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BIM-based Cultural Heritage Asset Management Tool. Innovative Solution to Orient the Preservation and Valorization of Historic Buildings

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ABSTRACT

Digital technologies are more and more needed to give access to Cultural Heritage (CH) and to allow for their curation and re-use. For this reason, it is necessary to increase the knowledge on the CH building stock to support sustainable maintenance, preservation and revitalization strategies through the development of user-friendly asset management tools to support the decision-making process towards an affordable and feasible conservation strategy. The Asset Management tool described in this paper is a software solution used for condition assessment on–site and management of assets with embedded Building Information Model (BIM) software. The main aim of the tool is to leverage the existing data in BIM to expedite and enhance the quality of building inspections. The solution provides the possibility to not only asses the condition in a professional way, but also to optimize the conservation maintenance planning according to different ambition levels and needs. A well elaborated and used standard for Condition Assessment is integrated and tailored on Cultural Heritage within the framework of H2020-INCEPTION project. In this context, the CH Asset Management (CH AM tool) is regarded mainly within the framework of decision-making for restoration, conservation and maintenance of historic buildings.

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Asset management; BIM; condition assessment; conservation plan; preventive maintenance

1. Introduction

Cultural heritage is a non-renewable, irreplaceable resource and a common good, but is frequently under threat from environmental challenges and climate change, disaster risks, neglect, decay and under-funding. *[https://ec.europa.eu/research/environment/index.cfm?pg=cultural]*

Several historical European Cultural Heritage sites are showing the status of the introduced hazards. To this end, the importance of building maintenance for conservation (Worthing, Dann, and Bond 2002) is well recognised and has been embedded into nearly all building conservation legislative frameworks and charters (e.g. the Venice Charter).

It is obvious the importance of coherent management of the Cultural Heritage assets in order to transfer its history to present and future generations. Despite this, preservation, maintenance (Straub 2003) and reuse of the Cultural Heritage is a complex challenge in consideration of the several and complementary aspects which play a crucial role (economic; social; historic; architectural/structural/technical; safety/security) in the decision-making process. Furthermore, it is not simple and sometimes not well harmonized, the cooperation of several experts involved in the process as architects, engineering, chemists, archaeologists, historians, owners, authorities and technical specialists. For this reason, it is important that any decision-making process on Cultural Heritage is based on collective learning among different actors, involving compromise as a crucial step in the process (Turk et al. 2019).

A cultural heritage conservation project relies on two linked aspects, the identification of historical and architectural values of the building and the evaluation of its physical consistency, both addressing conservation decisions (Simeone, Cursi, and Acierno 2019).

Decision on methods and intervention typologies is strictly depending on the conservation state of the Cultural Heritage asset (Osello, Lucibello, and Morgagni 2018).

The Cultural Heritage inspection and assessment program (Forster and Kayan 2009) become therefore significant in order to define possible re-use, maintenance and preventive decay interventions or to detect and predetermine building faults. From the technological point of view and material consistence, previous research has pointed out that regular inspection activities propose several advantages, such as preventive identification of emerging risk situation (Romãoa,

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Paupério, and Pereiraa 2016); improvement and updating of the maintenance plan and maintenance program; constant upgrading of the building knowledge including owners' feedback, it is cost-effective and is also the least destructive approach to conservation.

Inspection activities consist of structured monitoring actions on the construction or archaeological asset. Control activities consist mainly of inspection visits necessary for assessing the state of conservation of historical artefacts and archaeological sites, for identification of the most obvious critical points, and for verification of access and suitability for inspection. The information produced by the inspection must be accessible, shared and searchable through a specific database that can be implemented and integrated, and able to incorporate all the information that will be generated during the next planned maintenance or restoration (Cecchi and Gasparoli 2012; Tiano et al. 2019). Understanding of the material evidence of built cultural heritage and the information on its current state is important as it helps to specify measures necessary to preserve structures in an appropriate condition and ensure that the maintenance required to keep them at this level is well defined.

In this context, it is very necessary to increase the knowledge on the built cultural heritage stock to support sustainable maintenance and make valuable decisions regarding preservation and revitalization strategies. To this end, the development of user-friendly asset management tools (Al-Geendy, Osman, and Taha 2012) will enhance the understanding of possible and necessary (preventive) measures (Sánchez, Pontes, and López 2018), thus endorsing the decision-making process.

This paper presents a desktop (off-site) and mobile (on-site) application—conceived as an Asset Management Tool—developed within the INCEPTION project. This application equips the stakeholders involved in CH preservation with cost- and time-effective instruments for condition assessment (through condition survey), asset management, rehabilitation and maintenance planning of heritage assets. In fact, the project creates an inclusive understanding of European built CH across different disciplines using a set of relevant IT technologies and serving various business sectors and different stakeholders.

The Horizon 2020 INCEPTION project—Inclusive Cultural Heritage in Europe through 3D semantic modelling, is focused on innovation in 3D modelling of cultural heritage through an inclusive approach for time-dynamic 3D reconstruction of built and social environments.

The main aims are:

- to create an inclusive understanding of European cultural identity and diversity by stimulating and facilitating collaborations across disciplines, technologies and sectors;
- to develop cost-effective procedures and enhancements for on-site 3D survey and reconstruction of cultural heritage artefacts, buildings, sites and social environments;
- to develop an open-standard Semantic Web platform for accessing, processing and sharing interoperable digital models resulting from 3D survey and data capturing.

Other complementary objectives that characterize the project include the development of new methods and tools for condition assessment of cultural heritage based on predictive analysis (diagnostic, conservative, morphometric), non-destructive procedures (thermal imaging, level of reflectivity, integrated sensors, spectrophotometry, sonic surveys, etc.) and supported by economically sustainable technologies and devices.

In order to accomplish the expected aims the consortium partnership, which involved 14 partners from 10 European countries coordinated by the University of Ferrara—Department of Architecture, has defined a detailed workflow consisting of five main actions (Figure 1):

(1) the definition of a common framework for catalogue methodology, by mapping the stakeholder' knowledge demands;
(2) the development of an advanced integrated 3D data capturing;
(3) the identification of the CH buildings semantic ontology and data structure for information catalogue and modelling in Heritage-BIM environment, based on Open BIM standard;
(4) the implementation of the INCEPTION Semantic Web Platform;
(5) Deployment and valorization of 3D heritage models, to enable the sharing and enrichment of the information and interpretation of the models by users.

The main expected result of the project is represented by the Semantic Web Platform and additional application tools. Purpose of the platform is developing, collecting and sharing interoperable 3D semantic models "forever", "for everybody", "from everywhere". During the project's duration, the platform will be tested with several demonstration cases proposed by a dedicated stakeholder panel.

The Semantic Web Platform and tools are based on the development of a BIM model of the Cultural Heritage. The BIM model could be created with different software but, in order to guarantee to all end users of the platform

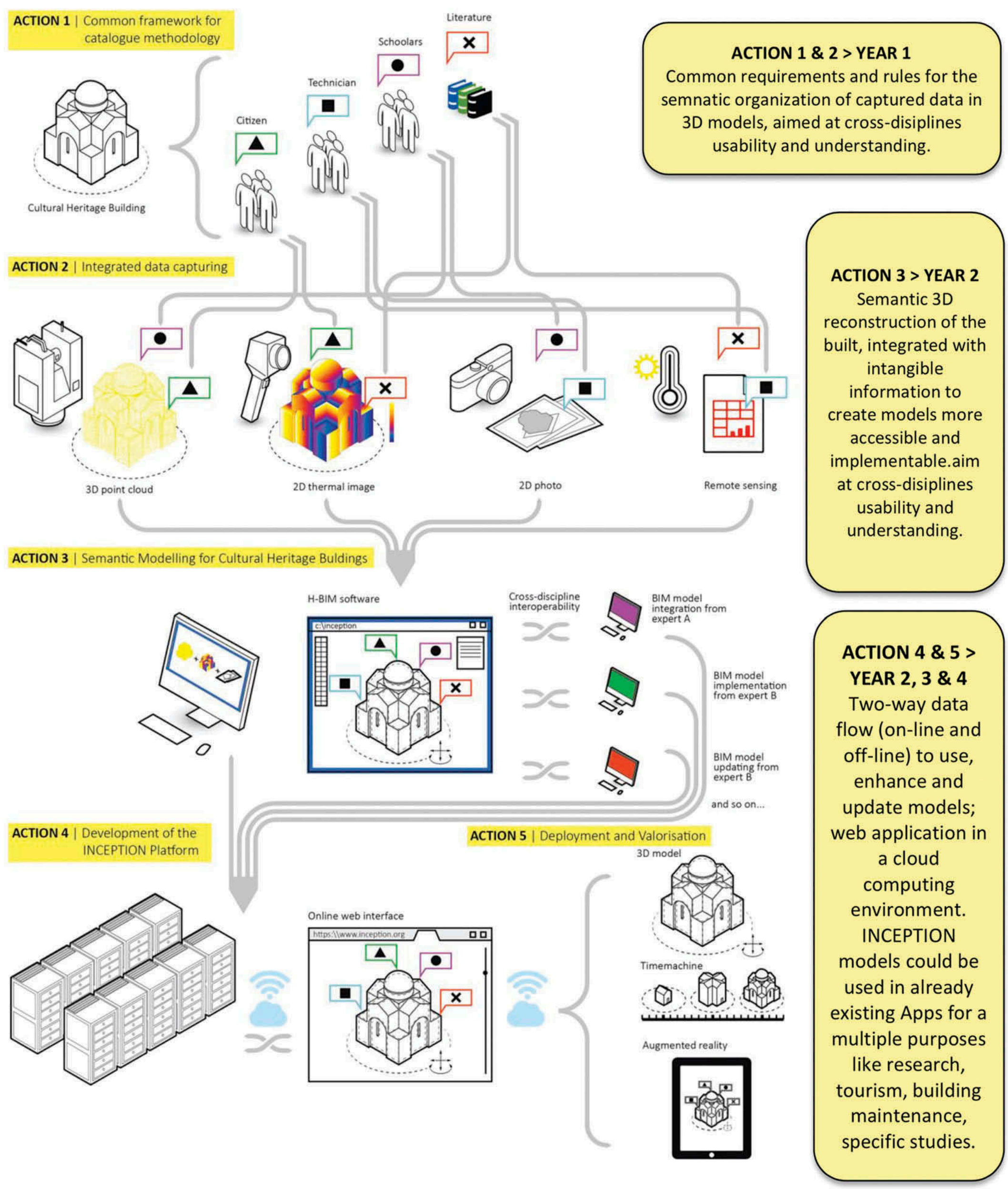

Figure 1. Action scheme.

the enriching of the models with new semantic metadata, new data and attachments, will be uploaded on the platform as open standard: IFC files.

The platform offers the opportunity to manage contents, such as single elements of a building, to visualize different historic phases, store data of previous interventions and links with external databases to increase the quality of reliable information. The possibility to share and make available documents linked to the geometric 3D model and the capacity to download 3D models with different scales of detail are very relevant tools supporting diagnostic procedures.

This could be particularly relevant to foster the use of 3D models for diagnostic procedures and as a very efficient assessment and decision-making tool. Digital data can be used to manage dimensional analysis of the buildings or sites, typological analysis, technological analysis and material assessment to determine the current condition (typical materials and structures and their damage) and state of conservation, technical solutions for preservation and overall maintenance planning (Di Giulio, Maietti, and Piaia 2019).

2. Background development of asset management tool

As introduced, in order to support technical stakeholders in Cultural Heritage sector, the INCEPTION platform is enriched with additional complementary tools as the dedicated BIM-based Cultural Heritage Asset Management (CH AM) tool developed by the Dutch company, DEMO Consultants B.V. as a partner in the project.

This tool offers advantages in the framework of decision-making for restoration, conservation and maintenance of historic buildings by collecting, structuring, analysing and disclosing data related to the buildings and their surroundings. The CH AM tool is usable both on-site as mobile application and off-site as desktop software.

