This project has received funding from the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement no. 826250 Assets4Rail).

ASSETS4RAIL

Deliverable D 2.2
Report on the development of real-time monitoring, analyses of sensory data and integrating into the BIM platform

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1. Executive Summary

The Deliverable D 2.2 titled "Report on the development of real-time monitoring, analyses of sensory data and integrating into the BIM platform" outlines various sensor data representation models which could be used for storing representative sensor values, extracted from raw sensors output, within the standardized IFC format. This BIM model format is already shared by a wide technical community but the sensor data integration aspect is still under much development. One of the main challenges of this report was to present general solutions to sensor data representation in BIM since there are many sensors and sensor models available on the market with new ones constantly appearing each having their own data storing architecture.

Besides the sensor data representation models, this report also presents some general characteristics and possibilities of how the sensor data transfer into the BIM environment could be carried out. This process involves many sides, from sensors in the field to servers, where sensor data is stored, and finally computer platforms where BIM models are stored along with software for manipulation and sensor data integration.

A special section of this report is dedicated to sensors covering safety and security aspects since these were not presented in previous reports. However, they represent an important monitoring aspect with some special characteristics and requirements; hence their inclusion into the sensor list is of absolute necessity.

Finally, this report describes, for the selected sensor examples, the methodologies of data processing. The main objective of this process is to extract vital information in the form of representative values from raw sensor data output. Since this process depends very much on the sensor (and even sensor model) this step was done only for a limited number of sensors with low data acquisition rate and well-defined set of representative values. However, in near future this step will have to be carried out for all other commonly used sensor systems, particularly the ones involved in this project's case studies.

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
SHM	Structural Health Monitoring
BIM	Building Information Model
IFC	Industry Foundation Class
GIS	Geographic Information Systems
RFID	Radio Frequency IDentification
GPR	Ground Penetrating Radar
TLS	Terrestrial Laser Scanning
LVDT	Linear Variable Differential Transformer
API	Application Programming Interface
PI	Performance Indicators
KPI	Key Performance Indicators
S&S	Safety and Security

3. Background

The present document constitutes the Deliverable D 2.2 "Report on the development of real-time monitoring, analyses of sensory data and integrating into the BIM platform" in the framework of the WS1, WP2, Task 2.2. of the Technical Demonstrator 3.5 (TD 3.5), defined in Shift2Rail Master plan Innovation Programme 3 (IP3) in line with Multi-Annual Action Plan (MAAP).

4. Objective/Aim

This document has been prepared to provide a short but general overview of possibilities for the implementation, visualization and interpretation of sensor data within the existing BIM/IFC infrastructure capabilities. It provides a somewhat different perspective on the sensor classification criterions from the previously prepared reports (Deliverables D 1.3 and D 2.1), namely from the point of view of different representations of sensor data within the BIM model. This classification and the description of four sensor representation models is the central part of this report. These models were established to incorporate not only sensory data in railway tunnels and bridges but have the potential to be used for monitoring purposes on any other BIM model.

The aim of this report is to establish a link between different sensor data output types, presented in Deliverable D 2.1 “Report on sensor type and data formats for monitoring and inspection solution with BIM integration for railway infrastructure”, and the BIM/IFC capabilities for their visualization (possible interpretation). It should be emphasized right at the start that this process is under much research and development in the broad BIM community with the IFC format upgrading and integrating more and more sensor related aspects. Since the final solutions to an effective structural health monitoring (SHM) using BIM as one possible tool are still not very clear and far from resolved, the preparation of this document was guided by following simple guidelines which in our mind reflect the trends of the future developments in which the monitoring process with all its infrastructure (sensors) becomes an integral part of the railway infrastructure’s lifecycle.

5. Possibilities of sensor data to BIM model transfer

Starting from where Deliverable D 2.1 ended, there are several ways of how the actual transfer of sensor (raw)data to BIM model can be carried out. In this section only some general remarks of this process are outlined because:

- there are many different sensors available each with specific, possibly binary, inherent data format (even sensors monitoring the same particular parameter may have different data format, depending on the sensor's vendor).
- Depending on the frequency of measurement acquisition, sensor data may require different storage models (e. g. in the form of simple tables or very flexible database systems).
- The overall control and access and finally the purpose of a particular sensor data may involve different parties, from sensor experts (including tasks of raw sensor data post-processing) to BIM development community.
- The BIM model and the sensor raw output are typically separated in terms of where the data is stored.
- The BIM software's purpose is to act as a "client" accessing the sensor data "servers" via a specially designed "sensor data integration module" in order to bring only a certain set of representative values (for each sensor) into the BIM model "on demand".

Based on these remarks one possible solution of this sensor data transfer is depicted in Figure 1.

