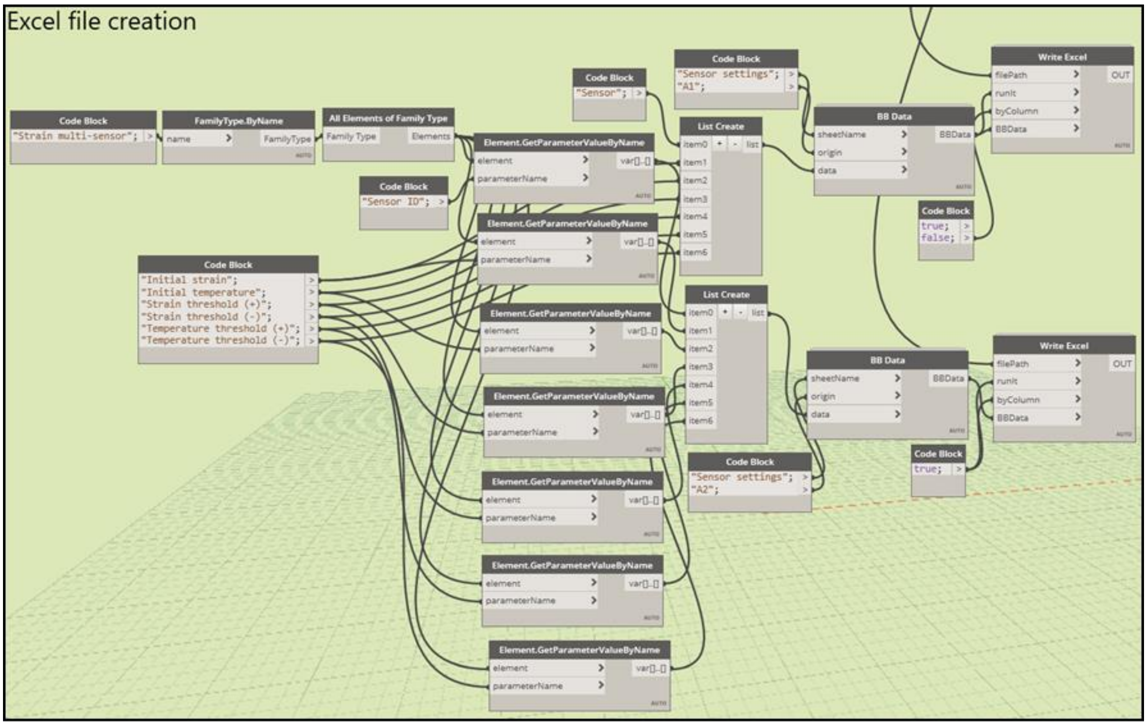
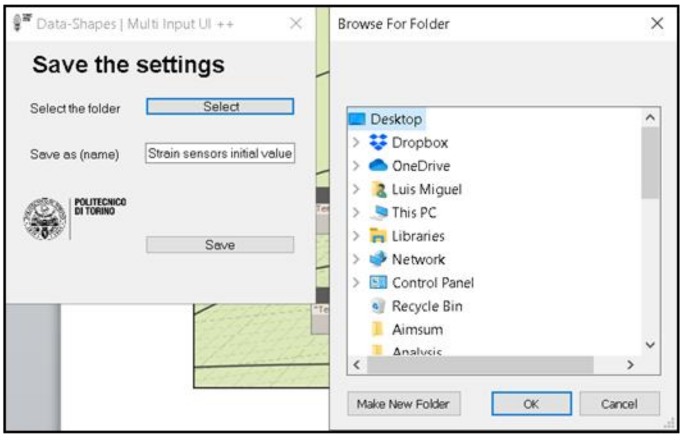


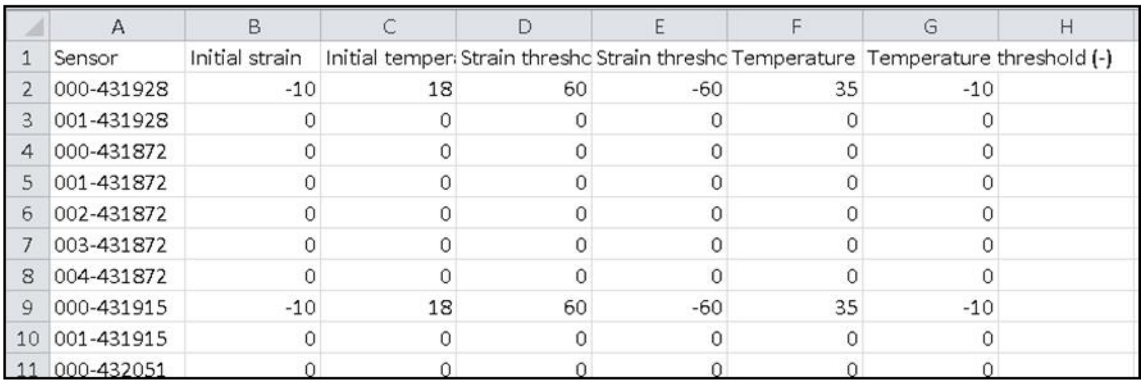
Figure 67: Bridge SHM initial values setting. Parameters setting.

4. <u>Writing the excel file</u>

Now that the initial values are set, the program also allow to export this data to an excel file. The Excel file consists in a table with all the sensors and parameters listed. Firstly the program asks the name that will have the excel file and the folder where it is going to be saved. After that by using the Archi-lab “Bumblebee” package the data is exported from the Revit model to the excel file.







	A	B	C	D	E	F	G	H
1	Sensor	Initial strain	Initial temper	Strain thresho	Strain thresho	Temperature	Temperature threshold (-)	
2	000-431928	-10	18	60	-60	35	-10	
3	001-431928	0	0	0	0	0	0	
4	000-431872	0	0	0	0	0	0	
5	001-431872	0	0	0	0	0	0	
6	002-431872	0	0	0	0	0	0	
7	003-431872	0	0	0	0	0	0	
8	004-431872	0	0	0	0	0	0	
9	000-431915	-10	18	60	-60	35	-10	
10	001-431915	0	0	0	0	0	0	
11	000-432051	0	0	0	0	0	0	

Figure 68: Bridge SHM initial values setting. Excel file creation.

1.4.3. SHM data management program

Once the files with the monitoring data are available and the initial values and thresholds of the parameters are established it is possible to continue with the next step that is the elaboration of the data management program. It follows the steps shown below:

1. Input form 1: selection of the folder that contain the files

This graph group creates an input form with which the directory where are located the text files with the monitoring data can be selected. The directory that is selected must contain only files of the single parameter that is wanted to be analyzed, for example: strains.

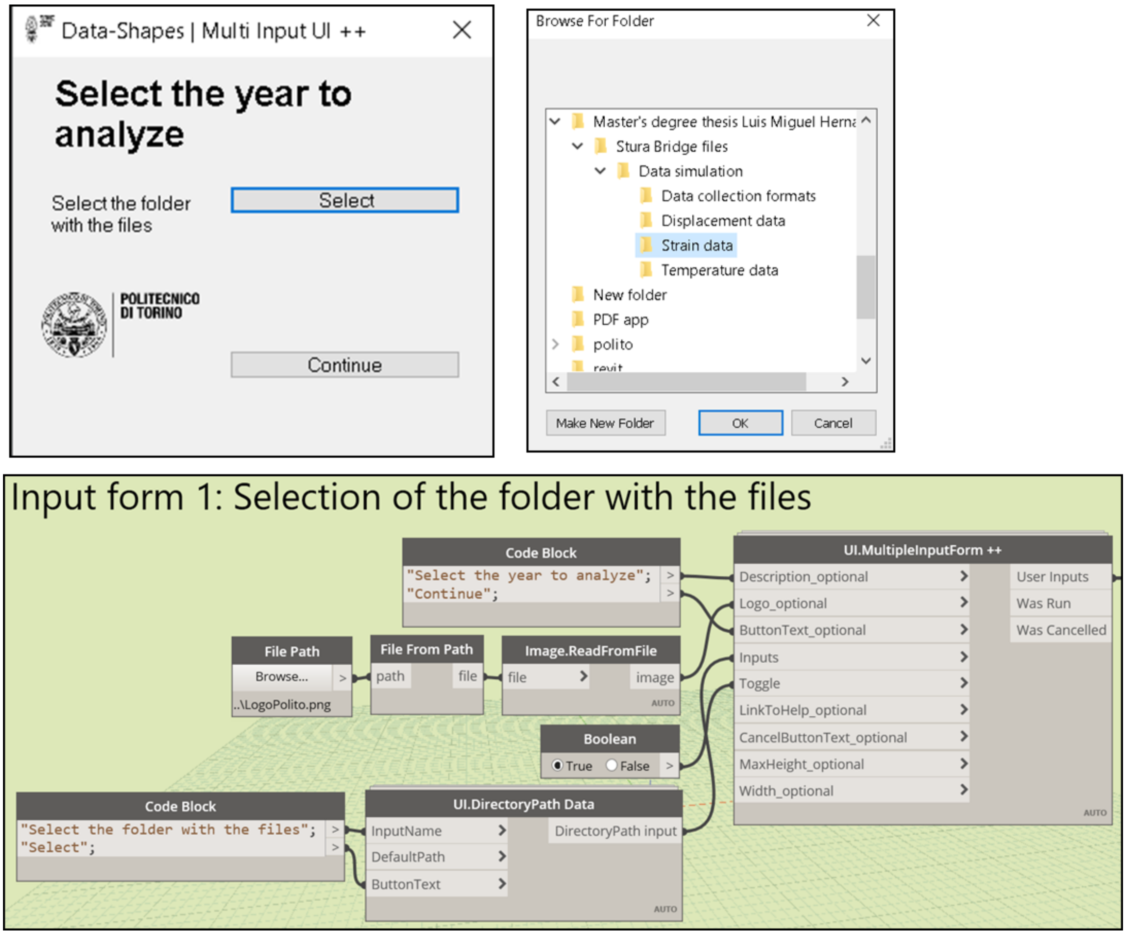


Figure 69: Bridge SHM data management. Selection of the data files.

2. Input form 2: Selection of the date interval to analyze

The following group, through an input form, selects from which to which date the analysis will be performed. The dates are introduced with a list view input where it is possible to select the dates of the entire year (from January 1st to December 31th). These lists were created with the help of a python scripting nodes “Dates”, one that give the list specifying the months in numbers and the other with their names. As an illustration will be done an analysis of 5 days, between the 1 and the 5 of October.

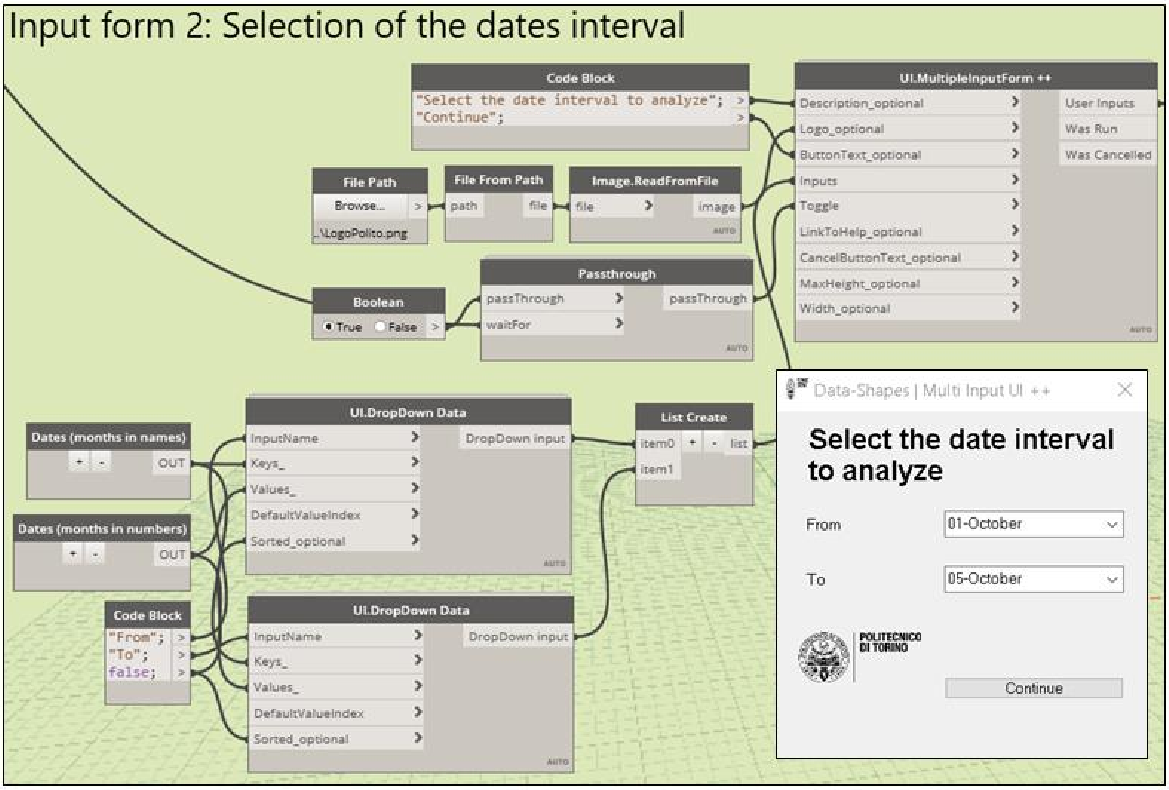


Figure 70: Bridge SHM data management. Selection of the dates.

3. <u>Loading the monitoring data</u>

Once the interval of dates is established the program must load the data from the text files that corresponds to the days selected. First, the graph group “Files in the folder”, extract the names of all the text files that the folder contains and is able also to retrieve their file paths. Then this list must be filtered. This task is done by the graph group “Available files” that by the using of a python routine eliminates from the list the text files of dates that are outside the interval previously selected.

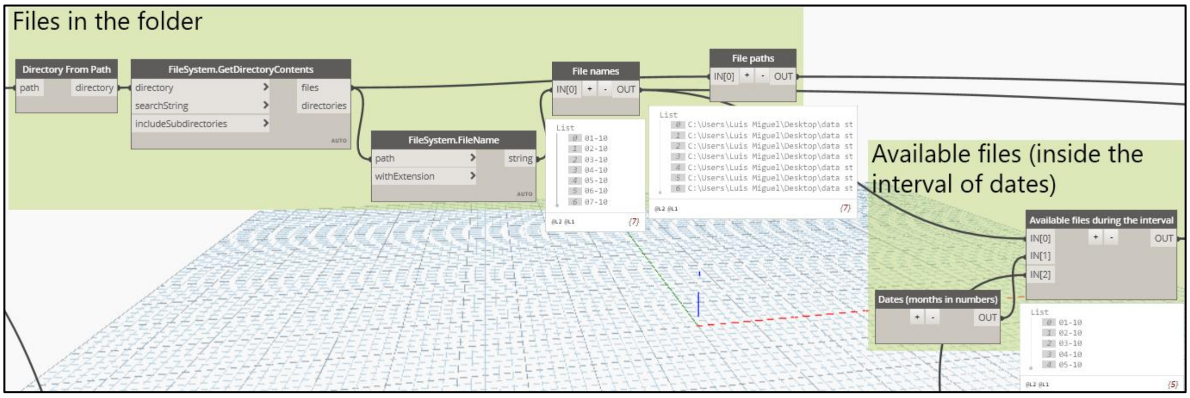


Figure 71: : Bridge SHM data management. Available files inside the interval

Once the list with files is cleaned the text files are loaded into Dynamo and then processed, transforming each text file that is simply a long string of characters, into a list of items, job done again with the help of a python script and many built-in nodes of dynamo that help with the string variables manipulation. Can be observed that just the analysis of an interval of 5 days means more than 3.7 million measurements, fact that demonstrate the power of Dynamo as regards with the management of large amount of data. Moreover another python routine extracts from the imported text files a list with all the times.

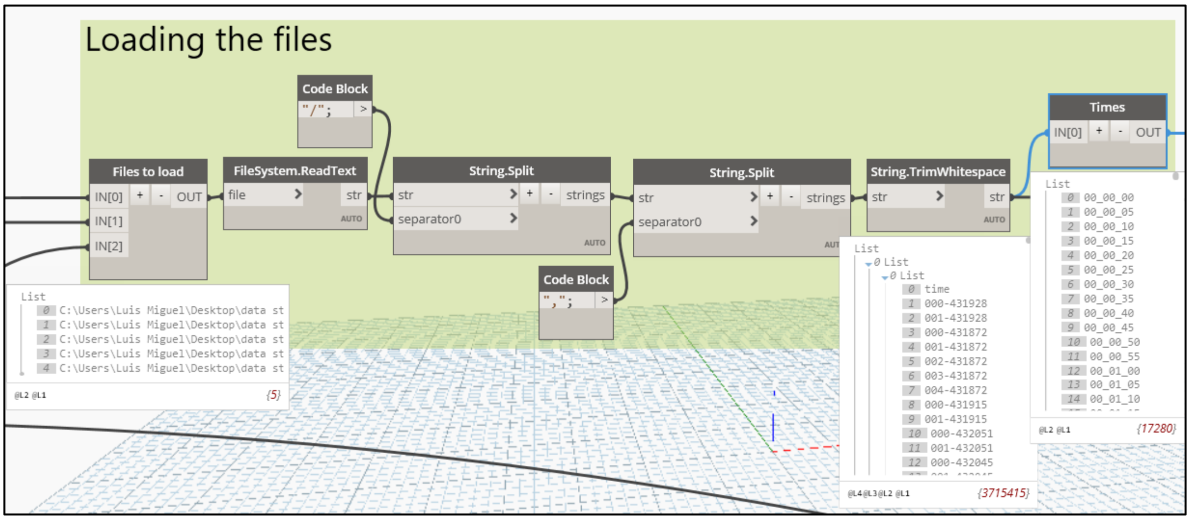


Figure 72: Bridge SHM data management. Monitoring data loading.

4. Input form 3: Selection of the sensor type

In order to continue with the analysis the program needs to know if it will be done for the Strain or the Displacement multi-sensors and that is exactly the goal of the following input form.

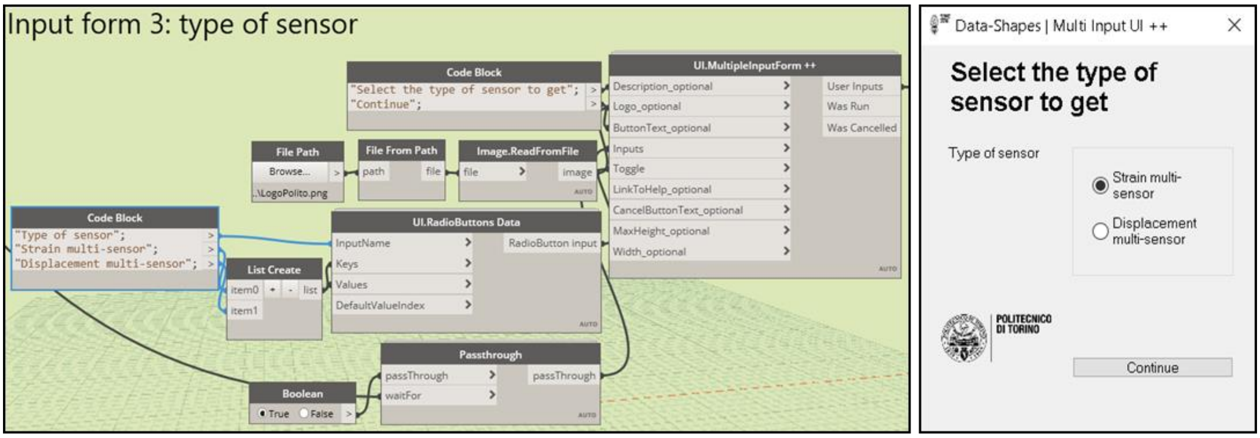


Figure 73: Bridge SHM data management. Selection of the sensor type.

5. Input form 4: Selection of the sensors to analyze

After the type of sensor is established the program asks which devices will be involved in the analysis. The scope of this input form is to allow the selection of these sensors, and it permits to do that in 3 different ways: all the sensors of the type can be selected no matter their location (All sensors option), all the sensors that are installed in a particular element (By element option) and selecting discreetly all the sensors that is desired to be included in the analysis regardless if they are installed in different elements. For instance, in this analysis was used the “By element” option in order to select the sensors installed in a specific beam of the bridge.

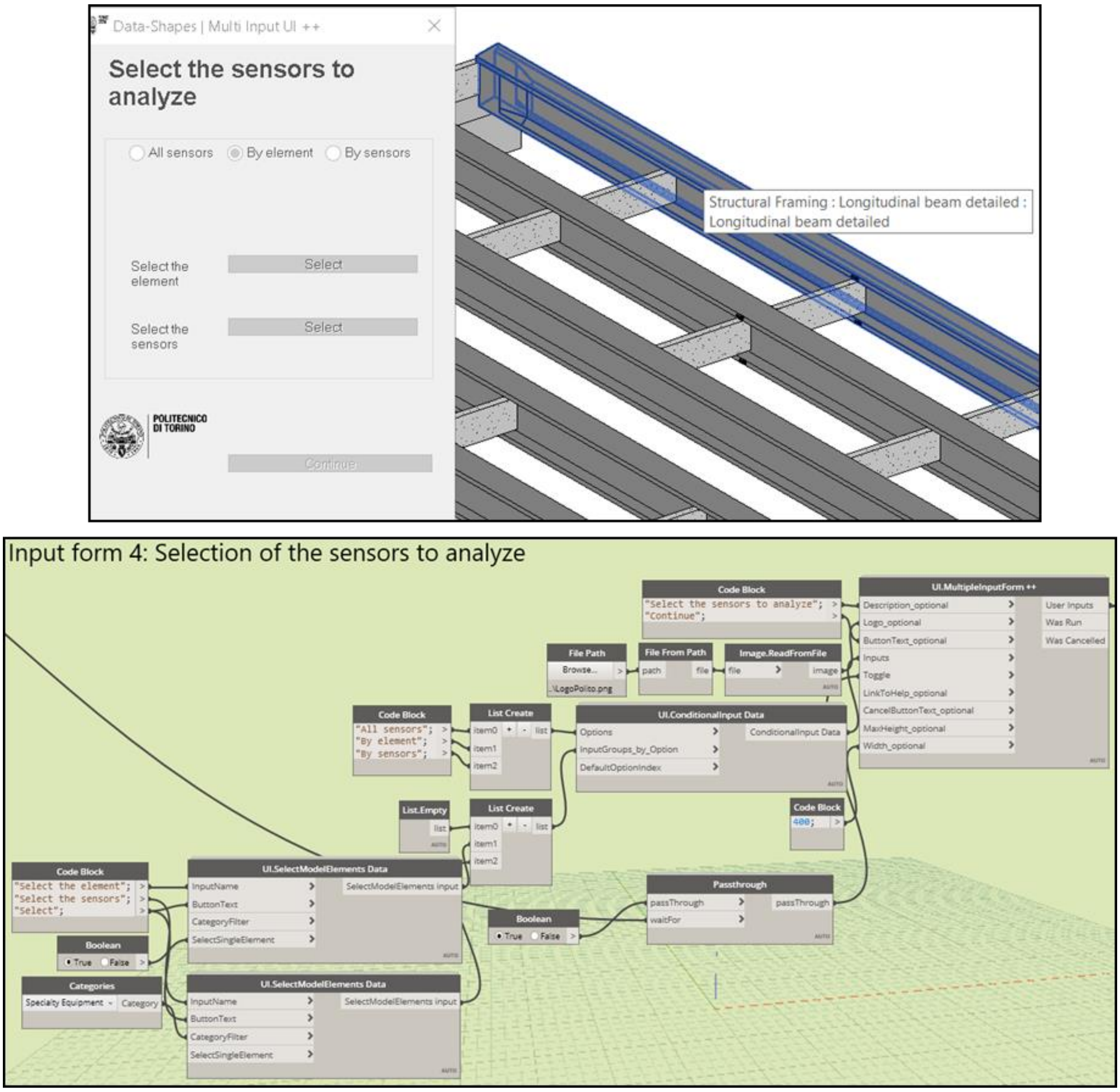


Figure 74: Bridge SHM data management. Selection of the sensors.