The starting point and basis for the CH AM tool development was the existing commercial software tool for real estate asset management developed by DEMO Consultants B.V.—RE Suite, applied daily in the process of condition assessment and maintenance planning. Through research in the INCEPTION project, this software solution was enhanced and extended with the purpose of:

- facilitating the utilisation of 3D semantic BIM dedicated to historic buildings and their specific characteristics;
- supporting the required on-site technical assessment and off-site analysis to determine the actual condition of the historic buildings; and
- enhancing the understanding of possible and necessary measures for the historic buildings, including the implications of these measures in relation to technical risks, monument protection regulations, cost management, and socio-functional building performance.

To this end, the physical scope of the CH AM in the built environment can take a multi-scale approach as illustrated below:

- Scale 1: CH asset portfolio;
- Scale 2: CH site;
- Scale 3: Monument and Historic building.

For a better understanding of this approach, see here below the example of UNESCO World Heritage Kinderdijk-Elshout in the Netherlands (Figure 2).

Besides the "physical scope" of CH to be addressed by the CH AM tool, attention should be given to the types of users and their roles in CH AM. The main scope of CH asset is to face different user applications to fulfil their requirements.

One of the most relevant use of the 3D models is related to condition assessment: "integral narratives" linked to 3D models include applications for technicians, site managers and local authorities dealing with technical and financial information related to the state of conservations, structural condition, maintenance,

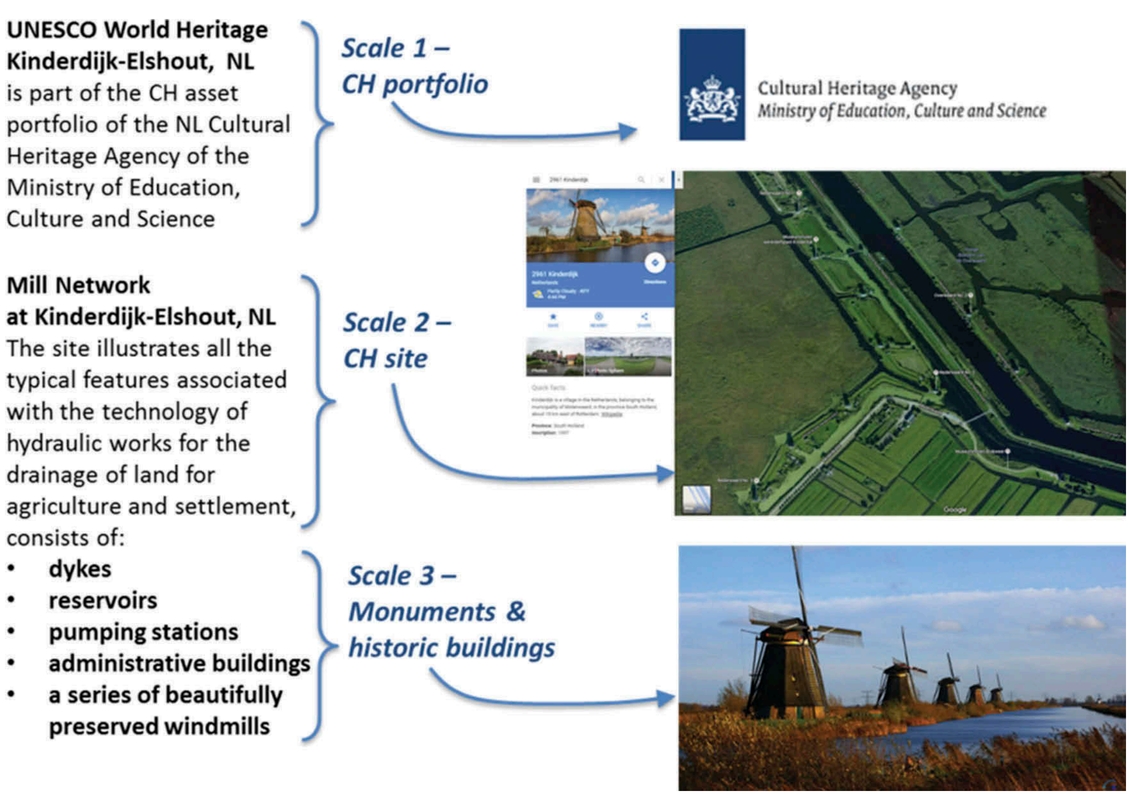

Figure 2. CH Multi-scale approach.

restoration, refurbishment, etc. Therefore, technical condition assessment and asset management is one of the added-values of the advanced 3D models, in addition to multiple purposes related to enhancement, semantic integration, cross-disciplinary researches, educations, etc.

2.1. Maintenance policy and existing procedures for built heritage

Historic buildings' preservation requires a knowledge-based background of its current state and previous interventions in order to support proper decision-making concerning compatible conservation materials and interventions. Documentation of a historic building's current condition should include materials characterization, decay and damage diagnosis with the use of non-destructive procedures. For this aim, the assessment of the actual condition of the buildings is an essential part of preventive maintenance and asset management.

Although maintenance is recognised as being fundamentally good for conservation, this is not yet reflected in current international policies. Maintenance policy is generally poorly integrated, with a lack of leadership and deviations from procedural systems (Dann and Cantell 2007). The existing approaches for inspection, diagnosis, monitoring and curative conservation are often intermittent, unplanned, overpriced and lack a methodical strategy.

One of the most successful implementations of national policies supportive of preventive maintenance is to be found in the Nordic countries. In the Netherlands, for instance, the process of condition assessment has been standardised in 2002 into the national framework, namely, the Dutch Standard (Straub 2009) for Condition assessment of buildings and infrastructural assets, NEN 2767. The aim of this standard is an objective assessment of the technical quality of building components, to provide property managers with unambiguous, reliable information about the technical status based on assessed defects using a 6-point scale.

During research within the INCEPTION project, an investigation has been conducted to verify the compatibility of this norm to available European standards for CH condition survey. One of the first adopted references during the AM tool development has been the EU-CHIC project (http://www.euchic.eu/), which proposed several categories for built heritage condition assessment:

- Building Pathology (Watt 2007);
- Surveying historic buildings (Watt and Swallow 2007);
- Conservation of Historic Buildings.

Further investigation considered in particular the CEN EN 16,096:2012: *Conservation of cultural property—Condition survey and report of built cultural heritage*. This European Standard provides guidelines for a condition survey of built cultural heritage. It states how the condition of the built cultural heritage should be assessed, documented, recorded and reported on. It encompasses evaluation of the condition of a building or other structure mainly by visual observation, together—when necessary—with simple measurements. The relevant data and documentation on the built cultural heritage should be collected and included in the report. This European Standard can be applied to all built cultural heritage such as buildings, ruins, bridges and other standing structures and applies a 4-point scale for defect assessment.

2.2. Condition assessment of buildings and infrastructure

The existing DEMO RE Suite, maintenance tool was developed and configured in the context of 'surveying historic buildings' having as basis the abovementioned Dutch Standard for Condition assessment of buildings and infrastructural assets, NEN 2767. This standard differs from the abovementioned European norm for condition assessment of built heritage as this gives a worked out, objective method with which a condition score can be calculated instead of more global and subjective descriptions given in the EU norms. At the same time, there are also relevant similarities to the CH standards with respect to surveying methods and maintenance planning that have been considered.

One of the other reasons justifying the choice for the Dutch NEN 2767 is that on international level it is expected that this survey method will be the standard for the whole of Europe. This is the result of last few years development of the norm within the context of in-depth research funded by the European Commission and conducted by a dedicated international consortium (i.e. EU project "Condition Assessment of Buildings and Building Components") which has defined clear directions for an effective and efficient condition assessment that can be easily adjusted for application in other European countries. As we speak, the CEN (European Committee for Standardization) is planning to realise a Technical Specification (TS) "CEN/TS 17,385;2019 Method for condition assessment of immobile constructed assets" that describes a methodology to carry out a physical condition assessment. The TS will describe an objective inspection method, which is usable for the determination of the technical condition of assets in a uniform way. The final version of this TS will be published at the end of 2019. This methodology is based on and has great similarity (i.e. in fact is it is the same method with some added texts for clarification) to the Dutch standard for Condition assessment of buildings and infrastructural assets, NEN 2767.

In practice, the condition assessment process according to NEN 2767 starts with locating defects in building components. Subsequently, the inspector assesses the following defect parameters: severity/seriousness of defects, intensity of defects and extent of defects as listed hereunder (Table 1):

The combination of these parameters gives the condition score of the building components (Table 2):

The methodology can be explained referring to the following example of defect classification of brickwork (Figure 3):

The methodology standardising the classification of defects to measure the physical quality of building components/buildings objectively and uniformly is the essence of condition assessment to provide insight into the maintenance condition of building components/buildings, to be used as a basis for determining maintenance costs and repair prioritisation and to enable better management and control of maintenance work on the building stock.

2.3. Maintenance planning

Condition scores can be used can be to formulate performance levels (or maintenance levels) to implement a desired differentiation of the technical quality of buildings. Varying performance levels is advisable in the case of a diverse portfolio and if the maintenance management system easily provides possibilities to do so. Formulating maintenance performance levels in planned maintenance involves deliberation about maximum performance loss, appropriate maintenance activities and the available financial means. Maintenance activities can be distinguished according to type (cleaning, repair and replacement), the part of the building component to which a

rehabilitation activity applies, the specification of materials, the quantity of the work, the frequency of short cyclical preventive maintenance actions and the nature of an activity (preventive or corrective). Maintenance or performance levels can be based on

Table 1.

Seriousness[1]	Intensity[2]	Extent
• Minor (esthetical) • Serious (degradation) • Critical (malfunction)	• Starting (hardly noticeable) • Progressing (clearly noticeable) • Developed (obvious)	• Incidental (<2%) • Partial (2-10%) • Regular (10-30%) • Frequent (30-70%) • General (≥70%)

[1]In the latest version of the CEN/TS 17,385;2019 the term 'severity' is used instead of seriousness.
[2]In the latest version of the CEN/TS 17385;2019 the term 'degradation level' is used instead of Intensity.

Table 2. Condition scores.

Condition score & Description		Condition state
1	Very good condition	Occasional minor defects
2	Good condition	Occasional signs of ageing
3	Reasonable condition	Localised visible ageing, components functionality not at risk
4	Borderline condition	Component functionality occasionally at risk
5	Bad condition	Ageing condition is irreversible
6	Very bad condition	Technical state for replacement/ demolition

the demanded minimum condition of building components after executing maintenance work.

An important sub-process of maintenance planning is prioritising maintenance work. Normally, maintenance work needed to secure safety performance has precedence over work just for aesthetic or sustainable reasons. The Dutch Government Buildings Agency uses arisk-priority matrix in tuning the annual maintenance stock for the available budget. The matrix (Figure 4) has been included as anon-standard appendix to the standard. By using the risk-priority matrix insight is given into the effect on different aspects when not repairing adefect.

Within the context of cultural heritage (Thurley et al. 2015), the risk parameter Cultural Value which describes the cultural importance of the assessed building components is critical. This aspect concerns situations where properties with an art-historical or architectural value are at risk of being lost if the defect is not remedied on a short term. The effects of not remedying defects are expressed on a 3-point scale, distinguishing between slight effect (1), moderate effects (2) and strong effect (3).In the light of the above-described investigation and the found compatibility of the Dutch NEN 2767 (Dann and Steel 1999) the existing DEMO RE Suite tool has been found eligible as a basis to develop the INCEPTION CH AM prototype tool at Technology Readiness Level (TRL) 6 as targeted by INCEPTION research and innovation action.

