

Lab test protocols and set-up

Deliverable report D5.1



Deliverable Report: 2nd revision after EC review, issue date May 23th, 2016

INSITER - Intuitive Self-Inspection Techniques using Augmented Reality for construction, refurbishment and maintenance of energy-efficient buildings made of prefabricated components.

This research project has received funding from the European Union's H2020 Framework Programme for research and innovation under Grant Agreement no 636063.

Lab test protocols and set-up

Deliverable report D5.1

Issue Date	May 23 th 2016	
Produced by	UNIVPM (P9)	
Main authors	Gian Marco Revel, Milena Martarelli, Giuseppe Pandarese, Antonio D'Antuono	(UNIVPM)
Co-authors	Jacques Cuenca	(SWS)
	Pedro Leronés	(CARTIF)
	Günther Riexinger	(FHGIPA)
	Jan-Derrick Braun	(HVC)
Version:	2 nd revision after EC review	
Reviewed by	Günther Riexinger	(FHGIPA)
	Pedro Leronés	(CARTIF)
Approved by	Rizal Sebastian	(DMO, Technical Coordinator)
	Ton Damen	(DMO, Project Coordinator)
Dissemination	Public	

Colophon

Copyright © 2015 by INSITER consortium

Use of any knowledge, information or data contained in this document shall be at the user's sole risk. Neither the INSITER Consortium nor any of its members, their officers, employees or agents accept shall be liable or responsible, in negligence or otherwise, for any loss, damage or expense whatever sustained by any person as a result of the use, in any manner or form, of any knowledge, information or data contained in this document, or due to any inaccuracy, omission or error therein contained. If you notice information in this publication that you believe should be corrected or updated, please contact us. We shall try to remedy the problem.

The authors intended not to use any copyrighted material for the publication or, if not possible, to indicate the copyright of the respective object. The copyright for any material created by the authors is reserved. Any duplication or use of objects such as diagrams, sounds or texts in other electronic or printed publications is not permitted without the author's agreement.

This research project has received funding from the European Union's H2020 Framework Programme for research and innovation under Grant agreement no 636063.

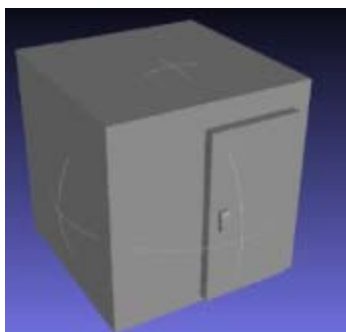


Publishable executive summary

The scope of task 5.1- of which this deliverable report is the result- is to select and to identify procedures, testing protocols and analysis methods for self-inspection techniques aiming at the reduction or elimination of quality and performance gaps between the design and construction phases. This document provides the guidelines for the application of the identified procedures and for carrying out the lab test activities and analysis of the findings.

Starting from the selection of a set of measurement parameters for the evaluation of thermal, acoustic and geometrical parameters and defined parameters from WP1, the procedures for their evaluation have been defined and described in details in this document, from Section 3 up to Section 6. An important effort has been put within Task 5.1, in the identification of positioning systems able to interface the different sensors allowing their integration/interconnection. A list of candidate positioning systems has been reported in Section 7. Once the results of each measurement procedures have been obtained they will be integrated into the Building Information Model of the building under test, the section 8 reports the protocol to integrate devices data and transfer them to BIM.

Another objective of Task 5.1 is to perform lab tests to validate the self-inspection tool based on measurement parameters in a simplified context. A pilot test case has been used for testing the identified procedures and building performances analysis. The test case is a simplified mock-up where the complete holistic tool developed in INSITER will be tested before its application in realistic contexts. Section 9 of this deliverable is focused on the presentation of the first results obtained by applying the thermal, acoustic and structural integrity procedures for the quality control and energy efficiency evaluation of the pilot test case. The first example of integrated results starting from the connection of sensors data to the BIM and ending up with their inclusion in an Augmented Reality application has been demonstrated. To conclude the work, section 10 introduce the guideline to evaluate the lab test and the follow-up R&D.



List of acronyms and abbreviations

- **BIM:** Building Information Modelling
- **HVAC:** Heating, Ventilation, Air Conditioning
- **MEP:** Mechanical, Electrical, Plumbing technologies
- **IR:** Infrared
- **AR:** Augmented Reality
- **GPS:** Geographic Positioning System
- **CAD:** Computer Aided Design
- **L:** Index of reflectivity
- **RTK:** Real Time Kinematic
- **DEP:** Data Exchange Plan
- **TOF:** Time of Flight
- **PS:** Phase Shift

Definitions

Not applicable

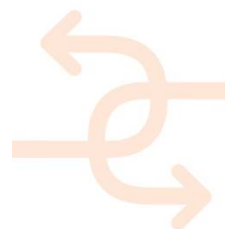
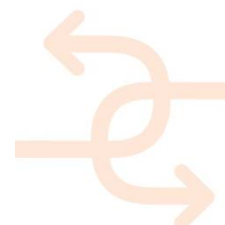


Table of contents

PUBLISHABLE EXECUTIVE SUMMARY	3
LIST OF ACRONYMS AND ABBREVIATIONS	4
1. INTRODUCTION	7
1.1 Objectives and structure of this deliverable	7
1.2 R&D methodology employed to achieve results presented in this deliverable	7
1.3 Main achievements and limitations	8
2. COMPARATIVE REVIEW OF MEASUREMENT DEVICES TO MEET INSITER PURPOSES	9
2.1 Main groups of INSITER measurement devices	9
2.1.1 Scientific Background of thermal test	9
2.1.2 Scientific Background of acoustic test	11
2.1.3 Scientific Background of geometric test	12
2.1.4 Scientific Background of humidity test	12
2.2 Inventory of available devices and technical specifications	13
2.3 Preliminary requirements for using the selected devices for self-inspection and BIM data integration	16
3. PROTOCOLS FOR THERMAL TEST	18
3.1 Thermal Transmittance	18
3.2 Thermal Bridge	21
3.3 Structural integrity	22
3.4 Practical hints for using IR camera	25
4. PROTOCOLS FOR ACOUSTIC TEST	28
4.1 Sound pressure level distribution	28
4.2 Sound intensity field	29
4.3 Sound transmission loss	30
5. PROTOCOLS FOR GEOMETRIC DISCREPANCY TEST	33
6. PROTOCOLS FOR HUMIDITY TEST	34
7. PROTOCOLS FOR POSITIONING SYSTEM TEST	35
7.1 GPS + RTK	35
7.2 QR-Code	37
7.3 Tracking and localization methods	37
8. PROTOCOLS FOR DATA INTEGRATION TO BIM	38
8.1 Data connection to BIM	38
9. EXPERIMENTAL PROOF-OF-CONCEPT	41
9.1 Proof-of-concept setup at the lab facility	41
9.1.1 Mock-up structure	41
9.1.2 Dragados Panels	41



9.2 Tentative outcomes from the proof-of-concept	43
9.2.1 Prof-of-concept following the protocols for thermal test	43
9.2.2 Proof -of-concept following the protocols for acoustic test	49
9.2.3 Proof-of-concept following the protocols for geometric discrepancy test with BIM and AR.	51
9.2.4 Proof-of-concept following the protocols for humidity test	56
9.2.5 Proof-of-concept following the protocols for positioning and tracking systems	58
10. CONCLUSIONS AND FOLLOW-UP R&D	59
10.1 INSITER guidelines to evaluate the lab test	59
10.1.1 Failure criteria and assessment of the procedure	59
10.1.2 Contingency measures	59
10.2 Anticipation of use of other devices in future demonstration projects	60
APPENDIX 1 - DATA EXCHANGE PLAN - INSITER WP2	62
3D Laser Scanning	62
3D Photo Scanning	62
3D Modelling	64
BIM	65



1. Introduction

1.1 Objectives and structure of this deliverable

This document is the result from Task 5.1 of the INSITER project and its main scope is to drive the guidelines for laboratory test to be exploited for the validation of the self-inspection procedures designed to measure buildings energy performances. After having identified a set of measurement parameters representing the building quality and energy efficiency, the following procedures for the evaluation of such parameters have been designed:

- Thermal test to measure U Value and thermal bridges, presented in Section 3.
- Acoustic test to evaluate sound pressure and intensity distribution and sound transmission loss, presented in Section 4,
- Geometric test, presented in Section 5,
- Humidity measurement procedure, presented in Section 6,

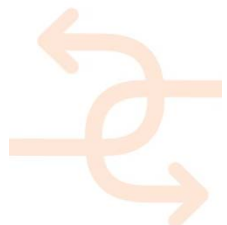
The main aim of INSITER is to develop a holistic toolset for self-inspection and in this view the different procedures have been integrated. The first issue to tackle this objective has been to reference each sensor among each other and to the site measurements. Several systems for the position estimation have been analysed and reported in Section 7.

In conclusion, Section 9 shows the application of the procedures into a pilot test case, a building mock up realised in the UNIVPM laboratory.

1.2 R&D methodology employed to achieve results presented in this deliverable

The first step for the design of the holistic tool for the quality and energy efficiency is to identify the parameters addressing quality and energy performance level. Those parameters have been defined in WP1 and reported in the deliverable D1.1. A set of those measurement parameters has been selected to be tackled in the lab-testing phase. The selection has been driven by the fact that INSITER aims at integrate measurement instruments addressing different physical parameters as thermal camera for energy parameters, SoundBrush for sound transmission loss and laser scanner for geometry data capture. The main measurement aspects addressed in the lab-testing phase are:

- Thermal aspects:
 - Thermal transmittance;
 - Thermal bridge;
 - Structural Integrity;
- Acoustic aspects:
 - Sound pressure level distribution;
 - Sound intensity field;
 - Sound transmission Loss;
- Geometric discrepancy;
- Humidity aspects.



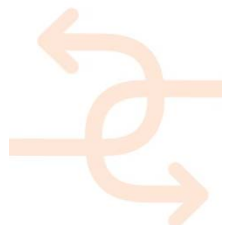
1.3 Main achievements and limitations

Achievements:

- Evaluation of the most common errors in the construction field;
- Evaluation of the actual standards and of the state of the art of the measurement procedures;
- Identification of the measurement tools available on the market;
- Definition of the new measurement procedures developed in the project for 2D and 3D test;
- Identification of the data format and potential structure for the integration between the different sensors.

Limitations:

- A deep uncertainty and sensitivity analysis to different sources will be performed in the next months;
- Too many data from the sensor make the process not achievable in real-time. The BIM and AR must be update in a separate phase in respect to the measurement phase.



2. Comparative review of measurement devices to meet INSITER purposes

2.1 Main groups of INSITER measurement devices

Each measurement parameters reported in the Section 1.2 can be evaluated with different sensors and diagnostic system in according with the actual standards. Innovative and more user-friendly procedures have been proposed within INSITER and will be developed during the project. Table 1 reports the addressed quality and energy aspects, the applied sensors and the associated measurement parameters for their evaluation.

Measurement aspects	Sensors / Measurement Instruments	Measurement Parameters
Thermal transmittance	Thermal Camera, Heat Flux Transducer	U Value [W/m ² K]
Thermal Bridge	Thermal Camera	H _D [W/K]
Structural Integrity	Thermal Camera	Thermal contrast [K]
Sound pressure level distribution	MEMS microphone array for Beamforming	Sound presser level [dB]
Sound intensity field	SoundBrush	Sound intensity level [dB]
Transmission Loss	SoundBrush	TL [dB]
Geometric discrepancy	3D Laser Scanner	Dimension difference [m]
Humidity	3D Laser Scanner	Index of reflectivity L

Table 1: List of sensors for each measurement aspects

2.1.1 Scientific Background of thermal test

Thermal Transmittance

The thermal transmittance evaluation of the building components is one of the most important parameters in order to classify the energy performance of the building. Problems during the construction phase like insulation loss or damages of the building elements could cause thermal transmittance losses and energy-saving loss. The equation below shows the correlation between the energy saving and the variation of U Value.

$$(1) \quad \Delta E = HDH * \Delta U * 1/\eta \quad [kWh/m^2y]$$

ΔE : Energy savings (per m² area of construction elements);

HDH : Thousands of heating degree hours (per year);

ΔU : Difference in U Value;

η : Efficiency of heat generation and distribution;

At present, there are different methods for the thermal transmittance evaluation, which can be classified in laboratory and in-situ procedures. The first class of those procedures is described in the standard EN 8990 (Determination of steady-state thermal transmission properties – calibrated and guarded hotbox), which defines the measurement of the thermal transmittance of a building component. According to this standard, the U Value of the component should be



evaluated by monitoring the electrical power needed to keep the temperature difference between the different sides of the wall at least at 20°C.

The second class of procedures is described in the ISO 9869-1 standard (Thermal insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance. Part 1: heat flow meter method). According to this standard, U Value is estimated on the basis of heat flux and temperature measurements by means of heat flux meters and thermocouples. The main issue in in-situ measurements is the temperature fluctuations inside and outside the building, causing a fluctuation of the heat stored in the building component, a wall for instance. The fluctuation of the stored wall heat, which depends on the thermal mass of the wall itself, influences the U Value calculation. That influence can be neglected only if the measurement is performed during a long time period since the averaging process allows reaching the actual U Value of the wall. The monitoring period required by the standard is of at least 72h. The U Value calculation is based on a progressive average approach, as shown in equation (2).

$$(2) \quad U = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{ij} - T_{ej})} \quad [W/(m^2K)]$$

where q_j is the value of the flux through the component measured with the heat flux transducer. T_{ij} and T_{ej} are respectively the value of the internal and external temperature at the opposite sides of the monitored component.

Thermal Bridge

The thermal bridge represents a local area with a density of heat flow greater than the other materials of the building components. It could be caused by the presence of different material (like metal), corner, moisture, and mold.

The effect is a reduction of the thermal performance of the building and, consequentially, a loss in terms of energy and effective costs.

One of the objectives of the INSITER Project represents the possibility to evaluate and estimate the thermal bridges contribution during the different phases of the building construction. This approach reduces the time and costs of a post analysis process, ensuring the intake of additional benefits to the realization of the building.

Actually, there are at least two standards defining the methods for the evaluation of thermal bridges:

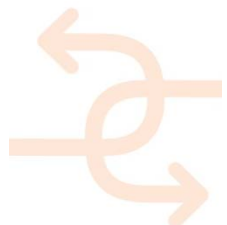
- the standard ISO 6781 (Qualitative detection of thermal irregularities in building envelopes - Infrared method)
- the standard EN 14683 (Thermal bridges in building construction - Linear thermal transmittance - Simplified methods and default values).

Structural Integrity

Structural integrity is the ability of a structure or a component to withstand a designed service load, resisting structural failure due to fracture, deformation, or fatigue. Structural integrity is a concept often used in engineering, to identify items that will not only function adequately for their designed purposes, but also to function for a desired service life.

Sometimes the presences of crack, delamination or deformation on the structures do not compromise the resistance or safety of the structure but could generate infiltration, thermal bridges, or reduction of the energy performance.

The structural integrity of a component can be monitored by IR thermography technique. It has been observed that buildings or structures with defects such as debonding render and mosaic or delaminating concrete emit differing amounts of IR radiation. If a concrete surface with an even colour and texture is viewed with an IR camera, it will appear quite uniform when the concrete is free of defects. However, if there are any cracks or delaminations within the concrete, the surface will heat up faster under solar irradiation in these areas and hot spot will be observed in the thermal record



during the transient heating and/or cooling phase. The passive method based on natural heating has been standardized in ASTM D4788-03 “Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography”, which defines restrictions and limitations of the method. The main issue of such method, lays on the emitted radiation from the surface (emissivity) caused by the residues, traces of damage, etc., together with required proper environmental conditions present for testing, varying environmental conditions during testing (temperature gradient, shaded or direct sunlight, cloud cover and surface water, deck should be dry).

2.1.2 Scientific Background of acoustic test

The estimation of acoustic performance of buildings is based, according to the standards, on measurement of airborne sound insulation against outdoor sound or transmission of indoor sound to the outside. If a sound field is generated inside a room, it generally propagates throughout air, if any gap in the envelope is present with dimension of the same order of the sound wavelength, or the structural paths exciting neighbouring rooms. The acoustic properties of the room assessing its acoustic performance are called sound transmission loss and acoustic insulation and depends on the construction materials the room envelop is made of and on the way those materials are installed. Sound insulation losses often appear after the mounting process and should therefore be tested in situ. The insulation properties of a room can be assessed by producing a stationary acoustic excitation via a sound source placed inside or outside the room and by measuring sound pressure level distribution or sound intensity field over the room envelope.

Sound pressure level distribution

The spatial distribution of the sound pressure level at the surface of a building component provides a direct and straightforward visualisation of the sources of noise and of its performances. Two experimental methods for sound pressure measurement are proposed, suitable for hardware solutions proposed for the project, namely the SoundBrush probe and a microphone array. As explained in the following sections, the SoundBrush probe provides the sound pressure at every measurement point where it is located, while the microphone array provides a hologram at the microphone positions, which is to be back-propagated to the panel's surface. The measurement follows classical methods, e.g. the international standard ISO 16032:2004, in particular for its application to MEP/HVAC components.

Sound intensity field

Sound intensity quantifies the magnitude and direction of energy flow across a region of space. It takes the form of a vectorial field and thus provides additional and complementary information to sound pressure level. The method is derived from international standards providing the method for the estimation of the sound power level of noise sources using sound intensity, e.g. ISO-9614-1, ISO-9614-2 and ISO-9614-3. More specifically, the methodology proposed here is an extension of ISO-9614-2. The latter describes the procedure to follow in order to obtain the sound power level of a source by scanning the vicinity of the source with an intensity probe. The method in the standard provides the value of the sound power level of the source as a sum accross the scanned area. In addition to its sound power value, the method using the SoundBrush probe provides the sound intensity at all scanned points, thus giving a spatial (1D, 2D or 3D) representation of the observed level and orientation of the sound propagation.

Transmission Loss

The sound transmission loss quantifies the acoustic energy loss arising from the placement of a wall or partition between two adjacent spaces. It characterises the sound insulation efficiency of the object. In this document, a method for the in-



situ estimation of the sound transmission loss of a building panel is proposed.

One of the international standards recommends the measurement of the sound transmission loss to be performed by placing the sample to be tested between two reverberation rooms (ASTM-E90-09, 2009). The estimation of its value is made by comparing the average sound pressure level in both rooms. Such a measurement requires the availability of the reverberation rooms and for the sample to be uncoupled from any other building component. An equivalent procedure is specified in the standards (ASTM-E2249-02, 2008), consisting of the placement of the panel sample between a reverberation chamber and an anechoic room and is based on the measurement of the sound transmission loss from the sound intensity level difference between the two faces of the sample. Such technique is also specific to laboratory conditions.

An international standard ISO-15186-1:2000 more adapted for the present purposes recommends the measurement of the sound transmission loss using an intensity probe by closely scanning the surface of the panel at both sides and performing the ratio of normal sound intensity level. This technique can be performed in any set of two spaces separated by a sufficiently large panel, provided that a broadband source is present at one of the sides. Therefore this method is used here by means of the general purpose SoundBrush probe, as described in the present deliverable.

2.1.3 Scientific Background of geometric test

Geometric discrepancy

Contrary to the design from scratch of a building in CAD/BIM environments, as-built surveys using 3D laser scanning technology provide users with detailed point clouds, which enable 3D modelling for diverse tasks including building inspection, reconstruction, plans & layouts, and enhanced data presentation with augmented reality.