6. <u>Input form 5</u>: Selection of the type of data to analyze

After the type of sensors is selected in the step 5, must be defined which type of data will be involved in the analysis, because as the devices are multipurpose they can measure several parameters at the same time. Initially were created two different graphs groups, one for the strain multi-sensors and other for the displacement multi-sensors. For example, as the selected type was the Strain multi-sensor, the graph flows and is used only this group, being the other group not included in the flow of the program; then as these sensors measure strains and temperatures (also acceleration but this data was not the scope of this thesis) one of them must be selected. In this case Strain was the chosen option, to perform a strain analysis.

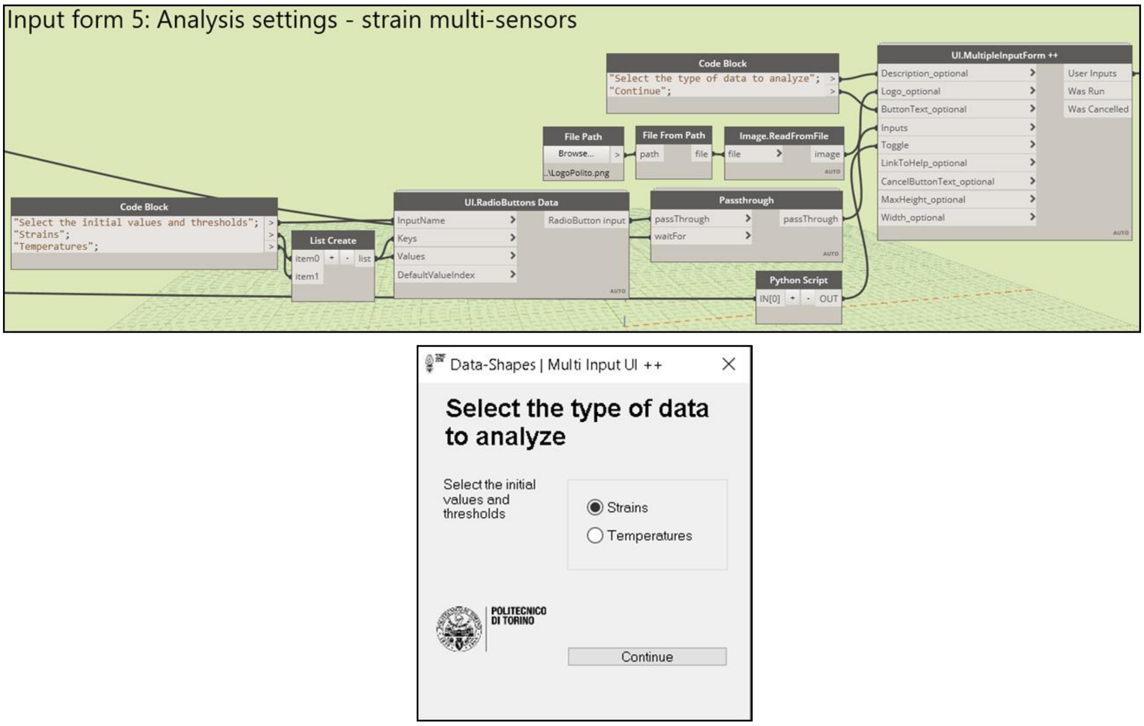


Figure 75: Bridge SHM data management. Data type to analize.

After the desired parameter is selected, the initial values are added to the measurements of the loaded data with the help of a python script node, that search in the strain list the correct sensors and adds their respective values that are stored in a family parameter. Can be observed that the amount of data for only 2 sensors is 172800 measurements.

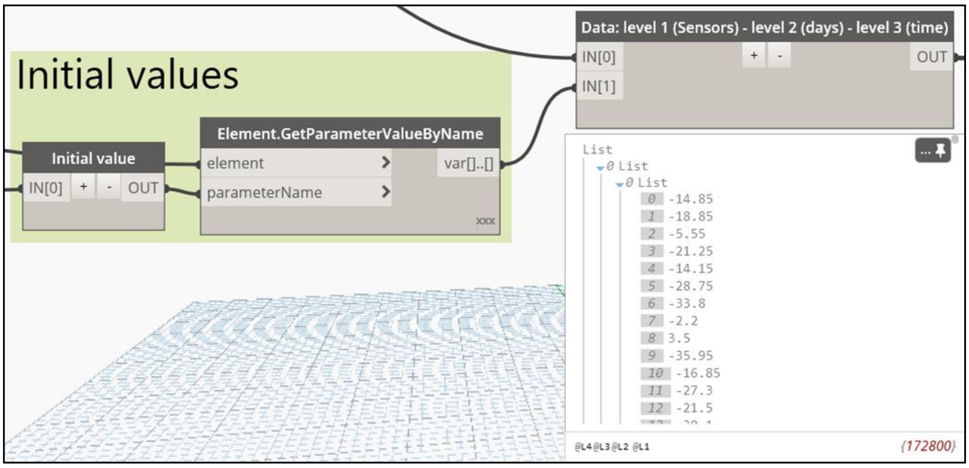


Figure 76: Bridge SHM data management. Adjusted data with initial values.

7. <u>Extraction of the maximum and minimum measurements</u>

With the list of measurements cleaned and adjusted by the initial values some indicators or interesting information can be obtained. By using some python script nodes written by the author the maximum and minimum values can be obtained and also the date and the time when these events happened are retrieved.

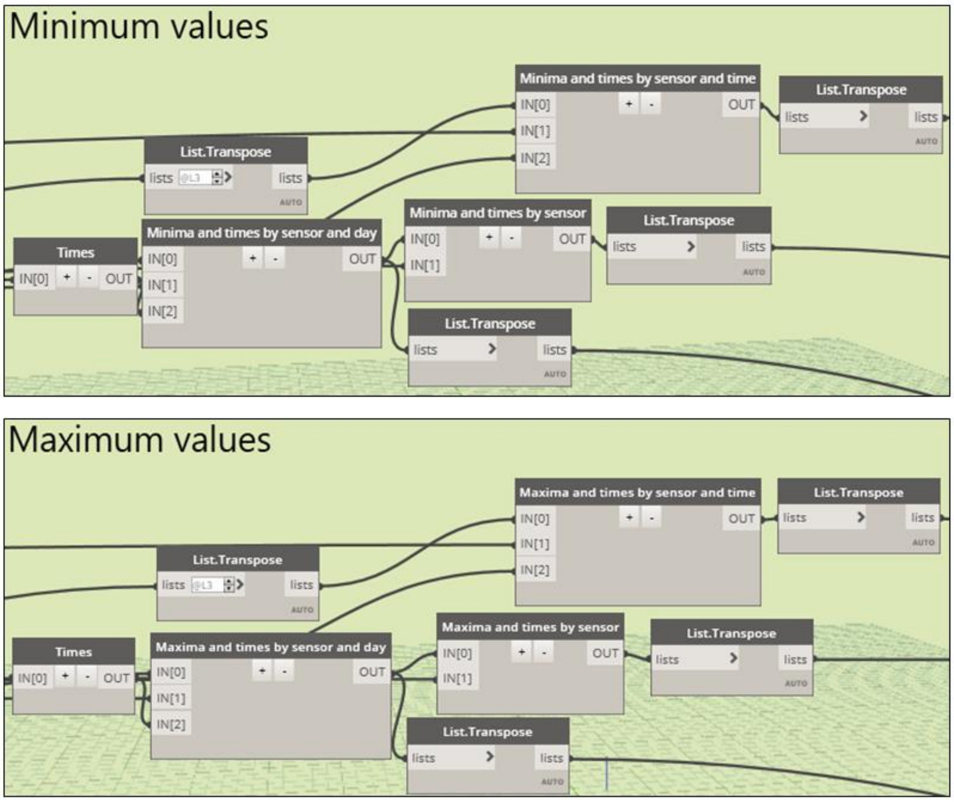


Figure 77: Bridge SHM data management. Maximum and minimum measurements.

With other python nodes it was also obtained the total number of measurements involved in the analysis, by day and by hour.

8. <u>Percentiles analysis</u>

In addition of calculating the maximum and minimum events and when they took place it is also useful to calculate the quantity of events that overcame the thresholds established before. Firstly, in order to perform this task, the percentiles must be defined being the calculation performed after:

8.1.<u>Input form 6</u>: Select the percentiles to analyze

The following graph group creates an input form in which the desired percentiles to analyze are chosen. They consist in numbers from 5 to 110 that represent the value in percentage of the threshold. At the end, with a python routine are calculated negative percentiles (for the negative measurements) and positive percentiles (for the positive measurements)

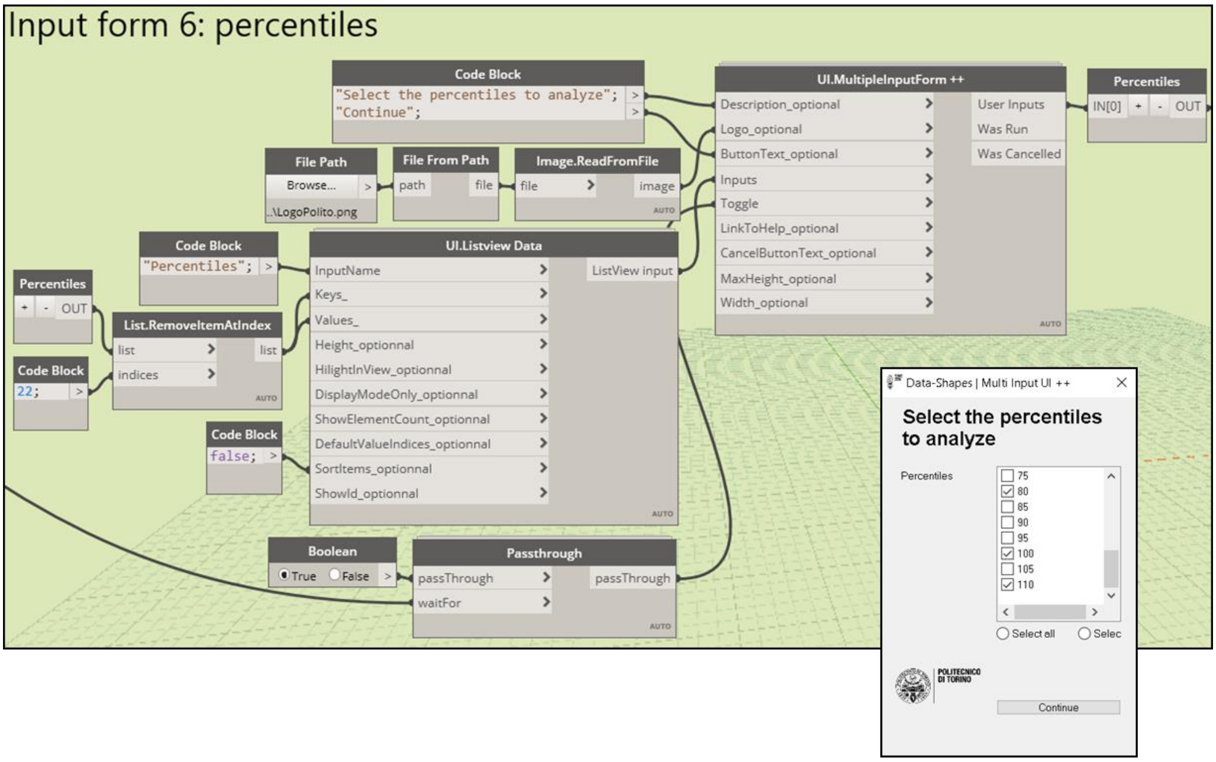


Figure 78: Bridge SHM data management. Percentiles selection.

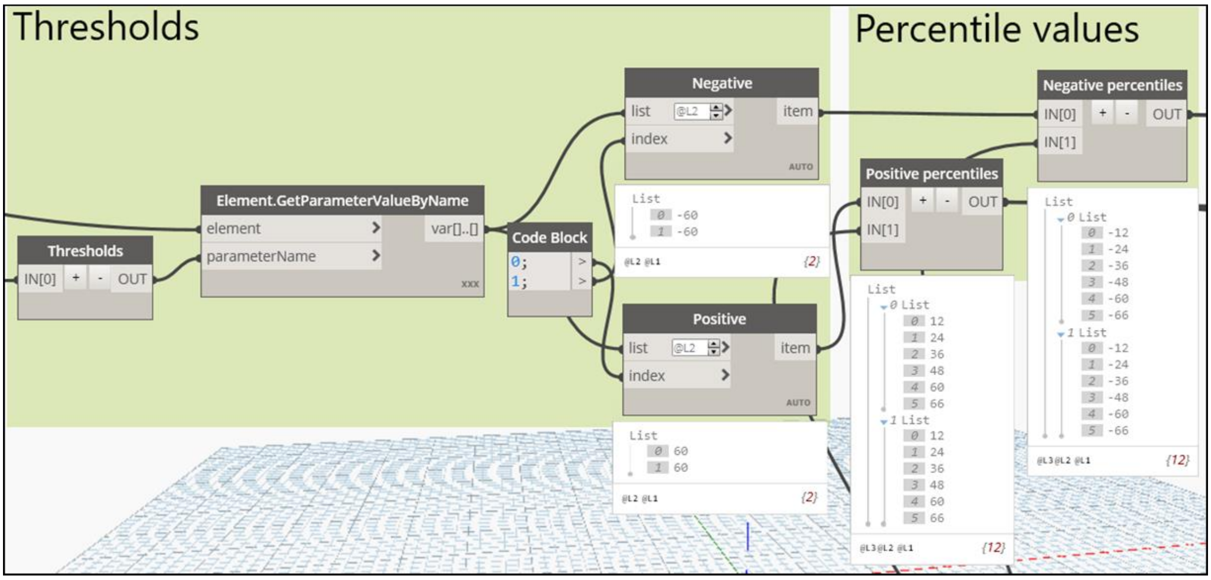


Figure 79: Bridge SHM data management. Percentile values calculation.

8.2. Calculation of the frequencies

The frequency refers to how many events overcome each percentile of the established thresholds. These frequencies are calculated for all the measurements, for the measurements depending the day and finally for the measurements depending the hour. For this task were written some python routines developed by the author:

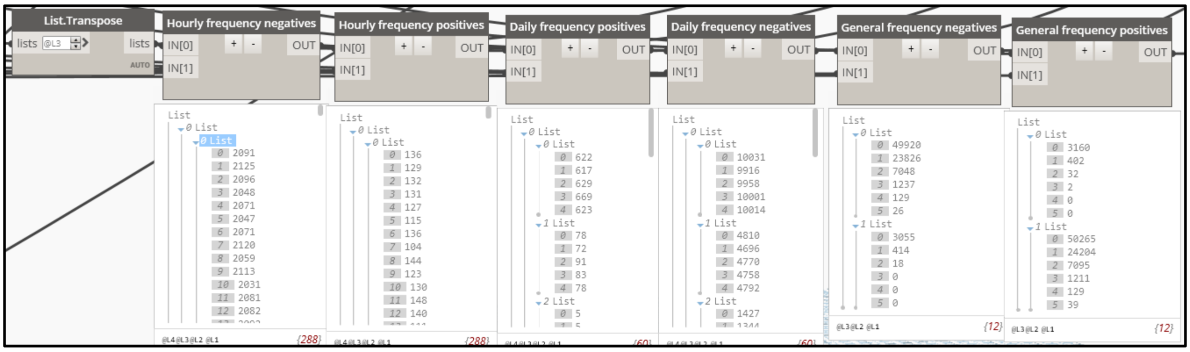


Figure 80: Bridge SHM data management. Frequencies calculation.

9. <u>Writing the excel file with the analysis</u>

After having the maximum and minimum values and the frequency data of the measurements and by the help of the external package Bumblebee, an excel file can be written.

9.1.<u>Input form 7: Saving of the analysis</u>

The following input form allows defining in which folder of the computer is desired to save the analysis and with which name this will be saved.

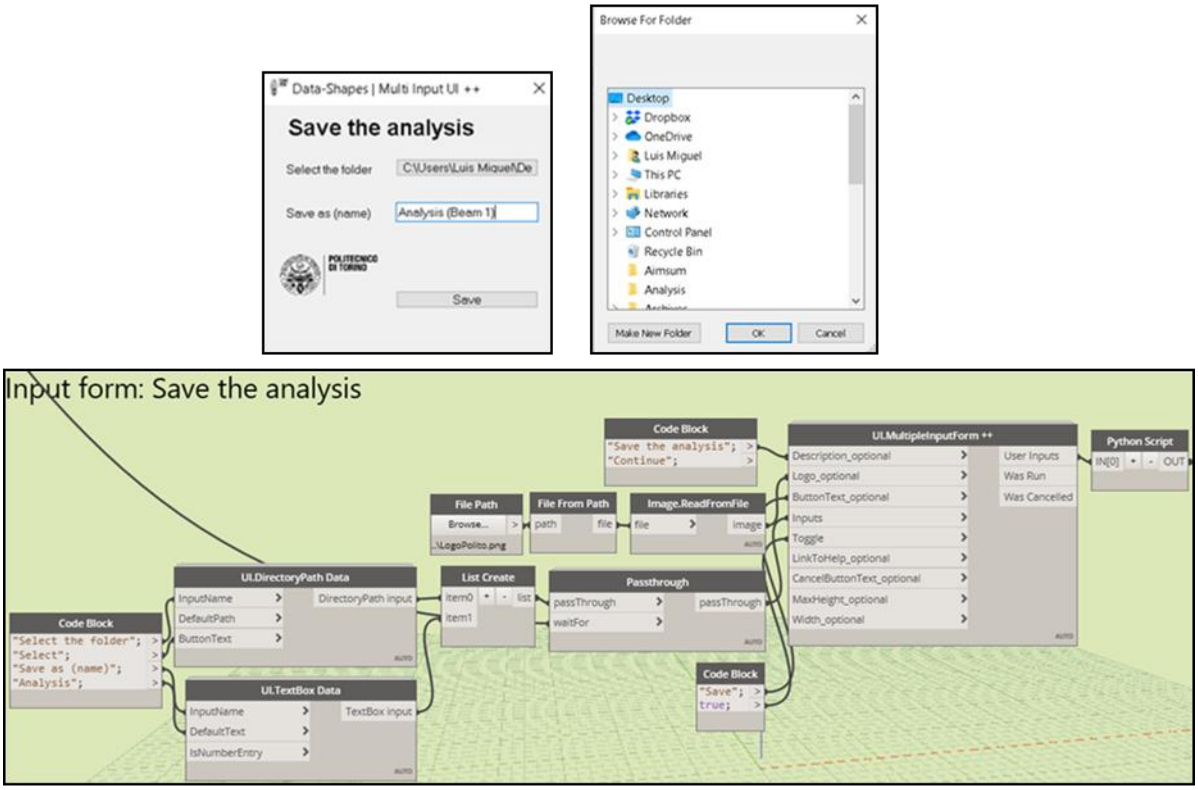
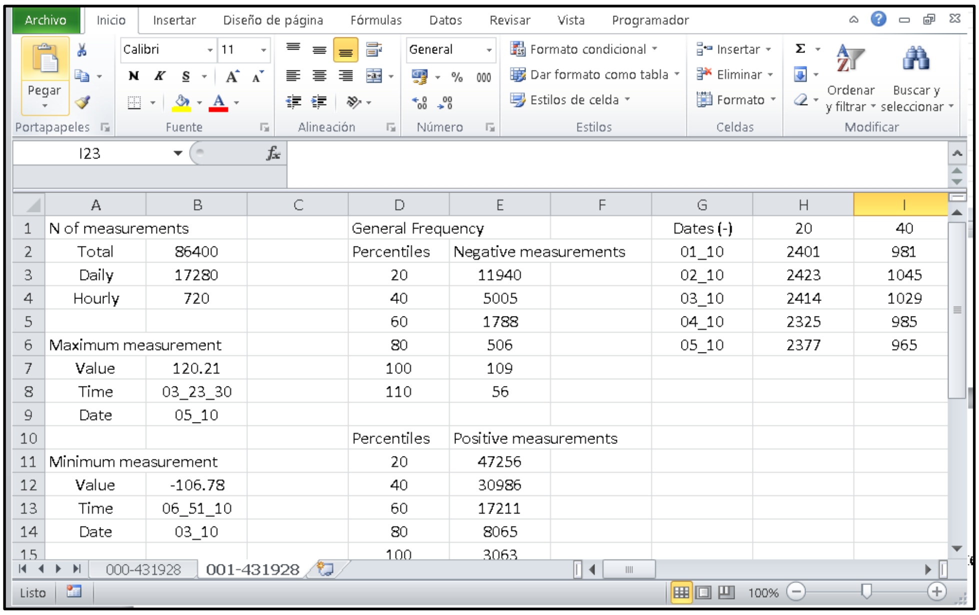


Figure 81: Bridge SHM data management. Excel file creation.

9.2.<u>Writing the excel file</u>

With the help of the Archi-lab *Bumblebee* package the data was exported to the excel file. For each sensor selected is assigned a spreadsheet with the name of the sensor ID. In each spreadsheet can be found the number of measurements, the maximum values, the minimum values and all the frequency analyses (general, by date and by time).



	A	B	C	D	E	F	G	H	I
1	N of measurements			General Frequency			Dates (-)	20	40
2	Total	86400		Percentiles	Negative measurements		01_10	2401	981
3	Daily	17280		20	11940		02_10	2423	1045
4	Hourly	720		40	5005		03_10	2414	1029
5				60	1788		04_10	2325	985
6	Maximum measurement			80	506		05_10	2377	965
7	Value	120.21		100	109				
8	Time	03_23_30		110	56				
9	Date	05_10							
10				Percentiles	Positive measurements				
11	Minimum measurement			20	47256				
12	Value	-106.78		40	30986				
13	Time	06_51_10		60	17211				
14	Date	03_10		80	8065				
15				100	3063				

Figure 82: Bridge SHM data management. Excel file with the processed data.

Now as the data is in excel, is very easy to create some graphs in order to facilitate the interpretation of the analysis, job that is impossible to do with the raw data stored in the text files.

2. Brenner Base Tunnel

2.1. Elaboration of the Revit model

2.1.1. Tubing Ring Segment family

The tunnel is constituted entirely by the tubing ring segments. For that reason, the first step to do is the creation of the tubing ring segments family in the Revit family environment. These are modelled as adaptive component objects, in which its shape depends on where and how are placed its points. As can be seen in the figure below, the shape of segment family created is controlled by 30 placing points. It is important to say that while more points are used in the placing of the object the accuracy in its shape is higher, due to the fact that its curves and surfaces are splines.