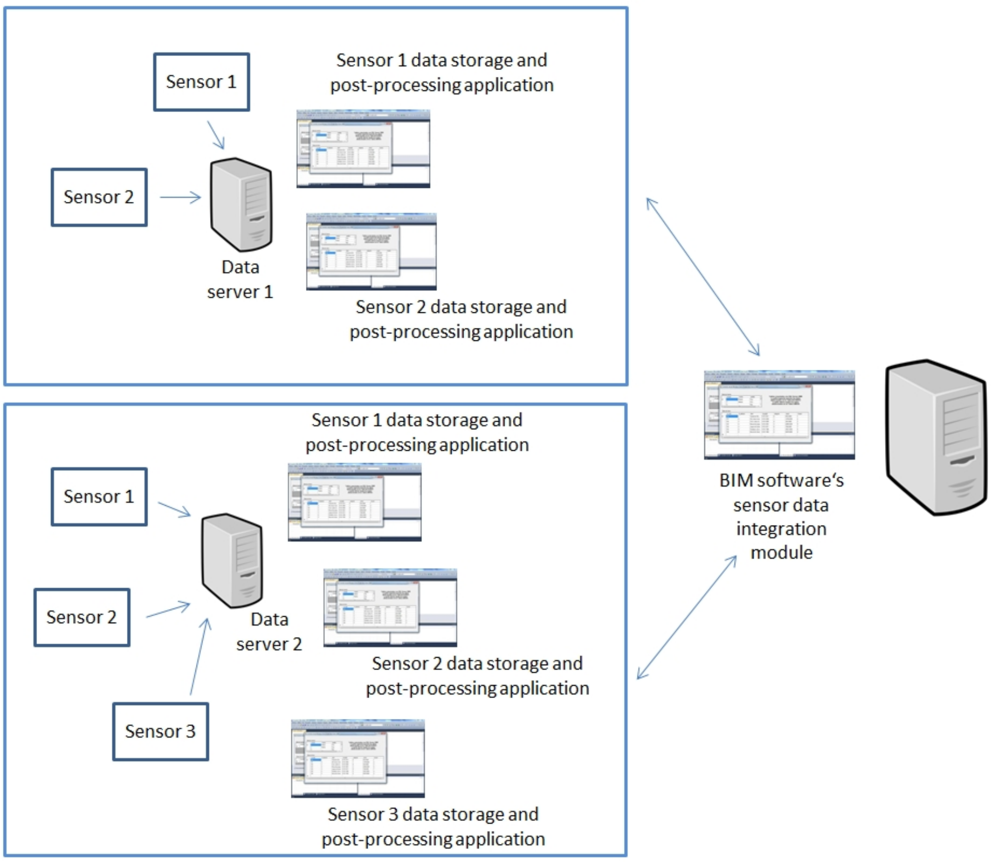

Figure 1 General sensor data to BIM model transfer architecture

In Figure 1 each of the two data servers is used for storing more than one sensor data layer. On the other hand, sensor system operators may store their own systems' data on different data servers. Besides storing the data, different post-processing applications may run on these servers to extract some representative values from raw data. In Figure 1 these two steps (i. e. data storing and post-processing) are carried out with just one application but other possibilities exist where the storing and extraction of representative values is done in multiple steps with several different applications. The architecture presented in Figure 1 does not include a large portion of monitoring activities and methods where more manual work is involved (e. g. visual inspection) and the data acquisition rate is much lower so the storing and post-processing of raw sensor output is much less automated. Finally it should be mentioned that the BIM model in Figure 1 is stored on a separate computer from data servers as well as the BIM software containing specific functionalities (in the form of software modules) enabling it to access the sensor representative values remotely on demand. This way the oversaturation of the BIM model with raw sensor data can be easily avoided.

Since many details of this sensor data transfer process remain undefined and may ultimately depend on the selection of sensors involved in practical field campaign examples, the design of this architecture is still debatable. The processing steps for extracting representative values from raw sensor output should probably be done on the server side since:

- different sensor operators want to have control over their monitoring system also in terms of data storage and post-processing.
- The software's sensor data integration module would require a lot of post-processing involving different methodologies with required expert sensor knowledge.

If the sensor data and the BIM software remain separated, the definition and calculation (or estimation) of representative values remain in the sensor experts' domain whereas the integration and update protocols of these representative values into the BIM software remain in the hands of software developers. Moreover, this way also the calculation of quality measures (e. g. precision, accuracy) for each sensor representative values could be done by experts of individual systems. The estimation of these quality measures is a very important (and in many cases not trivial) step that has direct impact on the level of reliability of SHM process. Without the inclusion of such measures into the BIM infrastructure from start it will be very difficult to make precise estimation and forecasting of the structures' future. Since for some sensors (e. g. geodetic sensors, including drones and laser scanners) an advanced knowledge for the estimation of quality measures is required, this task should remain in the domain of individual system experts. The quality measures should be included in all sensor data representation models.

In Figure 2 the sensor data supply and demand chain is shown graphically, including the server side (green box colour) and BIM model side (blue box colour).

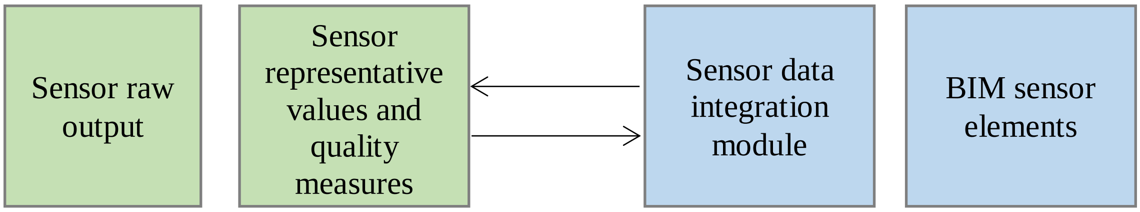

Figure 2 Diagram of a BIM software-to-sensor server relation

6. Safety and security assets monitoring and sensory data

As described in Deliverable D 2.1, there are different types of sensors that can provide input data to the BIM model. These sensors provide different types of information, from structural data of the bridge and the tunnel, the presence of blockages or problems in the drainage pipes of tunnels, emergency signals such as the fire sensors, air quality and air flow sensors, or also the state of the different safety and security assets.

Directive 2004/54/EC identifies a series of safety and security (S&S) assets in tunnels for the prevention of critical events that may endanger human life, the environment and tunnel installations, as well as by the provision of protection in case of accidents [1]. This Directive is mandatory for tunnels in the Trans-European Road Network with lengths of over 500 m. In addition, the Security Manual for European Road Infrastructure [2] gives some guidelines and measures to increase the security in road infrastructure; these include CCTV, movement detectors; automatic video detection for security purposes, dangerous goods detection by RFID or gas detection. The sensorization and connection of these assets to the BIM can give important information for an optimized maintenance decreasing possible errors and increase security in tunnels and bridges. Safety and security assets need of additional information for maintenance purposes. The methodology proposed for the identification of the information needed for those sensors related to safety and security assets can be seen in Table 1.

Table 1. Methodology to identify sensorization and monitoring information for safety and security assets.

Steps	**Description**
1. Safety and security inventory	Identification of the list of sensor data from/for safety and security assets.
2. Criticality level	It is understood as critical those failures or emergencies that produces an interruption of the service or a serious problem to the safety and security according to a Quantitative Risk Assessment. Those critical elements need to have a special monitoring on the BIM, so that any deviation should be highlighted at a first sight on the BIM.
3. Predictive/preventive maintenance	The BIM should also incorporate information about preventive, for no critical assets, and predictive maintenance, for critical assets.
4. Sensorization	Safety and security assets could include sensors to control aspects such as time, number of operations, and/or state. Two types of sensors could be used, type A and type B, depending on its relation with the BIM, if the BIM gives output data, or if there is an interchange of information, output-input data.

It has been identified two different possible types of communication that could be produced between the BIM, based on the preventive and predictive maintenance information, and the S&S

sensors (see Figure 3). Type A S&S assets would only receive information from the BIM. This type of assets include for example a light that can be in green or in red indicating an asset that needs to be maintained, since the established preventive maintenance time has been exceeded (e.g. fire extinguishers, fire detectors, etc.). On the other hand, type B assets send information to the BIM and the BIM could also send information back to the asset if necessary showing a green or red light if maintenance is needed or not. Some examples of type B include the pressure and fill levels of pressure equipment related to safety and security assets and other sensors to indicate the status of these assets (e.g. fire extinguishers, self-contained breathing equipment, water level of the fire tank, CO_2 level, level of foam and quality, charging level of the batteries used for the pumps of the firefighting water system, etc.).

