

Lab test report and recommendations

Deliverable report D5.2



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

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Lab test report and recommendations

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Colophon

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Publishable executive summary

The main goal of INSITER research on the measurement devices is: to optimise the measurement procedures to suit the use for on-site self-inspection. The current procedures are either too complex or take too much time to be applied during on-site construction process. The Lab Testing shows that the INSITER's innovation, which comprises optimised measurement procedure, is adequate for on-site self-inspection. After successful Lab Testing, these procedures will be tested, validated and demonstrated in factory and field situation respectively.

The main scope of D5.2 is to report the lab tests performed to validate the selected protocols described in D5.1 and the recommendation arisen in view of the application to the real test cases. The lab tests had the aim to implement in a controlled environment the protocols and methodologies related to the INSITER self-inspection system and to identify eventual problems that can be encountered in construction sites.

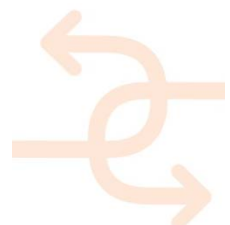
Within the INSITER project, 7 test cases have been defined, namely: Test case 1 – Thermal test case; Test case 2 – Acoustic test case; Test case 3 – Air tightness test case; Test case 4 – Humidity test case; Test case 5 – Geometry test case; Test case 6 – BIM test case; and Test case 7 – Augmented Reality test case. The test cases 4, 5, 7 have been described in the previously submitted deliverable D5.1 (approved by European Commission). This deliverable is focused on the remaining test cases and on test for MEP/HVAC components, based on humidity and geometrical aspects.

Therefore, the main topics tackled are:

- Description of the test cases developed at laboratory level for the validation of the procedures for thermal, acoustic and air leakage assessment (Test case 1, 2 and 3). Those tests have been performed in the cooling room at the UNIVPM laboratory.
- Reporting of the use of the 3D laser scanner for the inspection of MEP/HVAC in terms of installation and humidity performances. Those tests have been carried out by CARTIF in its CARTIF-3 Building.
- Connection between experimental data and BIM which has been developed by HOCHTIEF.
- Evidencing the main recommendations for the use of the INSITER protocols in the factory.

The main achievement of the deliverable is the applicability of the INSITER diagnostic tools for different measurement aspects assessment and the main advantages/disadvantages of those techniques with respect to the currently available in terms of the measurement aspects addressed.

Concerning the thermal transmittance the IR camera based soft sensing procedure allows to reducing the testing time by keeping the same level of accuracy. The current standard for in-situ thermal transmittance measurement by means of heat flow meter (ISO 9869) states that the U-value can be evaluated with an accuracy of about 8%, depending on the environmental conditions. The inspection time is a function of the building element thermal phase (or time shift related to its thermal inertia) and is influenced by the stability of the natural day cycle. The standard, in fact, is based on natural day cycles for the generation of a gradient between the internal and external surface of the building element. The minimal inspection time declared is of 72 h but the test can be stopped only if the U-value do not change more than 5% for three consecutive nights. Standard testing time is between 7 and 15 days. The IR camera soft-sensing method proposed as INSITER thermal transmittance measurement system is based on forced thermal cycles and an accompanying model which allows to decrease the testing time up to some cycles (between 20 and 60 hours) depending



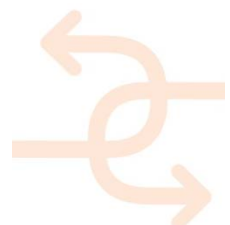
on the thermal phase of the building element (4 h for a concrete wall or 10 h for an high insulation wall, respectively). The cost of the equipment used in the current standard (ISO 9869) is of about 3000€ (cost of the heat flow meter) even though is strongly suggested to use an IR thermal camera to accurately position the heat flow meter on an region free of thermal bridges. The cost of the thermal transmittance tools proposed by INSITER is of about 5000€ (cost of the thermal camera). The same tool proposed by INSITER for the thermal transmittance evaluation (IR camera) is used for thermal bridge estimation and quantitative effect estimation on the global transmittance. The current standard ISO 14683 allow estimating the linear thermal transmittance of thermal bridges in building construction by numerical calculation. The INSITER procedure is based instead on real measurements.