Moreover this family must be assigned to a category that allows the placing of reinforcement bars inside of it. The only way that an adaptive component family can be created for supporting rebar is setting it inside the *Structural connection category.*

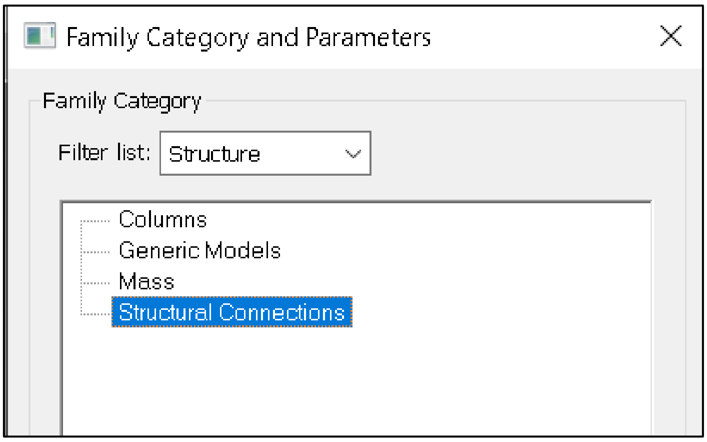


Figure 83: Tubing ring segment family. Category selection.

In addition are also included some family parameters that are will be useful in further steps. These parameters can be gathered in two types:

- <u>Identity data parameters</u>

Are instance parameters that are dedicated to make unique each segment and bring the possibility of differencing them. These are:

- *Ring and progressive*

These two parameters are thought of gather the segments of the same ring in the same group. The parameter *Ring* consist in a text input that specifies the number of the ring in which is located the segment, from 000 at the beginning of the route until the end at the number xxx. Progressive have the same scope of the previous parameter but it stores the progressive of the ring where the segment is located.

- *Segment location*

The segment location parameter stores the angle measured from the vertical in the clockwise direction to its center, allowing in that way to differentiate the sensors that belong to the same ring.

- *Segment type*

Despite of all the segments are totally referenced it is necessary to identify the type of segment, i.e., if it is key or standard.

- <u>Structural parameters</u>

These are also instance parameters which purpose is to store the ID's of the different reinforcement bars that the tubing ring segment contains.

- *Longitudinal rebar*

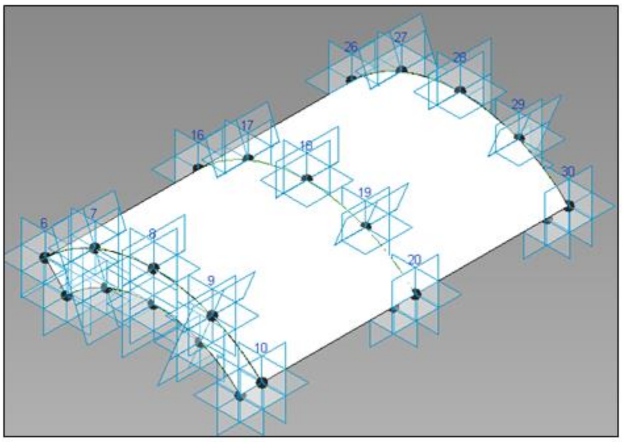
Stores the ID's of all the rebar placed in the longitudinal direction of the tunnel

- *Transversal rebar*

In this case it stores the ID's of every rebar placed in the transversal direction of the tube

- *Radial rebar*

The ID's of the radial rebar that work as stirrups are stored in this parameter.



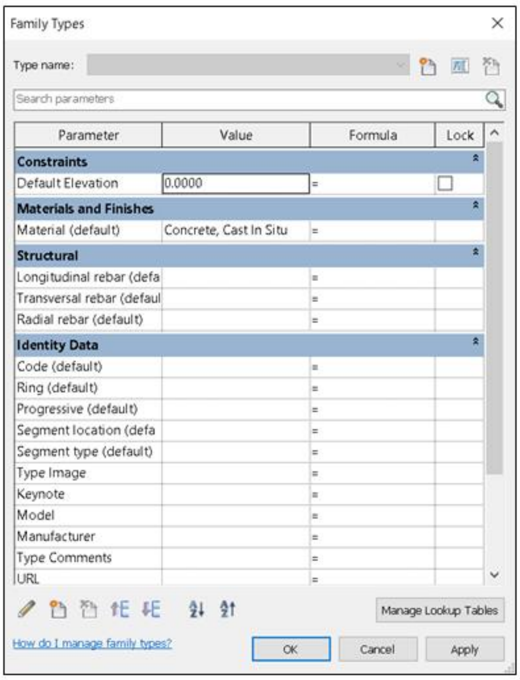


Figure 84: Tubing ring segment family. Adaptive component and parameters.

2.1.2. Revit model – tunnel segments

Now that the basic pieces that constitute the tunnel are created, these must be placed in their correct positions to simulate the shape of the tunnel. In order to perform this task is developed a Dynamo script.

1. <u>Selection of the tunnel alignment</u>

The first input that is necessary for the construction of the tunnel model is the definition of which route it will follows, i.e., its alignment. In practice this alignment is given by means of coordinates. The following graph group allows to select the excel file with the alignment coordinates.

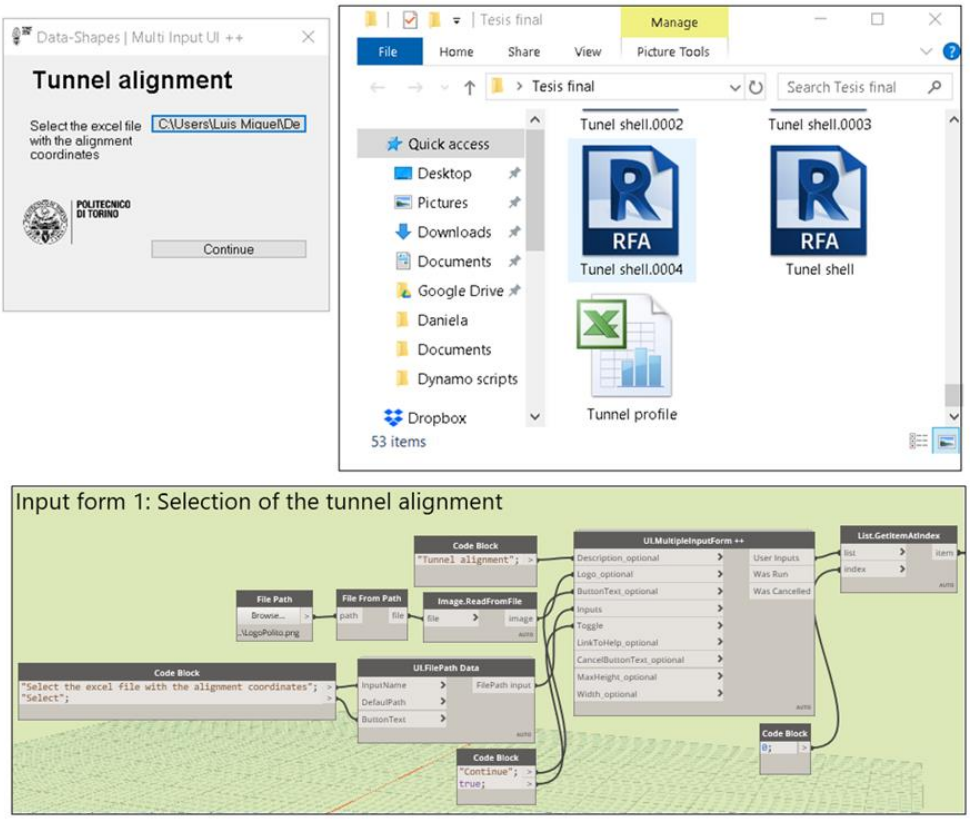


Figure 85: Tunnel creation program. Alignment selection.

Once the coordinates are imported to dynamo it is possible to create a Poly curve that follows these points. This methodology can support whichever alignment of the tunnel that can go to left or right, up or down but in the case of the Brenner base Tunnel the tubes are straight and flat.

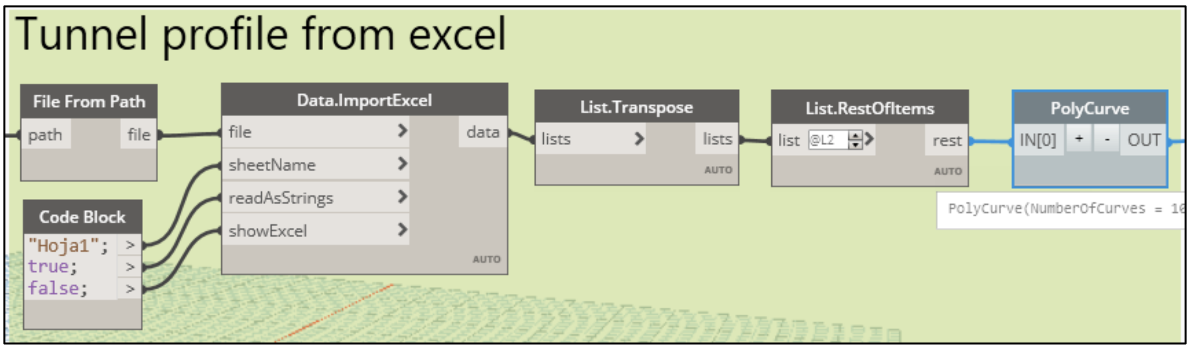


Figure 86: Tunnel creation program. Alignment poly-curve creation.

2. Tunnel geometry inputs

The other necessary inputs are then introduced to the program through two input forms. The first one requires the introduction of the longitudinal length of the segment, the external diameter of the tube, the thickness of the tube, and the rotation respect to the vertical that has the first ring. In the second input form are asked other geometrical features such as the angles (respect to an entire circle) of the initial part (back) and final (forward) of the key segment, the rotation of the rings respect to the previous one and the number of standard segments that complete the rings.

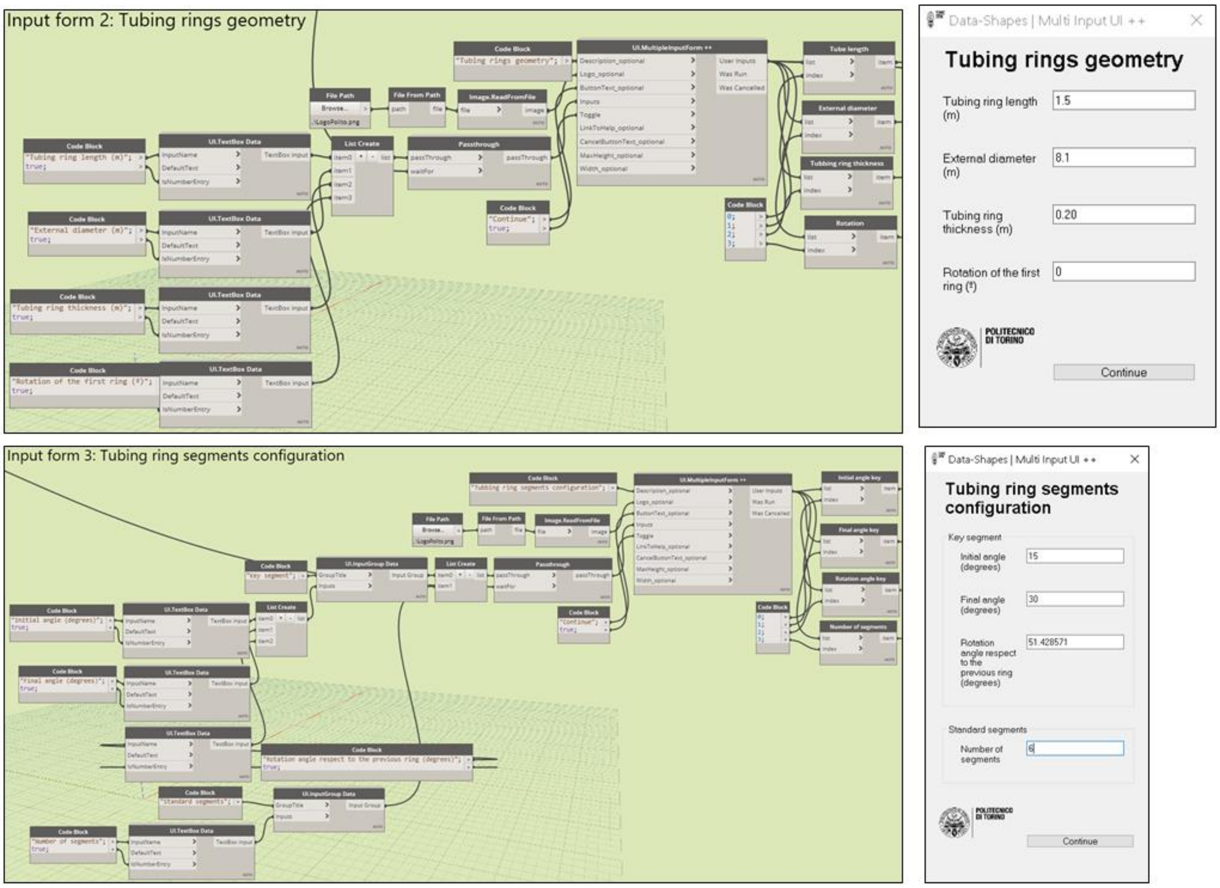


Figure 87:Tunnel creation program. Geometrical inputs.

3. Tunnel creation

After all the required inputs are inserted, the following graph group creates the placing points in which the tubing ring segments are placed. This is done by separating the polycurve made previously in segments with the same distance of the rings. Then circles are placed along this path and the placing points are located on this circles. This can be done by using some built in Dynamo nodes with the help of a python routine.

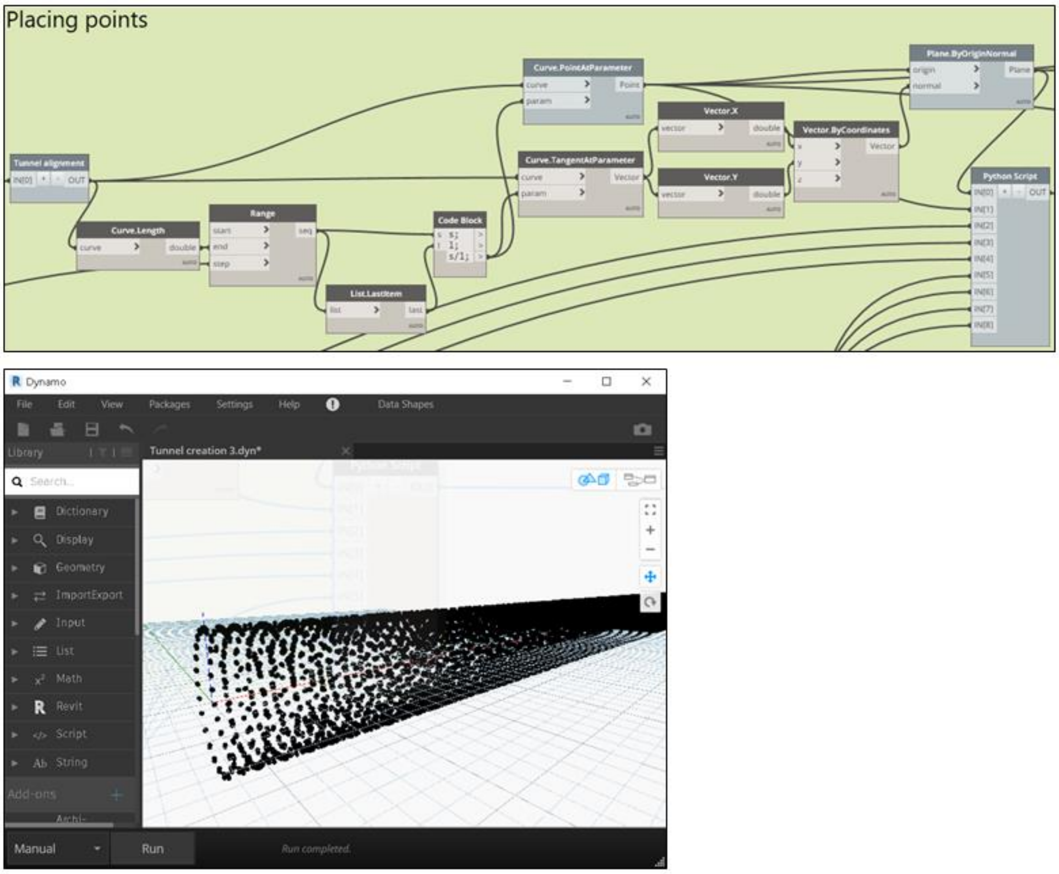


Figure 88: Tunnel creation program. Placement points creation.

Then the adaptive components can be placed in those created points through the "AdaptiveComoponent.ByPoints" node and the whole tunnel is created. If the visual sytle is set to shaded, consistent colors or realistic the visualization is the below illustrated.

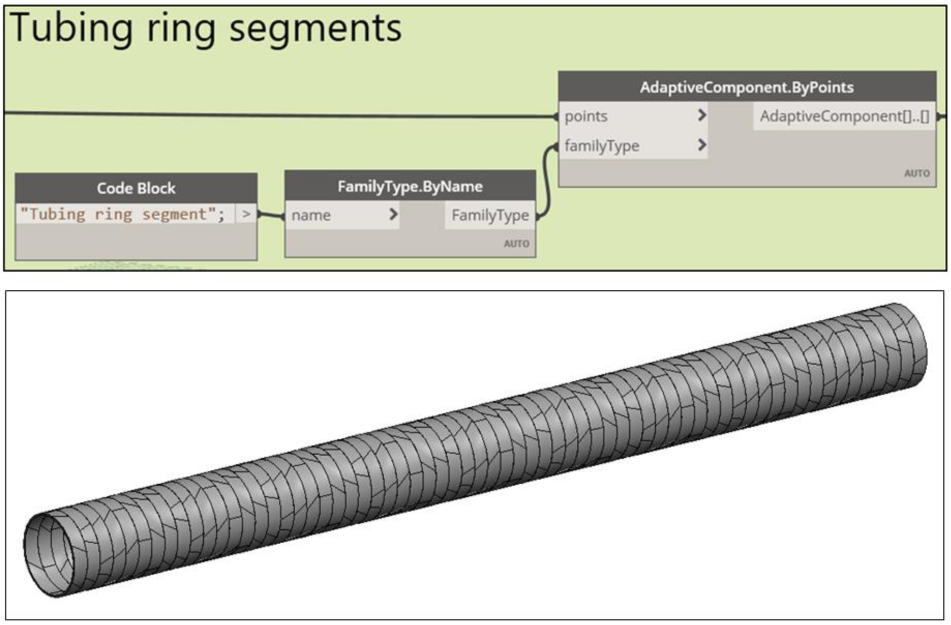


Figure 89: Tunnel creation program. Tubing ring segments placing.

4. Parameter settings

Once the ring segments are created, their parameters are established. By using of the graph groups shown below it is possible to set all the identity data for each tubing ring segment object. These graph groups include many python scripting nodes that permits to set many details such as de formats of the different parameters.

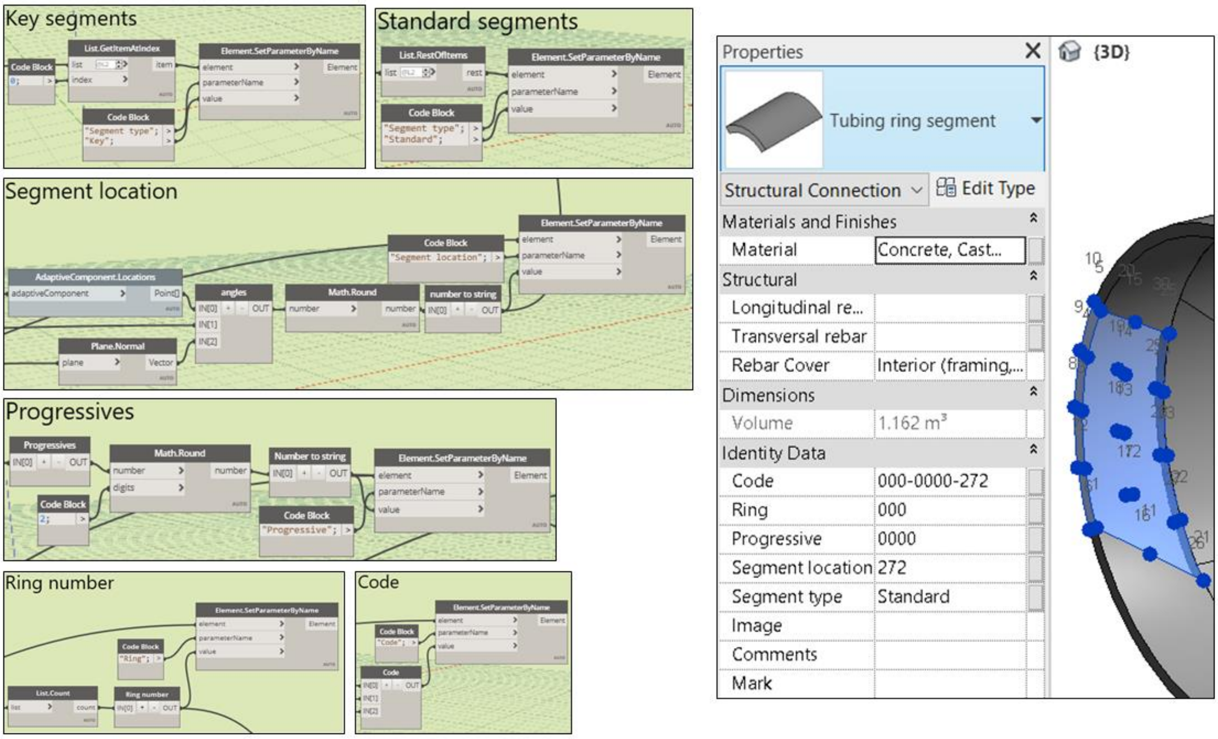


Figure 90: Tunnel creation program. Tubing ring segments parameters.

2.1.3. Revit model – reinforcement bars

The reinforcement is placed inside the tubing ring segments again by making use of a Dynamo script. The rebar that is needed for structural purposes is:

- Longitudinal reinforcement: parallel to the tube centerline
- Transversal reinforcement: perpendicular to the tube centerline
- Radial reinforcement: stirrups placed in the redial direction.

1. Inputs

For this purpose is developed an automatic Dynamo script in which are required some inputs useful for the creation of the rebar. These inputs are given to the program through an input form in which is asked: the bar diameter, the concrete cover, the number of bars in the longitudinal direction and the number of bars in the transversal direction. These inputs are asked separately for the Key and for the standard segments because the lasts are larger, therefore they require different amount of reinforcement steel.