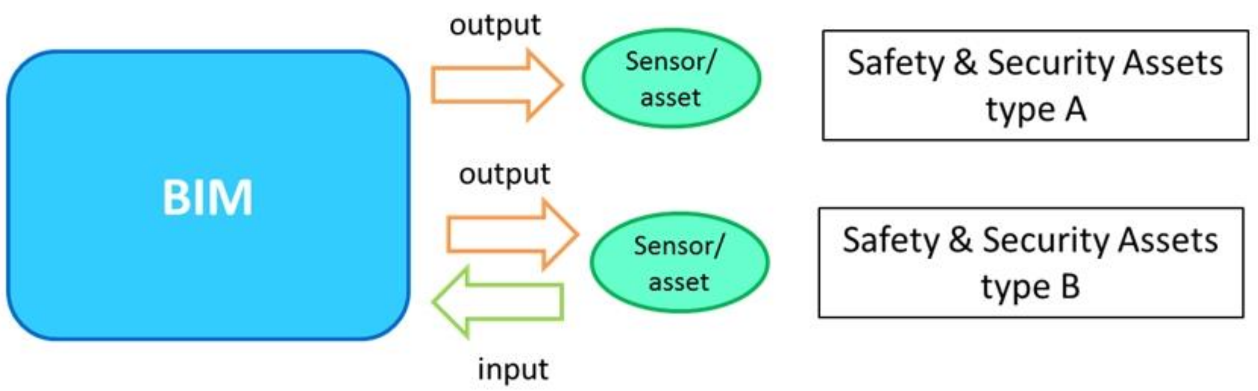

Figure 3 Safety and security assets types and communication with BIM

The sensors falling into this category constitute an important additional part to the already presented list of SHM sensors described in Deliverable D 2.1. Since some of these sensors would have to be directly accessed through the BIM software in order to transfer messages of alert, this sensor category seems to be even more challenging when considering possibilities of their integration into the overall sensor data to BIM model transfer architecture (see Figure 1).

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7. Sensor data representations

In the so-far prepared reports (see Deliverables D 1.3 and D 2.1), the sensors for SHM have been classified into two subgroups based on whether they are required to have direct access to the object under investigation (i. e. contact and remote sensing sensors). Besides this criterion many other exist, since there is a huge number of SHM sensors available with many more still under development. The design of a general solution for sensor representation within BIM presents a big challenge particularly due to the vast number of different sensor designs and data outputs.

For the purpose of this report the above mentioned criterion is not best suited. If one is to describe different ways in which SHM sensors could be visually or graphically presented within the BIM/IFC digital infrastructure then one should consider what possibilities already exist. For example, in 2D GIS environment the graphical elements, which are an abstract representation of physical entities, are typically depicted using points, lines or polygons. This is how the SHP file format works and has become the industries' standard.

If we want to apply or generalize certain ideas from GIS for the graphical representation of SHM sensor within BIM (inherently 3D environment) we first need to consider what kinds of sensors exist with respect to the output characteristics and domains or areas of information. Most sensors are of local character which means they measure a particular physical or geometric quantity in a particular location (or are located in a certain location for safety and security purposes). Hence, could be depicted in a 3D environment using point-like objects. Furthermore, there are sensors which could be regarded as more line-like or network-like. Finally, one has to consider also sensors which produce outputs of surface-wise character much like polygons are used in 2D GIS for the representation of area-like phenomena. In the following chapters these three groups of representations are described in more detail.

7.1 Point type sensors

The IFC format (see Figure 6 in Deliverable D 2.1 or [3]) contains an already established list of predefined sensor types which all basically fall into this category, e. g. smoke or temperature sensor. Examples can be seen in Figure 4 for a bridge and a tunnel.

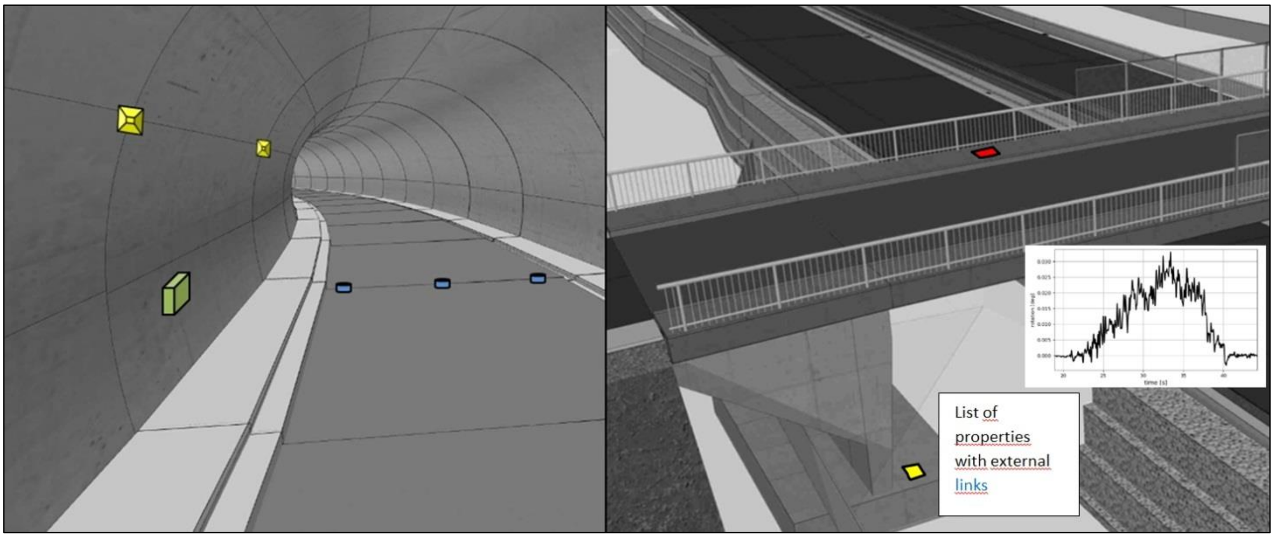

Figure 4 Point type sensor representations within the BIM model

In other words, the predefined sensors all represent point type sensors which can be visualized within a BIM model using various generic or custom made 3D elements. Any such sensor, depicted in Figure 4, is of local character therefore a point-like representation seems justifiable. For different sensor types, different graphical elements should exist similar to the idea of establishing standardized cartographic schemes used in GIS. Promoting standardized graphical elements for any sensor type should be regarded as a positive initiative since BIM projects usually span many different professions involving a lot of participants. In this report the visualization of sensors in Figures 4 and 5 is merely for demonstrative purposes, hence the use of simple box and cylinder style sensors. In reality, some sensor vendors already provide digital replicas of their products (along with the list of predefined properties) in specific software formats, e. g. Revit. In Figure 5 an example of a smoke and heat detector can be seen, which can be downloaded from [4].