However, implementing rehabilitation measures as a result of a condition assessment on a monumental building without harming the cultural value is a complex process, but one to consider as first. To this aim, among different functionalities (described in more detail in *Results and discussion* section), a special data field has been added to the tool in order to determine the monumental value of a building component. In this respect, the following monumental labels based on existing methods on cultural value assessment (van Beers 2004) have been inserted in the tool:

(1) Highly monumental

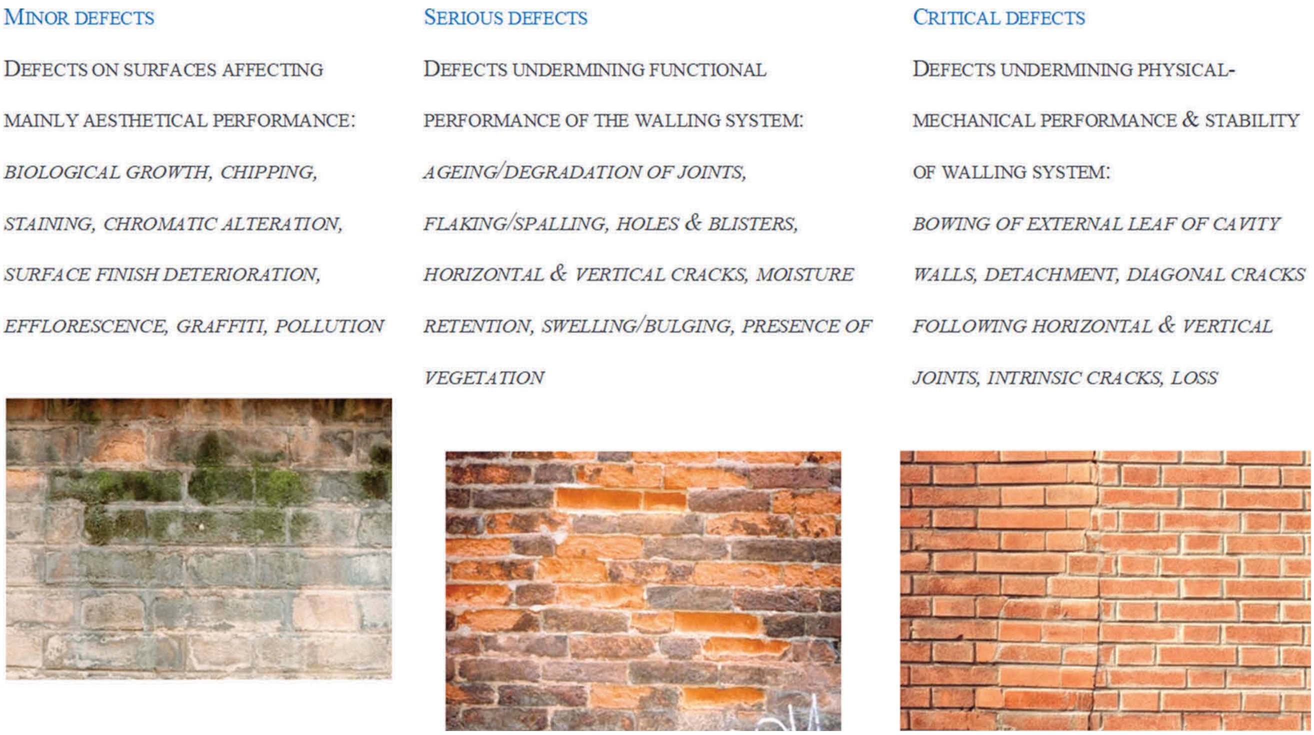

Figure 3. Classification of brickwork.

Users' safety/health (Safety)	(1)	(2)	(3)
Structural safety (Reliability)	(1)	(2)	(3)
Affected cultural heritage value (Environment)	(1)	(2)	(3)
Use and business process (Environment)	(1)	(2)	(3)
Technical consequential damage (Economics)	(1)	(2)	(3)
Increase in maintenance in response to complaints (Economics)	(1)	(2)	(3)
Perception, aesthetics (Political)	(1)	(2)	(3)

Figure 4. Risk parameters where 1 means low risk and 3 high risk.

(2) Monumental
(3) Not monumental
(4) Disturbing the monumentality
(5) Highly disturbing the monumentality

Detailed adjustment of the tool depending on the specific technical needs for CH survey (e.g. detailed assessment of certain building materials based on specific technical norms) can be accommodated in the follow-up TRL 7–8 development of the CH AM tool.

These types of new technologies and tools available allow us to create an integrated digital database able to collect dimensional data, information related to the historical structures and materials, state of conservation, diagnostic analysis and historical data, making condition assessment an overall integrated process in supporting sustainable decision strategies for conservation, restoration and enhancement of Cultural Heritage.

2.4. Conceptual workflow and software functionalities

Prior to the development of the CH AM tool, the research group has defined its expected scope and software functionalities. As result, the scope of the CH AM can be described as a software tool that provides the manager of a monumental real estate stock with insight into the current condition of objects, helps him/her define the desired condition, and provides him/her with the necessary information to make informed decisions on how to maintain the real estate stock within constraints with regards to monumentality and budget through the process of condition assessment.

Keeping the previous sections in this paper as underpinning, the workflow of the CH AM tool is further detailed and conceptualized in the form of a diagram. This diagram, and its corresponding legend, is displayed hereunder in Figure 5-6.

This section will start with an explanation of the diagram step by step using the CH AM tool as a description of the workflow. It will be followed by

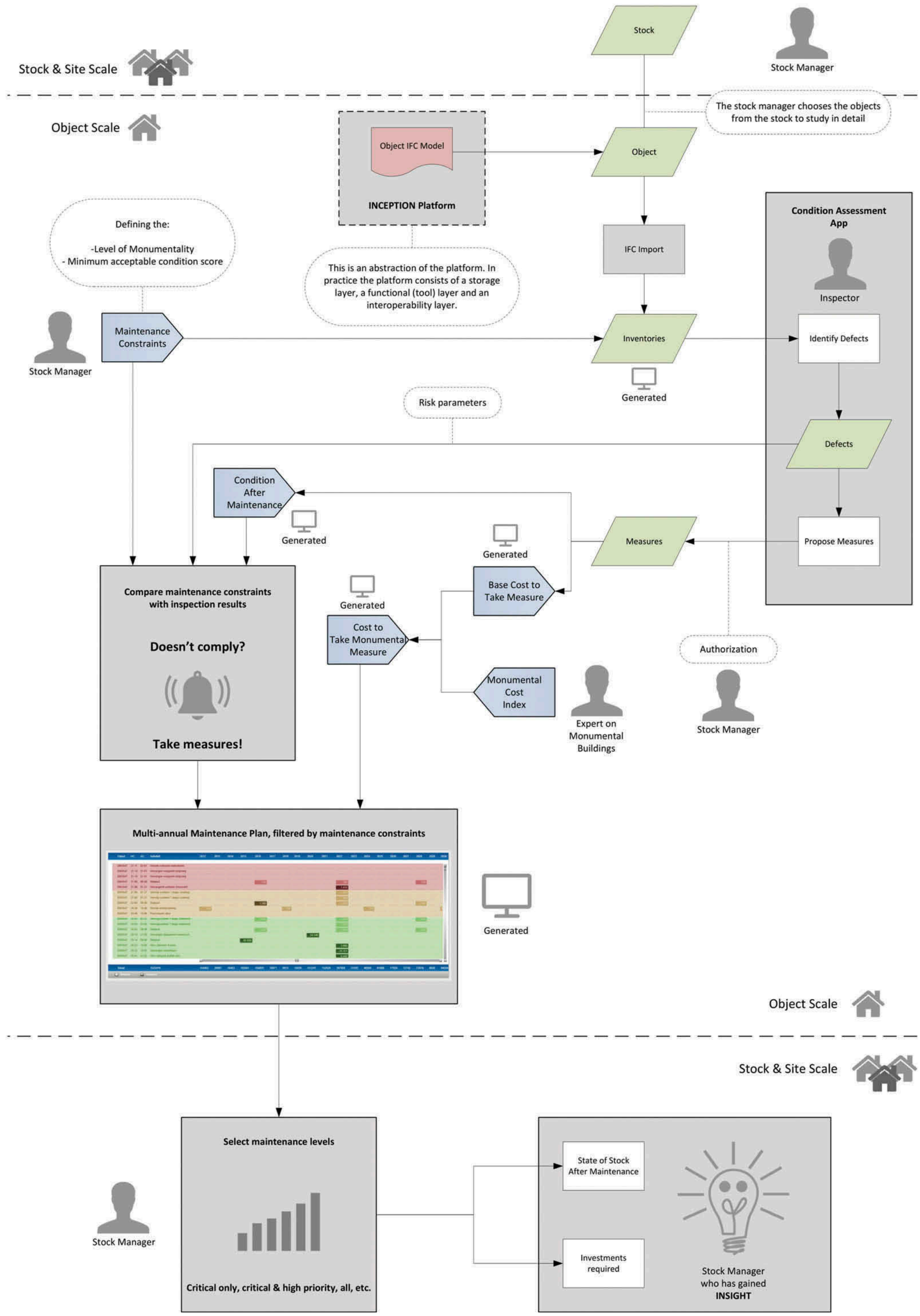

Figure 5 and 6. Diagram scheme legend CH AM Tool workflow.

a description of the implementation of the workflow in the software. Screenshots of the software are used to illustrate these processes.

3. Set up maintenance policy

- *Step 1: Creating and managing real estate objects*:

The first step in the workflow is to capture one's real estate stock in the software (data describing object in the work area; adding pictures, documentation and notes, etc.) This is done by adding real estate objects in the CH AM tool (Figure 7).

- *Step 2: Define(condition) ambition levels*:

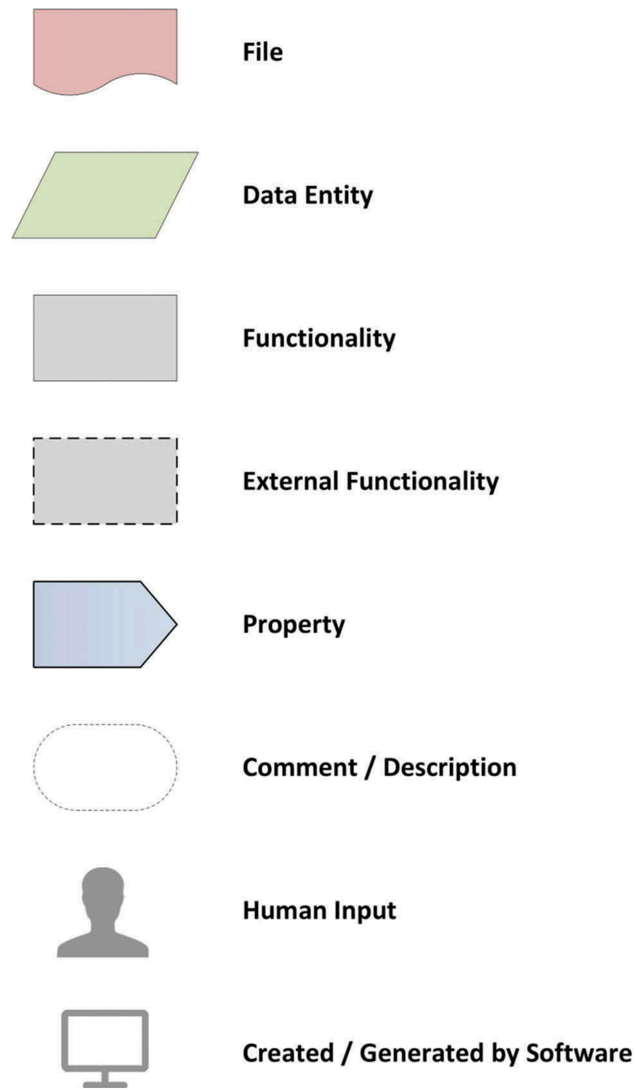

Figure 5 and 6. (Continued).

As described before, in order to make informed decisions regarding the maintenance of CH real estate objects it is important to define the (condition) ambition levels. This is done by entering a description of the maintenance level, the minimum acceptable value of risk parameters (described earlier in this paper) and the minimum acceptable condition score. (2) These values will be used to determine if a measure, defined after inspection of the object, is necessary to be taken. In the case of heritage objects, the risk parameter 'Experience and Cultural Value' is one of the main triggers to deploy rehabilitation measures (Figure 8).

- *Step 3: Assigning maintenance constraints to real estate objects*

Next, the maintenance constraint created in the previous step needs to be assigned to the real estate object created in step 1. This is done by choosing the envisioned maintenance level as defined by the owner/manager (Figure 9).