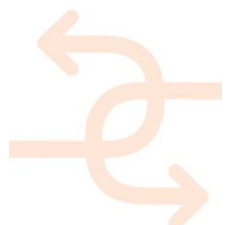
The point clouds obtained (or derived 3D models) can be contrasted to the original BIM project to evaluate the quality of the execution. Also, through successive scans of one area or element of interest of a prefabricated building, it is not only possible the geometry monitoring along time, but also the quantitative and qualitative analysis of its evolution, whether it represents a deterioration (slumps, cracks, tilting, warping, etc.), as it is a progress in the maintenance or refurbishment works.

2.1.4 Scientific Background of humidity test

Humidity

In the construction sector moisture detection is carried out by direct visual inspection. Once detected, the humidity content in specific points is measured at the discretion of the expert, using hygrometers or thermo-hygrometers, of which there exists a wide commercial range. Currently, there are no other specific devices for on-site moisture assessment. Wireless temperature and humidity acquisition systems are increasingly used to display real-time curves, but these systems are focused on environmental monitoring.

Thermography-based techniques, useful in the cases of limited areas (due to the small size of the 2D infrared images), could be used for the qualitative detection and location of moisture by skilled operators. However, given that the differences found in the infrared images may correspond to other phenomena than humidity (i.e. temperature differences, air bridges, biofilms and others), their transcription into images that clearly shows dampness requires the development of complex computer vision applications and the deployment of additional highly specialized equipment.



INSITER is rather aimed at presenting 3D scanning as a valid option for humidity revealing just using the data registered for documentation purposes (accompanied by quantitative validation with thermo-hygrometers -as required in thermography).

2.2 Inventory of available devices and technical specifications

Thermal test


Device	Datasheet
FLIR E8 	<ul style="list-style-type: none"> Spectral Range: 7.5 ... 14 μm; Detector: Uncooled Microbolometer FPA; Detector format: 160 x 120 IR pixels; Frame rate: 9 Hz (full screen); Temperature range: -20 ... 350 $^{\circ}\text{C}$; Accuracy: $\pm 2^{\circ}\text{C}$ / $\pm 2\%$; Temperature resolution: $< 0.09\text{ K @}30^{\circ}\text{C}$; Dynamic range: 16 bit.
FLIR T420 	<ul style="list-style-type: none"> Spectral Range: 7.5 ... 13 μm; Detector: Uncooled Microbolometer FPA; Detector format: 320 x 240 IR pixels; Frame rate: 30 Hz (full screen); Temperature range: -20 ... 350 $^{\circ}\text{C}$; Accuracy: $\pm 2^{\circ}\text{C}$ / $\pm 2\%$; Temperature resolution: $< 0.05\text{ K @}30^{\circ}\text{C}$; Dynamic range: 16 bit.
Infratec VarioCAM HD 	<ul style="list-style-type: none"> Spectral Range: 7.5 ... 14 μm; Detector: Uncooled Microbolometer FPA; Detector format: 1024 x 768 IR pixels; Frame rate: 30 Hz (full screen); Temperature range: -40 ... 1200 $^{\circ}\text{C}$; Accuracy: $\pm 1.5^{\circ}\text{C}$ / $\pm 1.5\%$; Temperature resolution: $< 0.05\text{ K @}30^{\circ}\text{C}$; Dynamic range: 16 bit.

Table 2: List of available thermal camera



Acoustic test





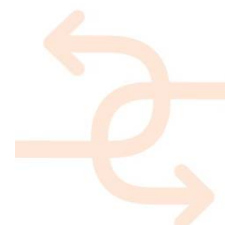
Device	Datasheet
LMS Soundbrush 	<ul style="list-style-type: none"> Linear frequency range: 100 Hz ... 4kHz; Dynamic range: 33 ... 150 dB(A) Class: 2 (IEC 61672-1); Outputs: USB
Brüel & Kjær Sound level meter 2270 	<ul style="list-style-type: none"> Channel: Dual-channel input; Linear frequency range: 4.2 Hz ... 22.4 kHz; Dynamic range: 16.6 ... 140 dB(A); Class: 1 (IEC 61672-1); Inputs: AC or CCLD, External Trigger; Outputs: Generator and Headphone; Communication: USB, LAN, GPRS.
Delta OHM Integrating Sound Level Meter HD 2010UC 	<ul style="list-style-type: none"> Linear frequency range: 4.2 Hz ... 22.4 kHz; Dynamic range: 30 ... 143 dB(A); Class: 2 (IEC 61672-1); Inputs: AC/DC; Outputs: AC/DC; Communication: USB, RS232.
G.R.A.S. Intensity Probe 50GI CCP 	<ul style="list-style-type: none"> Linear frequency range: 4.2 Hz ... 22.4 kHz; Dynamic range: 27 ... 146 dB(A); Class: 1 (IEC 61672-1); Sensitivity: 12.5 mV/Pa; Communication: BNC.

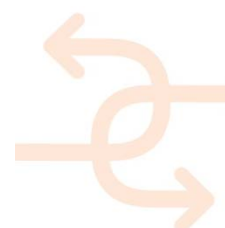
Table 3: List of available acoustic sensors



Geometric discrepancy test

Device	Datasheet
Leica HDS3000 	<ul style="list-style-type: none"> Position Accuracy: 6 mm; Distance Accuracy: 4 mm; Angle Accuracy: 60 μradians; Range: 300 m; Scan rate: 4000 points/sec; Point spacing: 1.2 mm minimum; Laser Colour: Green; Operating temperature: -25 ... 65 °C.
RIEGL VZ-400 	<ul style="list-style-type: none"> Position Accuracy: 5 mm; Distance Accuracy: 5 mm; Angle Accuracy: 500 μradians; Range: 600 m; Scan rate: 42000 points/sec; Point spacing: 1.2 mm minimum; Laser Wavelength: Near infrared; Operating temperature: -20 ... 40 °C.
FARO X 30 	<ul style="list-style-type: none"> Position Accuracy: 2 mm; Distance Accuracy: 2 mm; Angle Accuracy: 9 mrad; Range: 614 m; Scan rate: 122000 points/sec; Point spacing: 0.3 mm minimum; Laser Wavelength: 1550 nm; Operating temperature: 5 ... 40 °C.

Table 4: List of available laser scanner



Humidity test


Device	Datasheet
See Table 4	
Testo 635 	<ul style="list-style-type: none"> Resolution: 0.1 % RH; Accuracy: ± 2 % RH; Measuring range: 0 ... 100 % RH; Operating temperature: -20 ... 50 °C.

Table 5: List of available humidity sensors

2.3 Preliminary requirements for using the selected devices for self-inspection and BIM data integration

To gain the best benefit by combining measurement results and BIM, it is essential to gather several important information:

- What type of measurement device is used?

In case the measurement device is a sensor or similar which continuously submits values it is necessary to set-up an IT-environment which is capable of receiving those information. The to-be-developed IT-environment has to combine those information automatically with the BIM model.

In case it is a manually triggered measurement process the user must be enabled to upload the measurement results to the server where the information are linked to the BIM model.

- How should the results be used (use case scenario)?

This question has to be clarified to know how the information have to be provided and/or visualized.

There are several options to represent measurement results like e.g.:

- coloring 3D objects (e.g. objects which fail a specific test will be colored red),
- linking documents to 3D objects (e.g. complete measurement protocols are linked to an object),
- mapping images onto an 3D object (e.g. a thermal scan will be laid onto the surface of a wall),
- measured values are stored in an attribute of a 3D object (might be useful for post-processing)

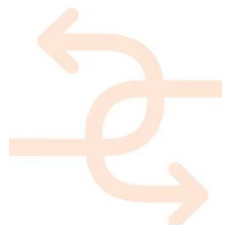
Depending on the given situation those information lead to requirements towards the BIM models and/or the IT-environment:

- Data- and File-Formats

The IT-environment and the used software and services must be capable of the incoming file-formats. It has to be guaranteed that the environment is able to process the incoming information.

- Structure of the BIM models

The structure of the available BIM models must correspond to the incoming information. It has to be avoided that the measured information use another allocation than the given 3D objects (e.g. a thermal scan refers to a specific wall in a specific room, but within the 3D model this wall is ongoing through two adjacent rooms).

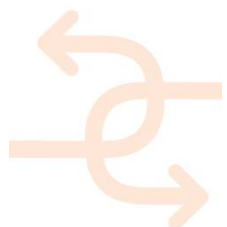


- **Usage of Augmented Reality**

If the measurement results should be used in Augmented Reality it is most important that the BIM model as well as the given information cover all requirements given by the AR-software (e.g. the BIM model must be accurate to enable the AR application to recognize the position and orientation on site).

Considering these requirements will lead to the benefit, in comparison to conventional inspection measurements, to be able to re-use the collected information during the whole life-cycle of the building and keep track of all issues which might be relevant for the energy-efficiency of the building. In addition to this the given results from measurements may be provided in a user-friendly way to suit the given use case best.

By using BIM it is possible to automate related processes (e.g. informing involved personnel about successful measurements) by creating workflows. Additionally information and measurement results may be directly stored at the correct location in the IT-environment avoiding loss of data and preventing human mistakes when storing data manually. Both of these mentioned benefits lead to immense time and cost savings.



3. Protocols for thermal test

3.1 Thermal Transmittance

Introduction

An alternative method for measuring the U Value, proposed in INSITER, is based on infrared (IR) thermographic techniques with the advantages of being non-contact and non-invasive and therefore less time consuming in the installation phase.

IR thermography is a process in which heat at any temperature can be converted into a thermal image using specialised scanning cameras.

Terms, definition, symbol and units

T_W : surface temperature measured with the IR detector.

T_{in} : air environment temperature on the internal side of the building component.

T_{out} : air environment temperature on the side in which the thermal load is applied.

T_W : surface temperature measured with the IR detector.

T_{ref} : reflected temperature from the radiative external sources.

ε : surface emissivity of the material.

σ : Stefan-Boltzmann constant ($5.67 \cdot 10^{-8} \text{ [W/(m}^2\text{K}^4)]$).

U : Thermal transmittance of the building component.

BIM : Building Model Information.

h_{in} : Convective coefficient.

t : Time.

A : Cross-Section of the wall.

Apparatus

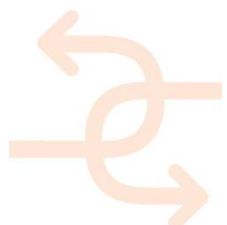
The test involves an infrared radiation detector, a monitoring system for the external and internal conditions and a BIM containing the design drawings and technical properties of the materials. The following sensors are required:

- Infrared radiation detector: able to measure in the range between $2 \mu\text{m}$ and $12 \mu\text{m}$ with an accuracy more than $\pm 0.5^\circ\text{C}$
- Thermometers: thermal sensor for the evaluation of the internal environmental temperature and the external temperature with an accuracy more than $\pm 0.5^\circ\text{C}$
- Hygrometer: to evaluate the humidity in the internal environmental
- Thermal load to realize a distributed and quickly variation of the temperature in one of the side of the component

Calibration procedure

The IR camera must be calibrated and maintained at regular intervals, following the procedure recommended by the manufacturer. Non-uniformity or flat field correction must be performed according to the manufacturer's instructions, or more frequently, if required to achieve optimum camera performance.

Before the beginning of the test, the thermal camera has to be calibrated according to the environmental conditions. For



this reason, properties like surface emissivity of the component and transmissibility of the medium between the camera and the component must be set. Internal temperature and humidity have to be monitored during the whole test duration for a correct calibration of the IR sensor.

The evaluation of the surface emissivity of the material is done in according with the standard ASTM E 1933 with two different methodologies (contact or non-contact sensors) by using thermometers on the surface to measure or with a reference object (near black body) with high emissivity value.

Measurements (Installation of apparatus)

- a) *Thermal load.* In order to evaluate the thermal transmittance of the building component, a thermal load is applied on one surface of the component. The load is applied for all the duration of the test by setting a desired value of temperature in order to have at least 20°C of difference through the building component (Figure 1).

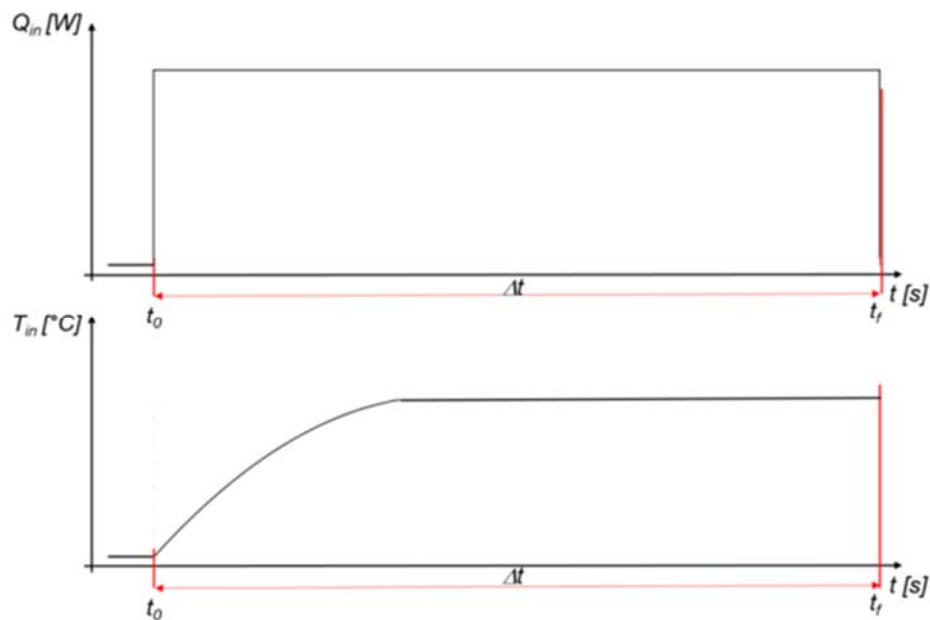


Figure 1: Thermal load (upper plot) and temperature (bottom plot) time profile during a test of duration of $(t_f - t_0)$ seconds

- b) *Thermocouple and hygrometer.* These devices are necessary in order to set the corrective parameters of the thermal camera. The thermocouple mounted on the load side must be covered in order to be not affected by the direct radiation of the lamps. During the test, the temperature and humidity in the vicinity of the thermal camera must be monitored continuously.
- c) *Thermal Camera.* The device is mounted on the opposite side of the wall with respect to the thermal load. The distance of the sensor from the observed component depends on the resolution and Field Of View (FOV) of the camera. With most sensors, present on the current market, a good spatial resolution can be preserved only if small areas are framed by the camera. It is suggested, to divide the total area of the wall in smaller subareas as described in the experimental case reported in Chapter 6. Since ambient radiation influences the IR sensor



and the measured temperature the device must be not shaded from external radiative sources. In order to take into account the reflected temperature, T_{ref} , i.e. the temperature due to the reflection of the surrounding radiative sources, a low-emissivity material is mounted on the scene observed by the infrared sensor.

Figure 2 shows the test setup.

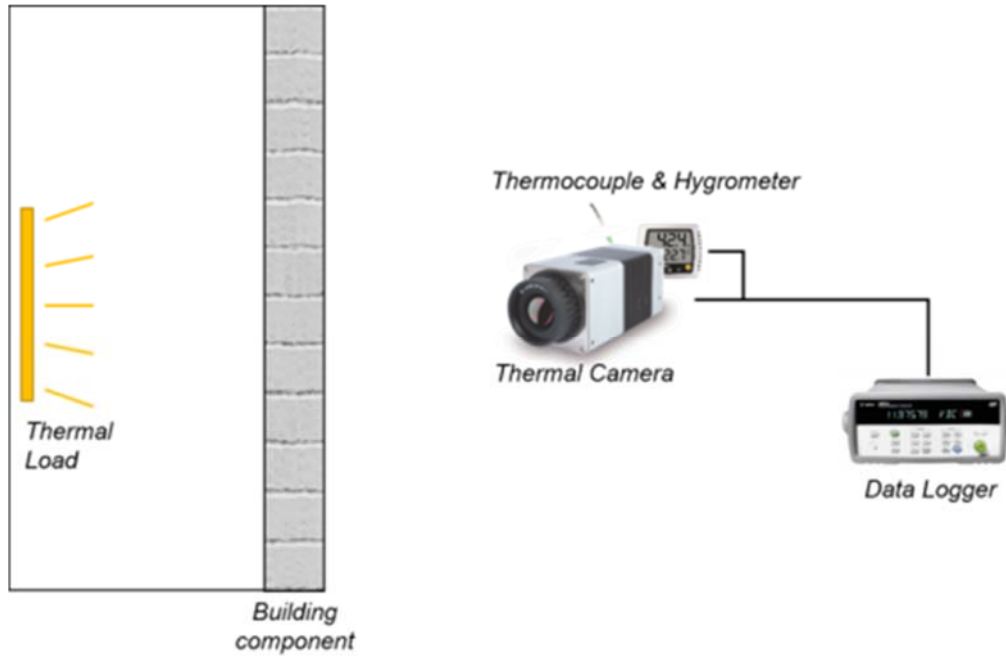


Figure 2: Measurement setup

Data acquisition and analysis of the data

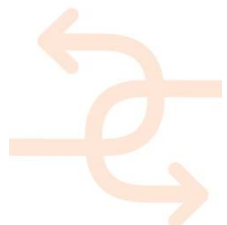
Since the U Value depends on the thermal gradient between the two sides of the wall (see equation 2) and, as discussed in the standards, since the measurement uncertainty decreases if the measurement is performed when thermal stationarity is reached, the measurement duration must be kept sufficiently long until the thermal gradient reaches a constant value. That time depends on the wall thermal inertia and time constant. The sampling frequency can be kept at low value, due to the fact that thermal processes are typically low frequency. Common data acquired during the test are temperature time profiles.

The relation between the U Value and the thermal gradient between the two sides of the wall can be derived considering the thermal energy equilibrium of the wall and it is given by equation (3):

$$(3) \quad U = \frac{4\varepsilon\sigma T_W^3(T_W - T_{Ref}) + h_{in}(T_W - T_{in})}{(T_W - T_{out})} \quad [W/(m^2K)]$$

The test must be long enough to have stationary conditions. It means that both sets of measurements (mean internal/ mean external temperature) shall yield a standard deviation non exceeding 1K during a period of 30 minutes. At this moment the final value of thermal transmittance must be evaluated.

The output data from the test is the U Value distribution or the global U Value of the component which has to be compared with the one estimated during the design phase in order to evaluate if there is any gap in energy-performance



between design and realisation.

3.2 Thermal Bridge

Introduction

The INSITER project will develop a non-contact procedure for the U Value estimation, based on IR thermal camera, for the qualitative identification of thermal bridges and for their quantitative evaluation, by measuring the transmission heat transfer coefficient of the observed object.

Terms, definition, symbol and units

See Section 0. In addition:

- Ψ_k : Linear thermal transmittance of linear thermal bridge.
- l_k : Length of linear thermal bridge.
- U^* : Expected thermal transmittance based on the technical drawings of the component.
- L^{2D} : Coefficient of thermal linear coupling.
- H_D : Transmission heat transfer coefficient.

Apparatus

See Apparatus in the same sub Section in the previous Section *Thermal transmittance*.

Calibration procedure

See calibration procedure in the same sub Section in the previous Section *Thermal transmittance*.