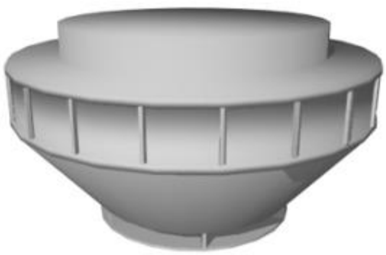

Figure 5 Smoke and heat sensor digital replica available online

Once a graphical scheme is defined, the point type sensors can easily be located within the BIM model corresponding to their actual location in the physical world. An actual sensor has thus become represented in the BIM model by a specific sensor element (whether predefined or custom made). Next, the IFC format also presents various possibilities of storing the sensor output (i. e. sensor data). These possibilities should be considered in connection with each new available sensor taking into account the following guidelines:

- if the sensor output is of a single value (e. g. temperature reading) then the property list of such sensor elements could contain only one numeric value.
- For sensors, measuring their corresponding quantities over a period of time there are two possibilities within the IFC infrastructure:
    - the signal with respect to time y=f(t) can be represented by a list of representative values, for example (mean values, standard deviations, minimum, maximum values, etc.).
    - The signal with respect to time y=f(t) can be represented as a time series.

Since some sensors can operate over longer time periods, storing all the data (in the form of time series) inside BIM software for viewing and manipulation is not the best option. Most likely, the sensor data will be stored and accessed remotely using the BIM software's sensor integration module. Before this transfer of sensor data to the BIM model is carried out, the above mentioned representative values will have to be estimated from raw sensor data. This way the sensor output will be distilled down to a few of these representative values whereas the original output could be obtained via an external link (see Figure 4). Inside a BIM software this would mean an operator could by clicking onto a particular sensor get access to its property list. This list will contain all the representative sensor values as well as the external links to original sensor outputs. These external links can include raster images, simple spreadsheets and data tables or PDF documents with possible data processing steps or entire field campaign reports. In this way the chronology for each sensor can be stored very effectively. In the sensor data to BIM model transfer architecture, presented in Figure 1, the generation and storage of these external link data is probably confined to the server side but the details of this particular topic are not defined within this report. Next to the representative values and their corresponding quality measures these external links represent a third component of the data package that will have to be transferred to the BIM/IFC model by the sensor data integration module.

Before moving to the presentation of the next sensor type let us mention a few sensors (and there are many more) which are typical members of this type: **thermometer** measuring temperature; **water level gauge** measuring vertical bridge displacement; **piezometer** measuring water pressure; **inclinometer** measuring rotation; **LVDT extensometer** measuring crack width or vertical bridge displacement; **geodetic sensors systems** with measured coordinates or displacements of specific point locations (height only or 3D point); **strain gauge** measuring strain; **pressure sensors** measuring pressure; **microphone** measuring noise or estimating fatigue on bridges; **vibrometer** measuring vibration; **electrochemical sensor** measuring corrosion; **accelerometer** measuring vibration etc. All these sensors have been presented in detail in previous reports. In addition, this representation group will get larger by including other sensors which have not been mentioned or are still not part of the standard monitoring process.

7.2 Network type sensors

Network type sensors can be considered as multiples of sensors working as a single group with each sensor having the same internal characteristics or properties. They comprise of a series of point type sensors connected into a larger entity thus covering more space and therefore enabling a denser sampling of a particular measuring quantity. The form or shape of this network can be different as can be the number of nodes (i. e. point type sensors) it contains. In Figure 6 two examples are shown representing the tape extensometer (the two green boxes indicating locations where the tape is fixing onto the tunnel wall) and a simple optical fibre cable (blue cylinders indicating the location of the cable.