4. Inventorying

- *Step 4: Creating inventories*

After an object is created and maintenance constraints have been linked to it, it is time to create an inventory for the object. This is done in three steps:

- Importing base inventories from an IFC-model;
- Manually adding detailed inventories for other components not already included in the base inventories;

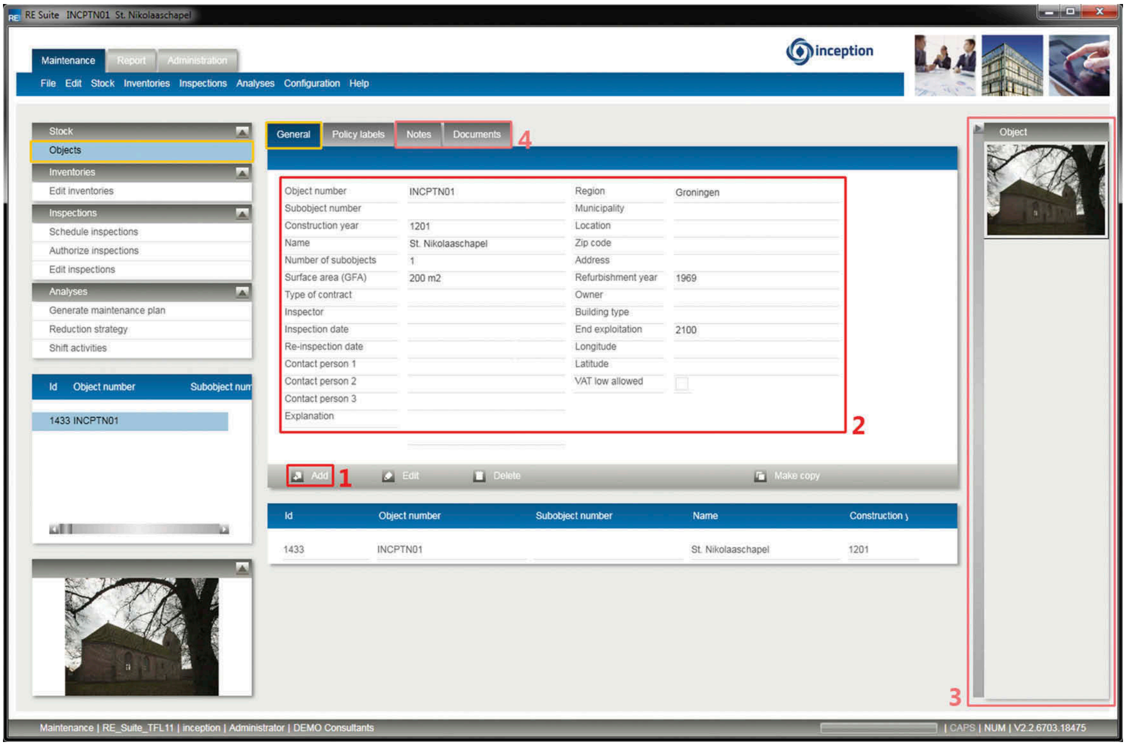

Figure 7. Creating and managing real estate objects.

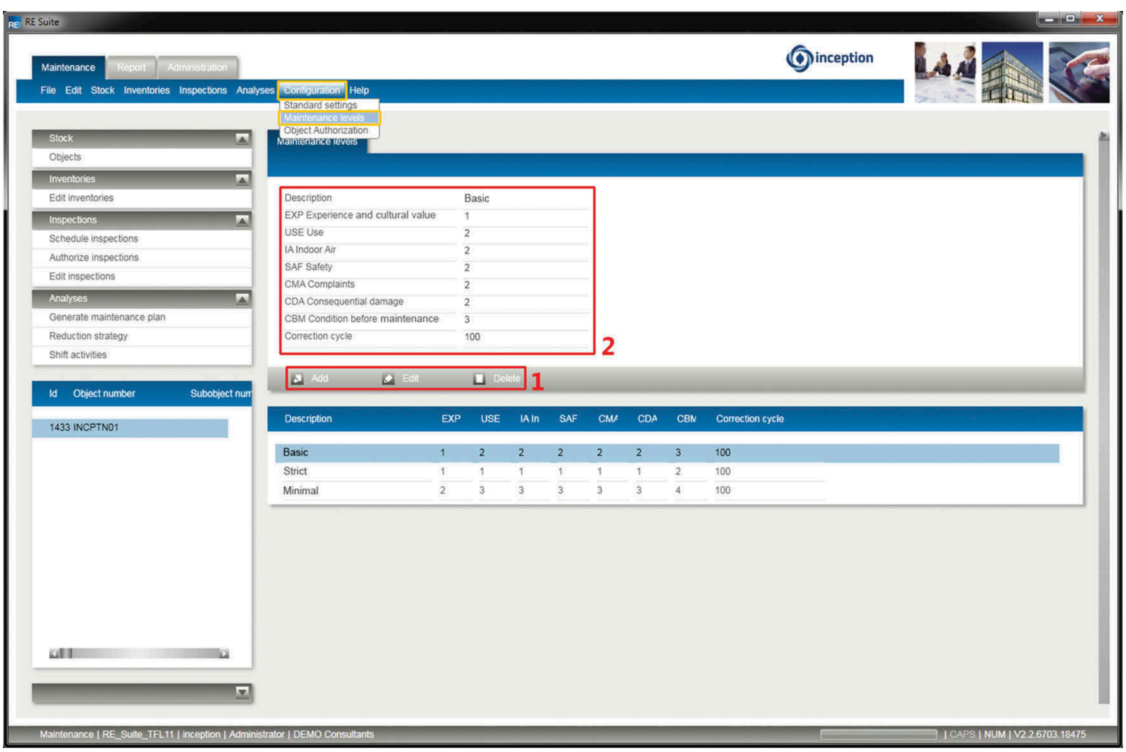

Figure 8. Managing Maintenance levels.

- Adding monumental statuses (i.e. labels) to the inventories.

To import the base inventories from an IFC-model, the tool retrieves a listing of available models from the

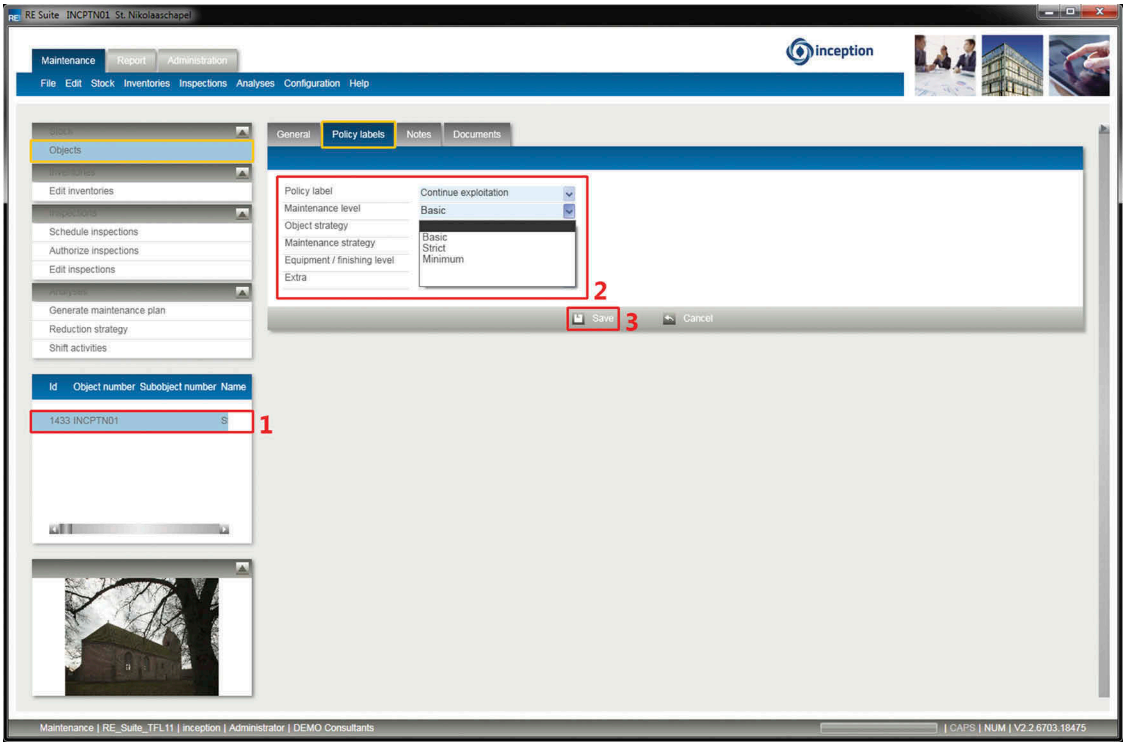

Figure 9. Assigning maintenance constraints to real estate objects.

external data source (e.g. INCEPTION platform) and imports it in the tool (Figure 10).

In addition, one can edit or add new inventories manually if these are not already in the IFC model (Figure 11).

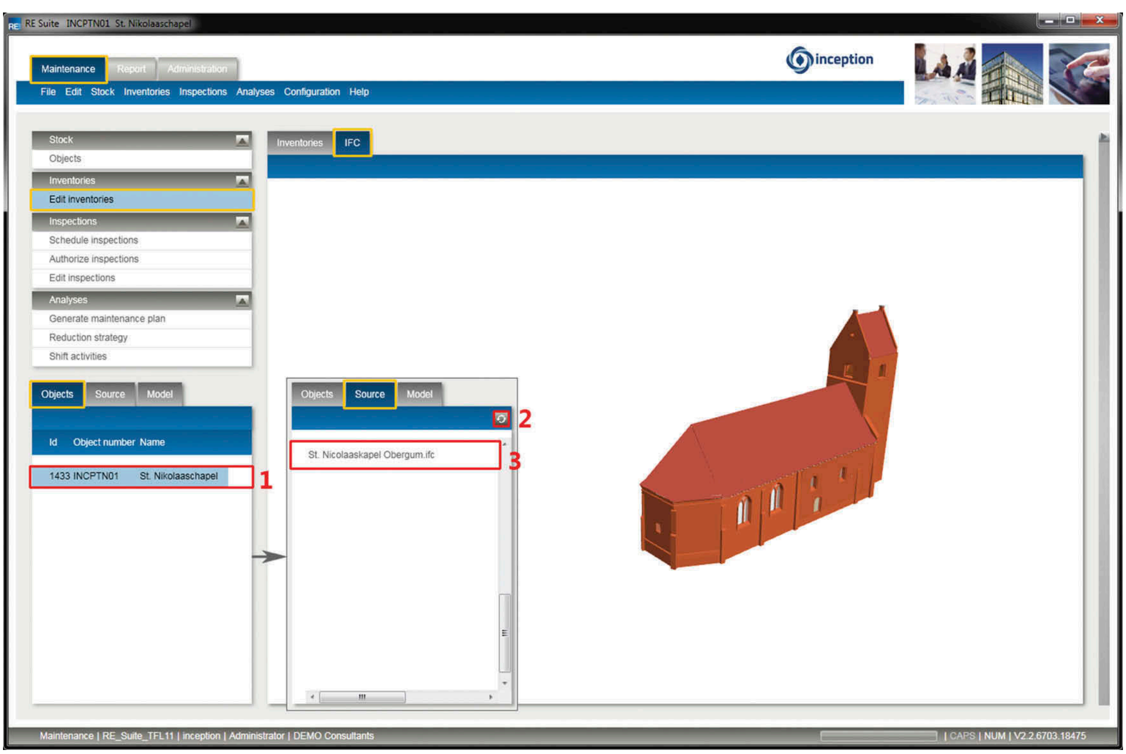

Figure 10. Importing base inventories from an IFC-model.