Concerning the acoustic aspect the tools proposed by INSITER are the SoundBrush and the acoustic beamforming for acoustic leakages identification. The first has the main advantage of having installed a tracking device able to localize the measurement position in relation to the testing element. The positioning system has been interfaced with the BIM in order to easily superimpose the measurement data to the 3D model. Beamforming also called acoustic camera is powerful tool since, as the name states, allows visualising acoustic fields and therefore localising sound insulation losses or acoustic leaks, superimposing them onto the visual image of the building component.

Finally, the method proposed as INSITER tool for air leakages localisation is an improvement of the current standard based on blower door test (EN ISO 9972) which allows only to assess if air leakages are present but not to identify their spatial position. INSITER proposes to use ultrasound probes to localise in spade air leakages of approximately 3-20 mm width. Only with sensors working in the ultrasonic frequency range (20-100 kHz), it is possible to identify such tiny cracks thanks to the small wavelength of the ultrasonic waves. For bigger cracks or gaps between building elements the tools proposed by INISTER for acoustic aspects assessment can be applied indifferently. Since they are working on a frequency range up to 10 kHz they are suitable for the detection of gaps larger than about 30 mm.

The table below summarises the main achievements and innovation of the INSITER tools for acoustic/thermal/air tightness aspects assessment. After successful Lab Testing, the procedures will be tested, validated and demonstrated in factory and field situation respectively.

Meas. Area	Main characteristics		Innovation for on-site self-inspection during construction and maintenance				Addressed challenges for on-site use
	Conventional procedures	INSITER procedures	Accuracy	Testing Time	Cost	User-friendliness	
Thermal transmittance	ISO 9869 In-situ measurement of thermal resistance and thermal transmittance - Part 1: Heat flow meter method	IR thermal camera measurement method accompanied by a numerical model of the building element (Soft Sensing based IR camera)	5% lower than current standard	Up to 50% of reduction with respect to the current standards depending on the thermal properties of the building elements and environment al stability	5000 € Higher than heat flow meter but IR camera is used also for thermal bridge assess-ment	IR camera is a non-contact measurement system, that simplify its application in field	Environmental conditions variation Thermal load application



Thermal bridge	ISO 14683 - Thermal bridges in building construction - Numerical calculation	IR thermal camera based method for the evaluation of thermal bridge influence on building element global transmittance	5% in line with the numerical model method	Increased time required for experimental data acquisition	5000 € The IR camera is used also for thermal transmittance assessment	IR camera is a non-contact measurement system, that simplify its application in field	Environmental conditions variation Thermal load application
Acoustic test	Sound level meter - ISO 16032:2004	Sound pressure level by Beamforming microphone array	Spatial leak detection in the order of 10 cm	Lower than 10 min for an area of 200 cm x 200 cm	Higher than a sound level meter	The acoustic field distribution is automatically superimposed to the visual image of the building component	Environmental conditions variation
	Intensity probe - ISO-9614 series	Sound intensity field by SoundBrush	Spatial leak detection in the order of 30 mm	About one hour for an area of 200 cm x 200 cm	Higher than a sound intensity probe	The position of the measurement point is automatically recorded by a tracking system	Environmental conditions variation
3D Air leakage test	EN ISO 9972 - Blower door test	Ultrasonic waves detection	Spatial leak detection in the order of 3-20 mm	About one hour for an area of 200 cm x 200 cm	3000 euro Similar to Blower door equipment	The ultrasonic probe is manually moved and its position tracked by automatic positioning system as the SoundBrush one	Noise in the ultrasound range



List of acronyms and abbreviations

Abbreviation / acronym	Description
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
AR	Augmented Reality
BIM	Building Information Modelling
CAD	Computer Aided Design
CF	Solar Correction Factor
ETTV	Envelope Thermal Transfer Value
FOV	Field of View
IHOW	Instantaneous Field of View
GPS	Geographic Positioning System
GRC	Glass Reinforced Concrete
HDCAM	High Definition Camera
HVAC	Heating, Ventilation, Air Conditioning
IR	Infrared
JSCAD	3D model format for the software OpenJSCAD
L	Index of reflectivity
MEMS	Micro Electro-Mechanical Systems
MEP	Mechanical, Electrical, Plumbing
QR	Quick Response
RMS	Root Mean Square
RTK	Real Time Kinematic
SC	Solar Coefficient
SNR	Signal to Noise Ratio
STL	STEREO Lithography interface format
X3D	File format