Measurements

The measurement procedure is the same presented in the sub Section of the previous Section *Thermal transmittance*.

Analysis of the data

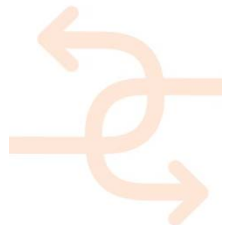
The data analysis is based on the same model described in the previous Section (same subSection). In addition, the test provides a map of transmission heat transfer coefficient H_D including the contribution of thermal bridges, according to the standard ISO 14683:

$$(4) \quad H_D = \sum_i A_i U_i^* + \sum_k l_k \Psi_k \quad [W/K]$$

where A_i is the area of the i-th element of the wall, it being considered as a stratification of layers with different thermal transmittance U_i^* . The linear thermal transmittance of the thermal bridge is defined in equation (5).

$$(5) \quad \Psi_k = L^{2D} - \sum_i U_i l_i \quad [W/(mK)]$$

where L^{2D} is the coefficient of thermal linear coupling through the component calculated according to EN ISO 10211 and U_i is the measured value of the thermal transmittance in correspondence of the thermal bridge.



3.3 Structural integrity

Introduction

The INSITER approach proposes the use of an active IR thermography process, which has been applied to inspect the structural integrity of prefabricate Glass Reinforced Concrete (GRC) panels.

In the ASTM D 4788-03, that uses a passive thermography approach, the following problems have been identified:

- Relatively low thermal conductivities of materials and large dimensions of civil engineering structures contribute to difficulties in achieving homogenous cooling of the monitored
- Defects in the construction elements that are not exposed to direct sunlight cannot be located
- Quantitative results cannot be supplied, but quantitative data are needed to characterize size and depth of the defects.

More advanced standards (ASTM E 2582-07) in use in the aeronautic field were taken as reference to develop the active approach. This practice has utility for testing of GRC panels with inspection surfaces that are sufficiently optically opaque to absorb incident light, and that have sufficient emissivity to allow monitoring of the surface temperature with an IR camera. Excessively thick samples or samples with low thermal diffusivities require long acquisition periods and yield weak signals approaching background and noise levels, so advanced post processing algorithms are necessary to improve the contrast in defected area.

Terms, definition, symbol and units

- Inspection surface: the surface of the specimen that is exposed to the apparatus.
- Logarithmic temperature-time plot: a plot of the natural logarithm of the surface temperature with preload temperature subtracted on the y-axis versus the natural logarithm of time on the x-axis, where time $t=0$ is taken to be the start of the cooling event. Either temperature or radiance may be used to create the plot.
- Glass Reinforced Concrete Panel (GRC).
- τ_{acq} : Acquisition period, IR detector recording data.
- τ_{load} : Thermal load time

Apparatus

In order to collect data on the area extent and location of the delaminations, the following apparatus is required:

- IR Camera — an imaging IR camera having a minimum thermal resolution of ± 0.5 degrees Celsius under ambient air conditions. The camera should be capable of uninterrupted monitoring of the sample surface for the entire duration of the acquisition. Thermal-camera wavelength should be in the 2-14 micron range. The IR Camera shall be mounted on the front of the inspection surface at a reach sufficient to allow solving the minimum defect searched. The IR camera shall be capable of producing a digital compatible image format (JPG, MAT, BMP, etc.) to be elaborated by appropriate software. The optics and focal plane should be sufficient enough so that the projection of nine contiguous pixels onto the sample plane is less than or equal to the minimum flaw area that is to be detected
- Contact Thermometer — having a minimum temperature resolution of ± 0.5 Celsius degrees to monitor the surface temperature
- Halogen lamps — at least one halogen lamp should be employed to provide uniform illumination to the sample surface. The array should be placed to avoid a direct path of the halogen energy into the IR camera lens opening;



- Acquisition System —The acquisition system includes the IR camera, halogen lamps and a dedicated computer that is interfaced to the camera or both the camera and halogen lamps;
- Analysis Software —the computer software should allow acquired sequences to be archived and retrieved for evaluation, and allows real time display of the IR camera signal. The software should allow viewing of the logarithmic temperature-time for specified pixels. Additional processing operations on each raw image sequence may be performed to improve detectability of subsurface defects, (for example averaging, subtraction, noise-reduction, calculation of first or second time derivatives, complex algorithm of image processing, etc).

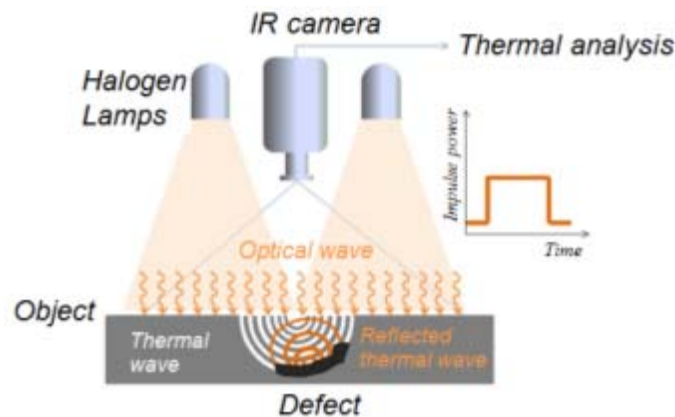


Figure 3: Measurement setup

Calibration Procedure

The IR camera should be calibrated and maintained at regular intervals, following the procedure recommended by the manufacturer. Non-uniformity or flat field correction should be performed according to the manufacturer's instructions, or more frequently, if required to achieve optimum camera performance.

Before the beginning of the test, the thermal camera should be calibrated basing on the environmental conditions. For this reason, properties like surface emissivity of the component and transmissibility of the medium between the camera and the component should be set. Internal temperature and humidity have to be monitored during all the test duration for a correct calibration of the IR sensor.

Measurement of the dimensions of a single pixel field of view can be achieved by placing an object with known dimensions into the field of view at the sample plane, and determining the number of pixels that span the object in either the horizontal or vertical direction.

$$(6) \quad \text{Pixel field of view size} = \frac{\text{object length}}{\text{number of pixel}}$$

More than nine pixel are necessary on the minimal size of defect that must be detected. Data sequence for the reference standard can be acquired by using the normal examination procedure.

In the analysis software, view the logarithmic temperature-time plot for a point on the surface that corresponds to the deepest feature or interface that must be detected.

The log plot in the cooling phase should be a monotonically decreasing straight line with slope approximately equal to -



0.5. In general, slope values should be in the range -0.55 to -0.35.

If the initial slope value is not in the range -0.55 to -0.35 after the previous steps have been taken, the following steps may be performed to improve performance: The power thermal load or load time could be increased and the sample surface may be coated with a washable paint to increase the optical absorption and emissivity of the sample.

Verify flash lamp array uniformity using the aluminium plate reference standard.

Measurements procedures

The apparatus has to be positioned so that the inspection surface is in the field of view of the IR camera and Halogen lamps.

The apparatus should be mounted to minimize thermal conduction to the surface in inspection.

IR camera will be focused, by placing a thermally reflective object (for example foil marker) on the sample surface and adjusting the camera lens until the edges of the object appear distinctly.

The inspection surface should be clean and free of dirt or grease. Obvious visual indications or features should be noted.

After that, the data acquisition and recording with the IR camera begins.

The data sequence should contain at least one frame acquired prior to the load event.

If the thermal diffusivity and thickness of the test panel are known, the acquisition period should be estimated to be at least

$$(7) \quad \tau_{acq} = \tau_{load} + \frac{2s^2}{\alpha} \quad [s]$$

where s is the thickness of the panel and α is its thermal diffusivity. This value is three times greater than the time required for heat from the inspection surface to reach the back, this is due to the temperature was monitored during thermal excitation period together with the cooling period.

Activate the halogen lamps for a time of middle of acquisition period.

Terminate IR camera data acquisition after a sequence of appropriate duration has been acquired.

Analysis of the data

The raw captured data sequence, or its first or second logarithmic derivatives, may be viewed as a sequence of images so that the entire volume of interest of the test material is interrogated.

Analysis of the raw captured sequence is based on visual identification of contrast between flaw indications and intact areas in the field of view. An advanced analyse usually is necessary for diffusive material with high thickness. Algorithm of Pulse phase thermography (PPT) or Principal Component Analysis (PCA) could be applying on the raw data.

Pulse phase thermography (PPT) is the active IR technique, which enables the collected data to be transformed from the time domain to the frequency domain using one-dimensional discrete Fourier transform (DFT). PPT is well known for NDT of materials and structures. It combines features of pulse thermography (PT) and lock-in thermography (LT) techniques and thus enables an easy data acquisition and fast data analysis.

Principal Component Analysis (PCA) is a statistical analysis tool used for identifying patterns in data and expressing the data in a way to highlight the similarities and differences in the patterns. The pattern matching of the data becomes very difficult when the data dimension is very high. In such situations, PCA comes in handy for analysing and graphically representing of such data. Once the patterns in the data are found, the data is compressed by reducing the data dimensions without much loss of information. PCA applied to the data in the form of thermograms sequence is called



PCT. The image data captured by the IR cameras consist of undesirable signals and noise along with the IR image data. These image sequences are to be processed to eliminate the undesirable signals and enhance the useful IR information. The PCT used for processing IR sequences is based on thermal contrast evaluation in time.

3.4 Practical hints for using IR camera

For performing quantitative measurements with IR cameras, the user need to know the radiation physics in order to perform accurate calibration and corrections accordingly. It is fundamental to understand that IR cameras acquire images representing the radiation of the framed object in the electromagnetic spectrum with wavelengths from 0.9–14 μm . IR cameras inherently measure irradiance not temperature, even though in practice their outputs are temperature maps, the so-called thermographs. The missing link is in the calibration procedure, which is based on effective blackbody radiance and temperature. Therefore, to estimate the actual body temperature the emissivity of the target object must be set accurately. Emissivity is the efficiency of an irradiated material in emitting in the IR field and it depends on the material properties and its superficial conditions, like roughness, type of coating, soiling or rust for metallic materials. The emissivity of smooth, glossy and shiny surfaces is generally lower than the one of rough and opaque surfaces of the same material. For instance, the emissivity decreases due to surface wear, like scratches or deterioration. For a correct temperature measurement based on IR irradiance, the emissivity must be set to a realistic value. Many commercial IR cameras are provided with a large database of common materials of known emissivity.

A further important aspect that the user must know is the influence of the measurement ambient and the building physics. The principal factors to be taken under control are:

- reflection
- air flows
- furniture
- wall thermal gradients
- building morphology
- influence from the external environment

Some materials reflect radiation in the IR field and they behave as mirrors, which reflect in the visible field. One of those materials is glass, as visible in Figure 4.



Figure 4: The window reflects the thermal irradiance coming from the IR camera operator, image courtesy of FLIR

Reflections of the thermal irradiance coming from the IR camera operator or from a light source placed in the room are interfering inputs causing wrong temperature reading. The measurement ambient must be accurately evaluated in order



to avoid framing area exposed to reflections. If there is a considerable difference in temperature between the measuring object and the surrounding environment, the reflections of the incident radiation will affect the readings of the IR camera. Many cameras allow taking into account the apparent temperature due to the reflections of the surrounding radiation.

Thermal flows acting in the building are interfering inputs as well: heating systems generate temperature differences that can cause an incorrect reading of the temperature distribution on the walls; the flows of cold air from the fans or air conditioners may have the opposite effect, cooling the surface.

Furniture (cupboards, shelves) and decorations (paintings, curtains) in contact with the opaque walls and/or windows modify the distribution of the temperature of the surfaces of interest, having an insulating effect. If such objects are removed from the wall, the thermal image would show cold areas in their place, which could be attributed to lack of homogeneity of isolation. In Figure 5, two thermal images of the same wall are shown. The outside temperature is less than that inside. The image on the right shows that the thermal image acquired after having removed the picture on the left from the wall evidences a cold area behind giving the impression of an area where the insulation is missing. It is important to remove objects from the wall at least 6 hours before the inspection.

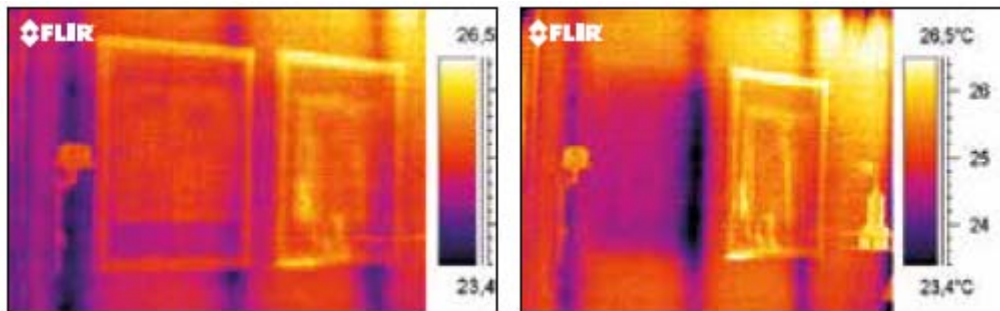
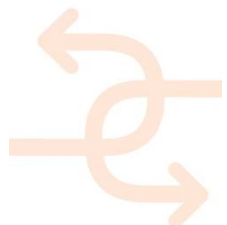


Figure 5: Influence of paintings on the wall temperature distribution, image courtesy of FLIR

In the use of the camera for diagnostics of thermal bridges on buildings elements (such as missing isolations) it is necessary that the element is subjected to a thermal gradient between the interior and exterior of at least 10 ° C between the two sides of the wall. To accurately operate the inside and outside temperature must be known and its changes monitored within 24 hours prior to the measurement. The building morphology is another factor that must be taken into account before defining the inspection procedure. For example, in the case where an air gap exists between the outer skin and the rest of the construction, the temperature measurement cannot be made from the outside because the air is an insulator. If the internal temperature is higher than the external one, any framework in the wall construction becomes colder seen from the inside. From the cold side it is the opposite situation. These are expected characteristic patterns and they cannot be interpreted as unexpected thermal bridges.

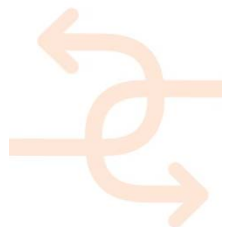
Finally, there are several external factors affecting the building physics:

- The sunlight that shines on a building affects the thermographic reading because light and shadow generate thermal unevenness on the exposed wall. Furthermore, due to the thermal inertia of the wall itself the effects of exposure to radiation or shade have long-term effects that depend on the time constant of the material constituting the wall itself. For example, the time constant (or dynamic response) of the brick is much slower than that of wood.
- The wind and air flows cool the outer surfaces of the walls, reducing the temperature differences between hot and



cold areas.

- The rain cools the outer surfaces of the walls and, in addition, the evaporation of water induces wall surface cooling after the rain.
- The snow increases the insulating properties and this should be taken into account.



4. Protocols for acoustic test

4.1 Sound pressure level distribution

Introduction

Two applications are here foreseen, namely the mapping of the acoustic pressure at the surface of a panel or window separating two spaces and the mapping of the acoustic pressure in the vicinity of an active component such as MEP/HVAC systems or ventilation apertures. For instance, a map of the sound pressure level at the surface of a panel gives an insight on the regions where the insulation performance is low. This may arise as a consequence of a defect in the fabrication of the panel or from leakages at the junctions between components, e.g. at window frames. The apparatus retained for the sound pressure mapping is a new MEMS microphone array, under development at SISW as of the writing of this deliverable.

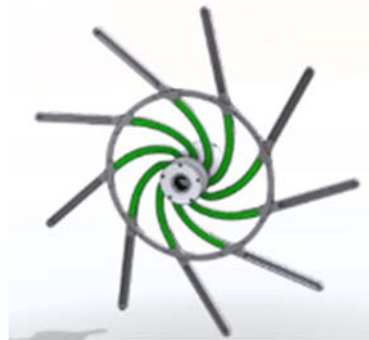


Figure 6: Siemens MEMS microphone array prototype

It is worth noting that the mapping of the sound pressure level can be performed using most commercially available microphone arrays. The proposed MEMS array has the advantage of being cost-effective and of requiring a minor number of steps for performing a measurement.

Terms, definition, symbol and units

The sound pressure is here denoted p and is measured in Pascals (Pa). The corresponding sound pressure level is denoted P and is defined as the level in decibels compared to a reference pressure, as

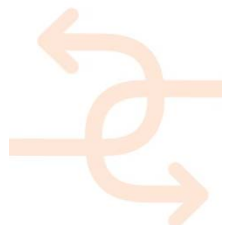
$$(8) \quad P = 20 \log_{10} \left(\frac{|p|}{|p_0|} \right) \quad [dB]$$

where $p_0=2e-5$ Pa is the accepted standard threshold of human hearing.

Apparatus

The microphone array consists of a range of MEMS microphones as shown in Figure 6. The array can be extended in size by means of extension bars shown in the figure and containing further microphones in order to increase the accuracy of the sound source localisation in low frequencies.

The device includes an optical camera providing a simultaneous visualisation of the sound field distribution and the



scanned object.

In addition, an infrared sensor provides the distance from the microphone plane to the centremost object placed in front. This defines the distance at which the sound pressure is back-propagated from the microphone measurements in order to obtain the actual sound pressure level at the surface of the object.

Calibration procedure

A calibration of the microphone array is not required for every measurement case. However, a laboratory calibration is required on a periodic basis. As of the writing of this document, the device exists as a prototype and therefore the specific calibration details will be specified in a further deliverable.

Measurements

The acquisition of the sound pressure level distribution for a panel or window is performed as follows. An acoustic source is placed at one side of the structure. Preferably, an omnidirectional broadband source is to be used. The array is placed in front of the structure such that the desired area to map appears in the camera image. The sound pressure level is displayed continuously and can be recorded and exported for further use, as a time- or frequency-dependent pressure distribution, or as a single average pressure map.

Data exchange

A crucial aspect is that the measurement phase must include the referencing of the coordinates of the acquired pressure map. The pressure map can be exported as a transparent image together with the acquired optical image of the measured area or building component. This will make it possible to include it into the BIM model as an overlay.

4.2 Sound intensity field

Introduction

The method proposed here for the in-situ measurement of the sound intensity consists of a generic procedure, applicable to panel or window junctions and also to active components such as MEP/HVAC systems or ventilation apertures. The apparatus retained for the tests in this project is the LMS SoundBrush probe (SoundBrush manual, 2014).

Alternatively, a conventional intensity probe may be used. The SoundBrush probe and software provide the advantage of a straightforward calibration and measurement procedure.

Terms, definition, symbol and units

Sound intensity is defined as the product of the acoustic pressure by the particle velocity vector. Intensity probes including the SoundBrush probe measure sound pressure at the microphone positions and provide an estimation of the sound intensity as a differential approximation.

The unit of sound intensity is W/m^2 .

Apparatus

The LMS SoundBrush probe consists of four microphones flush mounted on a rigid sphere, as depicted in Figure 7.

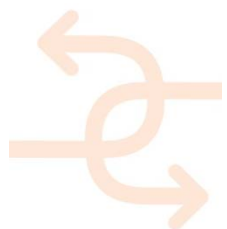




Figure 7: G.R.A.S. sound intensity probe

Among the other components of the probe are a processing unit and a luminous sphere for calibration. The microphones' positions describe a tetrahedron, which makes it possible to obtain the components of the sound intensity vector in the three directions of space.

Calibration procedure

The calibration is performed as follows.