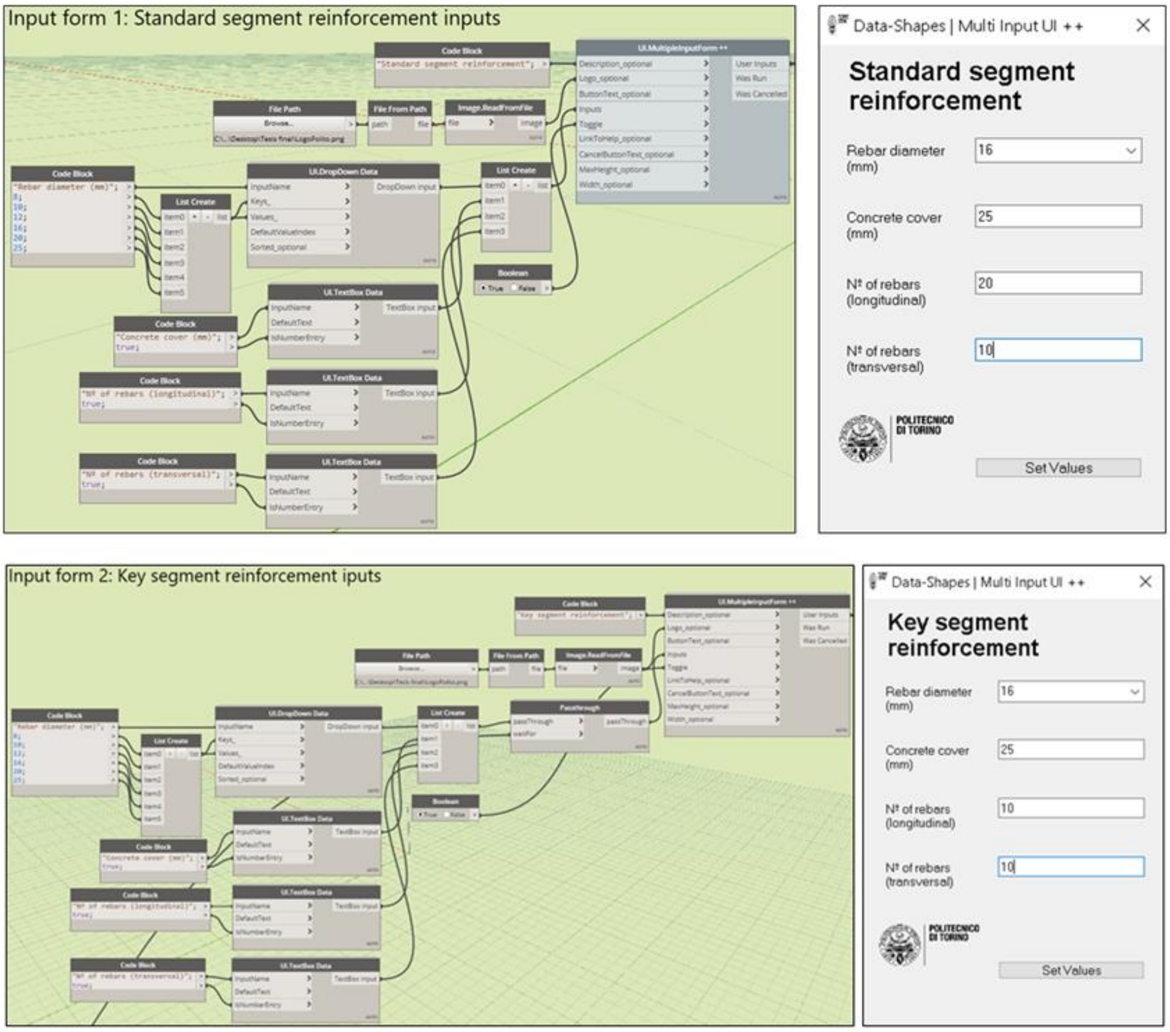


Figure 91: Tunnel reinforcement. Geometrical inputs.

2. <u>Curves creation</u>

The reinforcement bars will be formed from curves created in dynamo, so the next stage in the script is the creation of these curves. For this aim many steps are carried out:

First is needed to select all the tubing ring segments that constitute the tunnel and separate them in keys and standard segments. This filtering is done by using the family parameter “Segment type” and the by using a python scripting routine the two different types are separated. After that with the help of the node “Adaptive.Components.Locations” the points where the segments are placed are extracted.

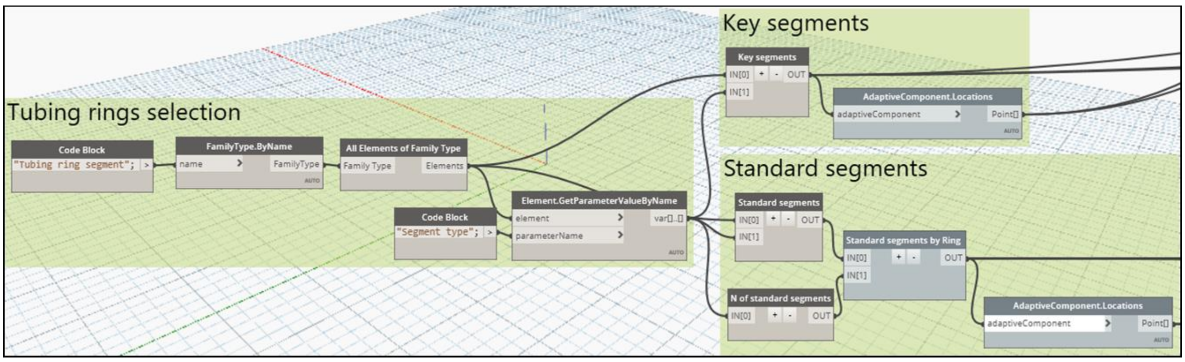


Figure 92: Tunnel reinforcement. Tubing ring segments selection and filtering.

Then, other adaptive elements called “cutting surface” are placed at the concrete cover depth in both the intrados and the extrados. These cutting surfaces are just a surface element that is adaptable to points as the tubing ring segment family is.

By using many built-in Dynamo nodes and python scripts nodes developed by the author the transversal and longitudinal curves are created. These curves are obtained basically by intersecting planes with these two cutting surfaces. Also are calculated the normal vectors for each curve, items that will be necessary for the creating of the reinforcement bars extreme hooks.

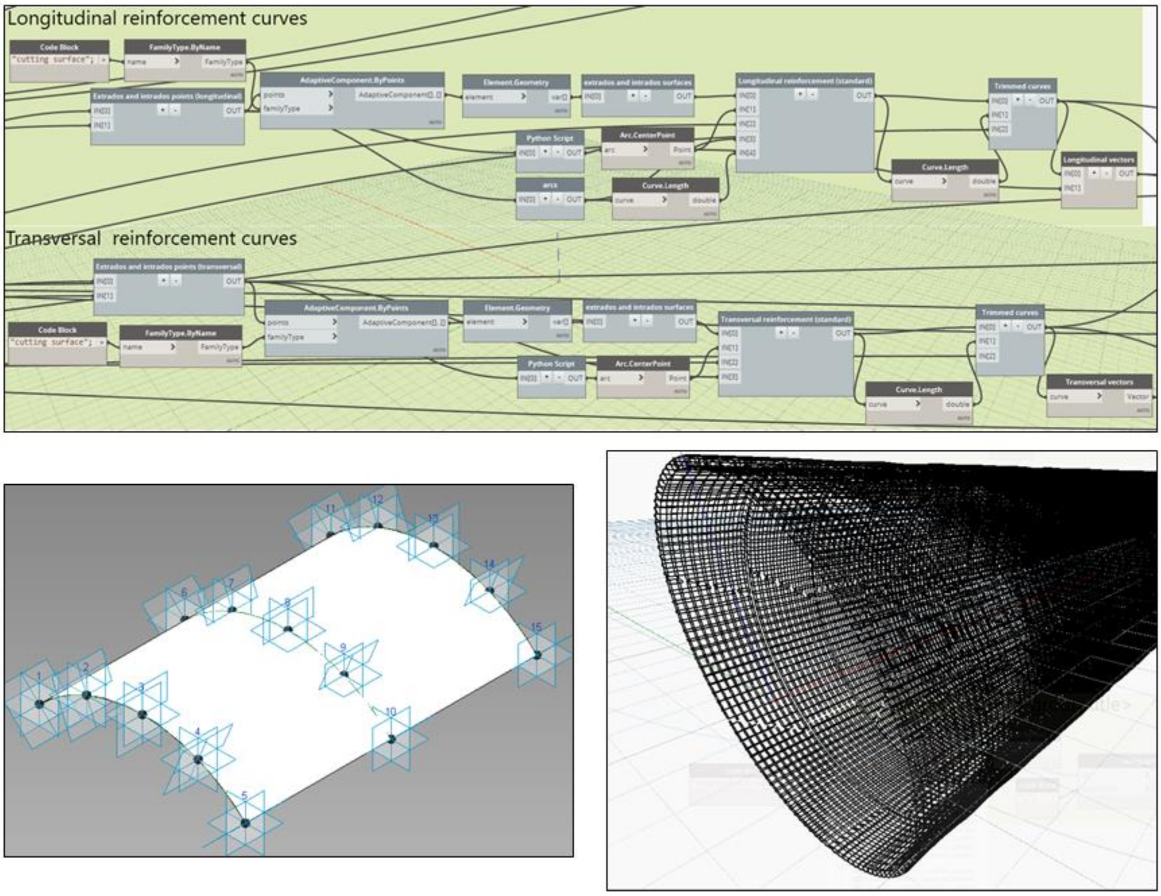


Figure 93: Tunnel reinforcement. Curves creation.

After that, the rebar are created by using the node “Rebar.ByCurve” available in the downloadable package “DynamoRebar”. This node requires as main input the curve along which the reinforcement bar will be created as well as the structural element that will be the host. Also is given the rebar diameter and hook types and finally the normal vector to the curve that allows assigning the hook orientation.

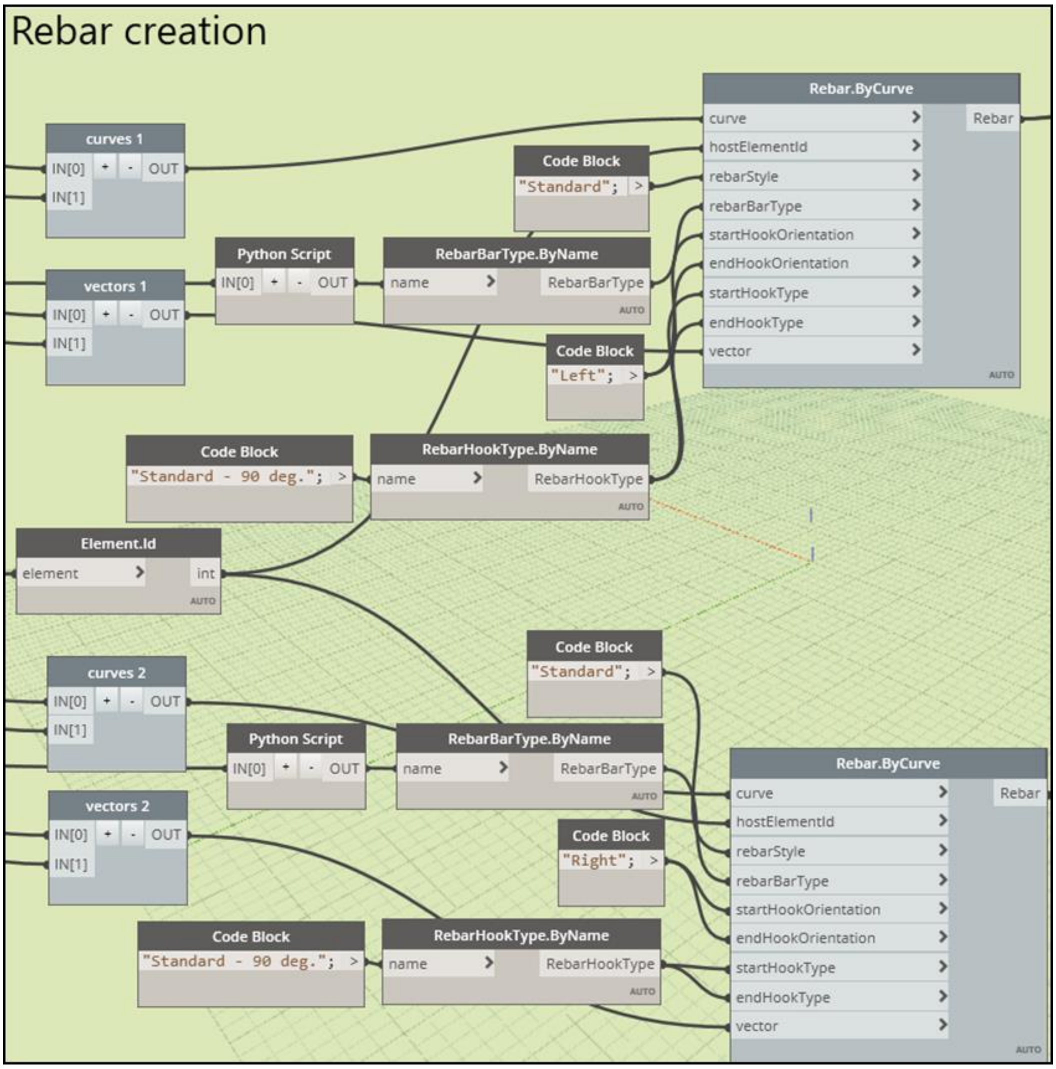


Figure 94: Tunnel reinforcement. Rebar creation.

Once the reinforcement is created a unique code is developed with the purpose of differentiating the bars:

- TE and TI for the transversal extrados and intrados reinforcement bars. This code is followed by the bar number, being the first that one in the minimum progressive of the segment.

- LE and LI for the longitudinal extrados and intrados reinforcement bars. This code is followed by the bar number, being the first that one in the minimum angle measured in the clockwise direction, following the whole tube circumference.

- RE and RI for the extrados and intrados central stirrups, followed by the bar number. This code is followed by the bar number, being the first that one in the minimum progressive of the segment, following the whole tube circumference.

This code is added to the mark parameter of the bars. Moreover are added the 3 structural parameters to the tubing ring segments with the goal of storing the Revit ID codes of the reinforcement bars that the segment hosts.

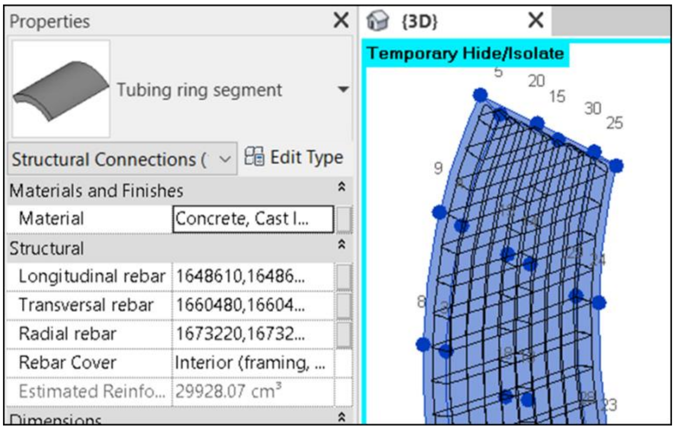


Figure 95: Tunnel reinforcement. Tubing ring segments reinforcement parameters.

The final product is a semantically rich BIM model of the tunnel in which every tubing ring segment is unique and gathers the information specifically related with it. This final model can be visualized as follows:

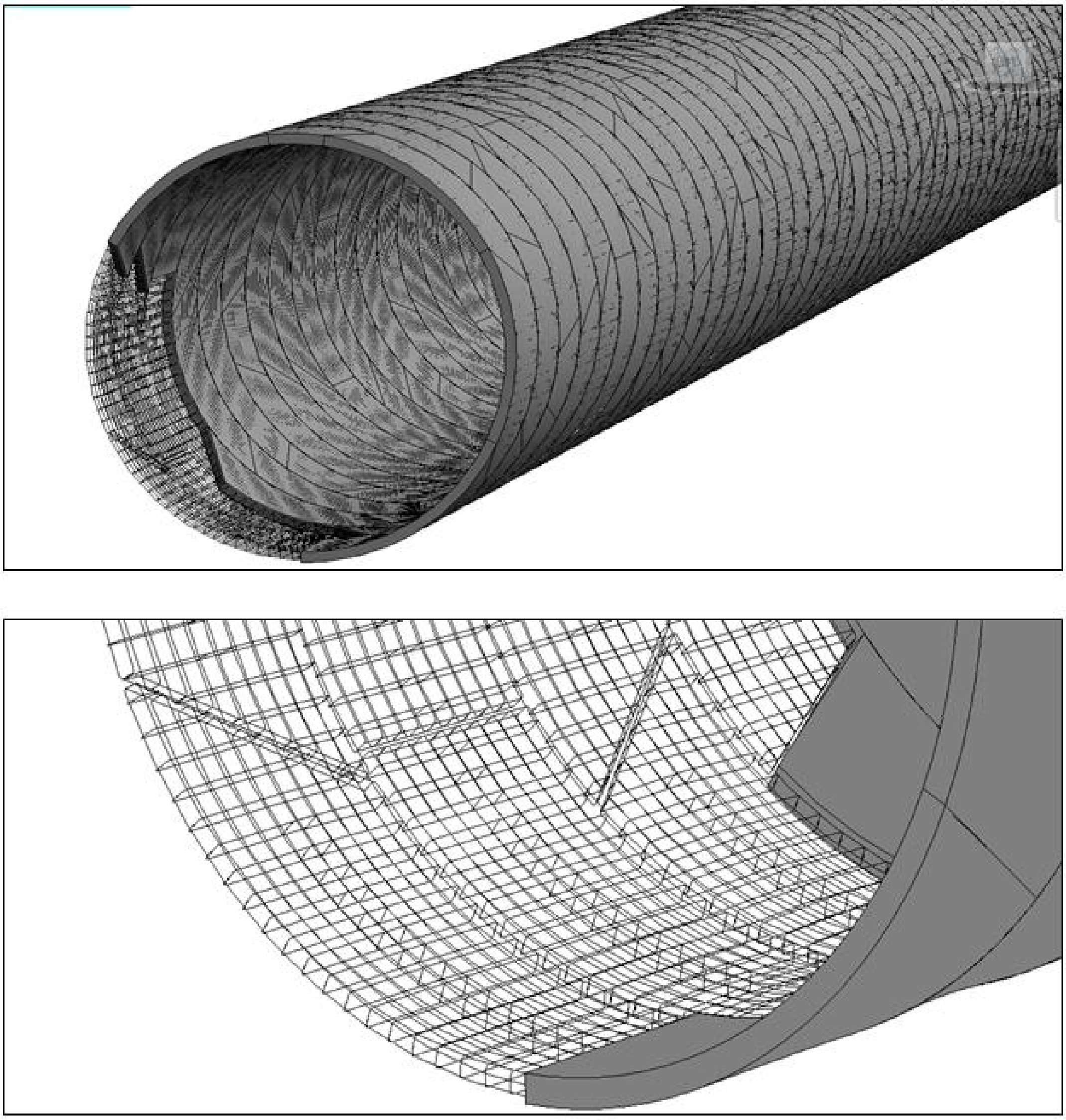


Figure 96: Tunnel reinforcement. Visualization.

2.2. Elaboration of the sensor families

Now that is created the model that emulates the real condition of the infrastructure, the components of the SHM system must be added to it. This new families consist simply in the virtual representation of the sensors and they are created as adaptive components by using the family editor of Revit, and set inside the category of *Specialty Equipment*:

2.2.1. Extensometers family

These sensors are created with a cylindrical shape constrained to two placement points. Moreover are added some new parameters with the aim of identifying the element, track its location and store monitoring data.

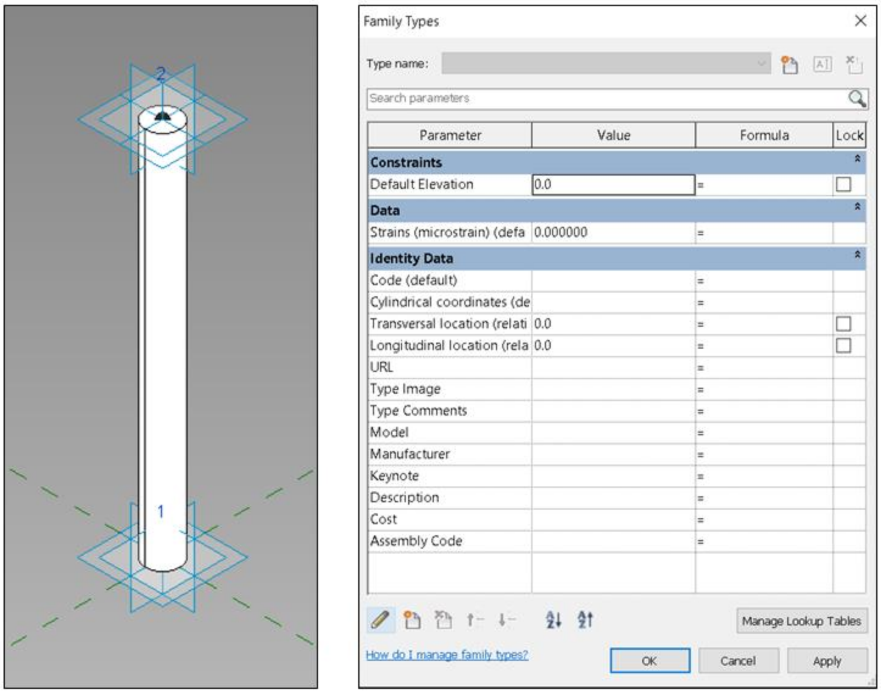


Figure 97: Extensometers family creation. Left: shape. Right: parameters.

- <u>Identity parameters</u>

  - *Code*

This parameter is thought with the aim of storing the unique name of the sensor that will differentiate the device from the others. It takes the same name of the tubing ring segment, i.e, *ring number – progressive – angle,* and add in the end the code the direction of the extensometer (T for transversal and R for radial), the location of the device (E and I for extrados and intrados in the case of the transversal extensometer or simple 1 or 2 in the case of radial) and the Greek letter ε, representing the strain measurements.

  - *Cylindrical coordinates*

Here is stored the unique location of the sensor. The first coordinate corresponds to the progressive where is placed the sensor, the second represents the angle measured in the clockwise direction from the vertical where can be found the device and the last coordinates corresponds to the radius measured from the centerline of the tunnel until the location of the sensor.

- *Transversal location*

It is the relative coordinate of the sensor inside the segment in the transversal direction, measured from the beginning of the segment (clockwise direction).

- *Longitudinal location*

It is the relative coordinate of the sensor inside the segment in the longitudinal direction from the initial border of the segment (minimum progressive).

- <u>Data parameters</u>

These instance parameters are created with the goal of storing some of the collected data by the sensor.

- *Strains and time span parameters*

These parameters store a multiline text variable that is the way in which Revit allows to write a vector. *Time span* is conceived to store the vector of time along which the measurements are retrieved.

- *Maximum strain and time of the maximum strain parameters*

Maximum strain allows storing the highest value of strain that happens during the time span, and it is contained inside the strains parameter. On the other hand, *time of the maximum strain* keeps the time in which the maximum strain happened.