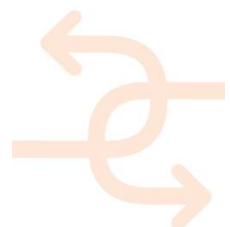


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1. Introduction

1.1 Objectives and structure of this deliverable

This document is the result of Task 5.1 and its main scope is to report the lab tests performed to validate the selected protocols described in D5.1 and the recommendation arisen in view of the application to the real test cases. The lab tests had the aim to implement in a controlled environment the protocols and methodologies related to the INSITER self-inspection system and to identify eventual problems that can be encountered in construction sites.

Since INSITER has defined 7 test cases (see Table 1). The test cases 4, 5, 7 have been described in D5.1 this deliverable is focused on the remaining test cases and on test for MEP/HVAC components, based on humidity and geometrical aspects.

Test Cases	
Test case 1	Thermal test case
Test case 2	Acoustic test case
Test case 3	Air tightness test case
Test case 4	Humidity test case
Test case 5	Geometry test case
Test case 6	BIM test case and Test case
Test case 7	Augmented Reality test case

Table 1: INSITER Test Cases

Therefore, the structure of this deliverable is as following:

- Chapter 2 reports the test cases developed at laboratory level for the validation of the procedures for thermal, acoustic and air leakage assessment (Test case 1, 2 and 3). Those tests have been performed in the cooling room at the UNIVPM laboratory.
- Chapter 3 describes the use of the 3D laser scanner for the inspection of MEP/HVAC in terms of installation and humidity performances. Those tests have been carried out by CARTIF in its CARTIF-3 Building.
- Chapter 4 illustrates how to connect experimental data to the BIM and has been developed by HOCHTIEF.
- Chapter 5 put on evidence the main recommendations for the use of the INSITER protocols in the factory.

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

This deliverable presents the main results achieved by applying diagnostic procedures identified by the INSITER project in lab tests in order to perform a first validation in simplified test cases. The INSITER procedures have been deeply described in the deliverables presenting the outcomes of the research performed in WP2, especially in D2.3. That document reports the basic theory, the scientific innovation, the detailed procedure for the assessment of thermal, acoustic, humidity, geometrical aspects that allow to monitor and diagnostic errors related to thermal transmittance of building elements, presence of thermal bridges, structure integrity, sound transmission loss, acoustic and air leakage, humidity and geometric gaps and/or clashes of prefab elements. The protocols related to different technologies detailed in D2.3 have been applied in several test benches and results reported in D5.1 and D5.2.

Specifically D5.1 describes the results of:



- Thermal transmittance/acoustic leakage assessment of building elements,
- Thermal bridges and structural integrity identification by IR camera,
- Humidity and geometric discrepancy evaluation by 3D laser scanner in building envelopes.

Specifically D5.2 describes the results of:

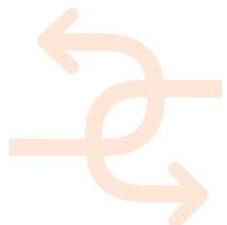
- Thermal transmittance/acoustic and air leakage assessment of building envelopes,
- Thermal bridges evaluation and their quantitative affects in terms of thermal transmittance,
- Humidity and geometrics inspection in MEP/HVAC systems.

Besides, this deliverable shows some examples of experimental data connectivity to the BIM in different use case scenarios for model 3D and 4D checks. And finally test planning and recommendation for factory tests are detailed.

1.3 Main achievements and limitations

The main goal of INSITER concerning the measurement devices is to optimize/modify/adapt standard or innovative measurement procedures to suit the use for on-site self-inspection. Because the current procedures are either too complex or take too much time to be applied during the construction process, INSITER has identified and developed alternative methods for improve easiness to use and decrease the inspection time keeping a sufficient level of accuracy.

The achievement of this deliverable is the applicability of the INSITER's innovation in lab testing thus demonstrating that the optimized/modified measurement procedures are adequate for on-site self-inspection. After successful lab testing, the procedures will be tested, validated and demonstrated in factory and field situation respectively.