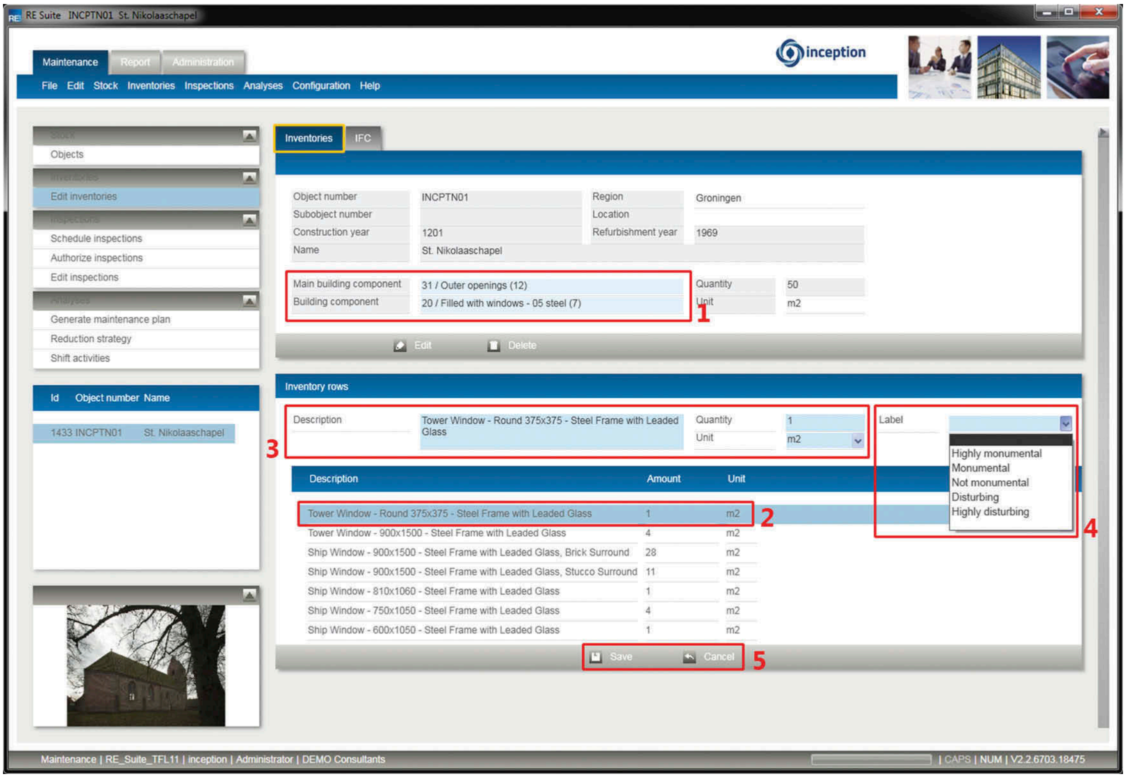

Figure 11. Editing inventories.

5. Inspection

- *Step 4: Conducting an inspection*

After an object has been inventoried and scheduled for inspection it is ready to be inspected. This is done on-site through the RE Maintenance iPad app. The inspector, broadly, follows a form (i.e. linked inventory to a specific component in the IFC file) representative for that specific heritage site and is guided through the process of condition assessment, consisting of the assessment of the technical condition and assignment of risk parameters according to the methodology set out in NEN 2767. Thus, the inspector can register (i.e. link) defects to selected components (Figure 12). When choosing the defect from the dropdown menu the inspector is being asked to state the intensity and extent of the defect from which the subsequent condition score is going to be derived (Figure 13). In addition, the inspector can also propose rehabilitation measures and activities to be undertaken, add observations and insert pictures to the inspected object. Once the inspector has conducted all inspection he/she will synchronize the results with the server and all inspection data is linked to the IFC model.

- *Step 5: Authorizing and editing inspections*

Once inspections have been conducted on-site and the inspection data have been synchronized with the server, the results of the inspection are available in the client application for the manager/supervisor to review and approval. Thus, the inspection results can be viewed, edited and authorized by the manager in charge (Figure 14). For each inspection result the following information is displayed and can be edited:

- The identified defect (A)
- The intensity and extent of the defect and the condition before maintenance (B)
- How the defect affects the risk parameters (such as Experience and Cultural Value) (C)
- The activity (if any) to be undertaken as a measure for addressing the defect (D)
- A cost correction factor (E). This can be used by an expert to offset the standard activity costs stored in a database to more accurately estimate the cost of conducting the activity.
- The condition after maintenance; the result of the measures taken to remedy the defect (F).

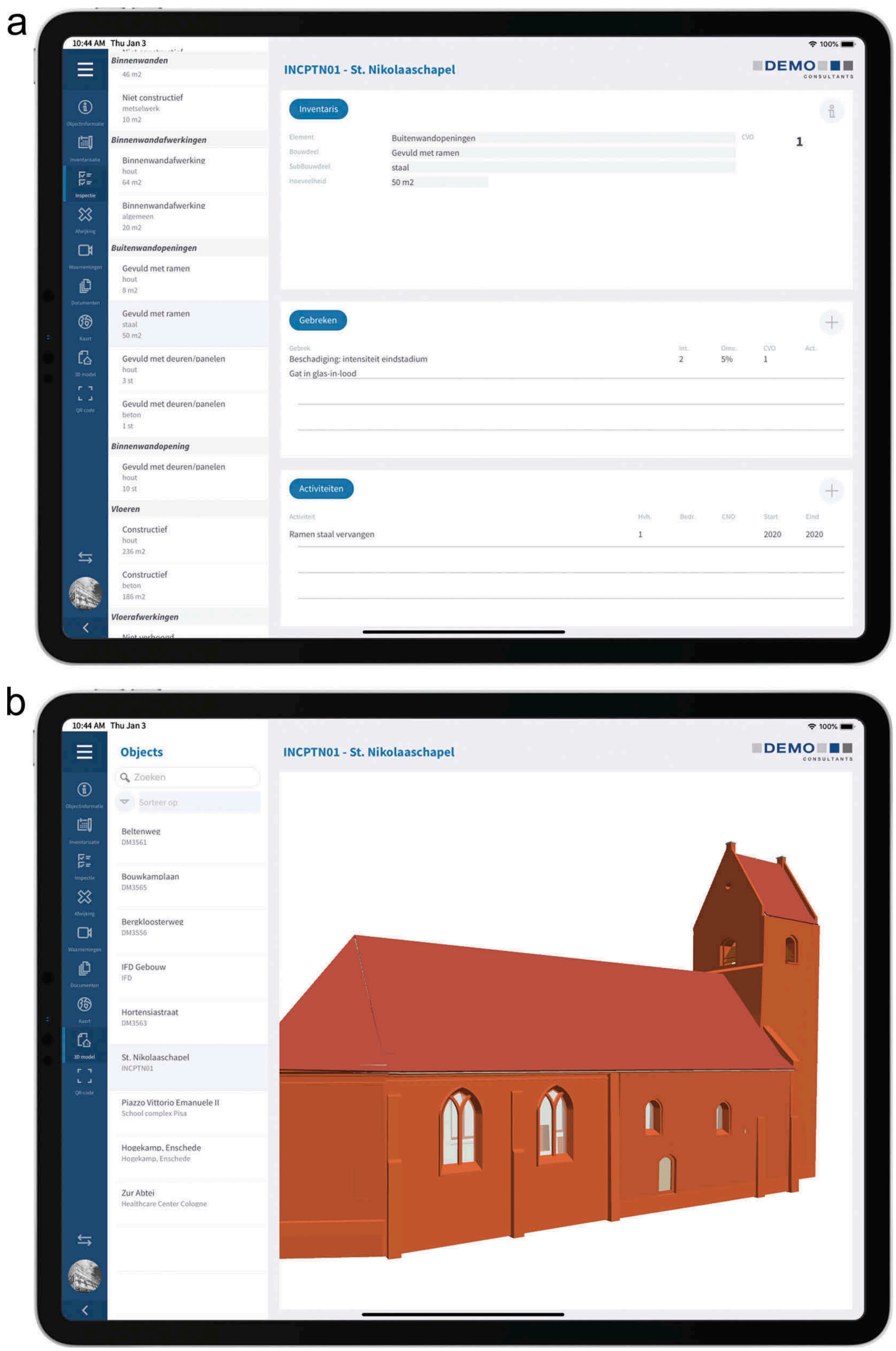

Figure 12. A) Conducting an inspection with the inspection app—linked inventory list. b) Conducting an inspection with the inspection app—IFC model on site.

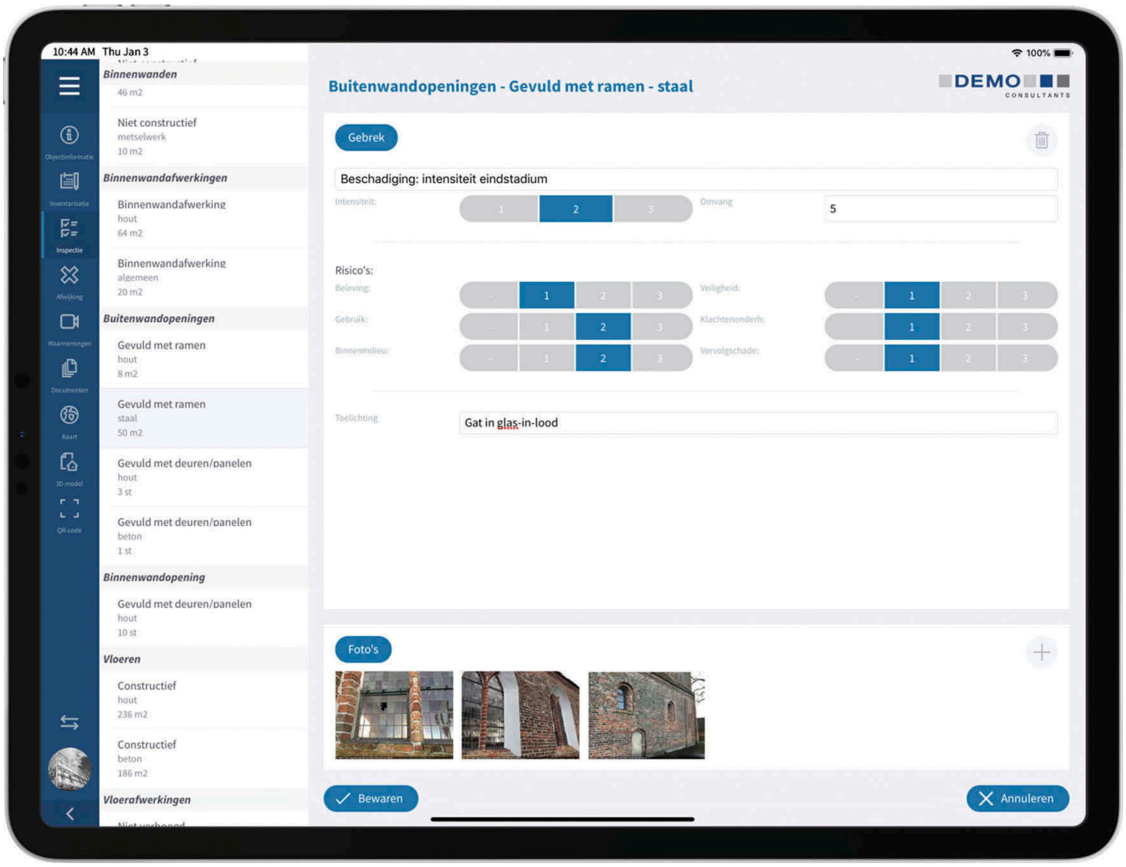

Figure 13. Conducting an inspection with the inspection app—Defect registration.