A tracking camera is placed in front of the object to be scanned. The probe is placed on a dock in an area visible for the tracking camera, which sets the reference position for the measurement. A distance and colour contrast calibration is performed by locating the probe in front of the camera. In case of using the SoundBrush probe, these steps are part of a natural workflow in the software.

Measurements

The measurement of the sound intensity vector field is performed as follows. In the case of the mapping of a passive component such as a window or a junction between two panels, a sound source is placed at one side of the panel or junction. Preferably an omnidirectional broadband source is to be used. The scanning is then performed in the vicinity of the junction and covering a sufficiently large volume to observe acoustic energy leakages from the structure. If the component actively produces noise, such as in the case of HVAC/MEP systems or ventilation apertures, the scanning area must exceed the dimensions of the object, such that the specific sources of noise are identified. The resulting data within the SoundBrush software consists of the time history of the sound intensity vector at every point of the scanned region, per third-of-octave band.

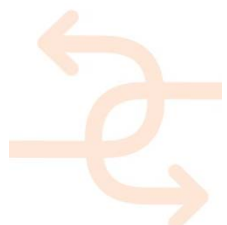
Data exchange

The sound intensity measurement consists of a vector field, thus in this case a three-dimensional point cloud may be created as an object to be overlaid in the BIM model, or an appropriate two-dimensional cross-Section of the vector field may be chosen from the SoundBrush software and exported as an image or dataset.

4.3 Sound transmission loss

Introduction

The international standards recommend the measurement of the sound transmission loss to be performed by placing the sample to be tested between two reverberation rooms (ASTM-E90-09, 2009). The estimation of its value is made by



comparing the average sound pressure level in both rooms. Such a measurement requires the availability of the reverberation rooms and for the sample to be uncoupled from any other building component.

An equivalent procedure is specified in the standards (ASTM-E2249-02, 2008), consisting of the placement of the panel sample between a reverberation chamber and an anechoic room and is based on the measurement of the sound transmission loss from the sound intensity level difference between the two faces of the sample. Such technique is also specific to laboratory conditions.

The procedure described in the present Section consists in inferring an estimation of the sound transmission loss from acoustic intensity or pressure measurements in the vicinity of the wall. Here, an in-situ method for an estimation of the transmission loss is proposed based on the incident and transmitted field in the vicinity of the panel or wall. In the present case, a methodology based on an intensity probe is proposed. The apparatus retained for the tests in this project is the LMS SoundBrush probe. It is worth noting that the sound transmission loss measurement described here may equivalently be performed using a conventional sound intensity probe. Nevertheless, the procedure is here detailed for the case of the retained probe.

Definition, symbol and units

The sound transmission loss is denoted here as TL and is measured in decibels (dB). The spatial coordinates of the wall are denoted as follows. For the purposes of the present document, it is assumed that the wall is vertical, with x the direction perpendicular to it and z the vertical axis. Thus, the sound transmission loss determines the energy loss for sound travelling in the x direction.

Apparatus

Please refer to the corresponding paragraph in the previous Section.

Calibration procedure

Please refer to the calibration procedure in the previous Section.

Measurements

The measurement of the sound transmission loss is performed as follows, by repeating the procedure described in the previous Section for the two faces of the panel. First, a sound source is placed at one side of the panel. Preferably, an omnidirectional broadband source is to be used. The measurement region on the panel is defined such that its area covers a region large enough for the estimation to be representative of the entire panel. A surface area of more than 1m^2 is recommended. The scanned areas at both sides of the panel must be identical and facing each other. Both sides of the wall are scanned covering the area as densely as possible with the probe, at a distance within a tolerance region of 2 to 5 centimetres from the panel. The resulting data within the SoundBrush software consists of the time history of the sound intensity vector at every point of the scanned surface at both sides of the panel, per third-of-octave band.

Analysis of the data

This Section illustrates the procedure for estimating the sound transmission loss from the measured data in the case of the SoundBrush probe. The measured data is exported as a text file containing the sound intensity vector per third-of-octave band at every position within the scanned surfaces. This makes it possible to compute the magnitude of both the incident and transmitted sound intensity vectors as the average across each of the faces of the panel.



The sound transmission loss is obtained as

$$(9) \quad TL(f) = 10 \log_{10} \left(\frac{|I_i(f)|}{|I_t(f)|} \right) \quad [dB]$$

where I_i is the average incident sound intensity and I_t is the average transmitted sound intensity.

Alternatively, the sound transmission loss may be estimated from a measurement of the acoustic pressure following the same procedure, as

$$(10) \quad TL(f) = 20 \log_{10} \left(\frac{|p_i(f)|}{|p_t(f)|} \right) \quad [dB]$$

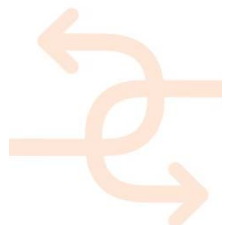
The latter may be particularly of use when a sound intensity probe is not available, thus rendering possible the use of a single microphone or sonometer.

Reciprocity compensation

Owing to the case-dependent nature of the measurement, it is hereby recommended to repeat the above measurement and data processing procedure with the sound source at the opposite side of the panel and consider the final estimation of the sound transmission loss as the average of both results, frequency by frequency.

Data exchange

The format of the estimated sound transmission loss is a curve or set of data related to a particular panel. Such information can be attached, for instance to a BIM model, as a dataset related to the panel or window. Additional information can consist of the scanned area of the panel, which may be uploaded to the BIM model.



5. Protocols for geometric discrepancy test

Introduction

Nowadays, the medium-long range 3D laser scanners are already known for their accurate three-dimensional measurements (X, Y, Z) for as-built documentation of any kind of buildings, being an alternative and a complement to classical measuring methods such as Topography and Photogrammetry.

The colour coordinates of the registered points (R, G, B) are optionally acquired by means of digital cameras, internally or externally coupled to the scanner.

Apart from geometry and colour, laser scanners might also provide additional information, as it is the reflectivity index (L), which helps distinguishing materials and can be related to moisture content on a particular material (see Section 6).

All related information can be geo-located by means of scanner's built-in GPS, as well as by a translation of local to absolute coordinates (GPS) by association of points of which these latter are known (see Section 7).

Scope

The present chapter is aimed at defining a novel methodology for obtaining point clouds comprising the information on geometry, colour and index of reflectivity in order to be usable within BIM tools in addition to evaluate geometric discrepancies in energy efficient buildings made of prefab components. These point clouds are used as a basis both for comparison regarding the BIM original project of the building and also for the definition of parametric elements in the context of construction, refurbishment and maintenance operations.

Terms, definition, symbol and units

These are the data provided by a laser scanner that can be toggled:

- XYZ: Spatial coordinates (usually Depth, Width, Height): all three are usually measured in meters.
- RGB: Colour coordinates (Red, Green, Blue): these three are dimensionless integer values ranging from 0 to 255 (256 values for each one).
- L: index of reflectivity: decimal value between 0 and 1.

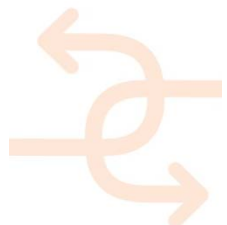
Time of flight (TOF) or phase shift (PS) laser range scanners operate allowing spatial (X, Y, Z) and, optionally, colour (R, G, B) coordinates to be obtained, as well as, in the INSITER case, the reflectivity index (L) of all those points that are recorded when digitizing a surface.

Two scanners are tried in field work for the project as representatives of the two main technologies:

- FARO Focus3D X330 (PS technology): <http://www.faro.com/products/3d-surveying/laser-scanner-faro-focus-3d/overview> (Accessed on January 2016).
- LEICA HDS-3000 (TOF technology): <http://hds.leica-geosystems.com/en/5574.htm> (Accessed on January 2016).

Measurements

Placing the scanner in different positions, a laser beam automatically sweeps the surface of a building to be digitized according to a pre-set configuration (geometric resolution, sampling frequency, observation window size ...). The coordinates of the registered points are obtained with respect to the position of the scanner, making a "cloud".



6. Protocols for humidity test

Introduction

Moisture is one of the main factors in the deterioration of buildings, causing mould, unwanted parasites and the decanting of salts. The existence of moisture does not only affect the building aesthetically, but it is also evidence of bad conservation conditions. It is thus extremely important to verify and assess the extent of the moisture, even though it may not be confirmed by mere visual inspection.

Scope

Developing a novel, practical method for obtaining 3D digital models that clearly show where moisture appears, and also where it is likely to appear in prefab-made buildings.

To this end, an applied research approach is proposed, which combines state-of-the-art 3D data acquisition, with a tailored computational algorithm for managing the reflectivity index (L) provided by laser scanning devices. Hence, a useful unique digital model, including geometrical, color and reflectivity information of complex shaped objects, could be readily obtained, thereby favoring not only documentation, but also revealing the moisture extension and content (using a thermo-hygrometer).

Terms, definition, symbol and units

These are the data provided by a laser scanner that can be toggled:

- XYZ: Spatial coordinates (usually Depth, Width, Height): all three are measured in meters.
- RGB: Colour coordinates (Red, Green, Blue): these three are dimensionless integer values ranging from 0 to 255 (256 values for each one).
- L: index of reflectivity: decimal value between 0 and 1.

Apparatus

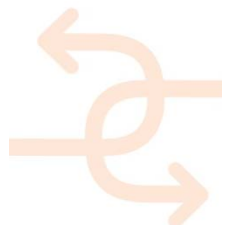
Time of flight (TOF) or phase shift (PS) laser range scanners operate allowing spatial (X, Y, Z) and colour (R, G, B) coordinates to be obtained, as well as, in some cases, the reflectivity index (L) of all those points that are recorded when digitizing a surface.

The reflectivity index is the fraction of the incident radiation that is reflected by a surface at a given point. The light intensity emitted by the laser scanner is taken as the unit value, then the total amount of light reflected by the material is less than or equal to that value.

Two scanners are used in fieldwork for the INSITER project: (1) FARO Focus3D X330 (PS technology) and (2) LEICA HDS-3000 (TOF technology). This last has a data acquisition speed of 1,800 points per second. The typical geometric resolution used (vertical and horizontal point-to-point measurement spacing) is 0.02 m @ 7 m away to the surface, enough to have a proper density of 3D points and a permissible file size.

Calibration procedure

It depends on the use and care of the laser scanner and should be performed when anomalies in the acquisition of 3D data are observed, requiring a HW and/or SW reconfiguration by the manufacturer. There is no specific need of a periodic calibration (as customary in other measuring equipment).



7. Protocols for positioning system test

One of the main important tools developed in the INSITER project is the positioning system in order to connect the data output from the devices to the BIM and AR. There are different approaches related to the instrumentation and building involved in the measurement, as shown in the table below.





Positioning System	Advantages	Drawbacks	
GPS for interior positioning + RTK (SmartTrack Technology)	Real time acquisition of the system position; Accuracy of GPS could be 2/4 cm after RTK on-field.	High cost for improving the indoor accuracy.	
QR Code, AR markers	Economic solution with many open source software to generate and read the code.	Number of the QR/AR markers, related to the FOV of the acquisition system; Difficulties in the positioning and referring system objects or defined components within featureless environments concerning QR/AR marker-based tracking.	 
Tracking, pattern and geometric matching algorithms	Low cost solution; Robust image processing algorithms.	Needs of references, markers, corners, contours or other building elements.	

Table 6: Different solutions for the positioning system

7.1 GPS + RTK

The best suitable positioning systems identified for 3D modelling of prefab-made buildings is a global navigation satellite system (GNSS), which is a space-based satellite navigation system that provides location and time information in all weather conditions anywhere on the earth (or near) where there is an unobstructed line of sight to four or more



navigation satellites. At this moment only the United States NAVSTAR Global Positioning System (GPS) and the Russian GLONASS are global operational GNSSs. China is in the process of expanding its regional BeiDou Navigation Satellite System into a global Compass navigation system by 2020. The European Union's Galileo is a GNSS in initial deployment phase, scheduled to be fully operational by 2020. All these systems are commonly known as GPS, so we will use this acronym to refer to any navigation satellite system.

To get better results it is important to use Differential Global Positioning System (DGPS). This is an enhancement to GPS that provides improved location accuracy, from the 15-meter nominal GPS accuracy to about 2-4 cm in case of the best implementations. DGPS uses a network of fixed, ground-based reference stations to broadcast the difference between the positions indicated by the GPS (satellite) systems and the known fixed positions.

3D digitizing of the exterior of buildings (laser scanning/photo-scanning) in combination with GPS allows absolute positioning. A typical DGPS has the characteristics given in the following table:

Accuracy	Data transfer protocols	Weight	Others
Real Time Kinematic (RTK):			
Horizontal: 10 mm + 1 ppm	3- serial ports 1- controller port (owner)	Receiver: 1.20 kg. Controller: 0.48 kg. SmartTrack Antenna: 0.44 kg.	Dual-frequency receiver. SmartTrack technology to obtain centimetre accuracy, RTK 20 Hz @ 30 km.
Vertical: 20 mm + 1 ppm	1 antenna port (standard)	Ion-Li battery: 0.19 kg. Carbon fiber cane with SmartTrack antenna and controller: 1.80 kg.	3D digitizing of buildings' outdoors in combination with GPS allows absolute positioning.
Static (post-processing):			
Horizontal: 5 mm + 0.5 ppm			
Vertical: 10 mm + 0.5 ppm			

Table 7: Characteristics of GPS + RTK system

The manufacturer/provider indications on this regard should be followed for use in all its products and services. National geodetic surveying organizations usually provides Global Navigation Satellite System antenna calibrations for specific antenna codes used for processing GNSS data.

Position the GPS unit in a static location. Determine the location according to the GPS coordinates and check for accuracy. If the unit is calibrated and clear of obstruction, the control point should be accurate and on target, ready to be recorded.

Place the tripod or antenna receiver you wish to use to triangulate or adjust the area to be covered. GPS surveying tools have pre-set control points of previously verified and surveyed locations. Move the receiver to the next point, and so on, to complete the survey, depending on the number of points needed.

Since 3D data acquisition allows relating indoors and outdoors views (by interSection of common areas / fiducial marks / geometrical features), a 3D geo-referenced point cloud could readily be provided.

Hence, the typical problems of using of GPS systems indoors are omitted. Accuracy of GPS could be between 2 to 4 cm after Real Time Kinematic (RTK) on field or further post-processing at office.



7.2 QR-Code

For a more accurate positioning system during indoor measurement, some artificial QR codes or marker could be used. This methodology represents a very low cost and simply solution for a quickly identification of the observed object in respect to the coordination system defined in the BIM. Furthermore, there are many software open source developed and this makes this solution very simple to apply.

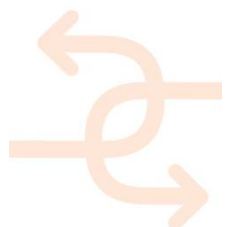
The problem of this solution is related to the number of the QR codes or markers needed for the complete recognition of the observed area. This number depends on the FOV of the acquisition system and to the distance between the devices and the component to measure. Another problem is due to the difficulties in the positioning and referring system on the components in respect to the absolute coordinates system of the BIM.

7.3 Tracking and localization methods

Concerning the new AR solutions, navigation and localization by capturing of camera images and use of tracking algorithms and feature or model based tracking will be applied. The detection of feature points means the tracking and computing of (camera) image information for computer vision algorithms and applications. Decisions are made, if parts of an image are set relevant as an image feature or not. The features are e.g. distinct points, curves, contours or regions. Feature points of objects and environments are the basis for feature tracking maps. Thus, feature-rich environments give a better accuracy then environments without distinct features. Thus, a feature-less environment cannot be used for feature-based tracking. In this case, additional tracking and localization methods are required such as additional or artificial QR codes or AR markers and feature-rich objects have to be introduced to the scene. Once an object is recognized and its location is known, simultaneous localization and mapping (SLAM) methods and algorithms can be applied to update the tracking map while moving to an unknown, but feature-rich part of a real scene and to keep track of the location simultaneously.

Another method is the derivation of the reference model from 3D CAD data to extract silhouette or contour information and compare this information with the near environment and available depth information. This often used for close objects and specific scenes with accuracy depending on the applied hard- and software. Additional hardware is needed for acquiring depth information such as MS Kinect or similar concerning depth based tracking systems. Moreover, advanced tracking algorithms allow the use of extracted silhouettes or contours in combination with 2D feature-based tracking algorithms, require a feature-rich building scene with recognizable contours that match exactly the provided 3D reference data models.

In the case of INSITER AR developments, feature-based tracking algorithms in combination with feature-rich objects, AR markers or additional user-interface location selection functionality are planned to be applied and will be described in detail within deliverable 2.1 and 2.2. If, for any reason, feature-based tracking is not possible (due to e.g. not enough features to be detected within scene, adverse lighting conditions or insufficient 3D reference model, which does not match the real building environment) the AR tool is not applicable. To visualize required planning information, other indoor positioning functionalities and planning applications would become necessary, e.g. including user-interfaced based location selection by the layout of the site and standard visualization of planning data. It is indispensable to know the correct position, orientation and where they are facing to for overlapping the environment through AR. Thus, corresponding features or AR markers must be present as a requirement to apply AR tools.



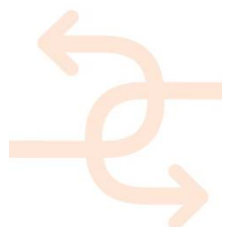
8. Protocols for data integration to BIM

8.1 Data connection to BIM

One of the challenges to be overcome in the INSITER project is how to interconnect the different measurement instruments and BIM. This is an interoperability dare because multiple formats need to be combined in the common standard IFC4, which is foreseen in INSITER. In this way and depending on the use cases, the following approaches might be provided:

MeshLab and RECAP tools: Within the WP2 tasks, the output from the measurement instruments is combined into the MeshLab software, which edits the unstructured 3D data from these sources in order to provide an enriched 3D model. This information is passed through RECAP in order to generate a compatible file with REVIT. Once finished, data can be imported into REVIT and exported via plugins into IFC2x3 or IFC4 so as to load the information in the server and make use of the BIM model for the self-inspection/instruction aims. The process is represented in Figure 8.

Middleware: There is a second case in which some data cannot be imported via REVIT. For instance, the textures are not overlayed in meshes and, thus, some of the use cases detailed in D4.1 could not be covered. In this case, the output from the measurement instruments should be treated in an intermediate layer, named middleware, in order to translate the XYZ, RGB or L formats into the common standard IFC, as illustrated in Figure 9. Within this approach, IFC4 objects need to be externally modelled, such as happens with the *IFCSensor* entity, described in D4.3. Then, a software tool developed in collaboration with WP3 would represent the measurement instrument as a „temporary“ *IFCSensor* whose measurement is associated to the *IFCTimeSeries* object. Moreover, the relationship between objects and properties are easily implemented following the data definition of IFC4, as well as the *IFCRelAggregates* and *PropertySets* (Psets). Finally, the usability of the IFC4 objects is assured in terms of integration with any of the BIM Servers stated in D4.3 or an IFC4-compliant database. Nevertheless, one requirement is the generation of the BIM model of the building in a previous step which already contains the geometry of the building and, then, this model and external data are combined via software.