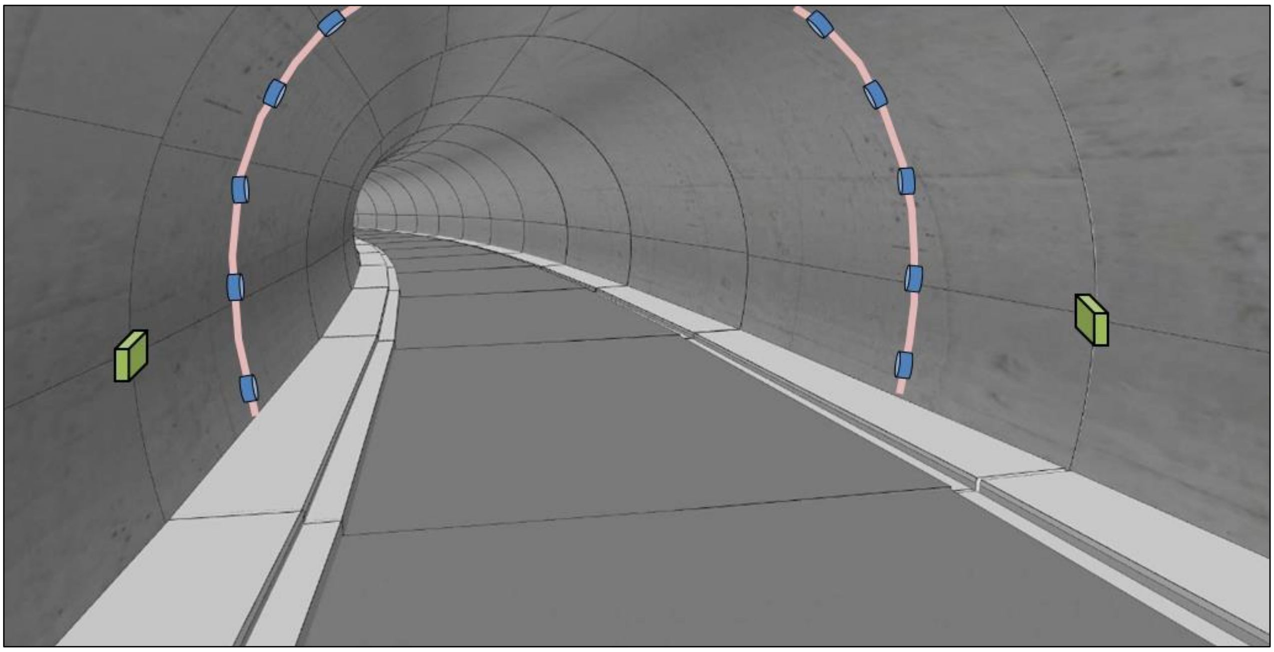

Figure 6 Examples of network type sensors inside a tunnel

The tape extensometer is basically a simple tool for measuring the tunnel tube deformations in relative terms. Hence, the location of both endpoint nodes is important indicating the direction of the deformation. The tape extensometer nodes represent the simplest two-node network whereas the other example from Figure 6 is more complex. Optical fibre sensors are line sensors typically used for measuring strain along the length of the fibre cable. In order to be able to visualize the near-continuous strain measurements, the line (or a network of lines) would have to be presented as a series of discrete point type sensors each containing measurement outcome as average values in a particular cable section. The visualization of such sensors measurements would inevitably require some additional raw data post-processing steps (on top of the regular ones, described in Deliverable 2.1) in order to transform it into individual sections. Each section could then be presented by a single point type sensor with property types much like the ones described in section 7.1.

Besides these two sensor examples, other even more complex forms of network sensing systems are a part of this representation type. Wireless sensors systems (e. g. RFID) can be regarded as network type systems measuring various quantities (including the progress and workflow on a construction site). The form of these sensor networks is even less strict depending on the shape of the structure and the monitoring requirements.

Finally, some remarks should be made concerning the density of point type sensors within a particular network. The spatial distribution of nodes should not exceed the operational capabilities of the BIM model. The distribution of nodes in the optical fibre network (particularly along linear sections) will depend also on the expected level of strain.

Extrapolating into the future, one can say with a high level of certainty that should the trend of using more and more sensors within BIM projects increase, more likely it is that individual point type sensors will become part of intricately connected networks. Following this scenario, not only will the graphical element relations between individual nodes and the network as a whole have to be considered (possibly standardized) but particularly the property lists will have to be defined for the network as a whole as well as for individual sensors within the network. Similarly to the previous representation model, through the BIM software's sensor data integration module not only will the representative values on an individual sensor level (stored in property lists) be updated but the property list of the network as a whole will be updated as well. In Figure 7 such network configuration is presented in a graphical way.

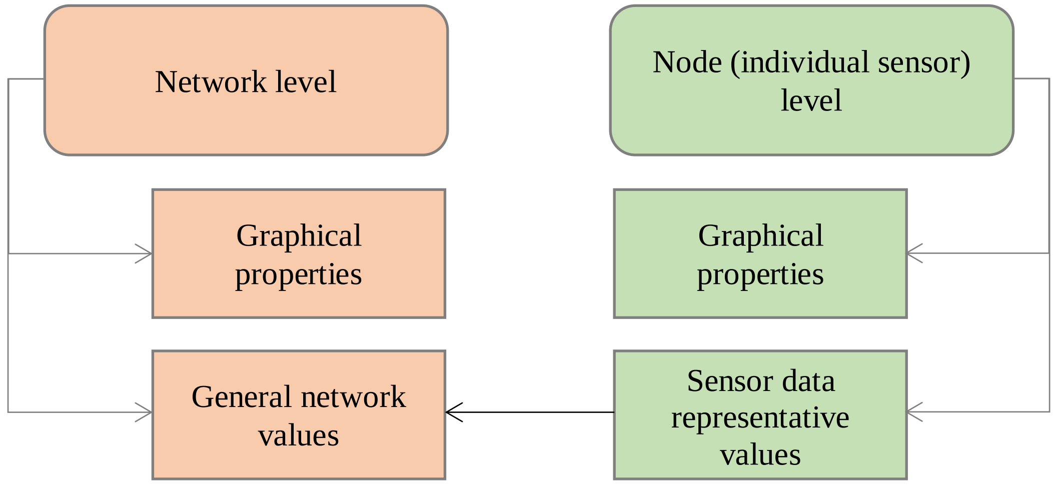

Figure 7 Network configuration relations

Based on network configurations such as the one depicted in Figure 6, it would be very useful to enable some kind of color-coding for sensor values exceeding their thresholds. This way the visual interpretation of a larger number of network sensors becomes much easier. As for the general values of the network as a whole, these would have to de defined for each sensor system separately containing vital information of the whole system as well as critical outcomes in some particular areas (nodes). Different color-coding schemes should exist for different sensors systems or monitoring aspects, e. g. for safety elements/assets, structural measures etc.

7.3 Surface type sensors

The third and final sensor representation group includes sensors which produce a surface-wise coverage of measurements of the surface under investigation. Most of these types of sensors operate by using different remote sensing principles to establish a 2D image (2D map) of the surface and its individual sections.

The challenges of visualizing the outcomes of these sensors in a BIM model environment (constructed on IFC format specifications) are numerous. On the other hand, the high density of measurement coverage coming from these sensors leaves little space for generalization. One way of representing such 2D maps would be to use texturing of BIM model surfaces involved in the monitoring process. However, this turns out to be cumbersome within the available IFC infrastructure. Even more so, when transferring BIM models from one software platform to another, these 2D maps would have to be transferred as well. The BIM model exchange process would therefore be much more complex. Moreover, not all BIM software platforms support surface texturing anyway which is yet another reason why this representation option seems less favourable.

After extensive consideration on the possibilities of representing results and not preferring to work outside the already existing BIM/IFC infrastructure capabilities, it was decided to follow the idea of linking these sensor type results with the existing BIM model constituent parts. A typical BIM model consists of digital representations of actual (i. e. physical) elements such as pavements, train tracks, road surfaces, tunnel lining etc. Compared to the first two sensors representation groups, where sensor element are depicted at specific locations (single or network based), sensor output (2D map) at a specific location is depicted here. To illustrate this, let us examine Figure 8 showing what seems to be at present time the optimal way of visualizing surface-wise sensor output.