2.2.2. Pressure cell family

In this case, is assigned to the sensor a square shape which position is set by 2 placement points. The two placement points are needed for placing the cell tangent to the extrados of the segment. Moreover, as in the case of the extensometer sensor are created some parameters:

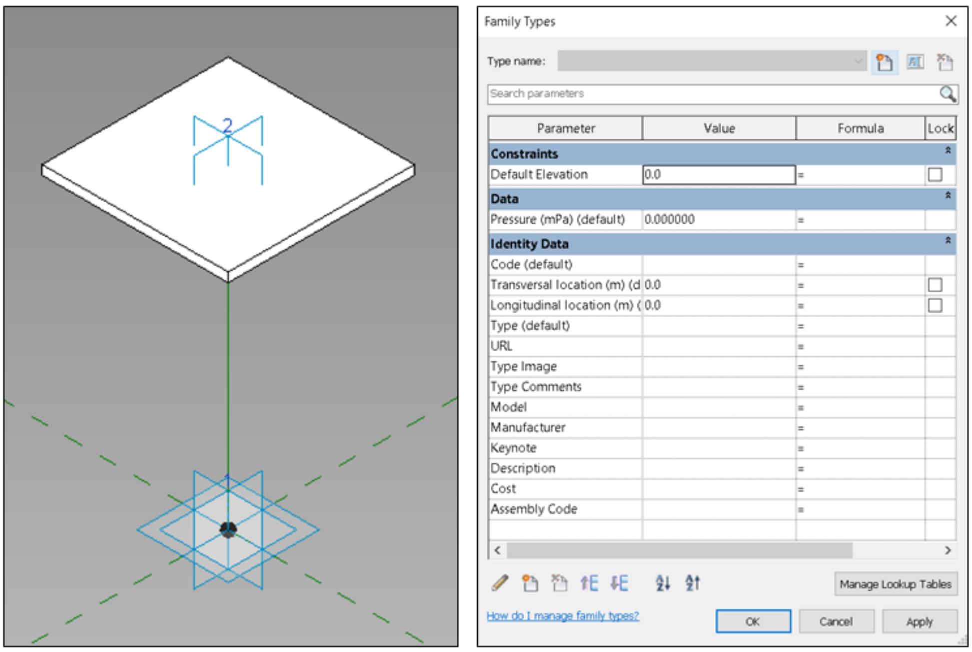


Figure 98: Pressure cell family creation. Left: shape. Right: parameters.

- <u>Data parameters</u>

These instance parameters are created with the goal of storing some of the collected data by the sensor.

- *Pressure and time span parameters*

These parameters store a multiline text variable that is the way in which Revit allows to write a vector. *Time span* is conceived to store the vector of time along which the measurements are retrieved.

- *Maximum pressure and time of the maximum pressure parameters*

Maximum strain allows storing the highest value of pressure that happens during the time span, and it is contained inside the strains parameter. On the other hand *time of the maximum pressure* keeps the time in which the maximum pressure happened.

- <u>Identity data parameters</u>

- *Code*

This works with the same methodology of the code parameter of the extensometers but in this case it is assigned to the end the acronym *PC*, the initials of pressure cell.

- *Transversal and longitudinal location*

These work in the same way that in case of the extensometer.

2.2.3. Lecture Box family

In this case is given a cubic shape (box shape) to the element that is controlled as in the previous case by two placement points. In this case the parameters assigned to the family are only identity data parameters, which are *code* and *Transversal and longitudinal location.* In the format of the parameter *code* is taken the code of the tubing ring segment adding in the end the word BOX.

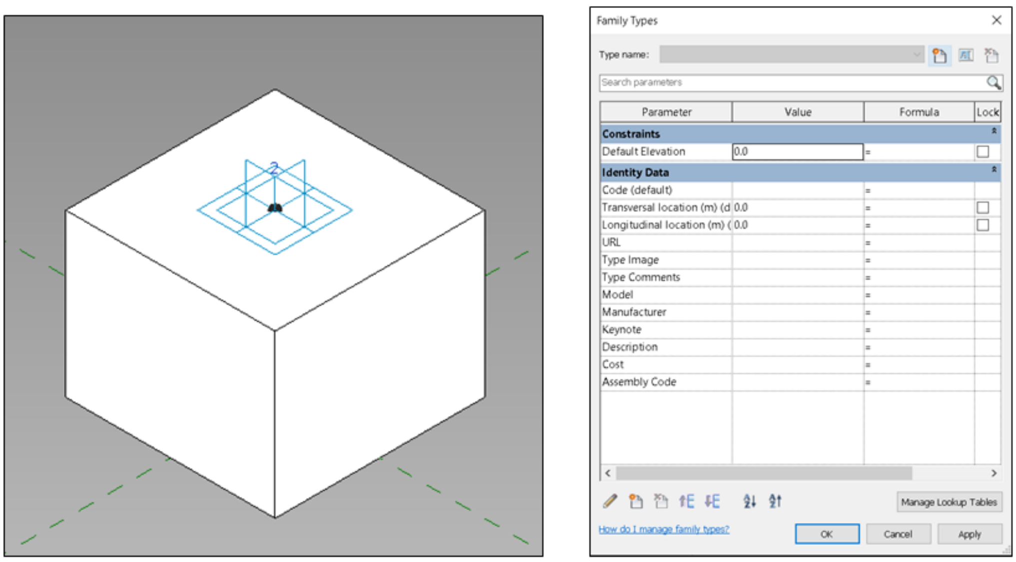


Figure 99: Lecture box family creation. Left: shape. Right: parameters.

2.2.4. Smart-sensor family

These sensors are installed inside the reinforcement and for this reason are not visible. Despite of that is assigned a small spherical shape with the purpose of visualizing them. As it was done for the other families, some parameters are created:

- <u>Data parameters</u>

    - *Strains*

The goal of this parameter is to store the strains in terms of microstrain.

- <u>Identity data parameters</u>

    - *Code*

The code assigned to the sensor is stored in this parameter and consist in the same code of the reinforcement bar, which includes information about the ring and the segment where is located, but adding at the end the number of the sensor in the same bar and the direction in which it evaluates the strain. The different directions are:

- Longitudinal: the sensor is located in a longitudinal bar in the longitudinal direction.

- Transversal: the sensor is located in a transversal bar in the transversal direction.

- Radial: the sensor is located in transversal, longitudinal or radial bars in the radial direction.

    - *Cylindrical coordinates*

In the same way of the extensometers, this parameters stores the cylindrical coordinates of the sensors.

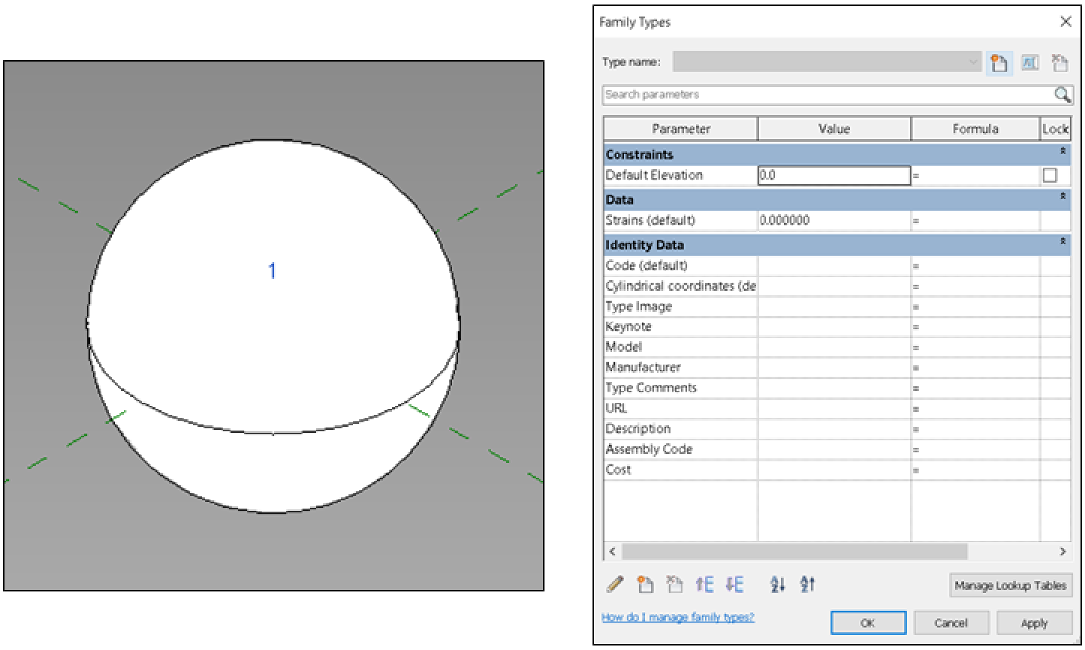


Figure 100: Smart-sensor family creation. Left: shape. Right: parameters.

2.3. Elaboration of the SHM system placing programs

Being all the different sensor devices and other equipment created, are developed a series of programs with the scope of providing an interactive interface that allow the installation of the SHM system in the tunnel. It is used Dynamo as it was used in the previous experiences shown in this work.

2.3.1. Extensometers placing programs

Two programs are developed with the goal of setting the location and configuration of the transversal and radial extensometer pairs in the selected rings of the tunnel section in study. They work in similar way and many steps are carried out:

1. <u>Listing of the tubing ring segments present in the model</u>

Firstly are selected all the tubing ring segments of the entire tunnel and are extracted their codes and ring numbers, information stored in their respective family parameters.

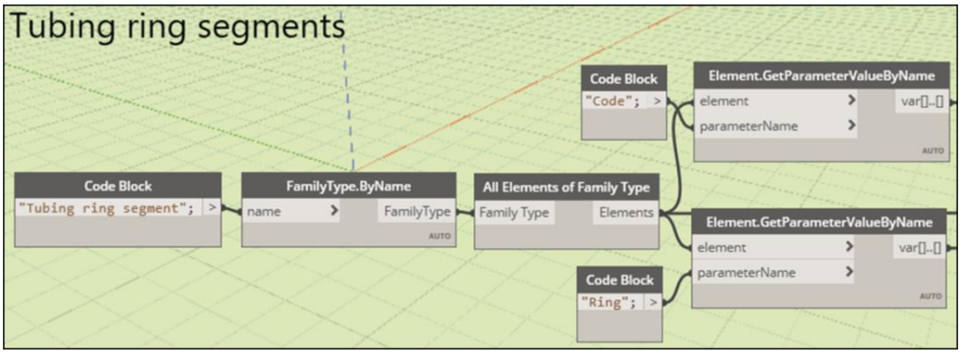


Figure 101: Tunnel SHM extensometers program. Tubing ring segments.

2. <u>Input form 1: Selection of the ring</u>

With the information extracted from the codes in the previous step and by using some python scripting nodes, can be created a list with all the different rings present in the model. Then, with the help of the input forms provided by the downloadable package "Data-Shapes", can be selected the specific ring where the extensometers will be installed.

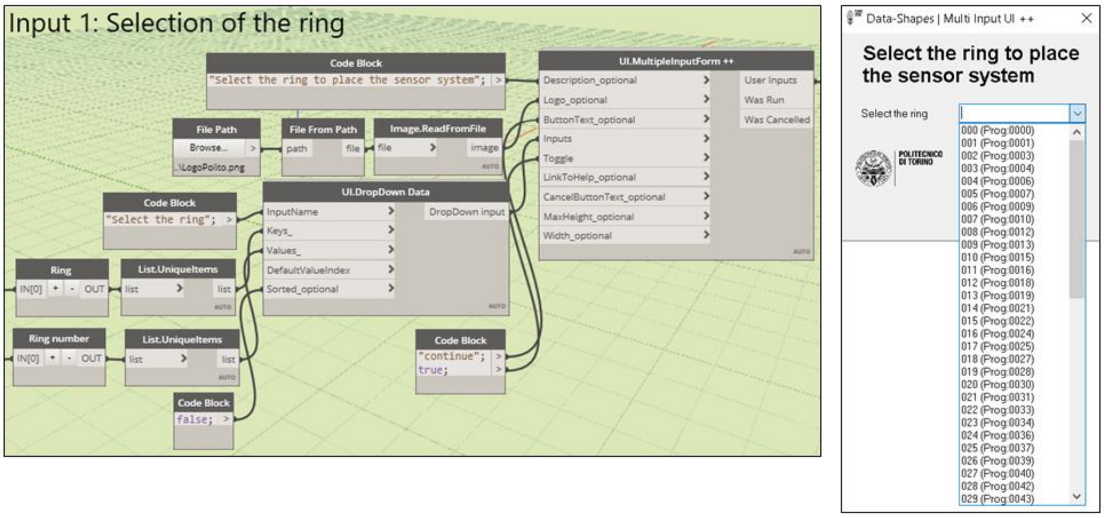


Figure 102: Tunnel SHM extensometers program. Selection of the ring.

3. Filtering of the segments and selection of the surfaces

Once the desired ring is selected are extracted the different segments that constitute it, but only the standard segments, because the SHM system is not installed in the Key ones. Then by the using of some python scripting nodes are selected the extrados and intrados surfaces of the segments, items that will be useful later.

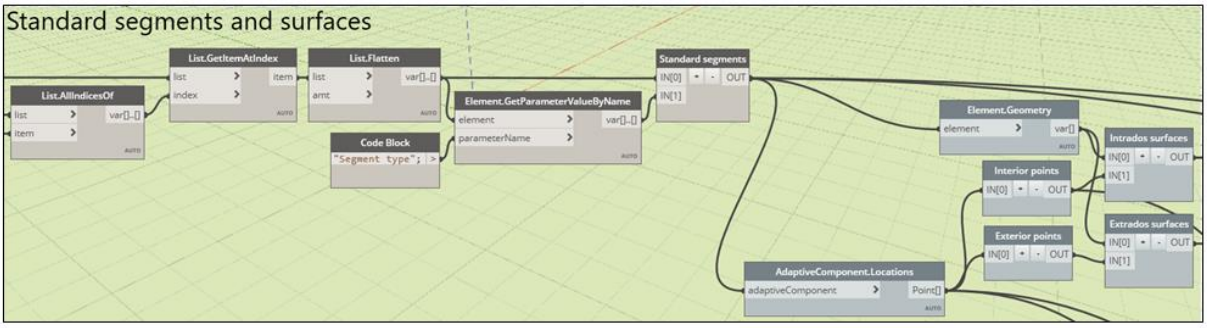


Figure 103: Tunnel SHM extensometers program. Filtering selection of the surfaces.

4. Input form 2: Sensor position

Then is introduced in the program the position in which the sensor is placed respect to the borders previously created. This position is introduced in relative coordinates (from 0 to 1). The other geometrical input that is needed in this step consists in the concrete cover of the segment that is the depth where the sensors are installed respect to the extrados and intrados of the concrete element.

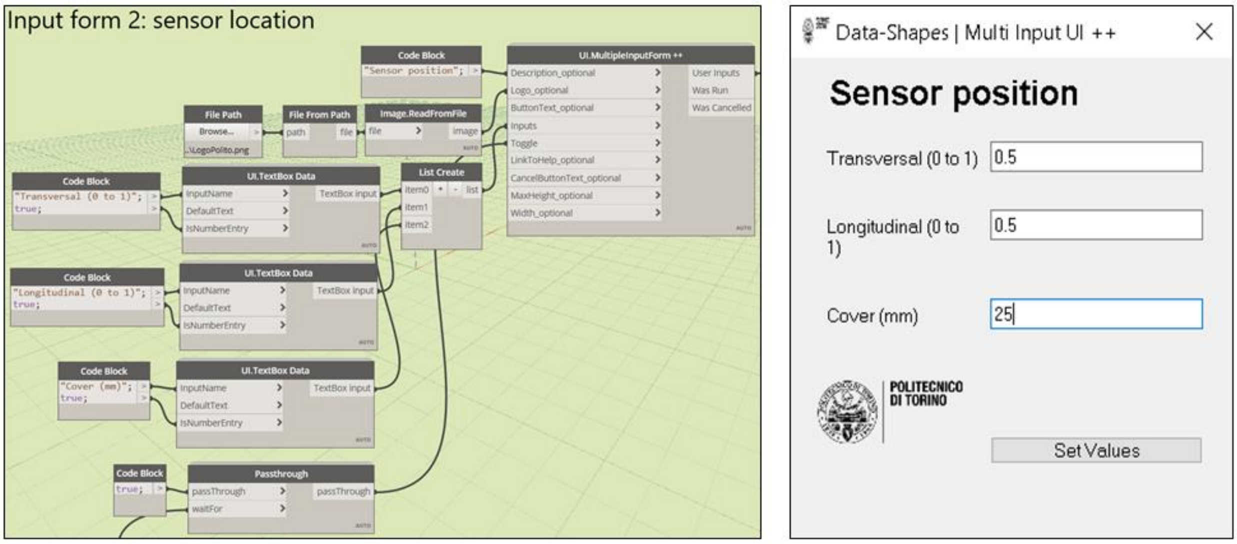


Figure 104: Tunnel SHM extensometers program. Location of the extensometers.

5. Extensometers creation

With the previously introduced inputs are created the points where the sensors will be placed as adaptive components. In the case of the transversal extensometers the points are created orienting the pair of sensors in the transversal direction, one in the intrados and other in the extrados, and in the case of the radial extensometers the points are created for placing the sensors oriented to the center of the tube. This task is done with a python scripting node with a routing developed by the author.

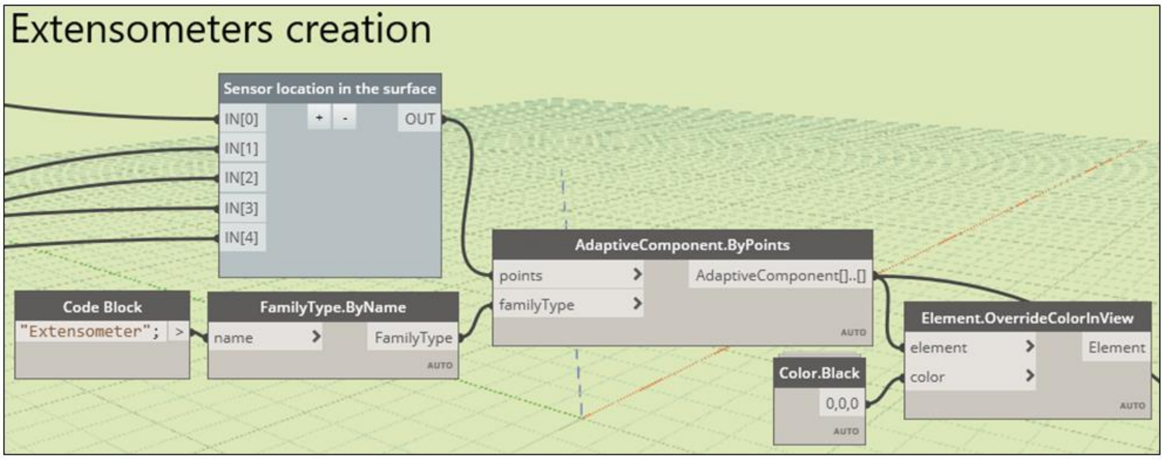


Figure 105: Tunnel SHM extensometers program. Extensometers creation.

6. <u>Parameters setting</u>

With python routines are calculated the cylindrical coordinates of all the sensors and are written automatically in the cylindrical coordinates parameter assigned to the extensometers family. In the same way the codes of the devices are assigned to the respective elements.

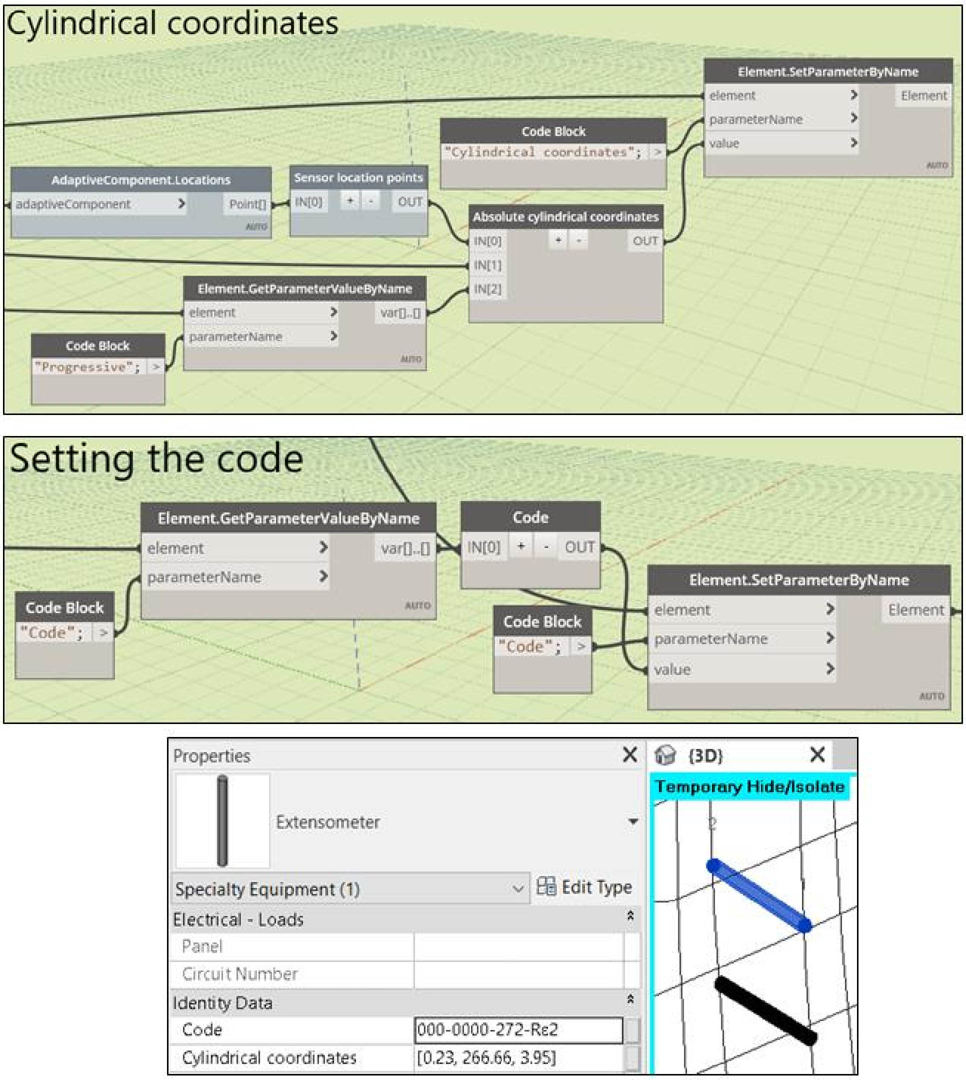


Figure 106: Tunnel SHM extensometers program. Parameters setting.

2.3.2. Pressure cell and lecture box placing programs

This programs work in a similar way of the extensometers one. The differences lies in the fact that pressure cell is located in the extrados surface of the tubing ring segment, therefore is not necessary to introduce the concrete cover to tell the program where to place the device. The same happen with the lecture box, because it is located in a certain position but always in the intrados of the segment. Also the cylindrical coordinates are not calculated because in both families this parameter is not established.