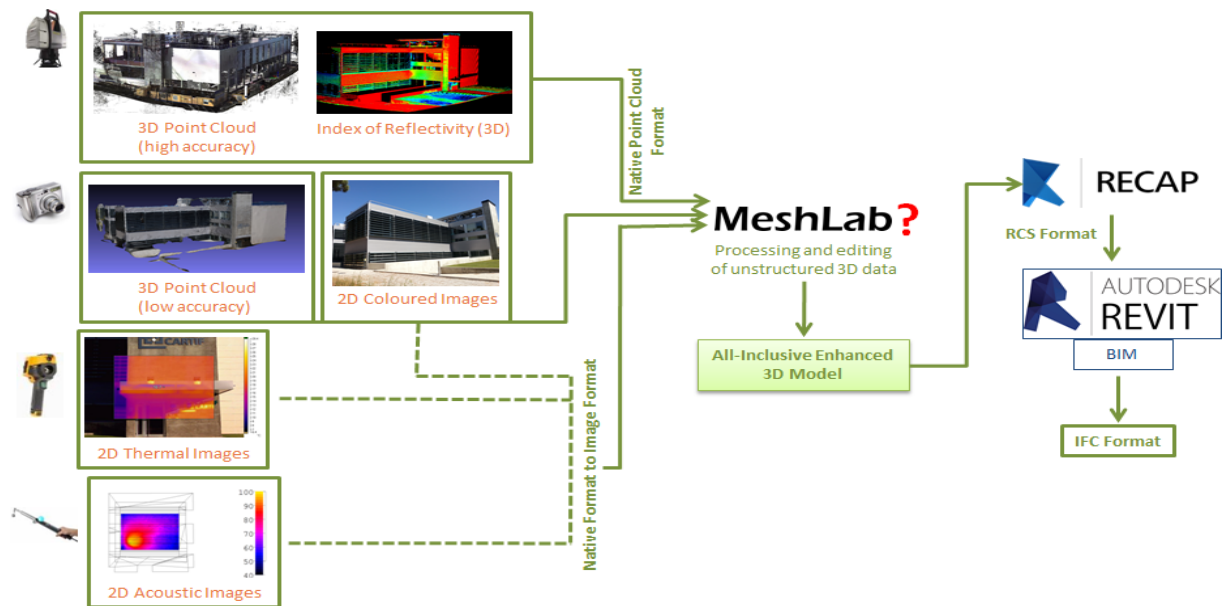


Figure 8: Data importation into BIM

Apart from the aforementioned procedures to connect the measurement instruments and BIM, there is a third point which is important to fulfill the use cases. That is positioning system. In order to face the geo-refering, REVIT is envisaged to allow the creation of a building model including the location. Similar to the first approach, any REVIT compatible format file (e.g.: DWG, SketchUp) can be imported into REVIT and exported in IFC format while maintaining the GPS location as demonstrated in Figure 10. However, the second indicated approach takes place too because the output from the measurement instruments needs to be merged via external software (or middleware). Then, when the use case requires geo-refering, an hybrid approach is recommended.

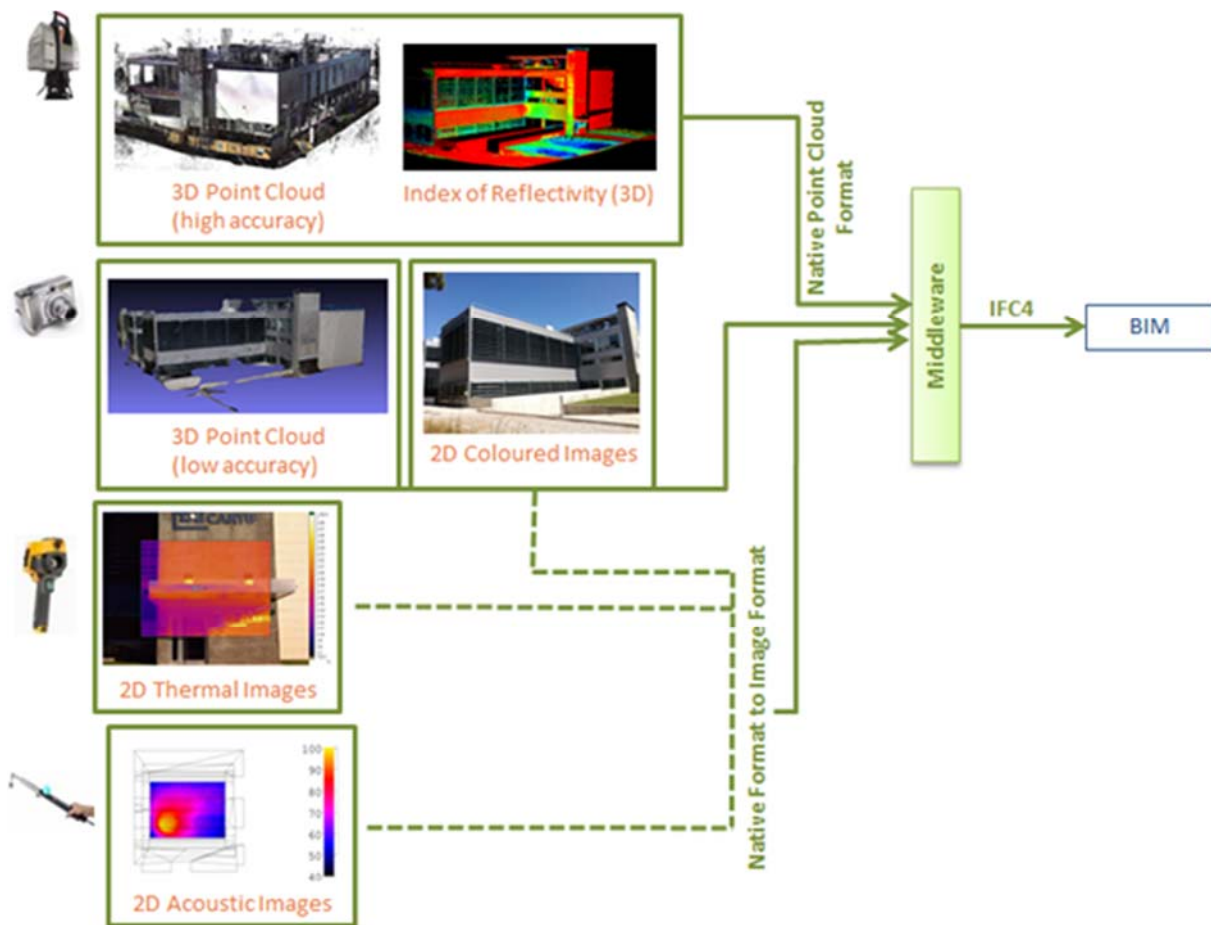


Figure 9: Additional combination of data

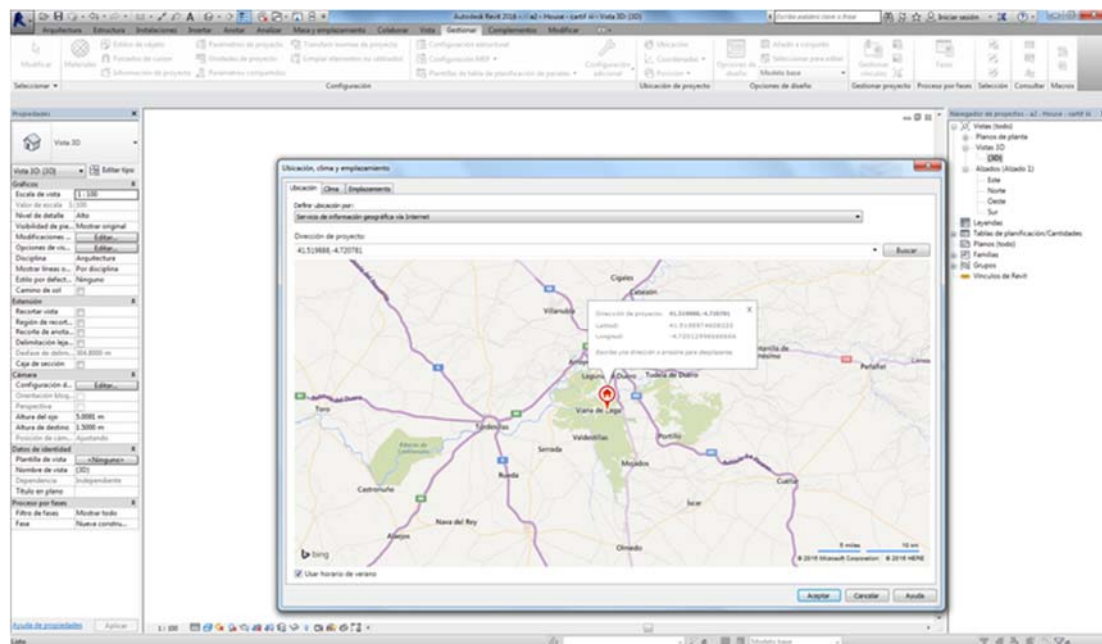
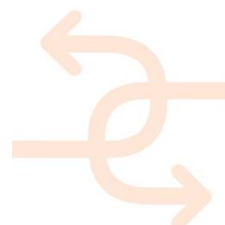


Figure 10: Geo-referred IFC model



9. Experimental proof-of-concept

9.1 Proof-of-concept setup at the lab facility

This Section describes the pilot test case used for the preliminary application of the thermal and acoustic procedures shown in the previous Section. The pilot test case is a mock-up installed in the laboratory of the University Politecnica delle Marche (Ancona, IT). At present, only thermal and acoustic tests have been performed on this mock-up.

9.1.1 Mock-up structure

The pilot testing mock-up consists of a climatic room available at the UNIVPM laboratory of dimensions of 2230x2230x2030 mm.

A detailed description of the mock-up is reported in the Section 3.1.2 of the deliverable 4.1.

9.1.2 Dragados Panels

Dragados had provided 4 different prefab panels shown in Figure 11.

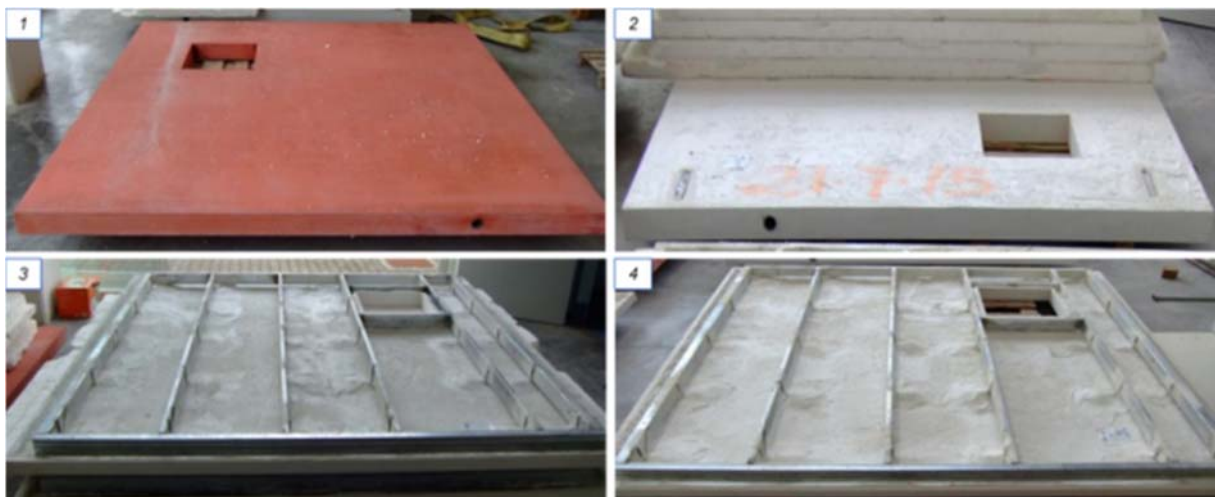
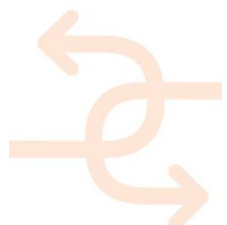


Figure 11: Dragados panels and their properties



Panel Identification Name	Inner Structure	Dimension [mm]			Layers
		Thickness	Height	Width	
1 Sandwich	Steel	100	2225	2230	GRC: Glass fiber reinforced concrete (10 mm) Extruded Polystyrene (80 mm)
2 Sandwich	Steel				GRC: Glass fiber reinforced concrete (10 mm) Extruded Polystyrene (80 mm)
3 Stud-frame	Steel	120	2225	2230	GRC: Glass fiber reinforced concrete (10 mm) None
4 Stud-frame	Steel				GRC: Glass fiber reinforced concrete (10 mm) with a polyethylene coating between the structure and GRC to reduce thermal bridges None

Table 8: Panel Properties

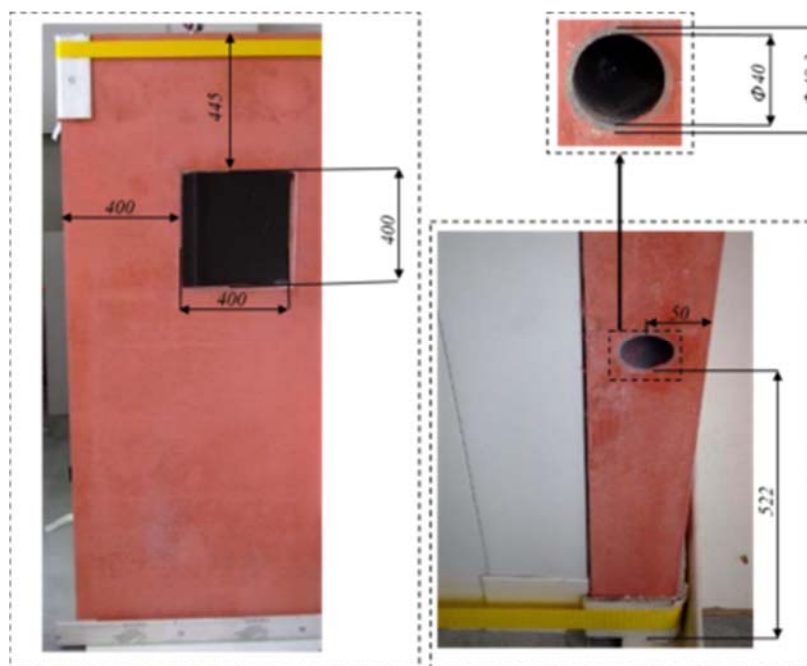
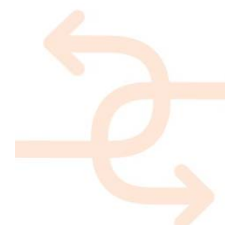


Figure 12: Details of pipe and window on the panel

Each panel presents an opening for a window, of 400x400 mm dimension, and a pipe of 40 mm diameter inserted at mid-thickness (Figure 12). A Plexiglas panel has been mounted on the opening to simulate a simplified window in the



wall. At this stage of the project, the panel number 1 in the Figure 11 has been mounted on the cooling room by replacing one of the existing wall as shown in Figure 13.



Figure 13: Dragados panel mounted on the cooling room

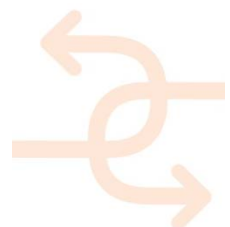
9.2 Tentative outcomes from the proof-of-concept

In this chapter the proposed testing protocols as described in Chapters 3 -7 are subjected to proof-of-concept. This is not real testing yet; the real testing will be performed in subsequent research, and the results will be presented and analysed in the follow-up deliverable D5.2.

9.2.1 Prof-of-concept following the protocols for thermal test

The thermal transmittance of the component has been evaluated according to the procedure defined in Section 2.1.

The thermal load used for the test has been realized with 4 halogen lamps (1kW_e for each lamp) positioned in a box realized with aluminium sheets. The lamps have been disposed with an angle of 45° in order to direct the radiation on the aluminium surfaces. This solution has been adopted in order to have homogeneous temperature inside the box and so homogeneous distribution of temperature on the surface where the load is applied. In Figure 14 the thermal load apparatus is depicted. The thermal load has been applied on the mock-up wall from the outside of the mock-up itself.



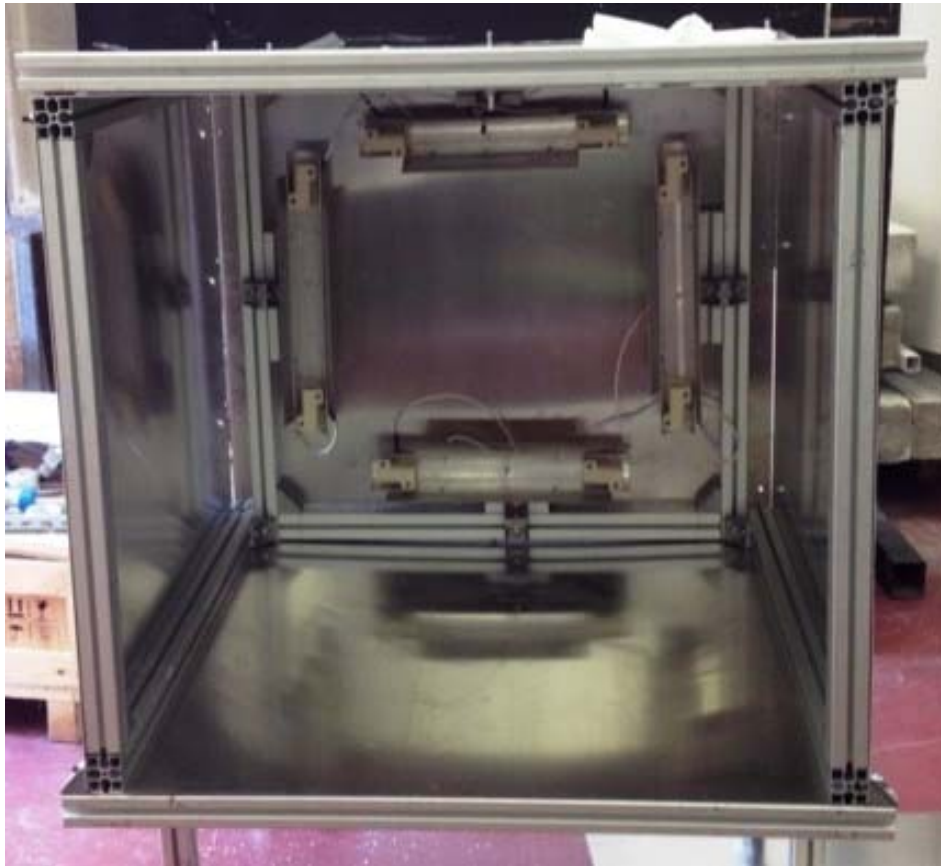


Figure 14: Thermal load applied on the component surface

The thermal camera has been mounted inside the mock-up, 2 m from the wall observed. Thermocouples and a heat flux transducer have been applied on the wall in order to have a reference in respect to the actual standard techniques.

Figure 15 and Figure 16 show the measurement setup respectively inside and outside the cooling room. Figure 17 shows the results obtained from the test. The hottest area represents the area corresponding to the thermal load area. In order to have an evaluation of the complete area of the panel, the box must be moved along the panel within different tests and the different results must be merged in a unique thermal map by using the positioning system described in Section 6.