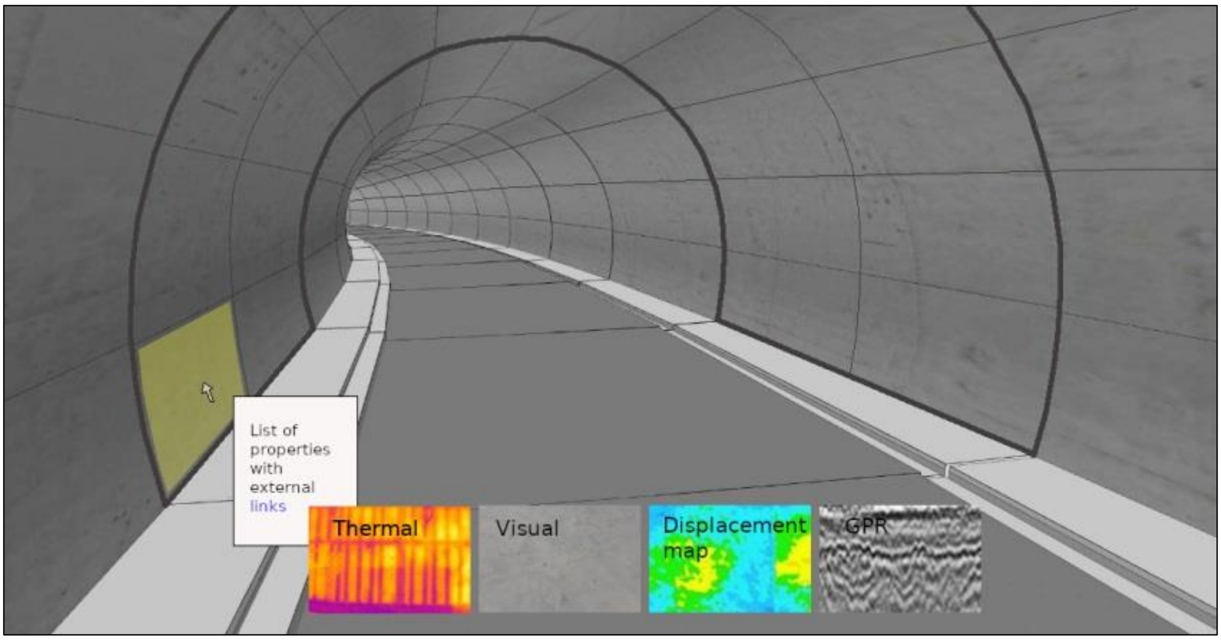

Figure 8 Surface-wise sensor output related to specific BIM model (sub) element

In Figure 8 the monitored surfaces of individual BIM model elements (e. g. tunnel lining compartments/sections) were subdivided into smaller sub parts (i. e. surface patches). This subdivision has been established in the BIM model construction phase. If such meshing of surfaces exposed to the monitoring process is available then the connection to the sensor output becomes straightforward. **The sensor element itself is nearly replaced by the surface patch the data refer to**. By clicking onto a specific surface patch the list of properties (containing again some representative values for the whole patch) can be obtained just like in the previous two representation models. Similarly to the network type model, the relations between individual patches and the BIM elements they belong to could be established (see Figure 6). Furthermore, the actual 2D maps representing the entire measurement scope can be accessed via external links. These external links can be in the form of 2D raster images as already mentioned or documents describing data processing steps.

In Figure 8 four examples of sensor technologies are represented which can produce surface-wise output stored in a rasterized form. Passive sensors (e. g. thermal and visual cameras) automatically store data within a regular gridded form whereas data from active sensors such as laser scanning or ground penetrating radar (GPR) can be transformed into such a form using the well-established data processing algorithms. In Figure 8 the displacement map represents the difference map from two consecutive terrestrial laser scanning surveys.

Visual inspection results in the form of manually (lack objectivity) drawn maps (2D) showing cracks, delamination areas, abrasion areas, spalling areas or other surface defections all fall into this representation category. In recent times more and more of these maps are being replaced by autonomous sensor platforms such as drones using high resolution digital cameras.

In order to be able to link individual surface patches with corresponding sensors maps, the latter would have to be aligned to these patches. This process may depend on how results from different sensors are stored and presented but all are probably embedded in some sort of coordinate frame that could be connected to the one used in the BIM model. The map alignment and subdivision into individual patches could in some cases be fully automated (e. g. in tunnels) if the sensor results would by default be presented in the intrinsic tunnel axis coordinates (chainage, horizontal and vertical offset). In Figure 9 an example of a crack map is presented inside a tunnel using these coordinates. All visual inspection results are usually presented this way whereas other remote sensing results can be transformed into this coordinate system. In Figure 9 the locations and widths (in millimetres) of cracks are depicted on a 1x1 m grid with the x-axis indicating the distance from the tunnel axis and y-axis indicating the tunnel chainage.

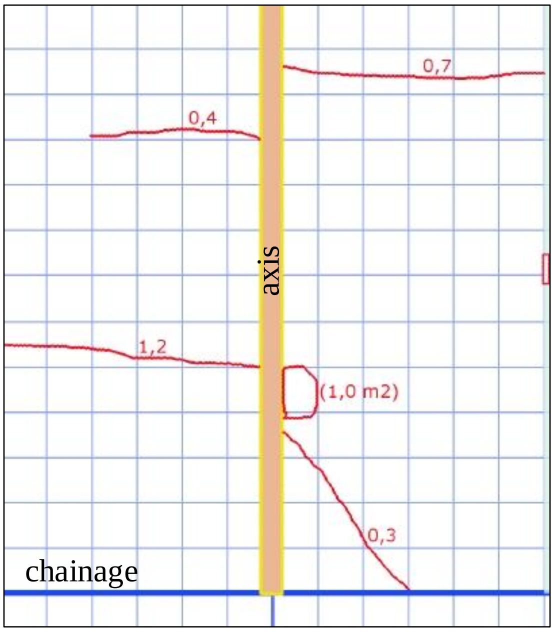

Figure 9 Visual inspection results in the tunnel axis coordinate system

Finally, when it comes to deciding what the patch size should be, this depends on certain criteria much like in the previous representation model:

- the patch number should not decrease the overall operability of the BIM model;

- in tunnels the patch size may also depend on the size of the tunnel lining sections;
- on bridges the size of the patch can depend on the dimensions and the number of surfaces involved in the monitoring (e. g. upper surface, supporting structure, etc.).

When presenting sensor results of this kind it will be useful to implement some kind of color-coding scheme for individual patches to be able to analyse the overall state of the structure and its parts faster and more efficiently. Since any patch can contain various sensor data the color-coding schemes will have to be designed for each of these datasets. This means the schemes would cover aspects from deformation to heat transfer (possible water leakage) and even surface or subsurface condition estimation.