2.3.3. Brenner base tunnel SHM system installation

Once all this programs are developed, the SHM system is installed in the first ring (Ring 001, Progressive 0000) in the middle ring (Ring: 033, Progressive 0050) and in the last ring (Ring: 066, Progressive: 0098)

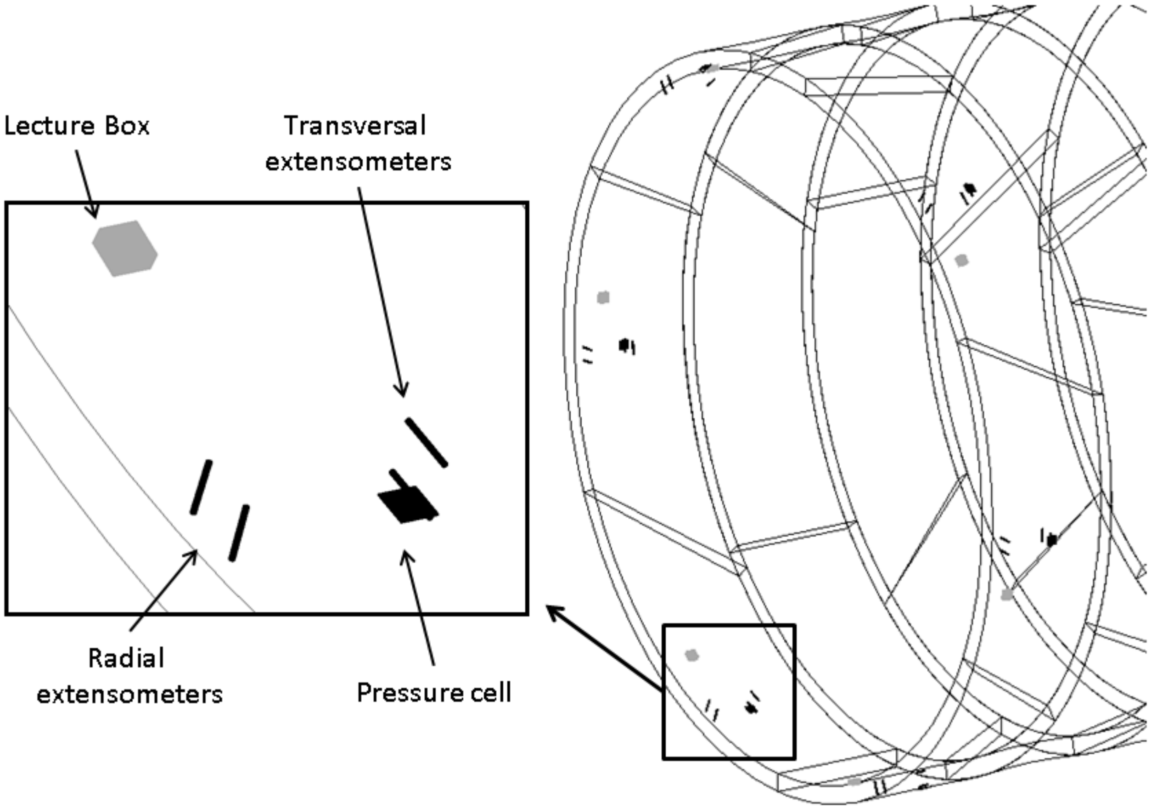


Figure 107: Tunnel SHM system.

2.3.4. Smart-sensor placing program

Now is developed a program with the goal of helping the in the Smart-sensors placing. In this case it works in a different way respect with the other programs because the sensors are installed in the reinforcement bars. It is explained below:

1. Listing of the tubing ring segments present in the model

Firstly are selected all the tubing ring segments of the entire tunnel and are extracted their codes and ring numbers. This is done in with the same coding written for the traditional-sensor placing programs.

2. Input form 1: Selection of the ring

With the information extracted from the codes in the previous step and by using some python scripting nodes, can be created a list with all the different rings present in the model. Then, with the help of the input forms provided by the downloadable package “Data-Shapes”, can be selected the specific rings where the smart-sensors will be installed.

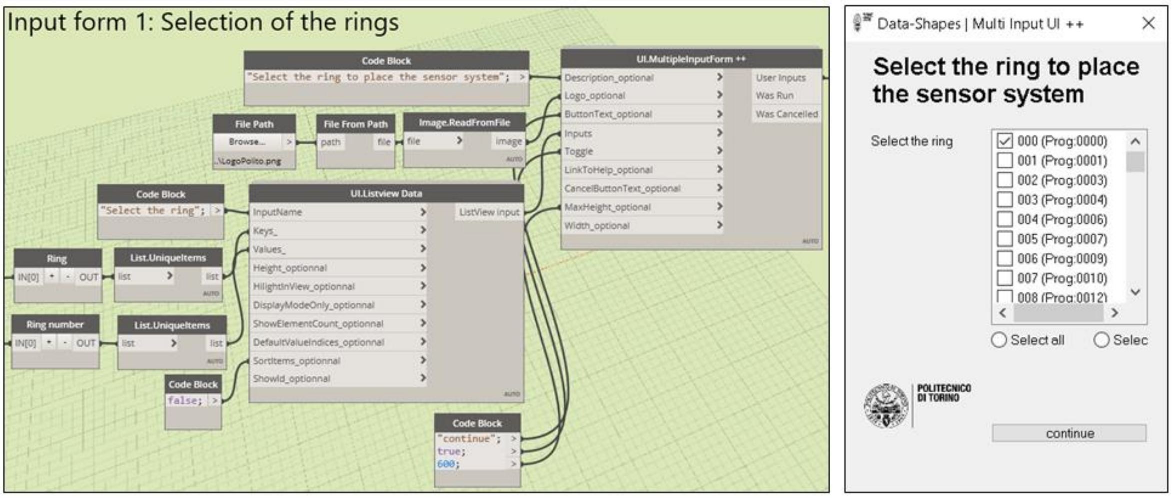


Figure 108: Tunnel SHM smart-sensors program. Rings selection.

3. Input form 2: Reinforcement type to place the sensors

Now that the elements where the SHM system will be placed are selected must be specified the type of reinforcement that will be used, because the criteria of installation is different depending on the direction of the reinforcement. It is the following:

- For the transversal reinforcement there must be always a sensor in the center of the bar and the rest of the sensors are placed every 50 cm in the both sides from this central device, until there is not more space for more sensors. This criterion is the same for both the extrados and the intrados rebar.

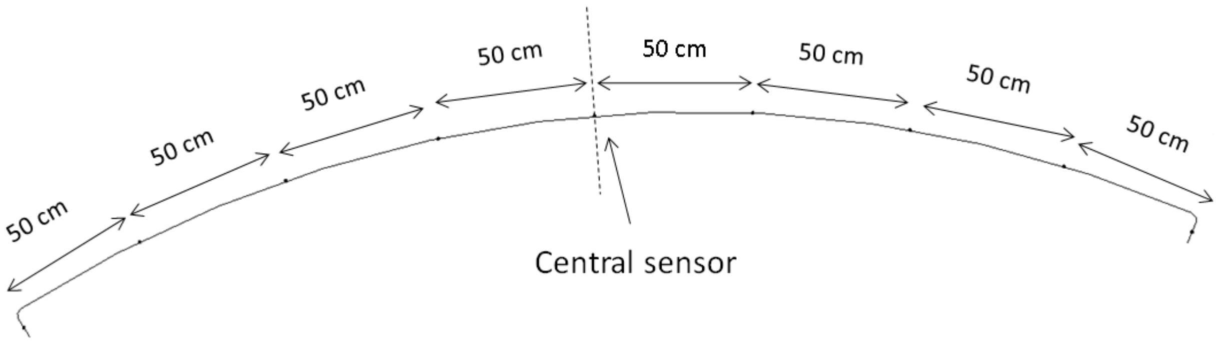


Figure 109: Smart sensor disposition. Transversal rebar.

- For the longitudinal and radial reinforcement the sensors are placed every 50 cm starting from a given length of the starting point (intrados reinforcement) and the final point of the bar (extrados reinforcement). In this way is assured that in every pair of bars (extrados and intrados) there will be always radial sensors at it ends.

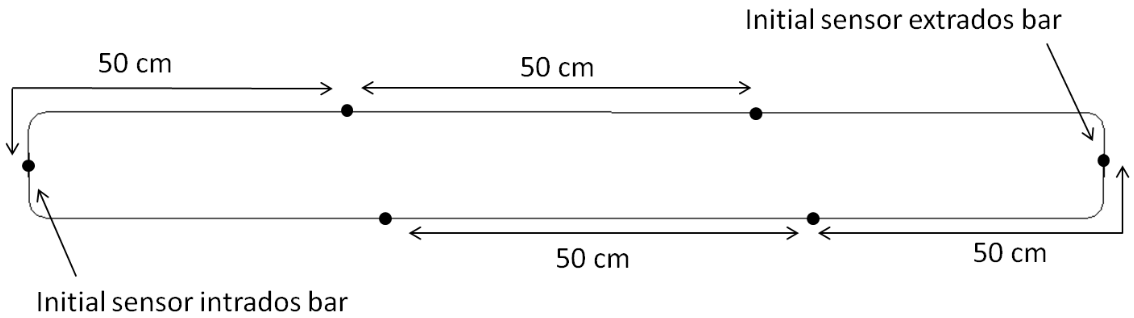


Figure 110: Smart sensor disposition. Transversal rebar.

Through the following input form is specified the reinforcement and then are obtained the specific bars that are contained in the previously selected tubing rings, separating them in extrados and intrados rebar by using a python scripting node. As an example the transversal reinforcement is selected.

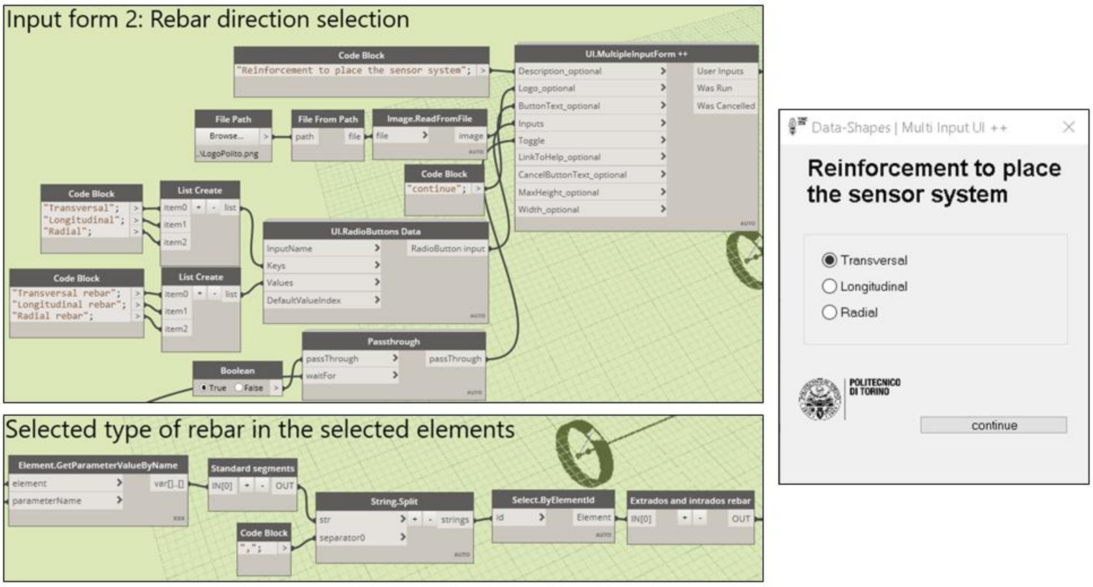


Figure 111: Tunnel SHM smart-sensors program. Reinforcement type selection.

Then, by using the node "Rebar.GetCenterlineCurve", provided by the package "BIM4Struc" the centerline curves of the selected rebar type of the selected rings is extracted from the reinforcement bars elements. These curves are then oriented with the help of a python routine, i.e, the beginning of the transversal curves is given by the clockwise direction and the beginning of the radial and longitudinal curves is set at the extreme with the minimum progressive.

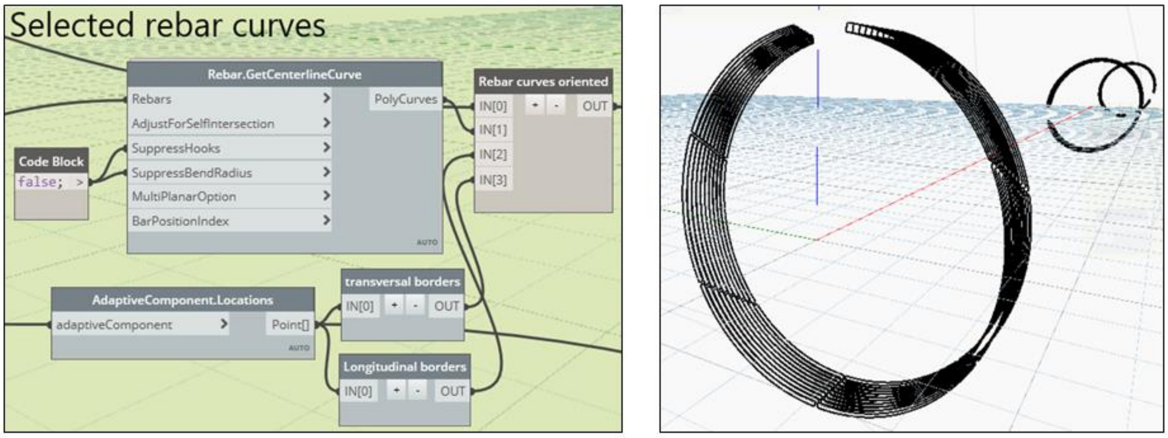


Figure 112: Tunnel SHM smart-sensors program. Rebar curves extraction.

4. Input form 3: Reinforcement bars selection

Now from these selected curves must be selected again those ones where the Smart-sensors will be placed. For this scope is used the following input form:

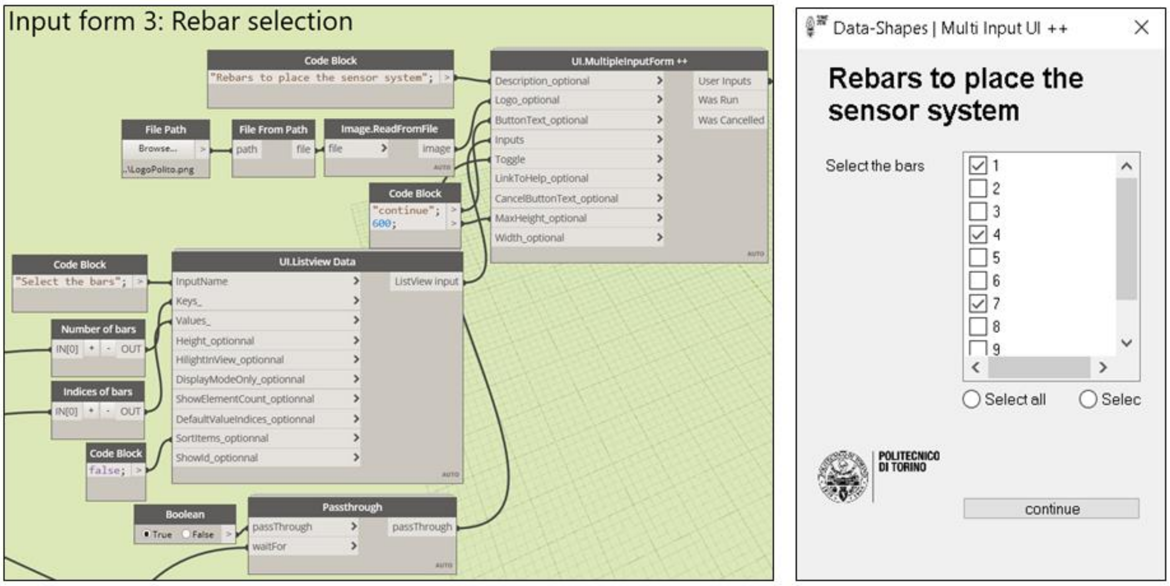


Figure 113: Tunnel SHM smart-sensors program. Rebar curves selection.

Having these curves it is now possible to create the placement points where the sensors will be placed. These points are located along the curves starting from the starting hook of the curves every 50 cm until the end. Finally is created the number of sensors that fit inside the curve length. This task is done by using a python scripting node.

The entire system is constituted by sensors placed in the transversal, longitudinal and radial bars and can be observed that in total 1668 devices are installed, a huge amount that is nearly 20 times larger than the extensometers. This task of installation and management of this large quantity of devices is impossible to do without using the power of a BIM tool as Dynamo for Revit.

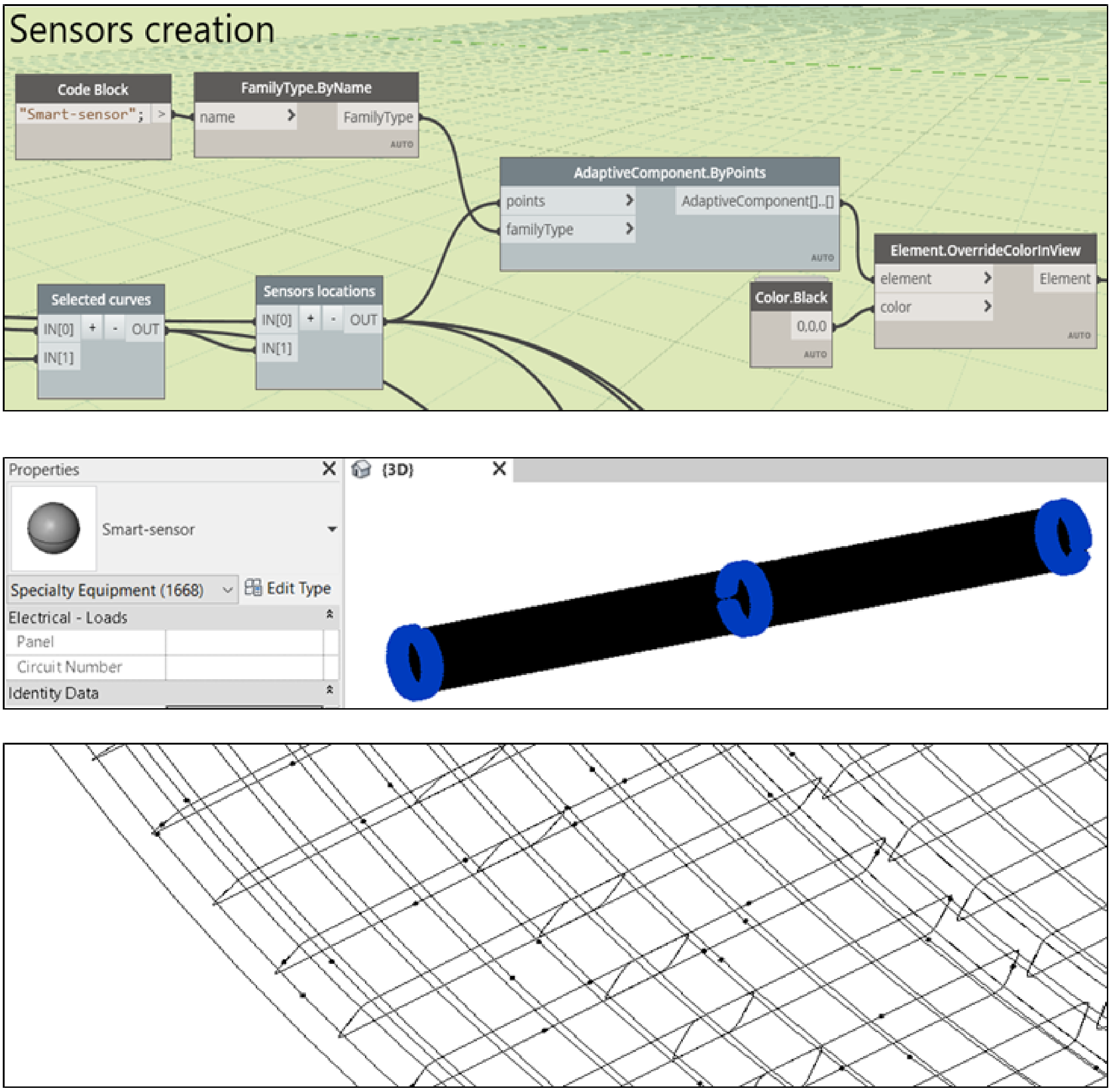


Figure 114: Tunnel SHM smart-sensors program. Smart-sensors creation.

5. Parameters setting

Finally as it was done in the extensometers placing program are calculated the cylindrical coordinates and the code of the sensors and then stored in their respective family parameters.

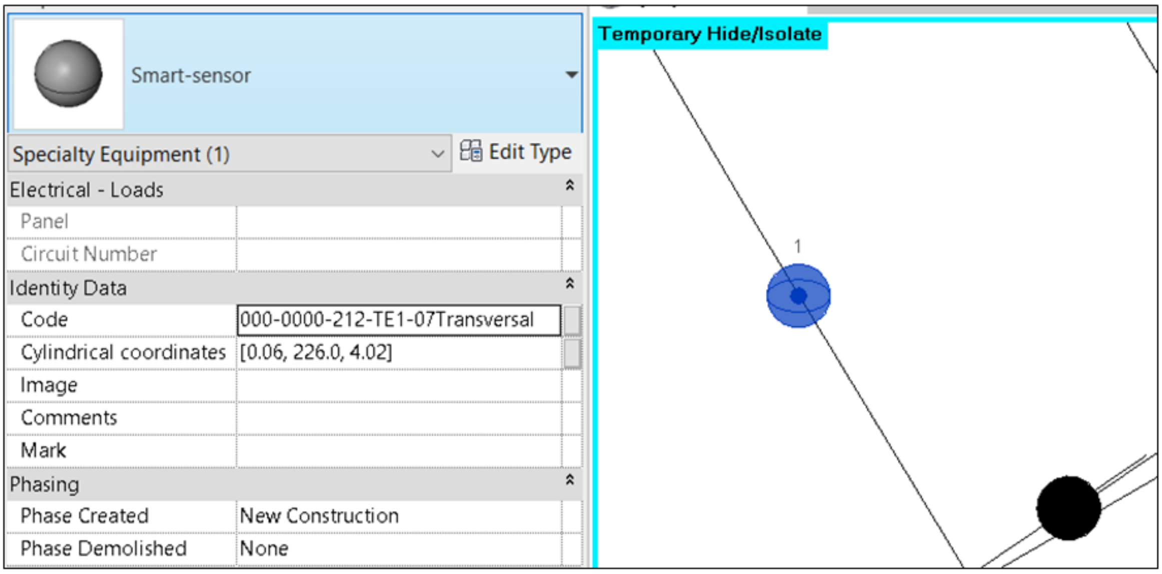


Figure 115: Tunnel SHM smart-sensors program. Parameters setting.

2.3.5. SHM data visualization program

The goal is to demonstrate that is possible to create a program that allows the interpretation of monitoring data in a visual and dynamic way, i.e, setting the Revit elements; color depending on the measurement value. For this reason is developed the following program that is able to show this features supported in the Extensometers placing program, particularly in the transversal ones.

First of all was necessary to simulate some strain data for the radial extensometers. This is done in the same way that it was carried out for the multi-sensor devices of the Stura Bridge. A normal distribution of strains is simulated in excel with the help of the built-in function NORM.INV ( ) being its inputs the probability (given by a random number with the function RAND ( ), the mean and the standard deviation (arbitrarily chosen). In the figure below can be observed and extract of the excel spreadsheet.

	A	B	C	D	E	F	G	H	I
1	Time	000-0000-034-TIε	000-0000-034-TEε	000-0000-088-TIε	000-0000-088-TEε	000-0000-148-TIε	000-0000-148-TEε	000-0000-212-TIε	000-0000-212-TEε
2	00_00_00	14.7	9.05	3.25	0.25	8.2	-19.5	-12.75	-13.1
3	00_00_05	-20	-11.85	-11.9	-34.4	-4.15	4.1	13.1	-12.15
4	00_00_10	1.55	-11.6	-11.4	18.6	1	-14.8	5.05	-18.5
5	00_00_15	16.55	1.2	-21.95	11.2	6.8	-1.3	4.85	-7
6	00_00_20	-25.45	-6.3	-0.2	-20.15	16.45	-16.45	-23.45	7.2
7	00_00_25	6.45	-21.6	6.55	5.5	2.85	-1.8	-33.8	14.5
8	00_00_30	4.55	15	-18.6	4.8	-32.05	-35.3	6.1	-9.7
9	00_00_35	12.95	-16	-3.3	-35.4	-24.35	-23.85	-3.75	-29.6
10	00_00_40	-0.65	14	11.1	10.1	-6.85	-18.9	26.6	-18.1
11	00_00_45	-6.9	-1.2	5.85	-19.7	15.05	29.25	-0.55	-2.9
12	00_00_50	-21.85	-9.9	-15.9	1.8	-15.9	5.6	5.95	-22.15
13	00_00_55	-8.5	-4.3	4.35	16	-7.4	-1.45	-4.55	8.1

Figure 116: SHM data visualization. Strains simulation.