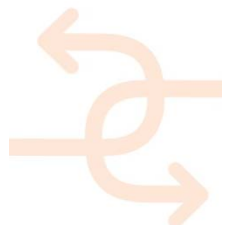




Figure 15: Sensors (IR camera, heat flux, thermocouples) positioned inside the mock-up



Figure 16: Thermal load applied to the wall



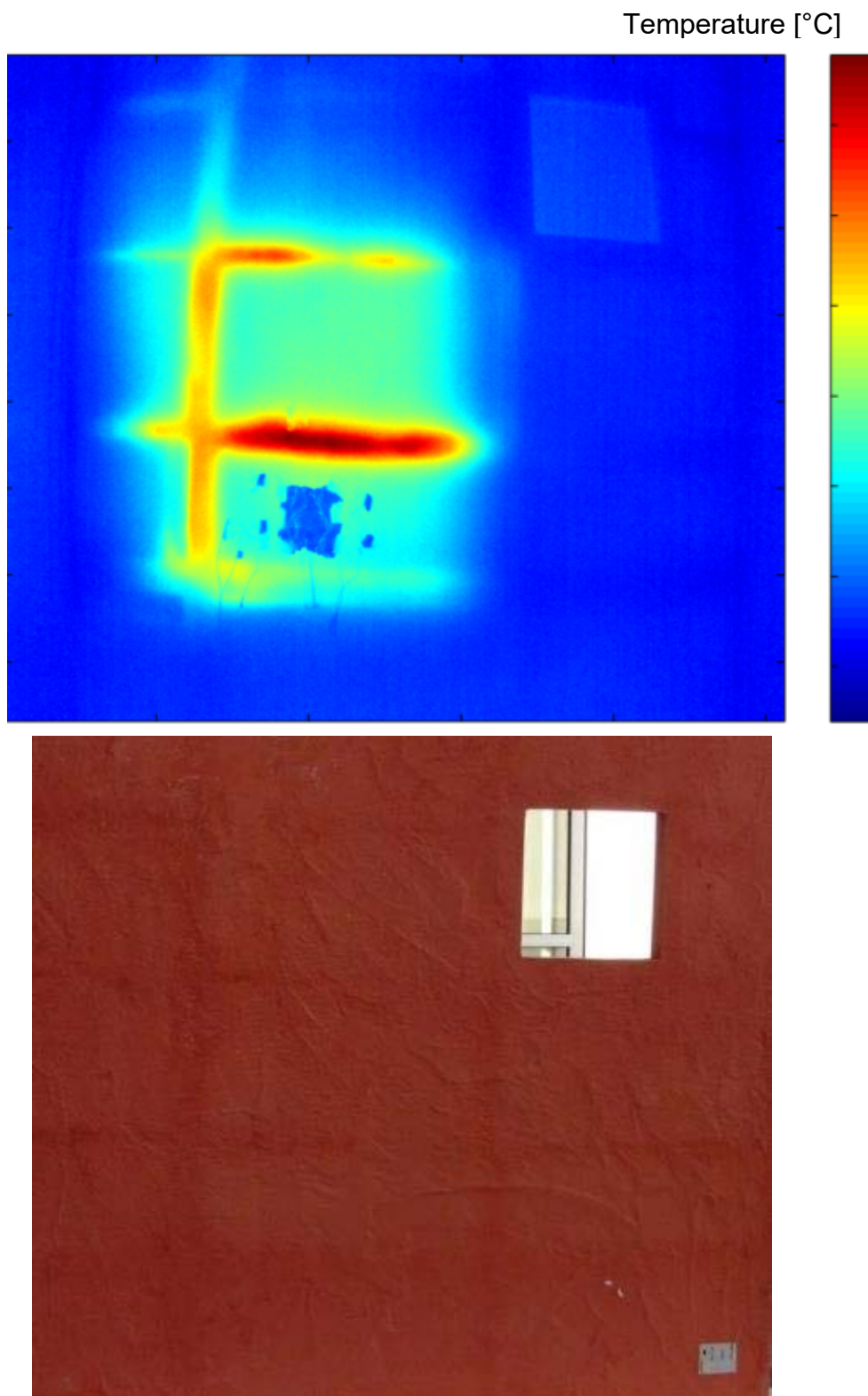
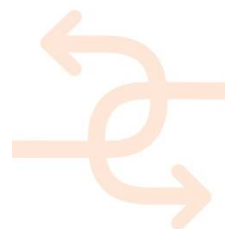


Figure 17: Thermal map obtained from the thermal camera and visio image of the component



Thermal bridges

For the evaluation of the component thermal bridge, if existent, the procedure developed in INSITER and shown in the Section 3.2 has been used.

The test has been done with the thermal camera placed outside the mock-up at a distance of 3 m in order to evaluate the total area of the panel. The thermal load has been positioned inside the pilot in order to have a uniform distribution of the temperature inside the mock-up. Figure 18 shows the positioning of the IR and visio-camera used for the superimposition of the thermal map into the visible image.

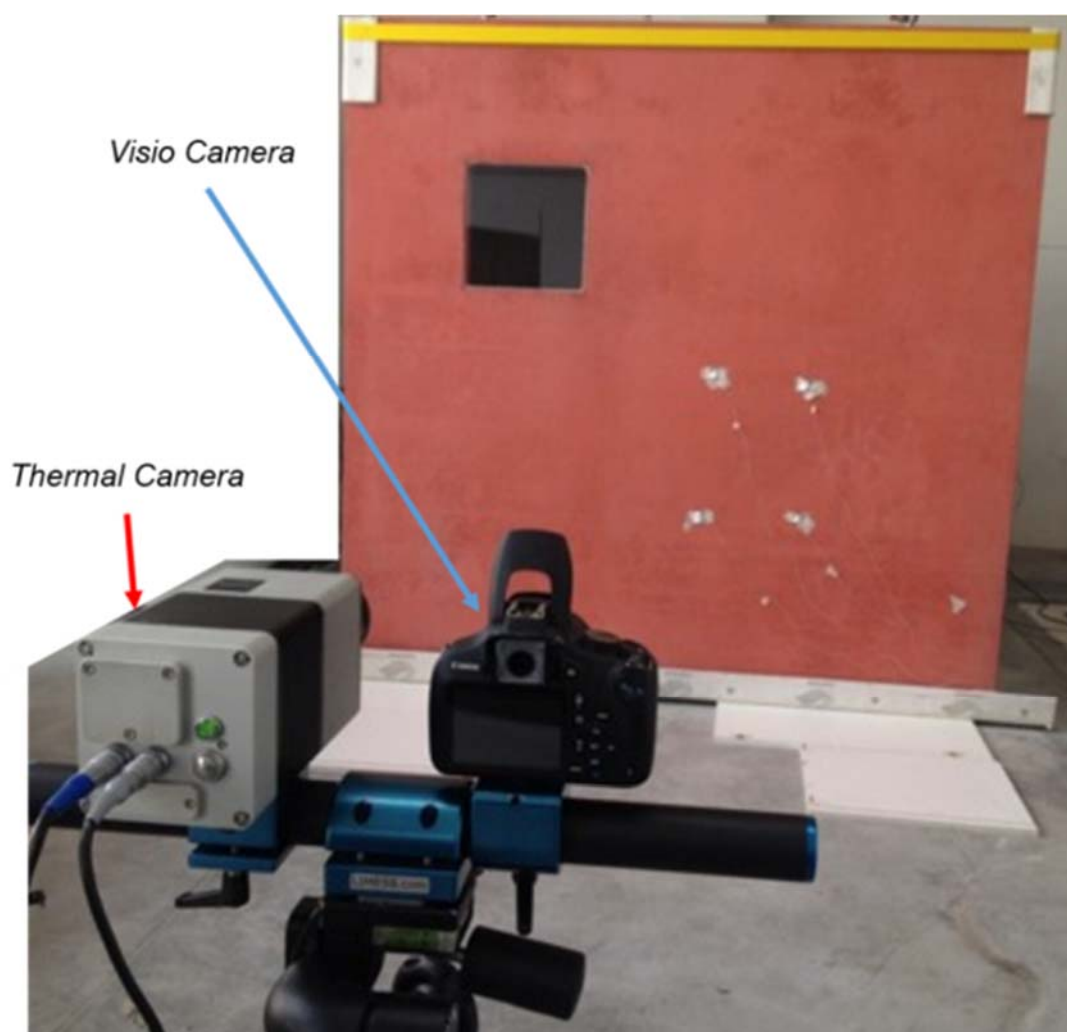
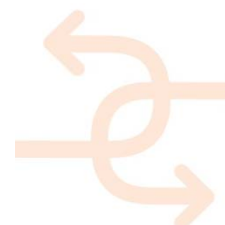


Figure 18: Measurement setup

In Figure 19 the thermal bridges corresponding to the internal metallic structure of the panel are visible and their location over the panel is facilitated by the superimposition of the thermal map into the visio-image.



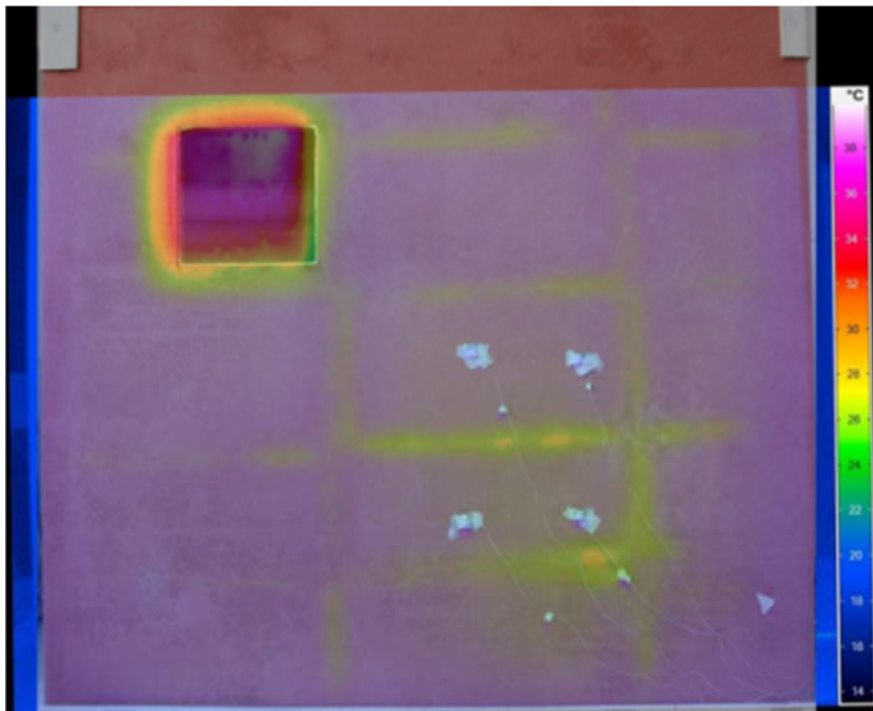


Figure 19: Thermal map superimposed to the visio image

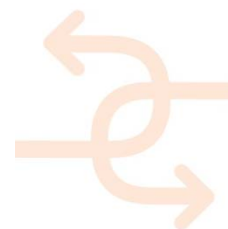
Quality control (discontinuity identification, damage detection)

Active thermography is applied on prefabricate GRC panels to inspect their structural integrity. An example of inspection has been performed on an open panel (panel number 4 in Figure 11). Two simulated defects have been realised on the panel:

- Defect A cylindrical hole of 10 mm diameter and 7 mm thickness
- Defect B cylindrical hole of 20 mm diameter and 7 mm thickness.



Figure 20: Dragados panel mounted for the quality tests



Tests have been performed in transmission mode, i.e. the IR camera and the thermal load are placed in the opposite sides of the panel, see Figure 21.

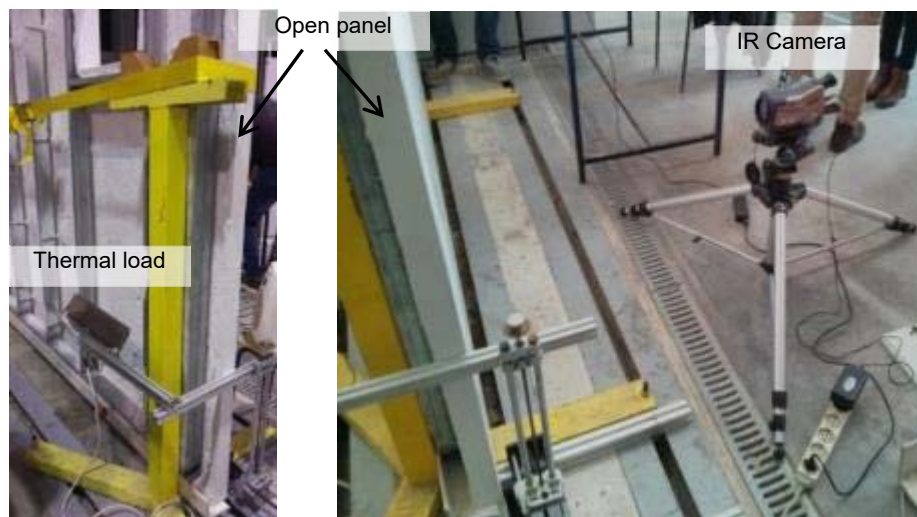


Figure 21: Measurement setup in transmission mode

Due to the thickness of the GRC panel (1 cm) the time of acquisition has been set to 5 min with a load time of 90 s. Results of test are shown in Figure 22.

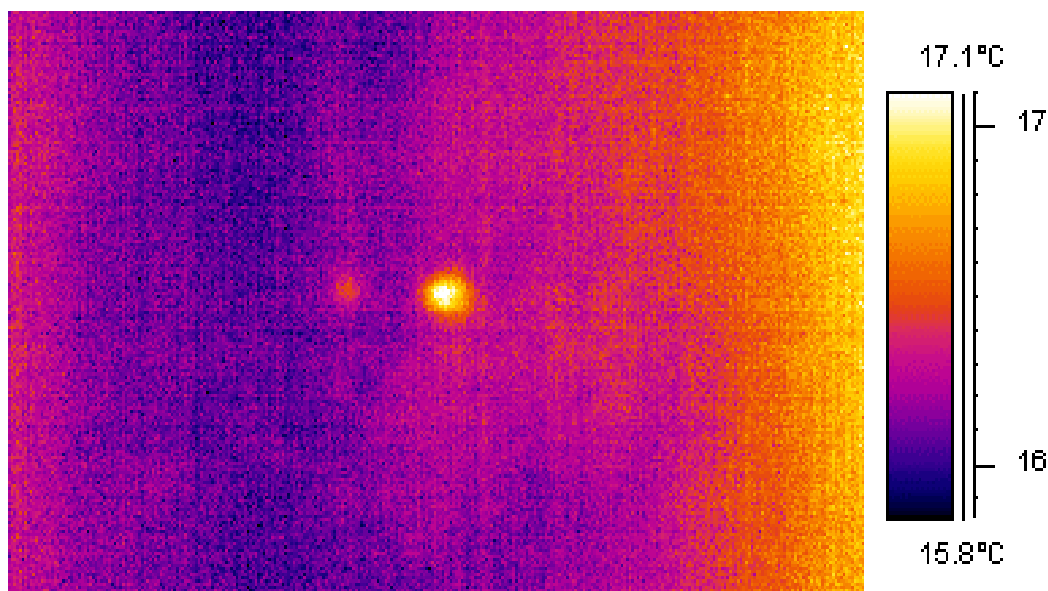
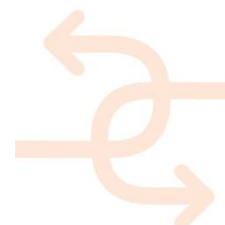


Figure 22: Thermal map obtained from the thermography test in transmission mode

9.2.2 Proof-of-concept following the protocols for acoustic test

This Section provides an experimental validation of the procedure proposed for the measurement of the sound intensity vector field and its application to the identification of acoustic energy leakage from an imperfect junction between two



prefabricated panels. The setup consists of the aforementioned Dragados panel, mounted on a cabin enclosure at UNIVPM.



Figure 23: Junction between the Dragados prefabricated panel (red) and the cabin (white) at UNIVPM

Figure 23 illustrates the imperfect junction and Figure 24 depicts the setup, including the SoundBrush probe dock and reference position, the tracking camera and the acquisition laptop. A broadband omnidirectional acoustic source was placed inside the cabin such that the expected intensity field provides an evidence of the acoustic energy outgoing from the junction.



Figure 24: Setup for sound intensity measurements. From left to right: tracking camera, SoundBrush dock and reference frame with docked SoundBrush probe, Dragados+UNIVPM mockup, control laptop. An acoustic source is placed inside the cabin (not in photograph)

The instruments provide acoustic map superimposed on the 3D model of the mock-up observed.



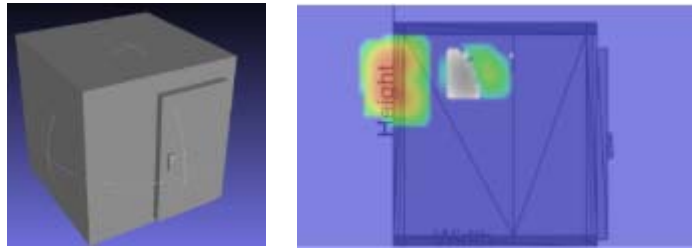


Figure 25: 3D geometric model of the mock-up (left) and acoustic field measured (right)

Figure 25 shows the measured intensity field, which can be observed to be directed outwardly from the defective panel junction. As described above, the procedure illustrated here can be used in a variety of cases, including single passive building components, junctions between components, and active components such as MEP/HVAC systems or ventilation apertures.

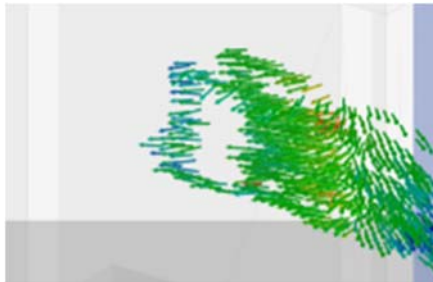


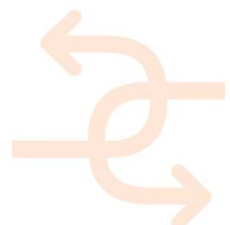
Figure 26: Sound intensity vector field in the vicinity of the junction

9.2.3 Proof-of-concept following the protocols for geometric discrepancy test with BIM and AR.

General quality control to detect discrepancies in components

For the evaluation of the geometric discrepancies in components, if existent, the procedure developed in INSITER and shown in the Section 5 has been used.

The test has been done with a 3D laser scanner placed outside the building in different positions in order to scan the total area according to the geometric resolution, sampling frequency, observation window size. Figure 27 perfectly describes the measured geometry.



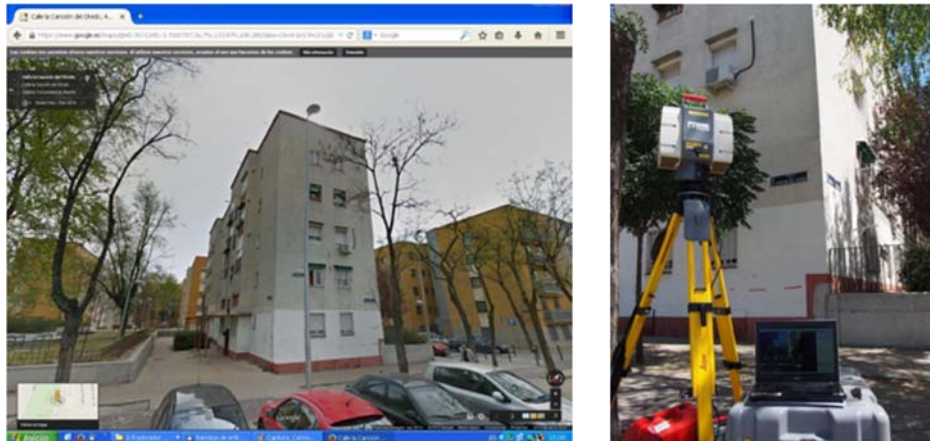


Figure 27: Scanning of a building made of concrete prefab elements

The colour coordinates of these points are optionally acquired by means of digital cameras, internally or externally coupled to the scanner. However, the computed colour varies throughout the process depending on the ambient lighting, also being limited by the geometrical resolution (Figure 27).