2. Lab test

The building quality passes through the continuous inspection of the installation process, product quality and building performance. The techniques developed in D2.3 and protocols described in D5.1 allow evaluating the performance of the building envelope components collecting essential data useful to:

- evaluate the presence of an error/damage,
- supply inputs to the self-instruction process
- and, once fixed the errors if there were any, estimate energy related parameters that are sent to the INSITER software to calculate building energy performance.

The lab tests described in this document have the aim of validating the inspection procedures for the evaluation of thermal (**Test case 1**), acoustic (**Test case 2**) and air tightness (**Test case 3**) performances of the building envelope. The same procedures have been already described in the D5.1 and validated for the evaluation of 2D components performances, i.e. building elements (facades or partition elements). In this deliverable, those procedures have been validated for the estimation of the **3D thermal, acoustic and air tightness** performances of the entire building envelope. As simplified test bench the cooling room available at the UNIVPM laboratory has been used.

2.1 3D thermal test

A 3D thermal test aims at the evaluation of the thermal transmittance and thermal bridges in a building envelope. The protocols for the thermal parameters acquisition are described in D5.1 Lab test protocols and set-up, chapter 3.

The tests have been performed on the pilot test bench installed in the laboratory of the University Politecnica delle Marche (Ancona, IT) already described in the D5.1 chapter 9. This test bench is a cooling room that can be thermally conditioned and controlled in order to generate thermal gradients between the interior and exterior environment. The test has been performed during the cooling of the room applied during the night.

IR thermal maps have been registered at the end of a cooling cycle of the cooling room on its four vertical walls. The cooling cycle consisted on a cooling, by a portable cooling system installed inside the mock-up, lasting 13 hours. The temperatures reached by the air inside and the outside the room and by the wall A, where a prefab panel supplied by DRAGADOS was installed, (see Figure 1) are reported in Table 2.

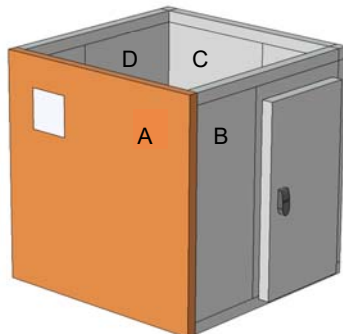
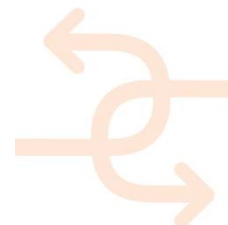


Figure 1 Cooling room wall nomenclature

Those temperatures have been measured by thermometers placed inside and outside the room (T_{in} and T_{out}



respectively) and by thermocouples cemented on the prefab panel interior and exterior surface ($T_{w,in}$ and $T_{w,out}$ respectively). At the end of the cycle, the thermal gradient between the prefab panel internal and external surface was of 8°C and the air thermal gradient between the room interior and exterior environment was of 10°C that guarantees the applicability of the method according to [7-1].

The humidity inside the room at the end of the cycle was 50% and outside 46%. The thermal time histories during the cooling cycle are given in Figure 2. It can be noticed the cooling trend of both the interior (blue line of Figure 2) and exterior environment (magenta line of Figure 2) during the night, however after 11 hours, at sunrise, the temperatures invert the trend and start to increase. Nevertheless, the temperature gradient was still about 10°C.

Parameter	Symbol	Cooling start temperature [°C]	Cooling end temperature [°C]
Indoor temperature	T_{in}	28	19
Outdoor temperature	T_{out}	31	28.9
Interior wall temperature	$T_{w,in}$	28.5	20.5
Exterior wall temperature	$T_{w,out}$	30.5	28

Table 2: Temperature conditions at the beginning and at the end of the cooling cycle.