Based on the above presented three sensor representation models, the following Table 2 summarizes the classification of common sensors according to this criterion. This list is not final since new systems are developing constantly with high tendencies towards automation and miniaturization.

Table 2. Common sensor systems and their classification according to the IFC representation model which are used in tunnels and on bridges.

Sensor	Representation model
LVDT Extensometer	Point type
Strain gauge	Point type
Inclinometer	Point type
Accelerometer	Point type
Piezometer	Point type
Thermometer	Point type
Water level gauge	Point type
Electrochemical sensors	Point type
Pressure cells	Point type
Safety and security sensors *(e. g. smoke detectors, visual cameras)*	Point type
Geodetic sensors *(GNSS, geometric levelling, total stations)*	Point type
Microphone	Point type
PH sensors	Point type
Ultrasonic sensors	Point type
Laser Doppler Vibrometer	Point type
Fibre optic sensors	Network type
Tape extensometers	Network type
Photogrammetric systems (e. g. drones)	Surface type

Laser scanning	Surface type
Ground penetrating radar	Surface type
Thermal camera	Surface type
*Visual inspection**	Surface type

* *Is not an actual sensor or a measuring platform but rather a monitoring method*

Some of these sensors (e. g. laser Doppler vibrometer) can be difficult to classify into the three representation models since several versions exist which means that the representation models may eventually depends not on the sensor type but on the sensor model.

8. Examples of data processing methodologies

The process of monitoring structures using various sensors (SHM sensors and sensors for safety and security aspects) can be carried out in two ways with respect to data acquisition rate:

- at specific time intervals (e. g. once per month, once a year etc.),
- or in a fully automated way with data being transferred one or both ways.

Due to this fact and the fact that a large number of sensor types and models exist it is very difficult to describe in detail the data processing steps for each of these sensor types and models to provide a list of representative values which could be transferred into the corresponding IFC sensor element property list entries. The details of these steps can vary to a significant degree, hence only a very general description of the processing steps can be outlined. The sensor processing steps become even more complex when a high rate of data acquisition is involved where automation of measurement recording, transfer and storing is needed.

These are the main reason why we have limited our description of sensor processing steps in this final chapter to a selected subset of examples which cover the aspects of displacement and deformation analysis. Despite the existence of several sensor models, the post-processing output (i. e. representative values) from these sensors is basically the same. Furthermore, typically these sensors have low measurement acquisition rate since the measurement process is usually carried out manually. In the following sections, for each of the three sensor representation types, one example will be presented in terms of basic processing steps and the estimation of representative values.

8.1 Point type

In Deliverable D 2.1 geometric levelling was presented to enable the determination of point elevations. This geodetic method measures height differences among a network of well-defined and stabilized points. These height differences represent the raw measurements which are used for the estimation of point elevations with respect to a predefined origin. The origin elevation point is located on a solid ground and is assumed to be stable.

Once the height difference measurements are obtained, these constitute the basis for the least squares adjustment calculus, a process well-known and described in detail in the existing literature (e. g. [5]). The main purpose of this process is to estimate point elevations and their corresponding precision values (i. e. standard deviations) which are to be treated as the representative values for the import into the BIM model. The following diagram in Figure 10 indicates the basic steps of this estimation process.

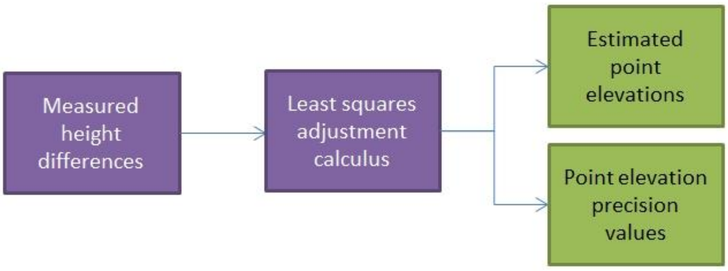

Figure 10 Representative values in the form of point elevations and precision values

In Table 3 an example of a list of estimated elevation points is shown.

Table 3. Representative values of the geometric levelling method

Point name	Elevation [m]	Standard deviation of elevation [mm]
1	348.8976	0.2
2	345.7789	0.3
3	344.9682	0.3
4	330.9546	0.2

In a series of consecutive geometric levelling field campaigns when the elevation differences are calculated, the precision values provide an important factor in the displacement analysis. Only by knowing the precision values it is possible to separate the measurement errors (noise) from the actual movements of these elevation points. The results presented in Table 3 should in the next step be transferred to the BIM model.

8.2 Network type sensors

In this section the tape extensometer measurements will be presented. These form the basis for local directional tunnel tube deformation analysis. The method provides only relative deformation readings with respect to the fixed endpoints on either side of the tunnel tube. With this method the deformations are monitored by directly measuring small changes in the distance between opposite walls. Readout is provided electronically via a front panel LCD (Figure 11).

Figure 11 Tape extensometer measuring equipment

The readings are carried out several times at each location in each field campaign whereby measuring also temperature in order to apply the change in length of the tape due to temperature. The average reading and standard deviation represent the final field campaign results at a particular location. When combining results from several consecutive campaigns, the results may be presented as a series of readings (usually in millimetres) indicating the level of deformation with respect to time. This means that for each measurement campaign the final output of this method is in the form (Point Name, time of acquisition, deformation in [mm] and standard deviation of deformation in [mm]).

8.3 Surface type sensors

Laser scanning is inherently a surface-wise measurement method due to the ability of dense sampling of the surface under investigation. When employing laser scanning to displacement and deformation analysis one needs to consider only a static, ground based, version since this is the only way to satisfy the high precision standards required.

The methodology to carry out a high precision terrestrial laser scanning (TLS) survey has been around for some time (see an example in [6]). In general, the steps of data processing can be summarized by the following diagram shown in Figure 12.