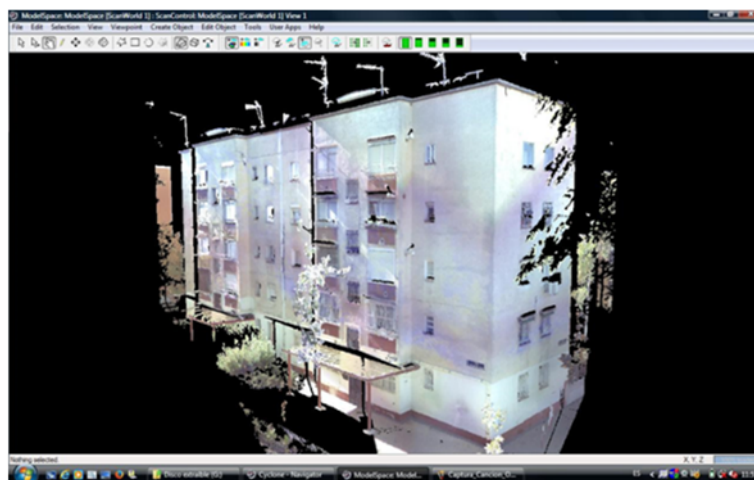


Figure 28: 3D coloured point cloud of the building

The partial point clouds from each position are aligned to give rise to the global point cloud that describes the pre-fab made building.

Analysis of the data

If there is a previous BIM model of the building, the point clouds can be contrasted against this BIM model to analyze geometric deviations at the time of the 3D acquisition in order to be compared to the theoretical model (building project). As it can be seen in Figure 29, those differences are shown qualitatively (color scale) and quantitatively (each color corresponds to a range of deviation in length units).



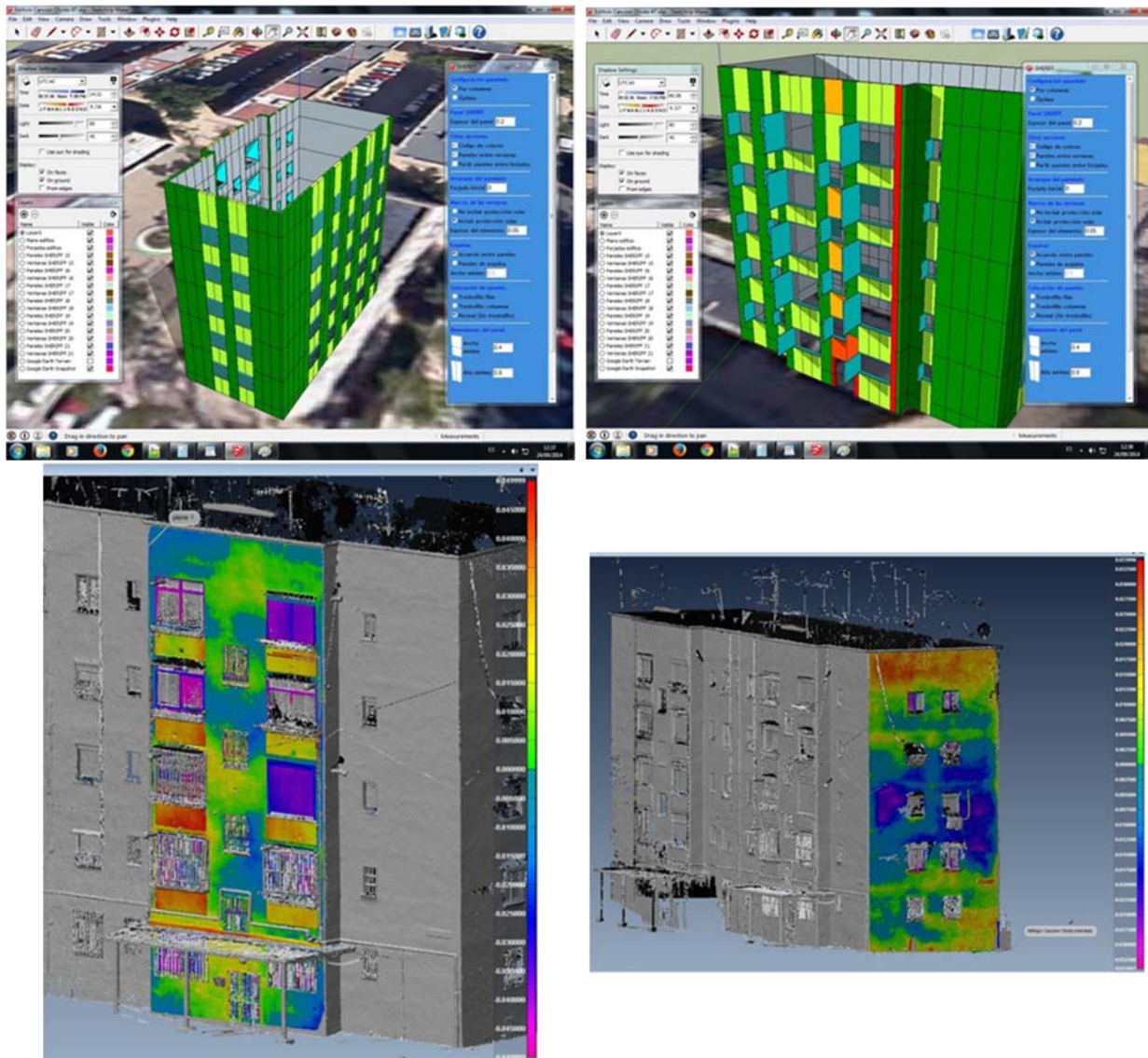
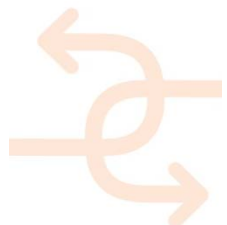


Figure 29: From top to down: BIM building model and analysis of deviations by means of the point clouds regarding the BIM for evaluation of geometric discrepancies (used software: PolyWorks)

The issue is that the information provided by a laser scanner should be made BIM interoperable as well. To achieve this, the point clouds from the laser scans should be transferred to IFC models (for example via REVIT as the world most widespread BIM software).

Since point clouds are not surfaces, and these are required for texturing and rendering, the points are likely to be meshed into triangles as the simplest form of a locally linearized surface. (Note: To cover most BIM use cases even surfaces are not sufficient. Therefore, these must be transferred to 3D solids later on). The case is that REVIT is not efficient dealing with triangle meshes, so these are not considered adequate for the purposes of self-inspection of the INSITER object.

None of the point clouds directly provided by the laser scanners in their native formats are optimized to be directly handled in REVIT. Point-clouds native formats (or converted to TXT) need AUTODESK (or equivalent software) for



integrating reality data directly into the design process, i.e. as previous step to being used in REVIT.

Thus the point clouds are converted to two types of formats without any loss of information using RECAP (AUTODESK supplementary software):

- RCS (indexed point cloud file)
- RCP (aggregation of multiple RCS point cloud files).

These formats are ready to be directly imported by REVIT as optimized point clouds.

Just in REVIT, using discipline specific tools (Arch/MEP) or fully manual modelling, the point clouds are ready to be used as 3D drawing templates (kept as bounded objects) to create parametric objects (pillars, windows, doors or whatever) which can be stored in two specific formats:

- RVT: REVIT Architecture project file
- RFA: REVIT Architecture family file

Any of these formats are able to be exported to Industry Foundation Classes (IFC) as the open and neutral data format for open-BIM (Figure 30).

More details about this process are given in deliverables D4.1 and D4.3.

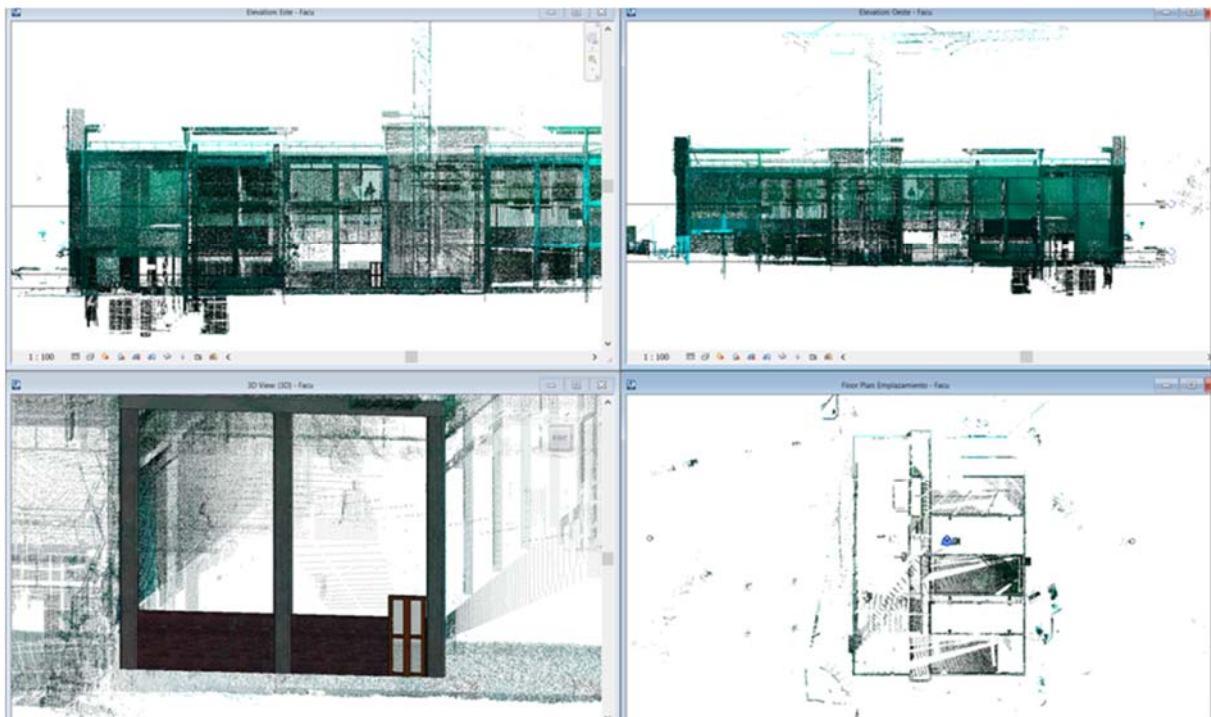


Figure 30: Geometry and colour coordinates example of the Southeast and Southwest facades of CARTIF-3 building

Proof-of-concept for BIM and AR

The AR application will be developed and applied according to defined INSITER use cases. Thus, data and information concerning INSITER measurement systems will be taken into account and integrated within the AR application accordingly. Tests with the AR tool are planned and performed during the development phase according to the use-case requirements and INSITER applications. The first pilot case is planned for the laboratory mock-up at UNIVPM and



described in the following chapter.

The intention of the AR system is to apply it for inspection or instruction situations, using a mobile device (tablet PC). The developed AR application will allow any user or stakeholders (e.g. construction worker, project manager) to inspect a defined building object or construction component with the help of the tablet PC camera, to get the required planning information visualized in AR. Feature-based identification functionalities for the defined objects will be implemented, in order to identify specific objects at the building site and overlay the corresponding information.

For the location tracking there are possible feature based tracking techniques to generate a tracking map, using texture based tracking (Capturing of camera images and detection of feature points), feature and contour based tracking (Capturing of camera images and detection of feature points and 3D-reconstruction and contour detection) as presented in Section 7.3.

According to the recognized features of the camera images, detailed information from the BIM Model or any other data source regarding the located object (e.g. a specific wall and its thermal data) will be displayed automatically or according to the information request issued by the user (see example for thermal image at Figure 31).

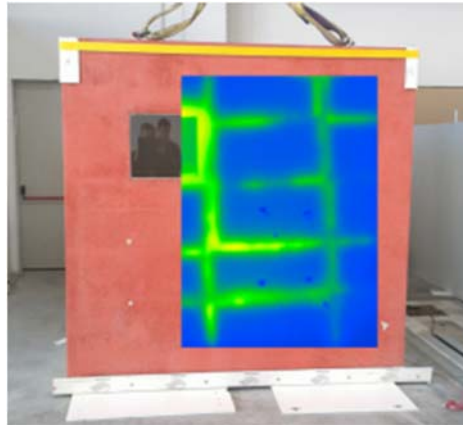


Figure 31: Example of thermal image superimposed on visio image

Besides self-inspection also self-instruction procedures or information can be visualized. The user could request certain AR instructions e.g. for the current assembly process or maintenance tasks, such as kinematic process simulations or information overlay to solve the current task on the building site.

These data (e.g. inspection instructions, thermal information from sensors, pictures) could be made available by the BIM model or via the INSITER BIM platform to be displayed within the AR application on request.

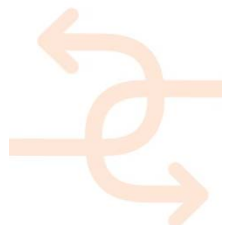
In order to implement a first AR application, an example pilot use case at lab level was defined and will be further advanced. For this use case, the different steps currently defined as an example are described as follows:

Step 1) Application of instrumentation devices.

The first step is the assessment of thermal and acoustic sensor data concerning a dedicated prefabricated facade panel of DRAGADOS. In this case, possible stakeholders are self-inspection for structural engineers or energy planner.

Step 2) Data Processing and Integration

The collected data will be further evaluated and prepared: E.g. Integration of thermal and acoustic images with 3D scans and 3D models. Within this step, the integration of defined sensor data with the BIM platform has to be considered in



order to make them available for other applications.

Step 3) Application of AR app for visualization of sensor data

Within this step the collected and prepared data (e.g. thermal and acoustic sensor data) can be displayed and visualised on the mobile device. (Stakeholder: Self-Inspection for Structural engineers, energy planner)

Step 4) Application of BIM planning application:

With the displayed data the worker cannot decide what has to be done to fix possible errors. Therefore a BIM planning application has to be used, in order to decide about insulation attachment based on all collected data within the BIM Data base. Then the decision to attach additional isolation is made. (Stakeholder: Project Manager)

Step 5) Application of AR app for self-instruction

After the final decision has been made, the BIM provides this information to the AR tool in order to give the worker on-site the correct instructions. The AR tool displays and visualizes the required additional isolation process with detailed workflow to attach additional isolation material to the specific lab scene (Stakeholder: Self-instruction for construction worker). In this context, a 3D model is overlaid to the captured live image of the real world. This will give the construction workers instructions or information they need (e.g. an animation of work sequence or some textual instructions).

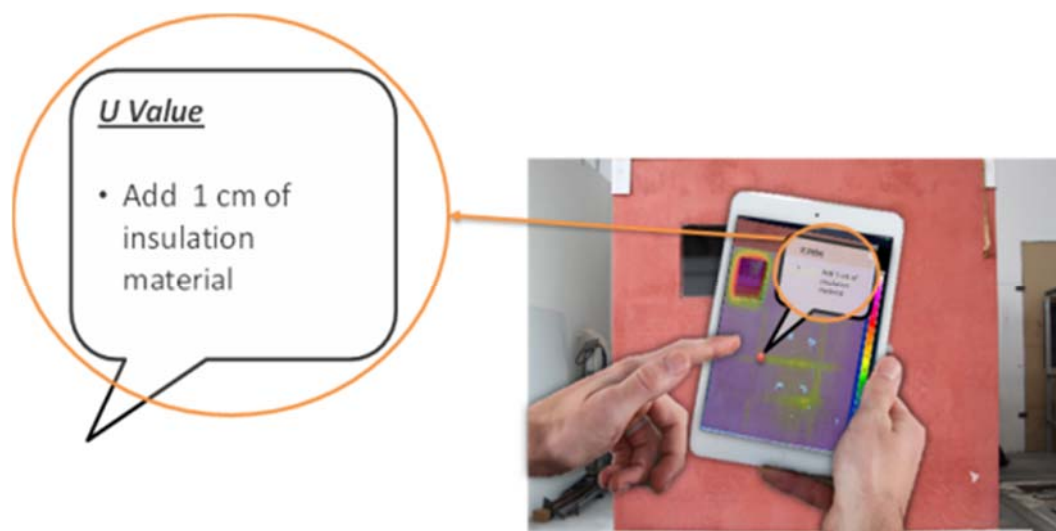


Figure 32: Example for additional information / Instruction on a mobile device

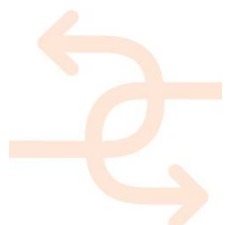
9.2.4 Proof-of-concept following the protocols for humidity test

Materials with rough and absorbing surfaces are darker when wet because they reflect less light. Considering this issue, the reflectivity index will be specifically used for the detection of moisture in prefab-made buildings.

The colour information is not currently used in moisture detection. The usefulness of colour information lies in being combined with the reflectivity information for accurate identification.

Two recommendations between consecutive scans are followed: (i) minimum overlap of 10%; and (ii) at least one change of shape or colour on the original surface.

Controlling the ambient lighting is quite difficult, especially when working outdoors. Scanners usually filter out the spectral range different from the laser wavelength, but the direct incidence of the sun on the device's optics must be avoided by placing the scanner in a shaded location (whenever possible), or even scanning at night if colour



information is not required for further purposes. Bearing this caveat in mind, and knowing that the laser provides a higher light intensity than the ambient lighting, further correction by this factor is not required.

Moreover, environmental conditions during data acquisition (such as temperature, airflows, etc.) do not affect the digitising process given that they are taken in the visible spectrum or in the near-infrared depending on the scanning device.

Analysis of the data

The reflectivity index value (L) acquired at each point needs to be adjusted depending on two groups of parameters:

- Scanning associated parameters
- Scanned surface associated parameters

Scanning associated parameters: (i) the environment lighting; (ii) the distance between the scanner and the digitized surface; and (iii) the angle between the surface normal and the laser incidence direction at the current point of the surface. Therefore, the raw reflectivity value has to be corrected in order to obtain a refined value, useful for moisture detection and assessment.

Scanned surface associated parameters: mainly surface material and surface temperature. The influence of these parameters is minimized by both properly identifying each type of material and recording 3D data under stable and equivalent temperatures for all scan-stations.

Consequently, the reflectivity value is refined for each scan-station data, and transcribed to a colour scale that allows an expert to appreciate the relevant variations. These corrected data are ready to be related to the measurements provided by a thermo-hygrometer upon on-site identifiable points, according to the colour scale, as the only way to obtain quantitative values of humidity for a certain material.

Finally, the alignment of all views is carried out in a straightforward way in a common framework for 3D data processing and editing (*PolyWorks 12.0*).