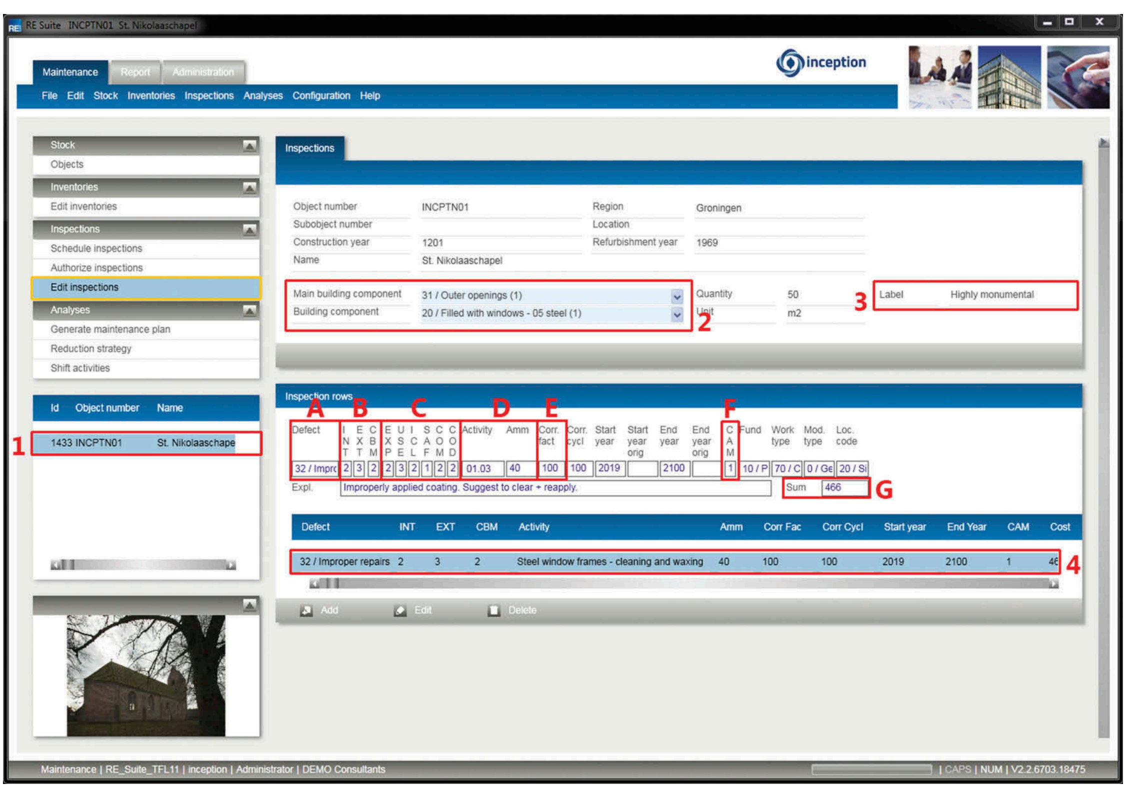

Figure 14. Authorizing and editing inspections.

- The cost required to conduct the activity and take the measure, taking into account the extent of the defect and the cost correction factor (G).

6. Asset management and policymaking

- *Step 6: Attaining an overview at stock level*

The end goal of inventorying and inspecting a building stock is for the building stock manager to attain an overview of the state of his/her real estate stock, the rehabilitation measures that need to be taken to keep the stock in an acceptable condition, and which costs these measures would incur. This overview is created when generating a conservation maintenance plan. In order to generate such a plan, one would need to consider the number of CH assets he wants to include in the analysis (one or entire CH stock), and define the maintenance level for each of them in order to understand the (financial) implications and risks. This is done as follows (Figure 15):

- Selecting 'Generate maintenance plan' process step in the side navigation
- Selecting one or more real estate objects in the object navigator (1). This can be done through checkboxes in front of each object. This way, one object, a collection of objects (for example, a particular CH site) or the entire stock can be selected.
- Next, a maintenance level can be selected in the upper panel (2). This maintenance level is used to filter activities defined during or after inspection by comparing, for example, the condition before maintenance of an inspected building component with the maintenance constraints defined beforehand (in step 2). If the condition of a building component is worse than the minimum acceptable level defined in the constraint, the activity is deemed necessary and included in the maintenance plan. This methodology also applies to other risk parameters, such as Experience and Cultural Value. After configuring maintenance plan options, one can generate a maintenance plan (3).
- After a maintenance plan is generated it is possible to modify the activities deemed necessary through the maintenance level filter (4). For example, it is possible to reschedule activities by dragging them horizontally.
- The total (financial) consequences of the maintenance activities can be seen in the bottom row of the maintenance plan (5).

To summarise to the above, the envisioned CH AM tool contains the following functionalities:

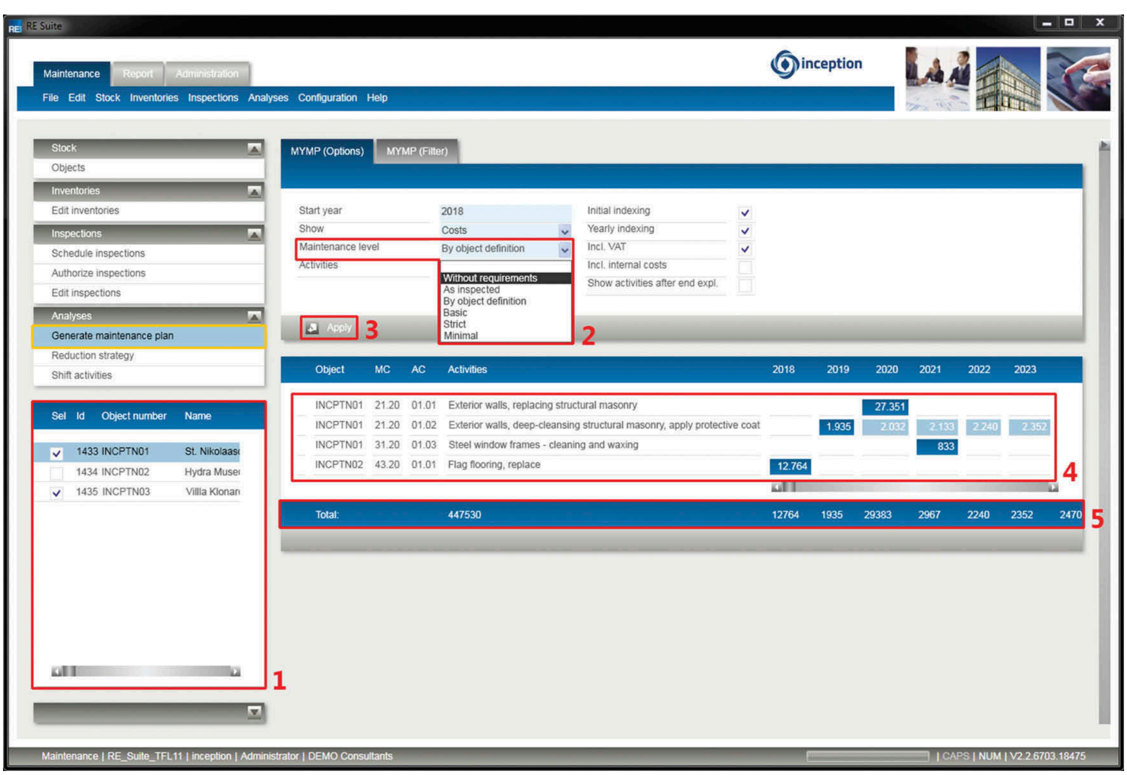

Figure 15. Attaining an overview on stock level.

- "Capturing a heritage real estate stock", creating and interrelating real estate objects, and being able to add all relevant information and documents to these objects.
- "Creating heritage real estate object inventories", in order to perform condition assessment, it is first necessary to decompose a real estate object into components or categories. Such decomposition is the basis for condition assessment. Part of this decomposition is automatically imported from the IFC file.
- "Defining maintenance constraints", in order to be able to take informed maintenance measures after condition assessment it is critical to define constraints beforehand. This includes the minimum acceptable condition, risk parameters, and monumentality constraints.
- "Performing an inspection", after a heritage object has been inventoried and constraints have been defined, an inspection of the object can be conducted. The software tool should facilitate this on-site process.
- "Defining measures to be taken", once an object has been inspected and its condition has been assessed, maintenance measures can be defined in order to keep the object at or bring the object to the desired maintenance level.
- "Generate a maintenance/conservation strategy", in the end, the manager of a heritage real estate stock needs to come to a coherent strategy for maintaining the entire stock. This necessitates that after individual objects have been assessed the outcomes of these assessments are summarized and educated decisions can be made on stock level while respecting the constraints defined on object level.

6.1. Results and discussion

6.1.1. BIM integration and requirements

As previously noted, the development of the CH AM tool was conducted in the framework of DEMO Consultants' primary software product: the Real Estate (RE) Suite.

This software suite contains a plethora of different applications and modules which have all been developed for one shared purpose: the management of real estate information.

Within the project development, the following key aspects were chosen as the focus for the extension of the existing solution and, thus, development of the CH AM tool:

- "BIM"

BIM is not (yet) commonly used within the heritage sector (Dore and Murphy 2017) since these kinds of buildings are often difficult to model in 3D, due to their irregular shapes and unusual building elements. Thanks to the development of automated technologies nowadays, the creation of a BIM model of an existing building becomes less expansive and labour intensive (Franco et al. 2015). BIM can be very effective and support the management of monumental real estate in their decision-making process and renovation designs (e.g. transformation plan) ensuring the preservation of cultural values.

In this context, the integration of BIM within the process of condition assessment is unique and has been found to have very large potential with regards to the integration of real estate lifecycles (and the information that is exchanged between them), as well as the automation of previously manual tasks (i.e. inventorying the building components).

At the same, in practice, it is very difficult to create the bridge between BIM and condition assessment (i.e. methodology) in a practical and user-friendly way. In the development of the CH AM tool, the goal was to achieve the first steps towards condition assessment BIM-integration.

- "Maintenance constraints"

One of the key considerations within the context of cultural heritage objects is the value it creates and/or represents which is not limited to its technical condition, but it also encompasses intangible aspects. At the same time, a CH stock manager is bound to financial limitations while having to maintain the real estate stock. In this combination lies a key challenge: how to make informed choices and avoid the loss of cultural value with regards to maintenance. To this end, a structure of maintenance constraint definition and checking was defined.

- "Norms and regulations"

One of the key challenges in the combination of cultural heritage and condition assessment is that a wide array of norms and regulations exist, as explained in the beginning of this paper; norms and regulations can differ from country to country, and some norms and regulations are more applicable to one type of cultural heritage object than to others. A key goal in the development of the CH AM tool was to provide the end-user with a framework that is adaptable to these differences, thus tailored-made to the different contexts. Therefore, a key aspect of the development process was to make the content of this framework user-configurable, so that the tool can be adapted for multiple use-cases.

- "Relation with the INCEPTION platform"

As previously mentioned, one of the key developments within the INCEPTION project is the creation of the platform. This platform is envisioned as a central storage—and the dissemination of information (data) for cultural heritage objects. For this reason, all end-user applications developed within the project are to be connected to and use the contents available on this platform for their own purpose. In this context, the platform contains a unique combination of BIM-models featuring both a physical and a semantic representation of the monumental real estate object and additional semantics linked to this model through semantic web technology.

Due to the BIM integration within the CH AM tool a connection with the INCEPTION platform needed to be established in order to be able to retrieve the BIM-model for a monumental real estate object and use the data within this model as the foundation for the condition assessment process (i.e. on-site inspection). Once this assessment has been performed, maintenance activities have been (pre)defined, and a holistic maintenance strategy has been formulated, this data is subsequently written back into the BIM-model and uploaded to the platform again.

In short, this "interactive connection" between the CH AM tool and the platform (Figure 16) can be explained as follows:

- IFC model created based on 3D point cloud is stored on the Platform;
- The CH AM tool will retrieve this model to be used for building inspection based on the BIM object decomposition according to the applied technical norms for condition assessment;
- The CH AM tool will link the information resulting from building inspection to the IFC model;
- The inspection results are uploaded to the platform. The semantically enriched IFC model, the so-called "As-Inspected BIM", is stored on the INCEPTION Platform. This enriched model can be used for further technical analysis and decision-making using the CH AM tool or other relevant (third-party) software tools.