The time step used is 5 seconds. Then the data is exported to text files and is simulated for a total of two days:

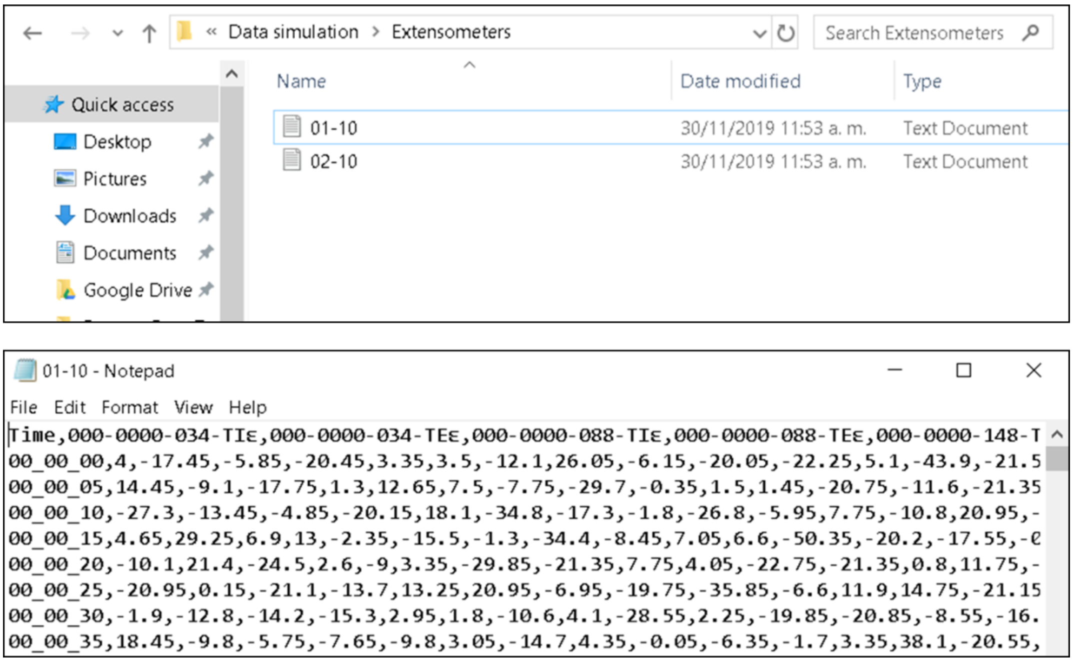


Figure 117: SHM data visualization. Strains simulation.

The program routine done in Dynamo is explained below:

1. <u>Input form 1: selection of the date interval</u>

The following input group permits to establish the interval of days that the program will retrieve from the text files and import to Dynamo. The days are introduced in the same way as it was done in the SHM data management program. Must be set the beginning and the end of the interval and as example is selected an interval comprising two days.

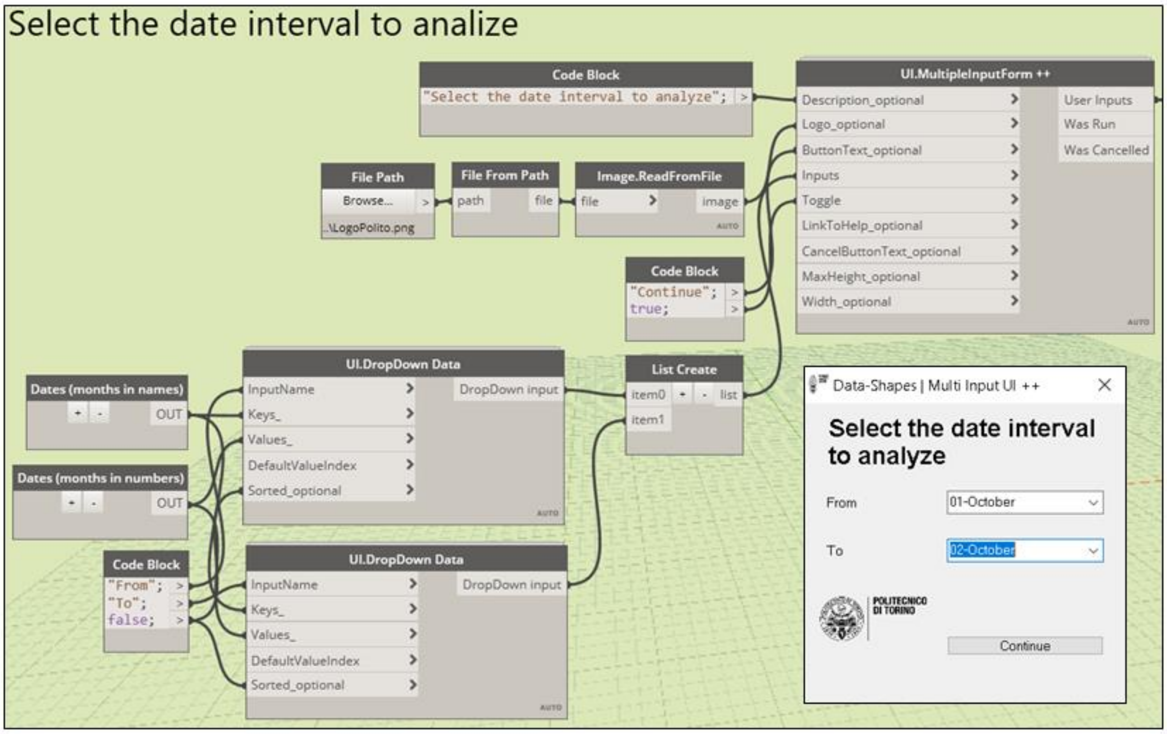


Figure 118: SHM data visualization. Date interval selection.

2. <u>Selection of the files</u>

Knowing the days that are involved in the analysis their data must be retrieved from the text files. The next graph group searches in the folder the files that correspond to the selected days and obtain their paths that are necessary for loading them.

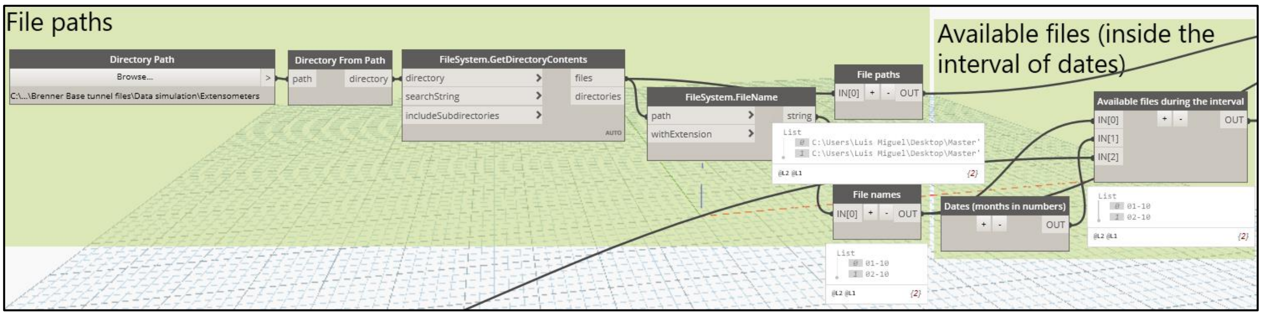


Figure 119: SHM data visualization. File paths of the days inside the interval.

3. <u>Data loading</u>

Having the file paths and by using the node "FileSystem.ReadText" is possible to load the data in Dynamo from the text files. Then this data must be sorted and filtered. First all the possible white spaces are deleted and after, with the help of a python scripting node called "Data in list", the string of measurements is converted in separated items. Finally the python routines "Sensors", "Times" and "Strain" are able to retrieve from this previous list a list with all the transversal extensometers, the list with all the times and the measurements. It can be seen that in total the measurements are more than 1.2 million.

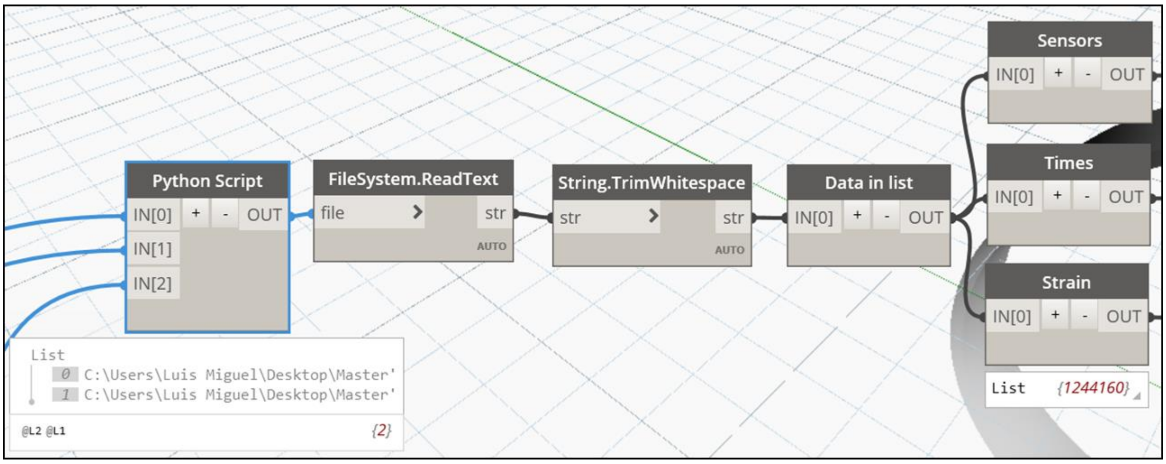


Figure 120: SHM data visualization. File paths of the days inside the interval.

4. <u>Selection of the time to analyze</u>

With the list of measurements loaded in Dynamo now is possible to select the exact time that is desired to analyze, but some code must be written to do this job because at the end is necessary to filter just few values from a list with a large amount of data. This is done with the following graph groups:

4.1. <u>Selection of the day</u>

The first step to filter this data is the selection of the day where is located the time that is wanted to be analyze. A way of doing this dynamically is with the node

“InputBoundedNumber.Slider” provided by the downloadable package Celery. With this is possible to create a slider input where the two limits are variable and depend of the number of days imported in Dynamo. For selecting the desired day is just sufficient with sliding the button. In the Watch day node can be see the day.

After that by using the python scripting node “Strain in the selected day” is selected the transversal strain in the segment, both in the intrados and the extrados extensometers. Finally with the python routine “Strain by hour” this list that contains one sub-list for each time of the day is organized in 24 groups, with the aim of gathering in new sub-lists all the measurements that are inside one hour.

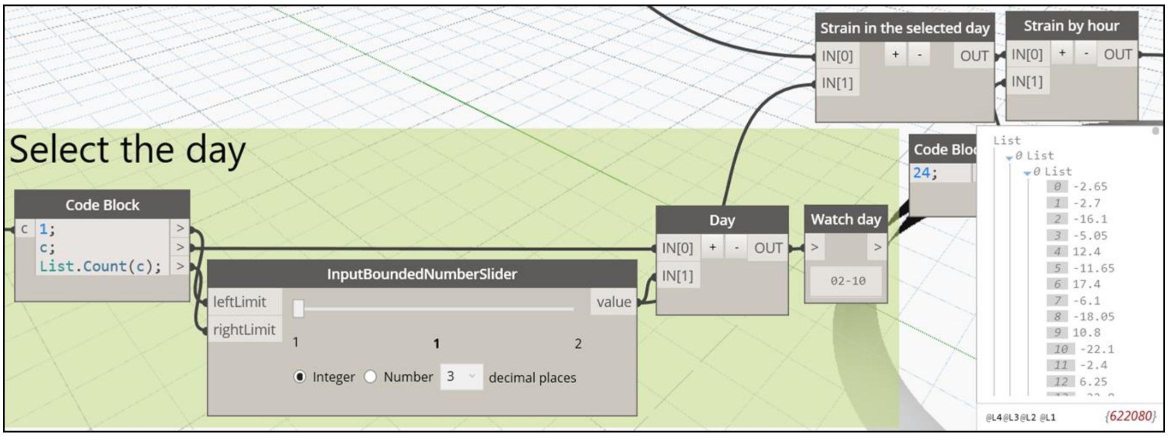


Figure 121: SHM data visualization. Day selection.

4.2. Selection of the hour

Now the hour must be selected. For this scope, as it was done in the previous step, is used the input slider provided by Celery with the limits corresponding to 0 and 23 hours, being the 0 the hour from 00:00:00 to 01:00:00 and the 23 the hour from the 23:00:00 to the 24:00:00. In the watch node can be seen that in the example is selected the hour 0, i.e, from the 00:00:00 to 01:00:00 hours. Then the sub-list corresponding with this hour is selected from the previous list with the python scripting node “Selected hour”.

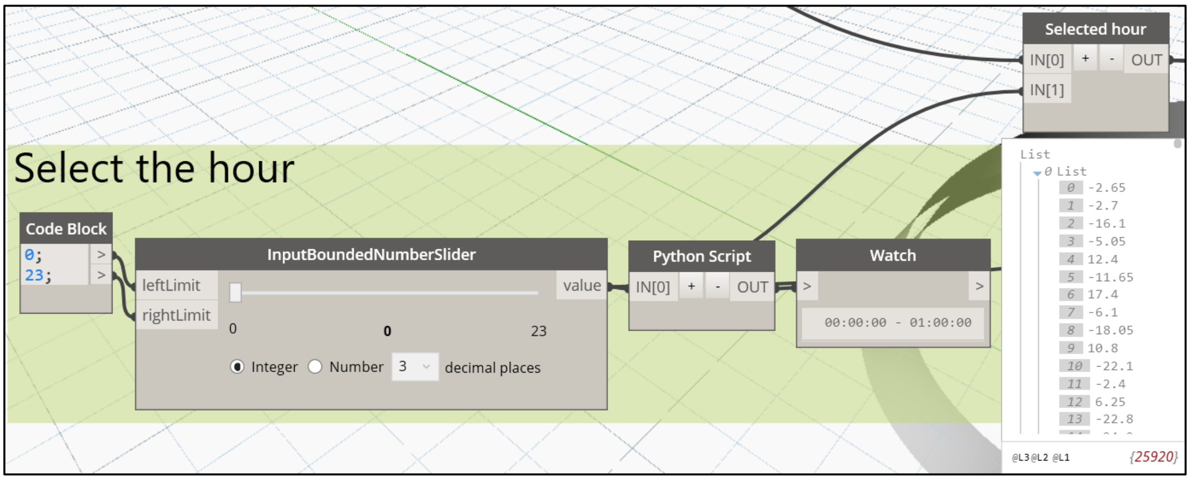


Figure 122: SHM data visualization. Hour selection.

4.3 Time selection

Finally the exact time inside the hour must be established. Again with the help of the slider input is possible to select dynamically the exact time for the analysis. In the watch node is visible the time selected in the slider and in the python routine node “Strains by segment” are the strains that correspond to the 18 tubing ring segments selected in the analysis, one for the intrados extensometer and the other of the extrados extensometer. For the example is selected the time 507 the interval that corresponds to 00:42:10.

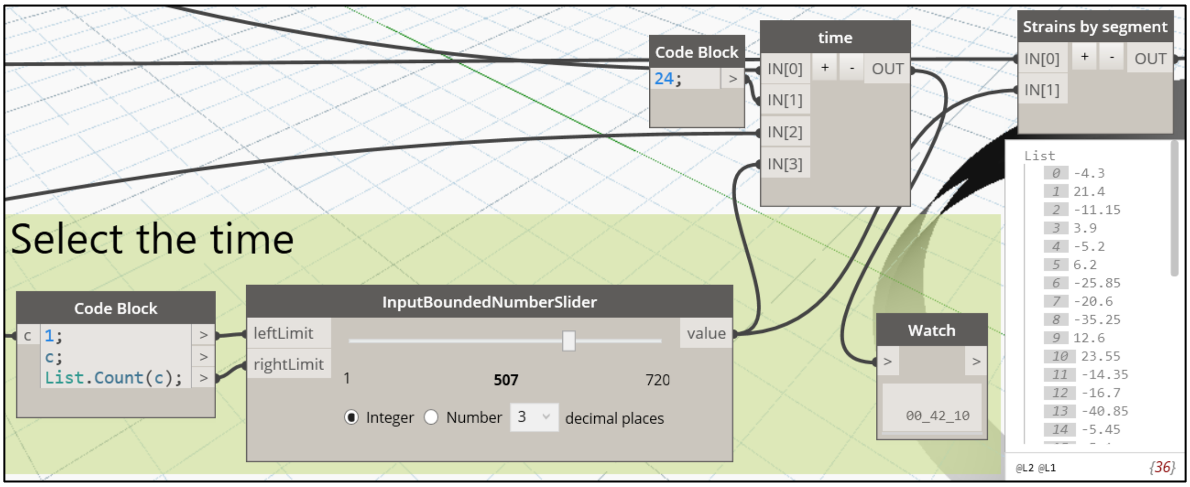


Figure 123: SHM data visualization. Time selection.

The most interesting fact is that Dynamo can be set to Automatic running of the program, making dynamic the analysis.

5. Color analysis

The final scope is to analyze visually the strain measurements.

5.1. Color range

For creating a color range is necessary to normalize the strains values determined in the previous step. First of all, the strain data coming from the last step must be organized in intrados and extrados values, task done by the python scripting node “Strains by position”. Then the color range is created and this is performed with the help of the code block node visible in the figure, where firstly the numbers are transformed to positive numbers by adding to all of them the minimum value in the list, and then are divided by the maximum number. After that is used the node “Color range” that is able to create a list of colors that correspond to interpolating the given numbers from 0 to 1 (value input) with indices (indices input) that at the same time are related with colors (colors input). As can be seen, the colors used in the this range variates from dark blue corresponding to the minimum values, passing through light blue, green and yellow, finally arriving to red in the extreme measurements positives or negatives.

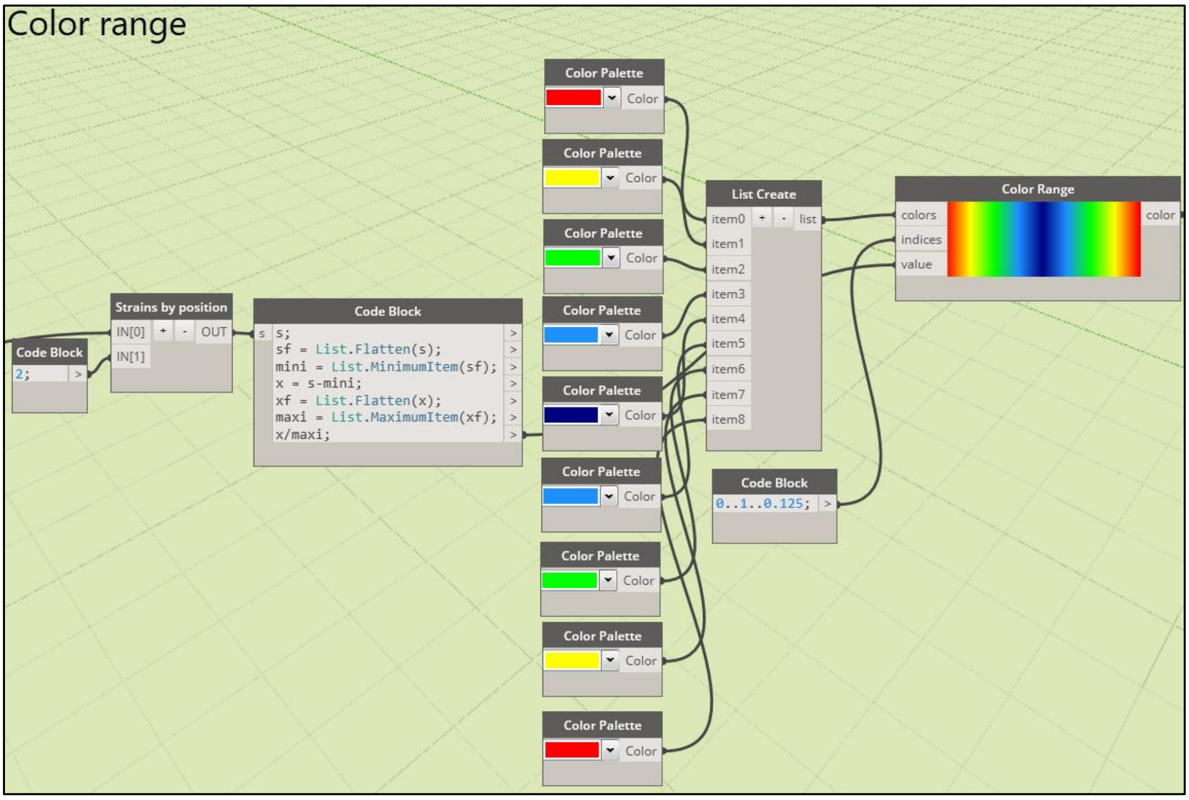
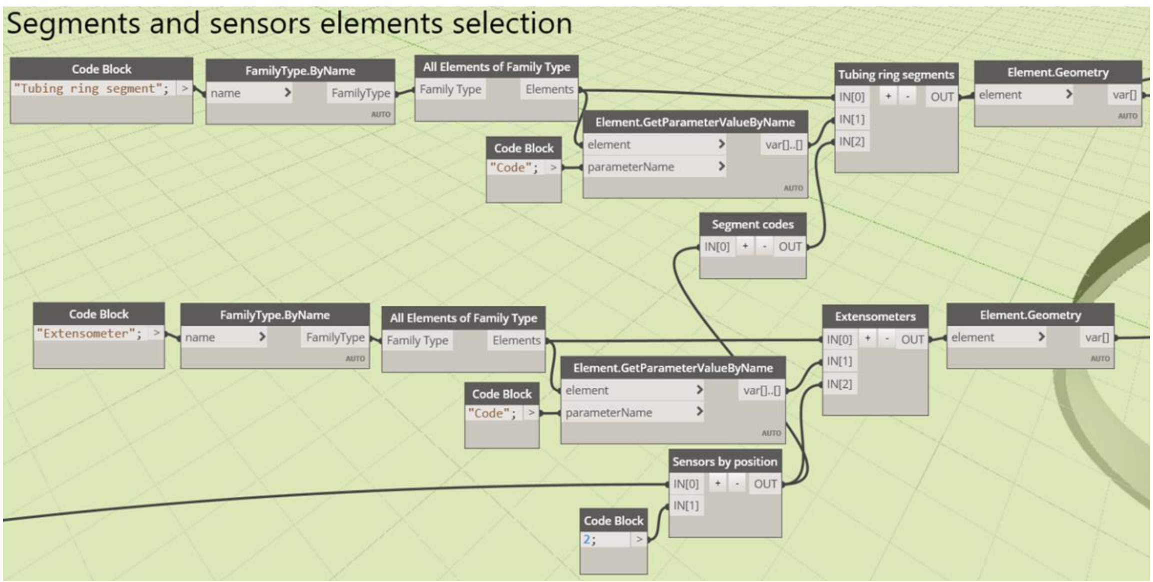


Figure 124: SHM data visualization. Color range creation.