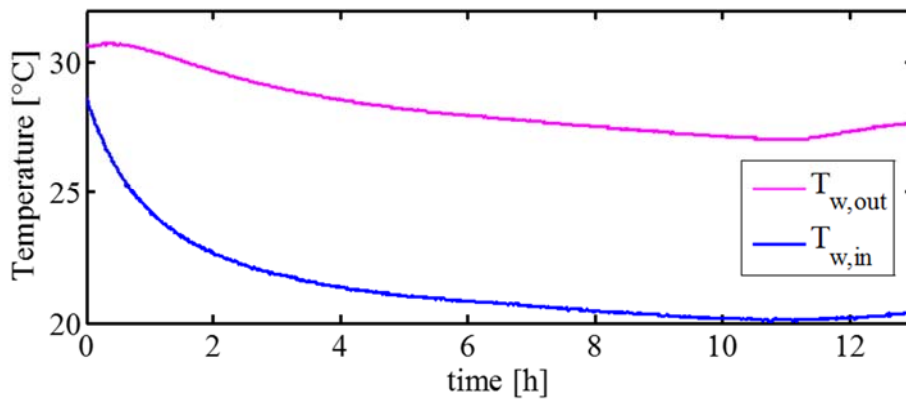


Figure 2: Internal and external wall temperature time histories

The thermograms registered during the thermal cycle when the thermal camera framed the prefab panel at four time instants are visualised in Table 3.

Frame at t= 3 min	Frame at t= 60 min	Frame at t= 300 min	Frame at t= 740 min

Table 3: thermograms at different instants during the cooling cycle

Increasing the frame time the thermal contrast increases and the thermal bridges are more evident.



The measurement of the thermograms in the four vertical walls has been performed at the end of the cooling cycle starting from the prefab panel (wall A) and following the sequence wall B, wall C, wall D. The complete set of thermograms have been acquired in 20 min and during this timeframe the temperature on the wall A, internal and external surface, varied of 1 °C, which is in the order of the thermal camera accuracy.

The thermal camera settings are summarised in

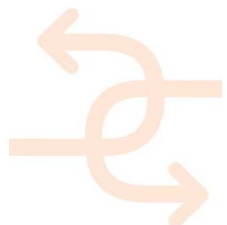
Table 4.

Tools and Configuration			
thermal camera	Infratec variocam HD		
lens	IR 1.0/15 LW JENOPTIK		
lens position	height	1,1	[m]
	distance	2,2	[m]
	angulation	normal	
wall emissivity	Panel: A	Panels: B/C/D	
	0.97	0.98	

Table 4: Thermal camera settings

2.1.1 3D thermal maps

The thermogram acquired on the prefab wall (called wall A) georeferenced by the QR with position (0.0;220.0;1986.5) is illustrated in Figure 3. The geo-referencing procedures are described in the D2.3 chapter 2.5. The string read on the QR is (0.00;220.00;1986.50).