The diagram displayed above conceptually outlines the interaction between the INCEPTION platform and the CH AM Tool. The communication with the platform is conducted programmatically, without manual intervention from the end-user, in which the CH AM Tool has the

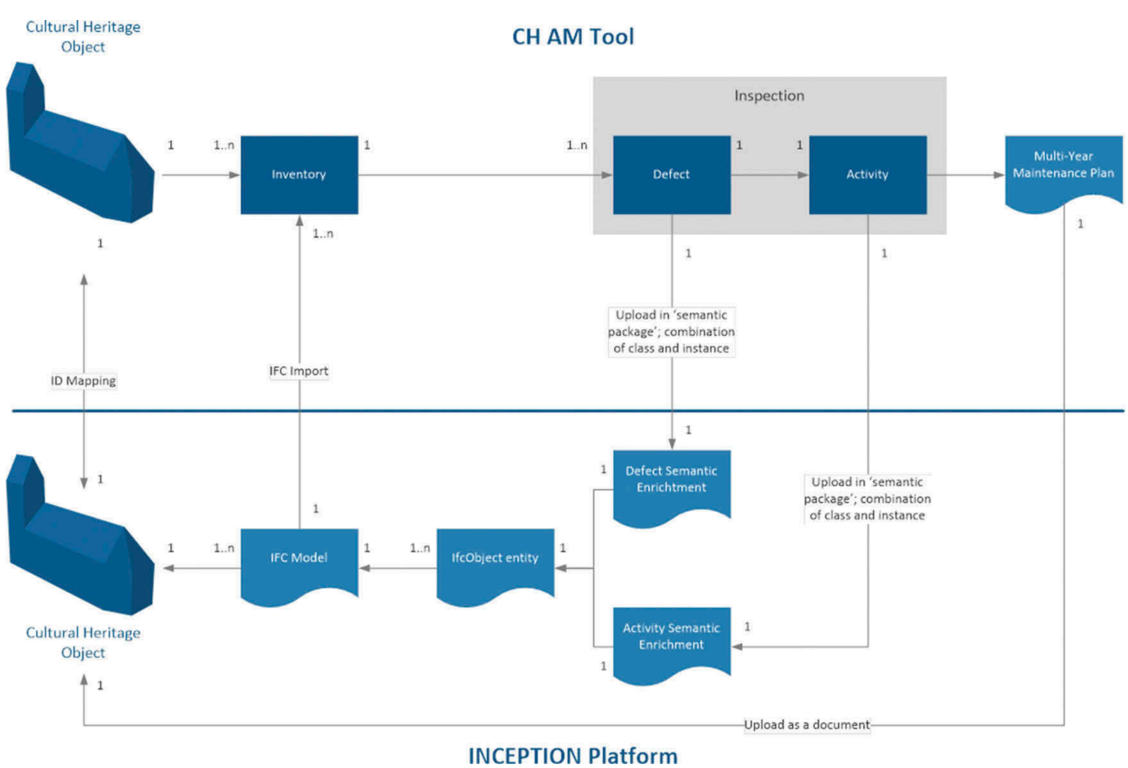

Figure 16. Workflow between CH AM Tool and the INCEPTION Platform.

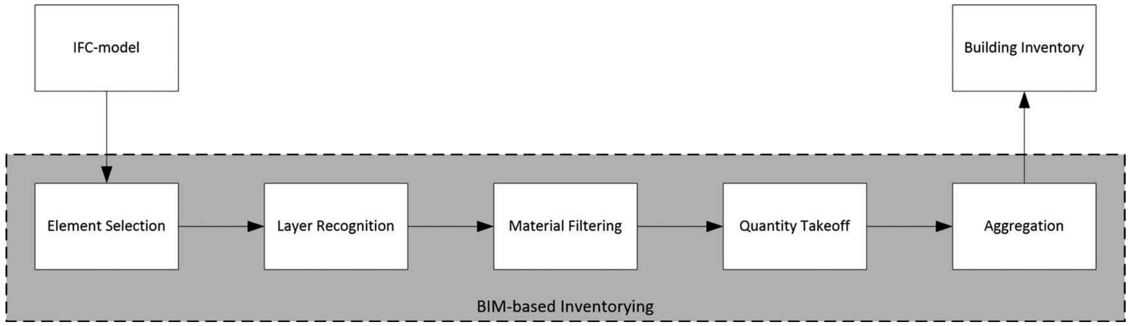

Figure 17. Schematic process of creating condition assessment inventories based on an IFC-model.

role of the requester/uploader and the platform the role of server/receiver of information.

The BIM integration into the condition assessment tool is based on the IFC model that is used as the source for (part of) the real estate object inventories. This has been a significant challenge due to, in particular, the nature of IFC. IFC as a BIM-format describes a structure to capture both geometric and semantic data. Crucially, IFC is not a very strict data format, leaving room for the end-user to use IFC in the way that is best for him/her. For example, many information elements are optional. Additionally, while IFC describes a set of standard semantics relating to building elements, it also gives the end-user the opportunity to add custom, user-defined, semantics (property sets in IFC terminology). This is a significant advantage; an IFC-file can contain pretty much any information the end-user desires. On the other hand, this fact also means that when an IFC file is used by another party, the structure of the information within becomes, at least partly, unclear without additional description or agreements. This is especially crucial when depending on optional or user-defined semantics within this IFC-model. A possible solution is integrating a reference to the Heritage BIM (H-BIM) ontology, which is part of the semantic approach of INCEPTION. The second challenge is related to the structure of condition assessment inventories versus the structure of an IFC model; these are vastly different. If one wants to use IFC as the source for a condition assessment process, a conversion has to be made between these two different worlds; the structure of an IFC-model needs to be mapped on the structure of condition assessment inventories.

To illustrate the process and methodology of this importing, mapping and conversion process a concrete example, in the form of a wall, will be used to walk through the creation of condition assessment inventories based on an IFC-model. This process is schematically displayed in Figure 17.

The first step in this process is to recognize, to select, elements that are relevant for inventory creation. At this point it is important to illustrate the difference between human and machine readability, while the geometry in the left of Figure 4 is interpreted by us, humans, as a wall, a machine will merely see this as an undefined geometric entity. It is therefore necessary that this geometry is given semantic meaning; it is required to have a 'label' attached to this element that denotes it as a wall, as illustrated to the right in Figure 18. In the case of IFC, these elements are captured in IfcWall and IfcWall Standard Case entities.

Next, once all wall elements have been selected from the IFC-model, it is important to realize that a wall is not necessarily one homogeneous entity; it can be composed of multiple (material) layers. The distinction between these different layers is very important in condition assessment. For example, one would conduct very different activities if a defect was identified for a wall finish then for a wall's structural layer. Therefore, material layers (Figure 19) are distinguished from each other by employing IfcMaterialSet entities assigned to the selected walls, which define a structure for representing layered element compositions.

Additionally, there is a strong emphasis on materialization in condition assessment. This, again, can be attributed to a distinction in potential measures between elements composed of different materials; one would conduct different measures for a masonry wall than for a wall with wooden cladding. To correctly map elements to condition assessment material categories, material information is read from the IFC-model (Figure 20). IfcMaterial, IfcMaterialList and IfcMaterialSet entities are all supported.

Once elements have been recognized, layers have been distinguished, and material information has been read this information can be correctly mapped to condition assessment inventory categories. Next, quantity information (Figure 21) is retrieved from the IFC-model and coupled with the information previously distilled from the IFC-model. Quantity information, such as square meters, is important for the condition assessment process because it allows you to attain comprehensive and realistic insight

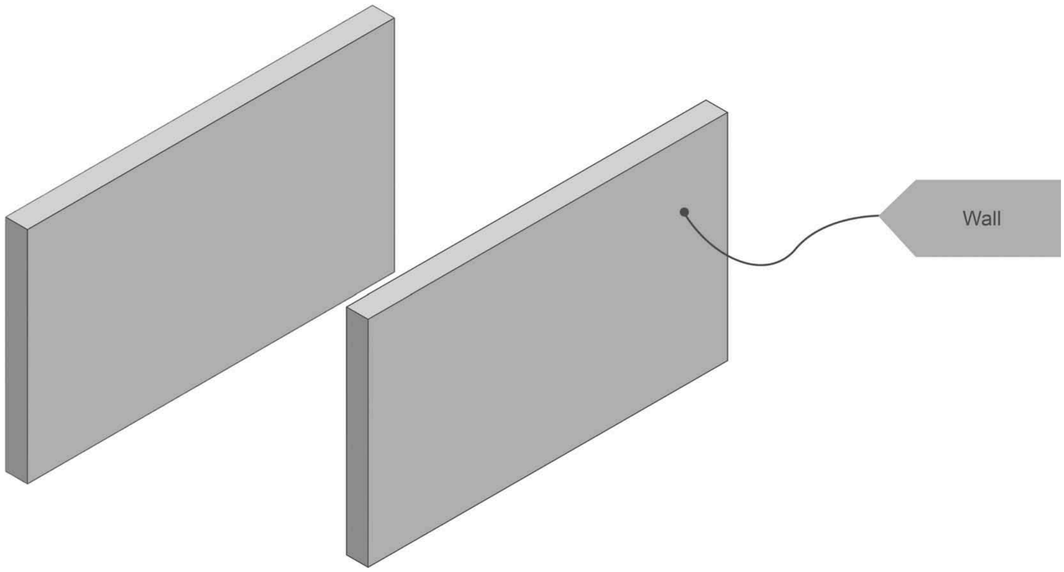

Figure 18. A wall represented purely by geometry (left), a wall given semantic meaning (right).

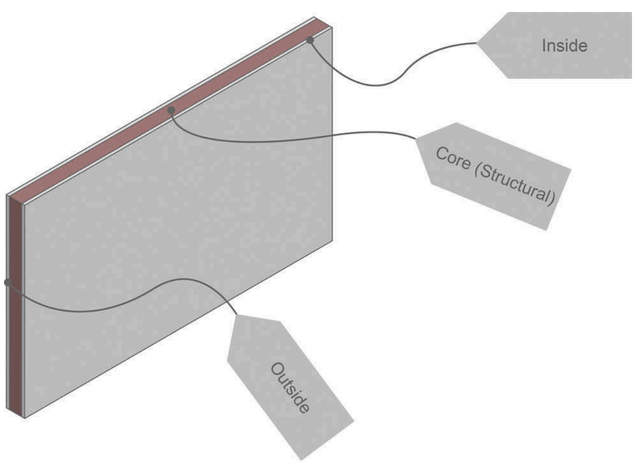

Figure 19. Layered wall composition.

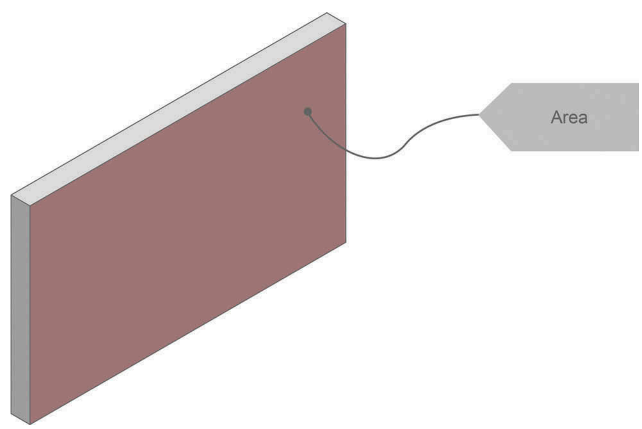

Figure 21. Retrieving quantity information from IFC elements.

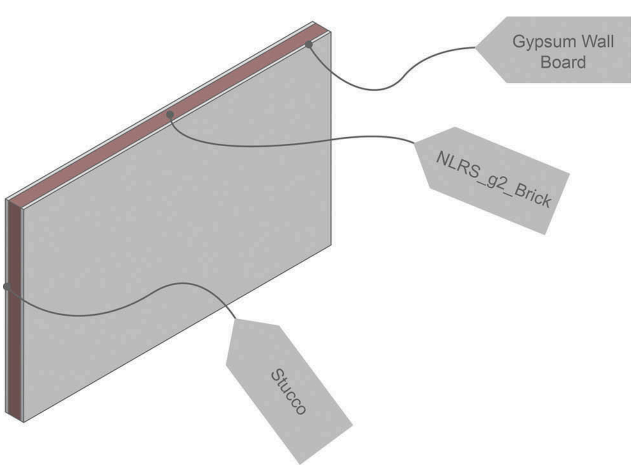

Figure 20. Material recognition and filtering.

into the state of a real estate object. In addition, it is also important to know the scale of defects and rehabilitation measures to be undertaken. This information is retrieved from the standard BaseQuantities property set associated with building elements in IFC.