5.2. Tubing ring segments and extensometers elements selection

The next necessary step is the selection of the tubing ring segments and the sensors involved in the analysis, which are the transversal extensometers. This is done with the following graph group. After the elements are selected by the “Tubing ring segments” and “Extensometers” python scripting nodes their geometry is obtained by the nodes “Element.Geometry” that allow to visualize the geometry of the elements in the Dynamo interface.



5.3. Extrados and intrados surfaces and color assigning

The last step is the extraction of the intrados and extrados surfaces from the tubing ring segments geometry. This is carried out with the python node "Intrados and extrados surfaces" that permits to select the surfaces of the segment that is closer to the extensometer. Then these surfaces are translated a very small distance outside the element with the aim of avoiding the overlapping with the segments. Finally by using the "Element.OverrideColorView" the color of the selected segments is set to the values in the color range, where in the intrados interface can be seen the color assigned to the strain of the intrados extensometer and in the extrados surface is visible the color that was matched to the strain of the extrados extensometer.

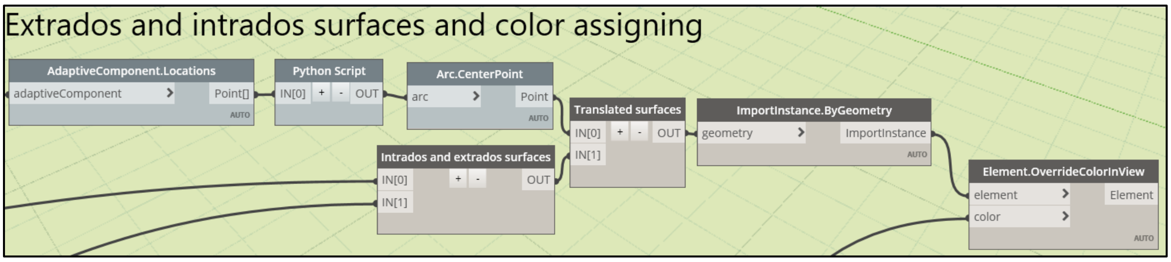


Figure 125: SHM data visualization. Intrados and extrados surfaces.

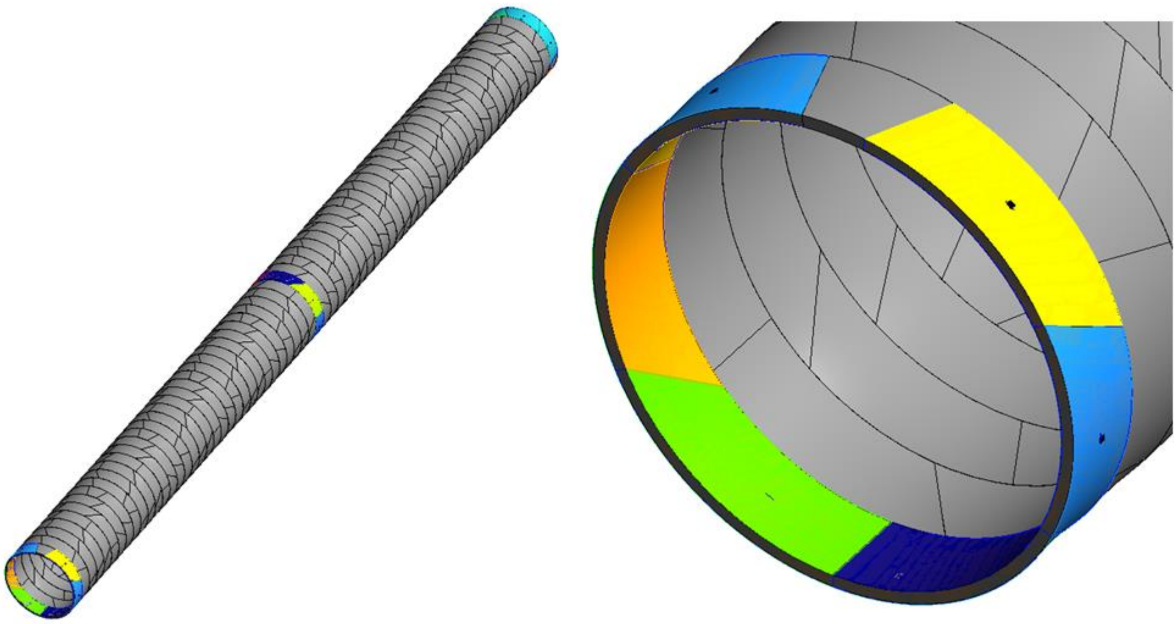


Figure 126: SHM data visualization. Visual dynamic analysis.

SHM data visualization program – Smart-sensors

This program works in a similar way of the previous one, with the difference that in this case it is thought for the smart-sensors data visualization.

Firstly some measurements are modeled as it was done before for the extensometers, but in this case for the Smart-sensors. Then, in the program, this data is retrieved in the same way that in the previous program and then filtered selecting the day, the hour and the exact time. After that are selected the transversal Smart-sensors involved in the analysis and their locations. This is done by selecting all the sensors and after that filtering those ones present in the retrieved strain data with some python scripting nodes.

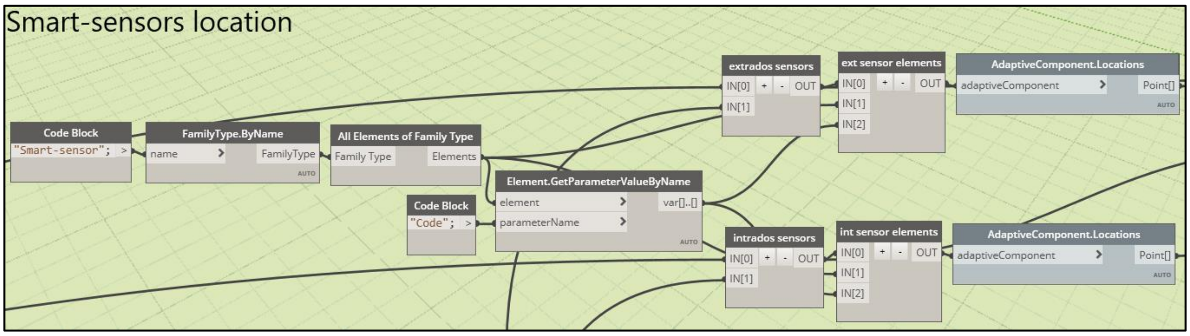


Figure 127: Smart-sensor data visualization. Sensors location.

Then is used the node “PointAnalysisDisplay.ByViewPointsAndValues” that allows to create a color range that will assign a color to the point depending on the value provided. In this case the provided values are the extrados and intrados strains and the analysis is created in the 3D view of the project.

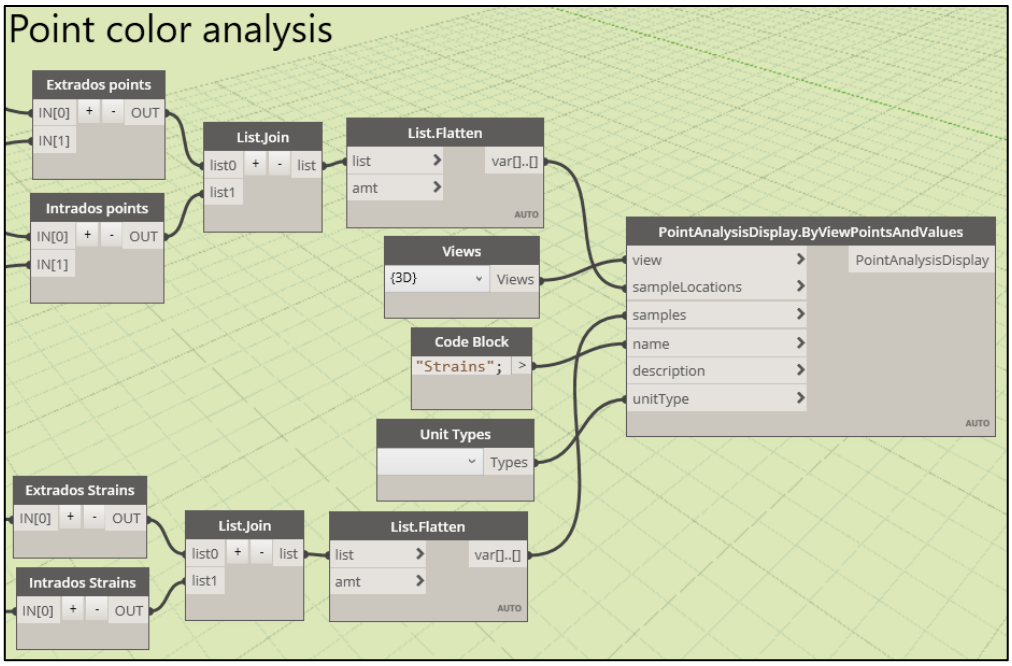


Figure 128: Smart-sensor data visualization. Point color analysis.

A final step before the analysis can be visualized; an style for the analysis must be created by assigning the colors.

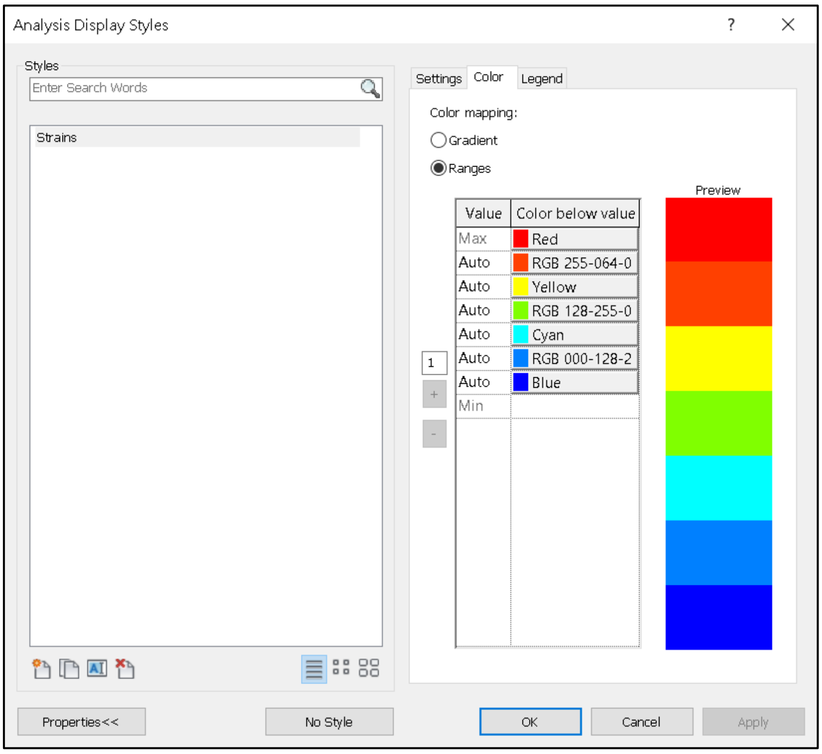


Figure 129: Smart-sensor data visualization. Analysis style.

After that the analysis can be visualized as follows:

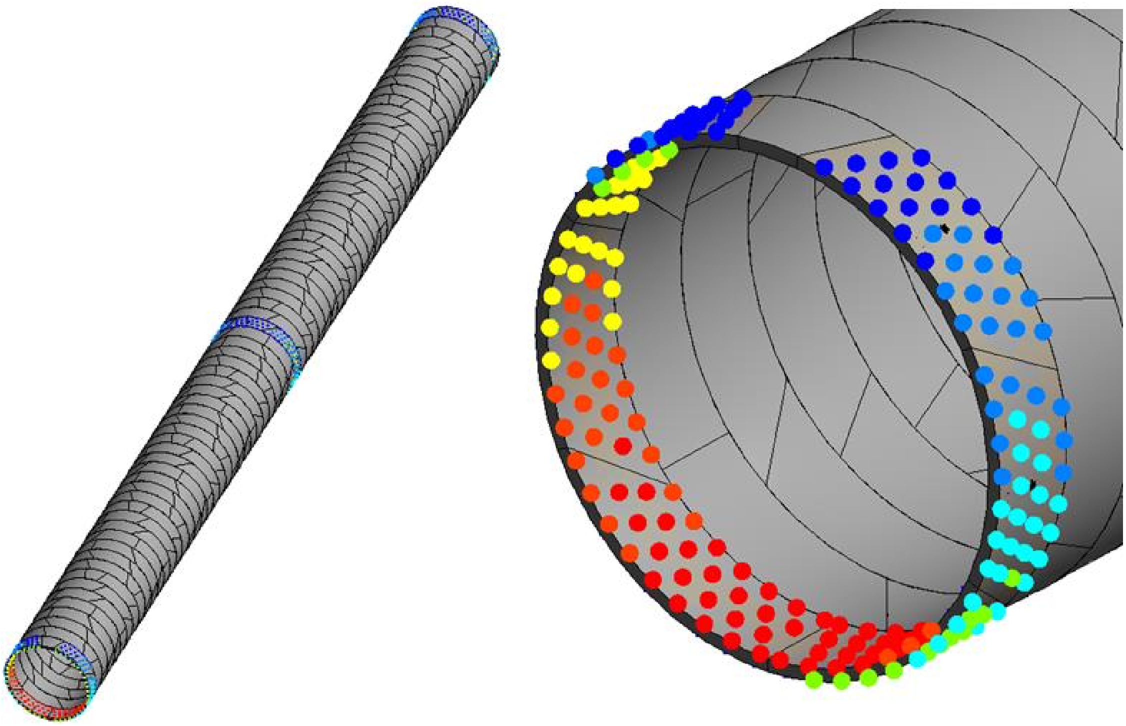


Figure 130: Smart-sensor data visualization. Data visualization analysis.

Section 4: Results, conclusions and future work

1. Results

As it was established in the section 2, the BIM context offers plenty of features that can be profitable for the SHM applications. The scope of this thesis was the evaluation of the potential of BIM using for SHM purposes through real cases of study, specifically as regards with the planning, design and installation of SHM systems and the management and visualization of monitoring data. All of this was addressed in the last section where were created the BIM models of the two cases of study and were developed and explained different programs, which results are discussed below:

1.1. Results in SHM system planning, design and installation.

This feature was evaluated in the BIM context specifically through the software Revit.

- BIM model creation and interoperability with Structural analysis tools

One of the most important characteristics of Revit is its interoperability and compatibility with different software, feature that becomes even more interesting in the case of infrastructure where it is necessary to use structural analysis software.

In the case of the Stura Bridge the model of the structure was carried out following as much as possible the recommended practices when is desired to perform a structural analysis by exporting the model to a software dedicated to this purpose. Particularly the model could be exported to Robot Structural Analysis by the direct link between Robot and Revit. Revit also gives the possibility of importing the analyzed model from Robot, and allows to visualize the bending moments, shear, deflection, and other effects. Despite of the model was not finally exported to Robot because performing a structural analysis was outside the scope of the thesis, this can be very useful at the moment of the designing and planning the location and all the relevant data regarding the sensors, due to the fact that the most critical places can be easily recognized.

- SHM system elements BIM modeling

The first noticeable thing is that Revit is not limited to the pre-established families that come with it by default. It offers the possibility to the user to enrich the variety of elements that can be included inside a BIM model, through the family editor environment. In that way, it was possible to model the sensors that constitute the central part of the SHM system in both cases of study, the Stura Bridge model and in the Brenner Base Tunnel model.

Despite of the structural sensors category is not currently included in the family library of Revit, they can be modeled in the specialty equipment category. In the sensors creation some aspects are taken into account: first, the sensors are created as adaptive components, characteristic that allow their placing in any location of the model, controlling its shape but more importantly their orientation respect to the structural elements where they are installed; and second some family parameters are assigned to the sensor families with the purpose of storing important data such as collected measurements, coordinates and identification codes.

- SHM system elements inclusion in the BIM project

By using Dynamo a series of different programs were developed with the same objective: helping in the installation and location of the sensors in the BIM projects.

In the case of the Stura Bridge 3 programs were created and they are able to support the user to place the sensors by selecting the element where they must be installed and the relative position of the devices in the surface of the element. The programs are also able to enumerate and give a unique code to the sensors, where are included the sensor number and host element where it is installed, information that is stored in some family parameters.

On the other hand for the Brenner Base Tunnel were developed many programs but in this case with the aim of making them more automatic, because the structural characteristics of the tunnel, as it is a structure made of a large number of identical prefabricated parts. Particularly, was addressed the installation of a traditional SHM system and a Smart-SHM system. In the case of the traditional one the program allows the user to select the tubing rings where is desired to place the equipment and the locations of the different sensors inside the segment; then it finds the geometrical coordinates depending on those inputs, creates the sensors and writes in the respective family parameters the unique code and the coordinate of the device. For the Smart system the sensors are installed in the reinforcement bars where each one can support a certain quantity of devices depending on its length and their spacings; in this case the program permits to select the bars of the specific tubing rings and then locates automatically the equipment along its distance.

With these experiences is demonstrated the great capability that BIM software can mean at the moment of the sensor installation, giving the possibility of making it easier, quicker, with a better accuracy and more organized, creating automatically codes for each device.

1.2. Results in SHM data management

This characteristic was tested also in the Revit environment.

- Sensor parameters managing

With a program developed in Dynamo was demonstrated that is possible to assign structural parameters to the simulated sensors of the Stura Bridge, such as initial strain or strain thresholds. The importance is that with the help of this program this activity, that is normally done manually, can be performed in a quicker and more accurate way, preventing possible errors.

It also brings the possibility of exporting the data to external tools, feature that is incredibly valuable. Dynamo allows the efficient and quick interoperability with excel, tool where monitoring and sensor identity information can be stored and shared with other professionals.

In in the case of the Smart-sensors installed in the Brenner Base Tunnel, by the using of Dynamo it is possible to export the monitoring data to structural analysis software, where a finite element model of the structure can be analyzed with the real effects measured by the sensors. Due to the large quantity of sensors that means the installation of a Smart-monitoring system based on embedded MEMS in the steel bars, it is necessary the using of special software that assist in the managing of the data, resulting BIM tools like Revit and Dynamo suitable for this operation.

- SHM data management and analysis

By using the SHM data management program created in Dynamo was tested the suitability of Revit for managing a large amount of data, in this case strains collected by the Strain multi-sensors installed in the Stura Bridge. First of all it allows the loading of monitoring data from text files, a common format in the transmission of data, that then is transformed in real measurements represented by numbers. After that, the data that corresponds to specific sensors of the model can be extracted and separated from the rest in an interactive way through the Revit interface. Then this can be manipulated, adding the initial values, obtaining the magnitude of the maximum events and the exact time when they happened and also are calculated the percentiles of the measurements with respect to the threshold values previously established. Finally, all this information can be exported to an excel file in an organized way, and once here it can be analyzed by the using of some charts and graphs, that help the user to interpreting it better.

1.3. Results in SHM data visualization

This important characteristic was evaluated with the Brenner Base Tunnel case of study. Extensometers and Smart-sensors data, stored in form of text files, was loaded in Dynamo following the same methodology of the SHM data management program. After that, the data that is desired to be visualized is firstly transformed in numbers and then filtered by day, hour and time. Finally, with this extracted data, can be created automatically a color range can be automatically created: this assigns different colors to the element in a scale depending on the magnitude of the strain. This colors permits to visualize graphically the level of strain to which is subjected the element. The importance of this experience is that it can be done for any type of effect (strains, temperature, pressure, etc.) and also the filtering can be done dynamically with the Dynamo interface.

2. Conclusions

The present thesis work was conceived with the purpose of evaluating if the capabilities and features of the current BIM environment are suited for the inclusion of different SHM applications in BIM projects. More specifically it was of interest the testing of the assistance and possible advantages that BIM can offers in three topics: installation of SHM systems, managing of SHM data and visualization of SHM data. After carry out some experiences which results were explained in the last point, the following conclusions can be established:

- BIM software, as it is Revit, permits the user to model the different elements that constitute the SHM systems. These created elements can store information as any other family of objects in the software, feature that makes possible the inclusion of monitoring information in the project.

- The BIM software interoperability or compatibility with other tools, such as Structural analysis programs, helps the structural engineer or the SHM engineer to make more accurate decisions regarding with the planning and designing SHM system, at the moment of recognizing the critical zones and to compare monitoring data with outcomes of structural simulations.

- With the help of visual programming tools, as it is Dynamo in the case of Revit, it is possible create programs that are able to access the BIM software API (Application Programming Interface) assisting the user in the process of the virtual SHM system installation in a quicker and more precise way.

- With the help of Dynamo, the visual programming tool built in the BIM software Revit, it is feasible to handle, manage and analyze a large quantity of monitoring data. This feature permits the engineer to perform this task in an interactive way through the software interface and gave to the professional a very useful assistance at the moment of interpreting the real data collected by the SHM system. Furthermore, the large amount of data managed by BIM can help to develop new SHM technology as reported in the case study of Brenner base tunnel where a high level of smart sensors integrated into reinforcing bars have to be handled.

- By making use of Dynamo to access the API of Revit it is possible to import SHM data inside the BIM environment and visualize it dynamically in a graphical way.

3. Future work and recommendations

With the experiences developed in this thesis work have been recognized many advantages and benefits that the BIM can provide for the SHM engineering. Although there are plenty of aspects where BIM tools can be useful for monitoring applications there is already a lot of work to do for developing this topic.

In broad outline Revit offers a very wide range of opportunities for SHM monitoring applications. Revit permits to simulate custom elements that don't exist in its default library, characteristic that for example allows simulating the SHM sensors in the BIM environment, but the process of elaborating them from scratch and the creation of different monitoring parameters results quite long and repetitive. This issue must be addressed by the main BIM software tools that should make the effort of developing a way of including the SHM system elements inside the BIM context.

One topic that was not addressed in this thesis was the application of the Revit MEP facilities to the SHM experiences that were carried out. The software allows the creation of electrical networks for lighting and other electrical equipment. This feature could be applied in monitoring purposes and it opens a wide variety of new possibilities for further researches, because it would permit to include in the BIM environment other components of the SHM systems besides the sensors, such as the Data Acquisition system or the Communication system.

On the other hand, Dynamo has demonstrated to be an incredible useful tool at the moment of automating the installation of sensors and managing the monitoring data. However, although the visual programming environment of Dynamo is oriented for the construction industry professionals that generally are not so familiar with programming languages, permitting them the access to the API of Revit in a friendlier way, when it comes to develop custom programs is almost a fact that is necessary to include some routines written by the user in a high level programming language. In fact, while more complex and versatile the program must be, more custom routines have to be included.

This issue is solved relatively thanks to the help of the very big community of Dynamo, where can be found solutions for similar problems that other users have encountered in the past, but also is available a huge library of downloadable packages with custom routines that may be useful for different tasks. But in reality, for developing better programs, that work more efficiently and offer a higher degree of versatility becomes more adequate the creation of an Add-in. In this case, writing the code would require the using a higher programming skill levels, because have to be used programming languages such as C-sharp or JavaScript but the effort will be rewarded with a better functioning.

Regarding to the visualization of monitoring data, Revit with the help of Dynamo has provided very acceptable results, permitting to import inside Revit collected measurements and allowing their graphic visualization by means of color scales. This can be improved by using a program better suited for data visualization purposes, as it is the game engine Unity that is currently used in the scientific world. For its utilization is also required a deepest knowledge of programming, but it allows the using of a wide variety of high level languages, as Python, C++, Java, among others.

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