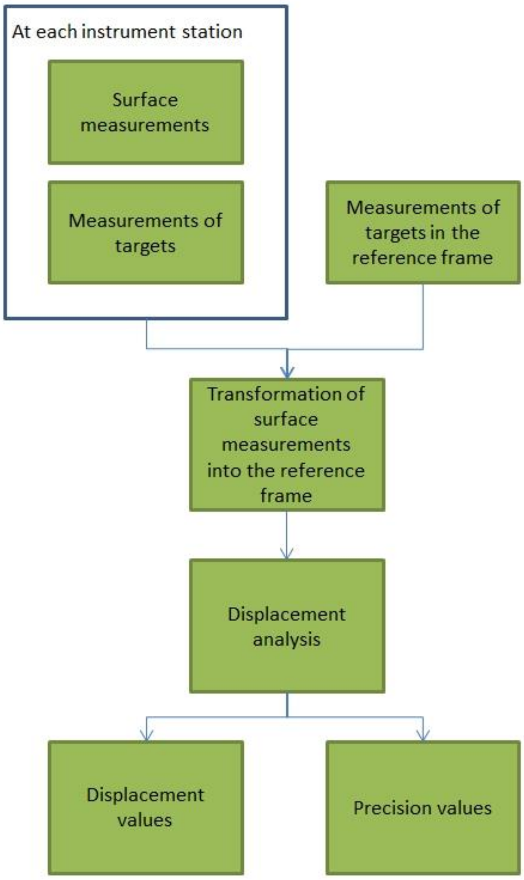

Figure 12 TLS data processing steps

As indicated in Figure 12, the connection (i. e. transformation) of TLS surface measurements with the reference points (reference frame) is usually achieved by special TLS targets which have coordinates known in:

- the instrument's internal coordinate system for each scanner station and
- the coordinate system of the reference frame (this is typically performed by total station measurements of the targets involved).

Once the individual station point clouds were transformed into the reference frame, the subsequent deformation analysis includes:

- the point clouds of the surfaces involved in the deformation analysis are extracted from the background;
- the resulting point clouds are divided into smaller (usually 10-20 cm) sized patches arranged in a regular, gridded pattern;
- for each surface patch with estimated reference normal vectors the distance along these reference vector directions is calculated for two consecutive scanning campaigns.

By following the above presented steps it is possible to obtain a type of result which has the following information (for each TLS patch):

- patch ID,
- x, y and z coordinates of the patch centroid in the reference frame,
- displacement value (in [mm]),
- precision value of the displacement (in [mm]).

As indicated in Section 7.3 such laser scanning survey results can be attached to individual IFC surface patches (see Figure 8) as long as these are not smaller than patches coming from the TLS analysis. Probably the most likely scenario is that the IFC patches will be much larger so a generalization of TLS analysis results will have to be involved. This means that for each IFC patch the displacement values (and precision parameters) will be calculated from many TLS patches. Hence, the representative values for each IFC patch will contain some averaged values, maybe with additional maximum and minimum values.

Finally, such TLS deformation results can be presented in a rasterized form which means that through external links present in the IFC patch property lists the original TLS deformation results can be obtained. To perform this final step one additional transformation will probably be needed in order to connect the TLS patches (located in the reference frame) with the IFC patches located within the BIM model coordinate frame.

9. Alternative approaches

This section will explore in some detail an alternative sensor data representation approach which seems reasonable in cases with a lot of overlapping sensor datasets. In all so-far described three representation models, the sensor infrastructure with its datasets is added as a separate layer to the already existing BIM model. This means adding sensor elements (with corresponding outputs) onto the model (see sections 7.1 and 7.2) or preparing the BIM model so that it can accommodate even surface-wise sensor technologies (section 7.3). These three approaches may all become somewhat disadvantageous when:

- a large number of sensors get involved (or large number of surface patches).
- The sensors operate autonomously with near real time measurement readings.

In such cases the BIM model may become an oversaturated repository of elements representing point or network type sensors or surface patches (based on division resolution). The SHM analysis and forecast could become even more difficult, complex and laborious if the sensor data integration rate (based the sensor integration module inside a BIM software) into the BIM model gets higher and higher.

To avoid this scenario the alternative approach (to the ones described in section 7) would be to avoid adding sensors as a separate layer group but to include only their output (i. e. sensor representative values) directly into the property sets of the already existing BIM model elements. Once these individual sensor representative values are stored for each BIM model element, some kind of performance indicators (PI) could be calculated for each existing element. These individual element PIs could further be used to estimate key performance indicators for the entire structure (e. g. bridge or tunnel). In this scenario, the best way would probably be to have a two-level structure, such as:

- a general level (for the BIM model as a whole) and
- an individual BIM model element level.

At the general level, the estimated KPIs would cover aspects such as safety, reliability, functionality, economical aspect etc. On the other hand, on a local element level the PIs would be more closely connected to sensor results so that in case of some kind of malfunctioning the problems could faster be isolated and resolved. Following this scenario, the direct visualization of any larger number of sensor datasets could completely be avoided with color-coding simply indicating which BIM elements are potentially problematic from the sensor measurement perspective.

The methodologies for calculating KPIs for various structures (tunnels, bridges) are inherently somewhat different due to the character of these structure themselves. However, in the future with BIM models covering also the monitoring phase of the structures lifecycle and including many different sensors such an approach would be more than welcoming. This way the sensor data aspect and the engineering interpretation of this data are separated which leaves more space for fine-tuning of both of these aspects during the sensor-to-BIM implementation phase.

10. Conclusions

This report outlines three different approaches for integrating and visualizing sensor data (actually representative values estimated from the raw sensor output) within the BIM/IFC environment. These approaches were established following simple guidelines:

- of being able to incorporate any new sensor available on the market regardless of its design or measurement principle.
- These approaches exploit a well-defined and a standardized BIM format, namely the IFC, which enables a transparent BIM model exchange process.
- The BIM model and the sensor raw output are separated in terms of where the data is stored.
- The full sensor data scope can be obtained through external links to avoid oversaturating the BIM model with sensor data.

Once the link between sensor data and the BIM model is established the interpretation can take place. This final step may be carried out in two different ways, i. e.:

- by employing some kind of color-coding scheme where particular (maybe even user selected) sensor representative values stored within sensor element property lists are coloured according to predefined threshold values.
- The color-coding is augmented by the introduction of PIs and KPIs as described in chapter 9.

Augmenting the visualization of sensor data in the BIM software with (key)performance indicators seems reasonable when the methodologies for their calculation are well-defined with results shared and understood by different parties involved in the monitoring and even asset management process. Again in this case the design and preparation of such methodologies is restricted to experts whereas the BIM software provides functionalities for their integration (e. g. in the form of additional modules, APIs etc.). The software should also include automatically generated alerts coming from sensors with measures out of the normal working range, indicating problems (e.g. safety and security elements for emergencies or structural problems).

Finally, the introduction of these performance indicators is welcoming when many sensors are involved with fast sensors data-to-BIM sensor element refresh rates. Since the introduction and implementation of sensor infrastructure into the BIM environment is currently a topic under much research and development, it is not yet clear which representation options will be most favourable. However, we assume some time in the future with more and more complex sensors involved automation in the SHM interpretation aspect may have to be included within the available BIM software.

11. References

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