Finally, within condition assessment, building components or elements are often aggregated by 'type' (Figure 22); for example, all stucco wall finishes are aggregated into one entry. However, within IFC entities this is represented as separate objects, regardless if they would be considered to be of the same type in condition assessment. Therefore, after all, individual elements from the IFC-model have been characterized and a quantity take-off has been performed, they are compared and aggregated according to their type.

As described earlier, some semantic elements within IFC are optional or can be defined by the user. In developing the IFC import functionality as described above, an

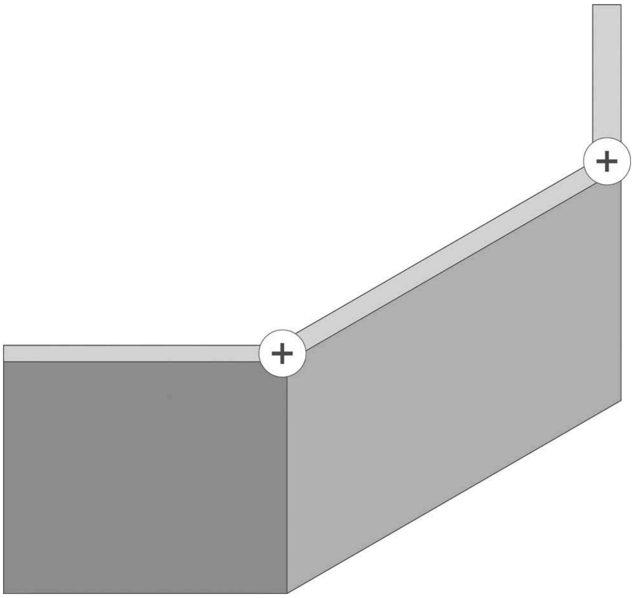

Figure 22. Aggregating wall elements of the same type.

emphasis was placed on employing as many semantics from IFC that are pre-defined and required within this data format. Nevertheless, it was not possible to base the import methodology solely on such semantics.

Therefore, it was necessary to create "BIM-requirements" for models that are to be used as input for the CH AM tool. An effort was made to base these requirements on other, international, standards in order to ensure a broad usability of the methodology and thus, that of the CH AM tool. These requirements, in summary, concern the following aspects:

- The correct and full export of the BaseQuantities property set in order to be able to conduct quantity take-offs. This property set is pre-defined albeit optional in the IFC format but is required to use the IFC- model for condition assessment;
- The classification of building elements according to the CI/SfB standard, and the export of this classification to IfcClassification entities in the IFC-model;
- The definition of element materializations in either IfcMaterial (single material), IfcMaterialList (multiple, unstructured, materials) or IfcMaterialSet (multiple, layered, materials) entities. The materials themselves can either be formatted as a free string (for example, 'Stucco') or by a string containing a CI/SfB material code (for example, 'g2_Brick', where 'g2′ is the material code).

To summarize the above, using IFC-models in the CH AM tool relies on the IFC data format and the CI/SfB standard for certain content in this model. The CI/SfB standard is a well-known and widely used, international, standard for classifying (elements of) the built environment. Due to this, and the fact that this is the only additional standard required for the IFC import process, this is seen as a reasonable additional requirement for the IFC-models when dealing with BIM-based condition assessment.

7. Semantic enrichment of the BIM

The BIM semantic enrichment by 'incorporating inspection results as additional technical properties in the IFC model' specifically targets building technicians and owners (i.e. technical expert users of the CH AM tool). In the CH AM Tool, it has been deliberately chosen to base the (INCEPTION) platform interoperability on the BIM-aspect of the platform. This is better suited to the users of the tool, i.e. technicians. In fact, this specific approach highlights one of the key strengths of the platform: the ability to facilitate different (data) use-cases and audiences from one single, central, data store.

Within the broader concept of INCEPTION, the semantic enrichment can be done in different ways depending on the purpose and targeted users. For tourists and scholars for example, the semantic enrichment of BIM models with photos and multimedia files can be done through Linked Data approach on the Platform instead of incorporating various types of data in an oversize BIM model.

Having this in mind, for the purpose of maintenance planning and asset management, the semantic enrichment of the BIM model was implemented by assigning two new property sets to the IFC file in order to store the condition assessment data in the file (i.e. "As-Inspected BIM"). In Figure 23, you can see the semantic inspection data related to the **Defect** assessed and the rehabilitation **Measure** proposed as new IFC property sets.

Enriching the IFC model with information about the technical condition of building elements gives insight into necessary maintenance and maintenance costs over time. In addition, it supports the CH owners/managers in making a risk-based maintenance planning due to the insights given into the risks connected to the defects as well.

Using the Dutch NEN 2767 will allow the communication about the technical condition and connected risks to be done in a uniform way. It is important to realize that the level of detail of the model in relation to the level of detail (building decomposition) used for Condition assessment conform NEN 2767 has consequences for the usability of the information and the effort needed to acquire the information.

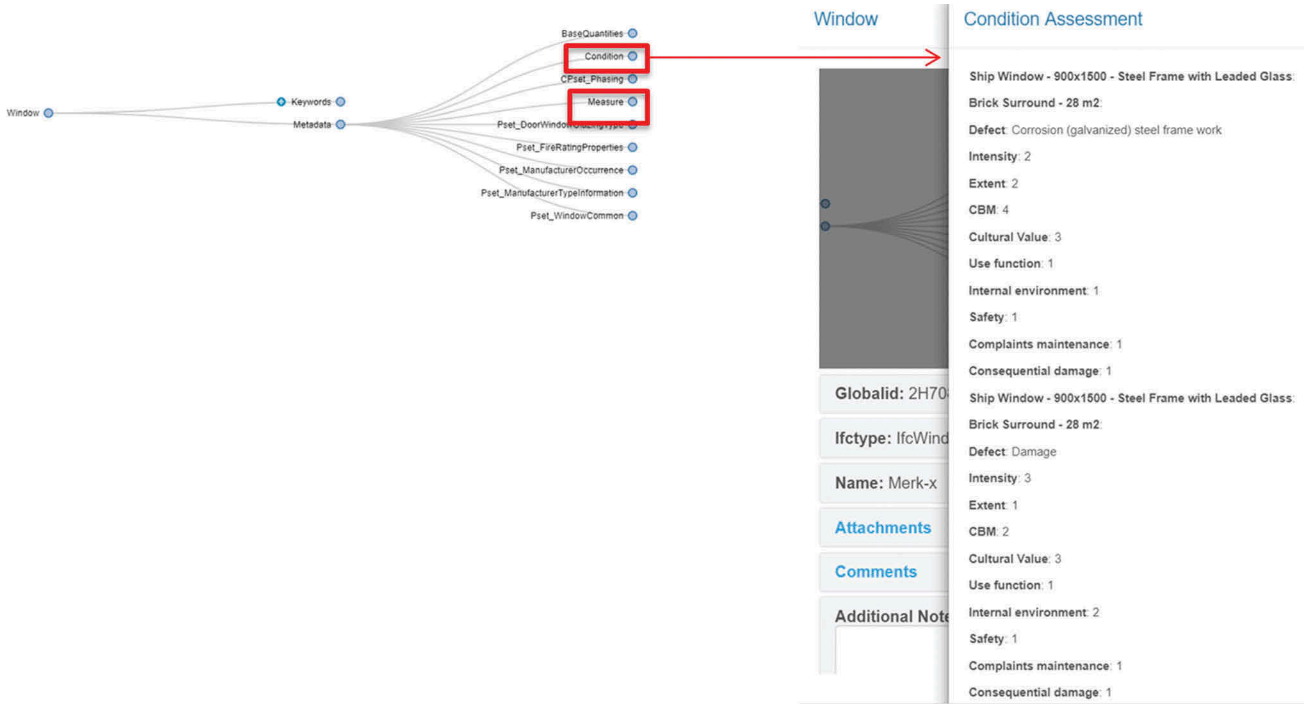

Figure 23. Inspection results as two different property sets in IFC.

For a more precise overview, it would be very valuable to know exactly which defects are located where (i.e. the exact location in BIM) and to what extent are these occurring. But the effort needed to collect the necessary data and process it is not proportional to the added value of the assessment process at this moment. Thus, more research and development are needed on inspection methods and tools that can be used to acquire the data needed for a high level of detail in an efficient way.

Condition assessment conforms NEN 2767 focusses on a level of detail that is needed to set up a maintenance planning and predict maintenance costs for budgeting purposes. For that reason, information is needed at building element level and specifically for building elements that require periodic maintenance (i.e. roof covering, wall finishing, etc.).

This means that at this moment, the model has to be adjusted to the NEN 2767 decomposition (or vice versa) to ensure usability of the data. As a result, the pilot case run in the Netherlands (on a Romanesque church from the 13th century) early 2019 has given insight into points of attention regarding level of detail of data collection and processing. Further research on this topic is advised (and is already being done in other on-going EU projects (e.g. BIM Speed) and development of Dutch standards (NEN 2660).

In relation to the INCEPTION platform, the enriched BIM with survey data (i.e. Condition and Activity property sets) can be seen as a condition record of the building's condition, which has at the same time, archival purposes. A condition record of such kind is an essential tool in the management of monumental real estate stock. It contributes to a decision that something should be preserved. A condition record in an IFC file is of historical value and can provide evidence when defining conservation needs and priorities. The information it contains can be of interest to the public, enhancing their understanding and appreciation of cultural heritage.

8. Conclusion

The CH-AM prototype tool has now been tested within the INCEPTION project on aDutch demonstration case and: is intended as the (first) pilot case to lead towards more replications across Europe.

The validation of the tool on this demonstration case remarked the following needs of the stakeholder and was done in relation to the INCEPTION platform implementation:

- Need for reliable and complete 3D information model of the building since no up-to-date information (i.e. drawings, technical details) exists.

- Need for an insight into the actual condition of the building and the associated risk estimation due to more than 50 years of obsolesce.
- Need for a preliminary indication of the short-term investment and long-term cost for renovation and conservation of the building considering the envisioned transformation plans.

The first need has been met through the integration of BIM in the CH AM software tool for analytical purposes. Technical information has been embedded in the properties of the IFC BIM model. The second need has been facilitated by the condition assessment module and the associated mobile app as part of the CH AM tool. The third need is supported by the cost analysis functionality of the tool and can be extended with additional cost indexes related to the proposed transformation plans.

Testing and demonstration based on a real pilot case have also contributed to improve the effectiveness of the newly developed prototype toolset.

While the prototype toolset has validated the proof-of-concept, further developments as described in the previous section of this paper are still needed to increase the Technology Readiness Level (TRL) of the innovative solution towards TRL 8–9 and prepare the toolset for practical implementation and market exploitation. The recommended actions at this point are as follows:

- Replacing or updating the technical norms and procedures of CH AM/historic building condition assessment as used in the software toolset with the applied norms depending on the EU/national/local regulatory framework;

It is to be expected that as a result of the European standardisation of theDutch NEN 2767, condition surveys for historical buildings will become more reliable and as a consequence more popular among CH owners/managers or other large-scale CH property owners. Building inspectors can be trained in using one method for all situations. To this end, it makes the data suitable for asset management and benchmarking purposes.

- The standard NEN 2767 is a tool to assess the technical status of the real estate objects to underpin the long-term maintenance expectations. This has been tested that can be applied on monumental buildings. Nevertheless, supplementary (expert) information is needed in the phase of preparing the execution of rehabilitation (specialist) work. This may be the precise location of the defects and causes of defects to take adequate conservation/maintenance actions;
- Enriching the BIM model with the technical information obtained from on-site condition assessment on building level (i.e. Defect and Activity) including the exact location of the defect and visualisation of the monumental labels with colour schemes which will support the design phase for renovation plans;
- Detailing the risk parameters for monumental buildings depending on the asset management policy of the stakeholders;
- Creating in-depth cost analysis of the recommended cultural heritage conservation or maintenance measures referring to the specific characteristics of the historic buildings, for example, the building typology or material properties.

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FprEN 16141 Conservation of cultural heritage - Guidelines for management of environmental conditions - Open storage facilities: definitions and characteristics of collection centres dedicated to the preservation and management of cultural heritage.

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