Having simultaneously obtained the three dimensional coordinates (X, Y, Z) and the level of reflectivity (L), not only current but potential emerging moisture can be clearly visible in the space throughout the 3D point cloud that describes the studied immovable asset, which is not the case when using 2D thermography-based techniques. Anyway, it is worth remarking that it is not possible to see how moisture varies within the walls. Figure 33 shows geometry and colour coordinates example of the Southeast and Southwest facades of CARTIF-3 building, while Figure 34 shows an example of reflectivity index measured on the Southeast and Southwest facades of CARTIF-3 building.

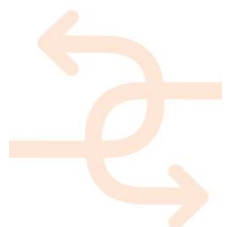




Figure 33: 3D registration of the geometry of the Southeast and Southwest facades of CARTIF-3 building

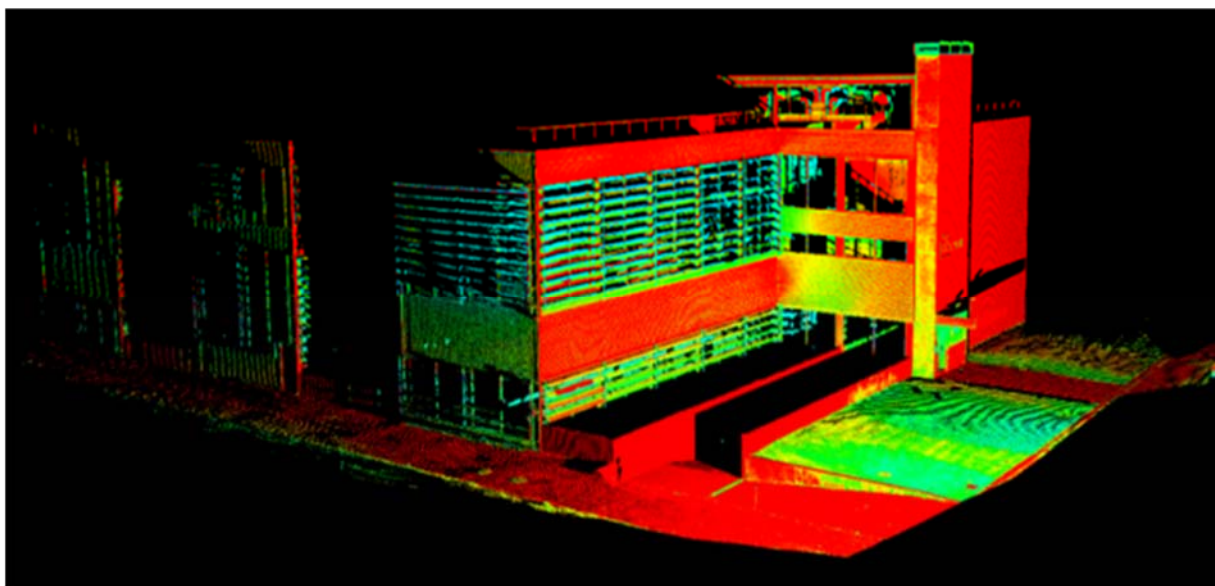
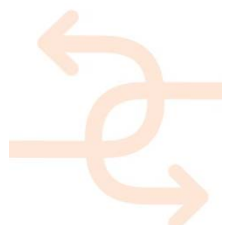


Figure 34: 3D registration of the reflectivity index of the Southeast and Southwest facades of CARTIF-3 building

9.2.5 Proof-of-concept following the protocols for positioning and tracking systems

Added explanation: Proof-of-concept is not intended to be done in lab environment, but in field demonstration cases. This will be carried out in a later stage of the project, in conformity with the original work plan in INSITER.



10. Conclusions and follow-up R&D

10.1 INSITER guidelines to evaluate the lab test

10.1.1 Failure criteria and assessment of the procedure

The lab testing activities and their results should have a system to evaluate the quality standard applied, the deviation from an operating procedure, and a contingency plan if the test fails the expected results. Various factors, such as personnel, accommodation and environment, test methods, method validation, equipment, reference standards, sampling and the handling of test items contribute towards the accuracy and reliability of results and determine largely the uncertainty of the measurement. These factors should all be taken into account when developing methods and procedures, in the training of personnel, and in the choice and use of equipment.

There should be an appropriate level of quality control for each procedure phase and results at the required frequency. Results from the random re-analysis of samples should show an acceptable measure of agreement with the original analyses. Where deficiencies or opportunities for improvement are identified, there should be a process for taking appropriate action.

Once verified the test and the equipment conditions follows the requirements established by the procedure, the test can be performed in order to evaluate the specimen. The test must be repeated at least three times in order to verify the repeatability and validate the results obtained. The results obtained by repeating the procedure must be not exceed $\pm 10\%$ of deviation between the different tests. If this criterion is not respected, the test must be considered wrong and the procedure must be repeated for other three times.

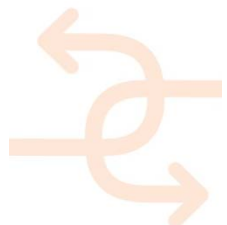
In addition to the test and the equipment conditions, other risks of failure depend on the contingent measurement conditions that must be differentiated depending on the measurement aspect addressed, as reported below.

- Thermal transmittance and thermal bridges: direct radiation from the environment, incorrect assessment of the specimen emissivity, limited temperature gradient between the wall two sides (below 10 °C), incorrect assessment of convective contribution;
- Structural integrity: incorrect estimation of the thermal dynamic response of the material, low emissivity of the specimen, inadequate thermal load, complex stratigraphy of the specimen;
- Sound pressure level distribution, sound intensity field and Transmission Loss: background noise level, stationary waves, reflection from the walls, low distance between the sensors and the room walls, airflows;
- Geometric discrepancy: no risk. The 3D laser scanner represents the state-of-the-art for measuring the geometric discrepancy;
- Humidity: environment lighting, distance between scanner and digitized surface, angle between surface normal and laser incidence direction, surface material, surface temperature, air temperature and humidity.

10.1.2 Contingency measures

If the failure criteria are not respected a set of contingency measures can be applied, depending on each measurement aspect:

- Thermal transmittance is measured according to the standard EN 12664 – “Thermal performance of building



materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods". According to this standard the thermal transmittance of building components is estimated by using temperature thermocouples, for measuring the thermal gradient between the component sides and heat flux transducer for measuring the heat flux through the component;

- Thermal bridges are evaluated according to standard ISO 14683 – "Thermal bridges in building construction - Linear thermal transmittance - Simplified methods and default values". The method proposed by the standard is a numerical calculation of the linear thermal transmittance by considering the inner structure of the component and the junctions between different layers and materials;
- Structural integrity is assessed according to the procedure proposed in the journal paper "Advanced NDT methods for the assessment of concrete structures". This paper describes a set of available NDT techniques for the structural integrity assessment like ultrasonic test, tomography, Ground Penetrating Radar and Laser-Induced Breakdown Spectroscopy;
- Sound pressure level distribution and transmission loss are estimated according to the standard EN ISO 10140 – "Measurement of sound insulation in buildings and of building elements". The standard defines the procedure for measuring acoustic properties of building partitions placed between two acoustic rooms, the source and receiving room. A noise source is applied in the source room and the acoustic pressure in the receiving room is measured by using microphones positioned at specific distances from the partition and from the other walls of the room. The standard defines the calculation method for the estimation of the partition transmission loss, starting from the measured sound pressure level or intensity filed in each room. Other procedures can be applied for TL evaluation as the one defined by the standard ASTM-E2249-02 (see Section 3.3.);
- Humidity is evaluated according to the standard EN 13187 – "Thermal performance of buildings - Qualitative detection of thermal irregularities in building envelopes – Infrared method." The standard defines a qualitative method to see the thermal irregularities in a building component. The humidity present in the wall produces a mottled and widespread distribution of temperature.

10.2 Anticipation of use of other devices in future demonstration projects

In this deliverable the acoustic leakages has been considered like a parameter to monitoring, it being related to sound transmission loss. However it has to be distinguished from air leakages because openings smallest than the order of the sound wavelength do not contribute to acoustic leakages but they do impact on airtightness lack. The acoustic toolset proposed in this deliverable, like SoundBrush, should not be used as a tool for detecting air leakages. This is because the sound intensity probe on the SoundBrush is limited to frequencies below 4 kHz. In practice this means that openings as large as of the order of a centimetre could remain undetected because the wavelength is large in comparison with the openings dimension. Considering that the lack of airtightness is important for the building envelope not only in the field of energy loss, but also in the field of lack of comfort, moisture problems into the construction and the lack of sound insulation a possibility to monitoring this aspect with an appropriate ultrasound system will be considered in the next step of the project.

UltraSound devices (as Leakworx, SDT) can be applied to identify airtightness lack. They measure the difference in the ultra sound pressure level between an open situation (reference value) and the closed situation. Since the ultrasound wavelength is very small (approximately micrometers) tiny openings can be detected. Those devices consist of a ultra sound source, a ultrasound probe receiving the signal emitted from the transmitter if air gaps are present in the

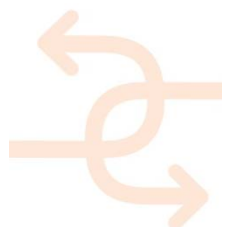


enclosure and a camera for visualization. An example of airtightness map superimposed to the image stored by the camera is reported in Figure 35.



Figure 35: Example of airtightness distribution

Although ultra sound testing seems a good way for air leakages detection and results can be made visible, there is still a challenge in evaluating the test output. For this reason those tests are not generally accepted testing protocols and at present the output results depends on the experience of the people who operate the equipment. For continuous quality improvement and product development, a feedback loop is needed. A link from the quality check on site to the factory and from the factory to the model can be driven by BIM.



APPENDIX 1 - Data Exchange Plan - INSITER WP2

Data Exchange Plans (DEPs) details what data the project will generate, and how will be processed, used and re-used.

3D Laser Scanning

PTX ASCII based interchange format for point cloud data. It utilizes the concept of separate scans, each with points defined in their own coordinate system and also a registration of all of those point clouds into a single coordinate system. Each point cloud starts with a header.

Cyclone¹ sw exports PTX with 7 columns: (x, y, z, L, R, G, B). x, y, z are the point coordinates [in meters]; intensities (L^2) use the decimal range [0, 1]; R (red), G (green), B (blue) have the integer range [0, 255].

3D Photo Scanning

Input (Image³ Formats)

JPEG	Acronym of the Joint Photographic Experts Group, which created the standard. It is a commonly used method of lossy compression for digital images, particularly for those produced by digital photography.
TIFF	Standard file format native to the Microsoft Windows GUI found in most paint, imaging, and desktop publishing programs. TIFF's extensible nature, allowing storage of multiple bitmap images of any pixel depth, makes it ideal for most image storage needs.
PNG	Replacement after the GIF format/CompuServe/LZW compression-patent stuff. It is a lossless image compression format, which allows a large range of applications.
BMP	The Microsoft Windows Bitmap file format is one of several graphics file formats supported by the Microsoft Windows. It is the native bitmap format of this operating environment and is used to store virtually any type of bitmap data.
PPM	The Portable Pixmap forMat (PPM), the portable graymap format (PGM) and the portable bitmap format (PBM) are image file formats designed to be easily exchanged between platforms. They are also sometimes referred to collectively as the portable anymap format (PNM).
OpenEXR	It is a high dynamic-range (HDR) image file format developed by Industrial Light & Magic (ILM) for use in computer imaging applications. OpenEXR is used by ILM on all motion pictures

¹ CARTIF uses a LEICA HDS-3000 laser scanner with associated Cyclone software.

² It refers to the luminance (luminous intensity per unit area at a given direction). As working with point clouds, the area is a dot, so it is understood as the luminous intensity in a given direction. Since this intensity is quantified with respect to the incident unit value, it really means the reflectivity of the target.

³ A digital camera with reasonably high resolution (5 MPix or more) should be used to acquire images.



currently in production.

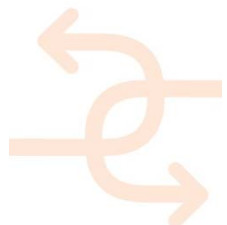
MPO	Multi Picture Object format was developed by The Camera & Imaging Products Association (CIPA). The specification actually allows for any number of JPG files to be saved into a unique MPO file, but the most common use is for stereoscopic images.
------------	--

Output (Point Cloud Exporting Formats⁴)

OBJ	<p>In Wavefront's 3D software, geometric object files may be stored in ASCII format (OBJ file extension) or in binary format (MOD file extension). The binary format is proprietary and undocumented, so only the ASCII format is considered.</p> <p>The OBJ file format supports lines, polygons, and free-form curves and surfaces. Lines and polygons are described in terms of their points, while curves and surfaces are defined with control points and other information depending on the type of curve.</p> <p>OBJ supports rational and non-rational curves, including those based on Bezier, B-spline, Cardinal (Catmull-Rom splines), and Taylor equations.</p>
PLY	<p>Describes an object as a collection of vertices, faces and other elements, along with properties such as colour and normal direction that can be attached to these elements.</p> <p>The typical information in a PLY file contains just two elements: the (x,y,z) triples for vertices and the vertex indices for each face, so occasionally does not provide colour information. However, the properties red, green and blue are commonly associated with vertex elements.</p>
XYZ	An XYZ file is either an ASCII file or a binary file that contains a set of vertices and no other data unless an optional header is used.
LAS	Public file format for the interchange of LIDAR ⁵ data between vendors and customers. It is a binary file format that maintains information specific to the LIDAR nature of the data while not being overly complex. Is an alternative used by many companies to proprietary systems or a generic ASCII file interchange system.
E57	<p>The ASTM E57 Committee on 3D Imaging Systems has develop this format to meet the critical need in the 3D imaging industry for open standards that promote data interoperability among 3D imaging hardware and software systems.</p> <p>The E57 file format for 3D imaging data exchange is capable of storing point cloud data from laser scanners and other 3D imaging systems, as well as associated 2D imagery and core meta-data.</p>
U3D	<p>Universal 3D (U3D) is a compressed file format standard for 3D computer graphics data.</p> <p>This format was defined by a special consortium called 3D Industry Forum that brought together a diverse group of companies and organizations (including Intel, Boeing, HP, Adobe</p>

⁴ From native point cloud generation.

⁵ The term LIDAR was actually created as a hybrid of "light" and "radar". It is popularly used as a technology to make high-resolution maps with applications in geomatics, archaeology, geography, geology, geomorphology, seismology, forestry, remote sensing, atmospheric physics, airborne laser swath mapping (ALSM), laser altimetry, and contour mapping.



Systems, Bentley Systems, Right Hemisphere among others) whose goal was getting a universal standard for three-dimensional data of all kinds, to facilitate data exchange.

3D objects in U3D format can be inserted into PDF documents and interactively visualized by Acrobat Reader (version 7 and later).

PDF	3D format natively supported by Acrobat Reader to encourage users and customers not familiar with 3D graphic applications viewing and interacting with 3D data and models.
------------	--

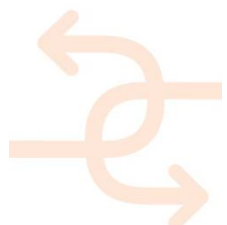
3D Modelling

3D models represent a real object using a collection of points in space, connected by various geometric entities such as triangles (creating meshes), lines, curved surfaces, etc. 3D modelling can be done by hand, algorithmically (procedural modelling), or automatically.

3D Scanning Outputs

DXF	Drawing Interchange Format, or Drawing eXchange Format is a CAD file format developed by Autodesk for enabling data interoperability between AutoCAD native DWG (Drawing) and other programs.
JT	3D data format developed by Siemens Product Lifecycle Management (PLM) Software, used for product visualization, collaboration, and CAD data exchange. It can contain any combination of faceted data, boundary representation surfaces (NURBS), Product and Manufacturing Information (PMI), and Metadata (textual attributes), either exported from the native CAD system or inserted by a Product Data Management (PDM) system.
IGES/IGS	The Initial Graphics Exchange Specification (IGES) is a vendor-neutral file format that allows the digital exchange of information among CAD systems. IGS can be used by many CAD programs as a standard ASCII text-based format for saving and exporting vector data, and can store wireframe models, surface or solid object representations, circuit diagrams, and other objects.
IV	Open Inventor ⁶ files that can be used to customize various 3D elements, such as geometry, lighting, cameras, textures, sequencing, and colour.
NAS	NASA STRucture Analysis file, which is oriented to finite element analysis (FEA).
OBJ	See description in Section "3D Photo Scanning".
PLY	See description in Section "3D Photo Scanning".
STL (STLA/STLB)	STereoLithography is a file format native to the stereolithography CAD software created by 3D Systems. STL has several alternative acronyms such as "Standard Triangle Language" and "Standard Tessellation Language". This file format describes only the surface geometry of a three-dimensional object without any representation of colour, texture or other common CAD model attributes. It describes a

⁶ An object-oriented toolkit used for developing 3D scenes and animations originally developed by Silicon Graphics International (SGI).



raw unstructured triangulated surface with vertices ordered by the right-hand rule and the triangles using a three-dimensional Cartesian coordinate system. STL coordinates must be positive numbers, there is no scale information, and the units are arbitrary.

This file is widely used for rapid prototyping, 3D printing and computer-aided manufacturing. It is supported by many software packages and allows both ASCII (STLA) and binary (STLB) representations. Binary files are more common, since they are more compact.

WRL	VRML (Virtual Reality Modelling Language) is a standard file format for representing 3D interactive vector graphics, designed particularly with the World Wide Web in mind. VRML is a plain text file format where, e.g., vertices and edges for a 3D polygon can be specified along with the surface colour, mapped textures, shininess, transparency. It has been superseded by X3D format.
------------	---

3D Photo Scanning Outputs

DXF	See the equivalent in the previous table.
OBJ	See the equivalent in the previous table.
WRL	See the equivalent in the previous table.
PLY	See the equivalent in the previous table.
STL	See the equivalent in the previous table.
3DS	It is one of the file formats used by the Autodesk 3ds Max software for 3D modelling, animation and rendering.
FBX	Acronym of FilmBoX, is a proprietary file format owned by Autodesk since 2006. It is used to provide interoperability between digital content creation applications.
U3D	See description in Section “3D Photo Scanning”.
PDF	See description in Section “3D Photo Scanning”.

BIM

DWG	This format is almost universally accepted by most model viewing/authoring programs. Also commonly referred to as CAD files, this might be the most ubiquitous digital file format in the AEC industry ⁷ . Generally, these files are editable in any CAD-based program such as <i>Autodesk AutoCAD</i> , <i>Graphisoft ArchiCAD</i> , and <i>Bentley MicroStation</i> . A common misconception with DWG files is that they only contain 2D information. Although that is typical, DWG files can absolutely contain 3D objects as either basic planes or full components (known as “blocks”).
DXF	See description in Section “3D Photo Scanning”.
IFC	These are arguably the most information-rich BIM files out there and can be opened by a number of programs including <i>Autodesk Revit</i> and <i>Navisworks</i> . These are similar to PDFs in that they are not

⁷ Architecture, Engineering and Construction.



	meant to be edited and are a read-only format.
RVT	This is Autodesk's proprietary format for <i>Revit</i> tool. These can vary significantly in size depending on the level of development. They can only be opened in <i>Revit</i> .
NWD	This is proprietary format for <i>Navisworks</i> tool. NWD files are also read-only, although they are able to be saved under a new name and edit from there if the file was saved with that option enabled. These can only be open in <i>Navisworks Freedom</i> or <i>Navisworks Manage</i> .