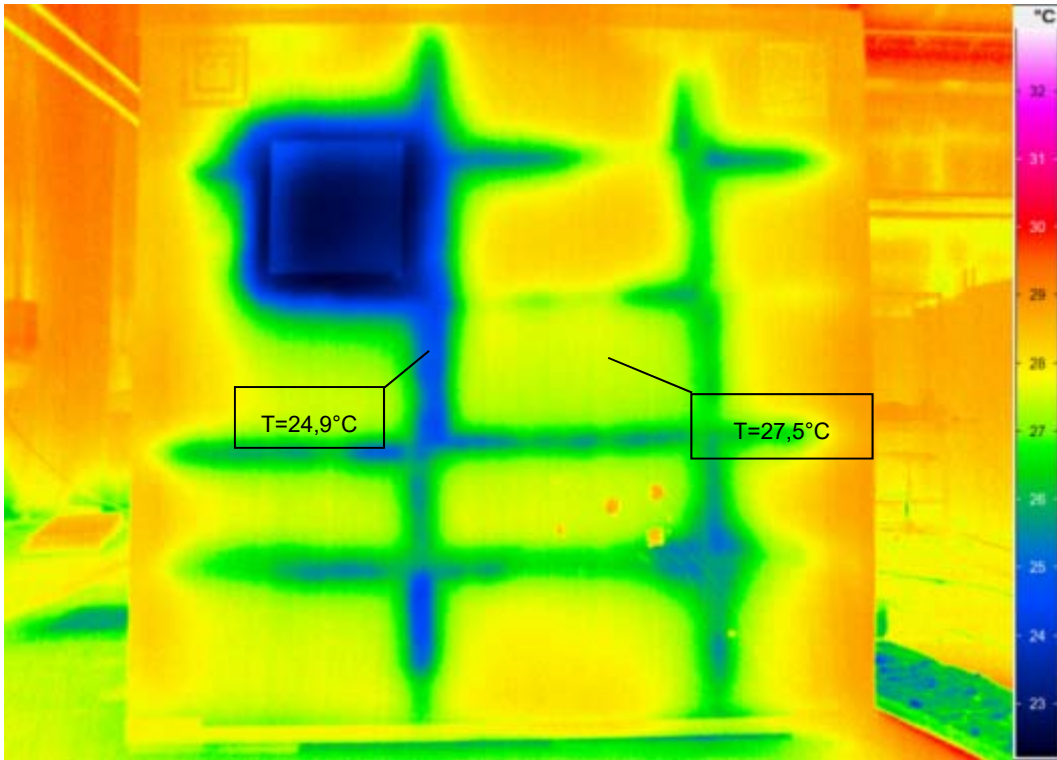


Figure 3: Wall A picture (top) and thermogram (bottom)

In Figure 3 - Figure 6 thermal cold spots are visible. They highlight areas of temperature altered by thermal bridges.

The thermogram acquired on the wall (called wall B) georeferenced by the QR with position (325.0;0.0;1986.5) is illustrated in Figure 4. The string read on the QR is (325.00;2225.00;1986.50).



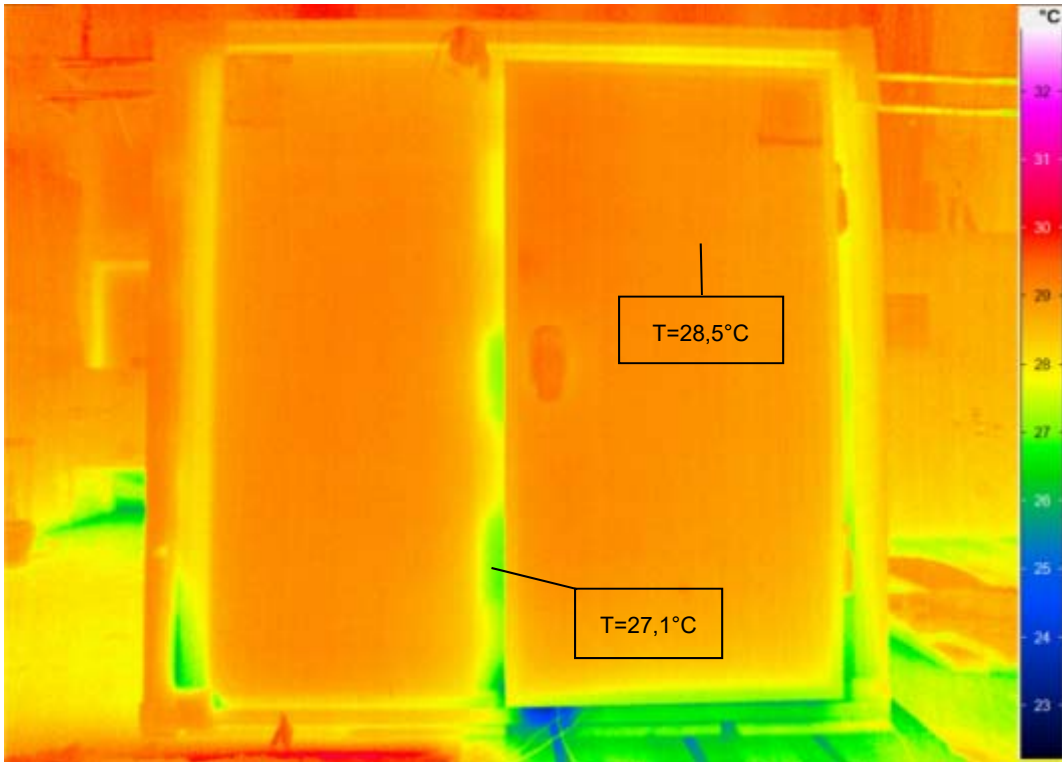
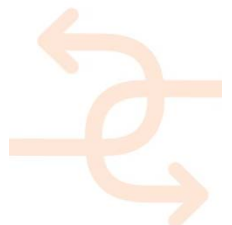


Figure 4: Wall B picture (top) and thermogram (bottom)

The thermogram acquired on the wall (called wall C) georeferenced by the QR with position (2346,0;2005,0;1986,5) is illustrated in Figure 5. The string read on the QR is (2346,00;2005,00;1986,50).



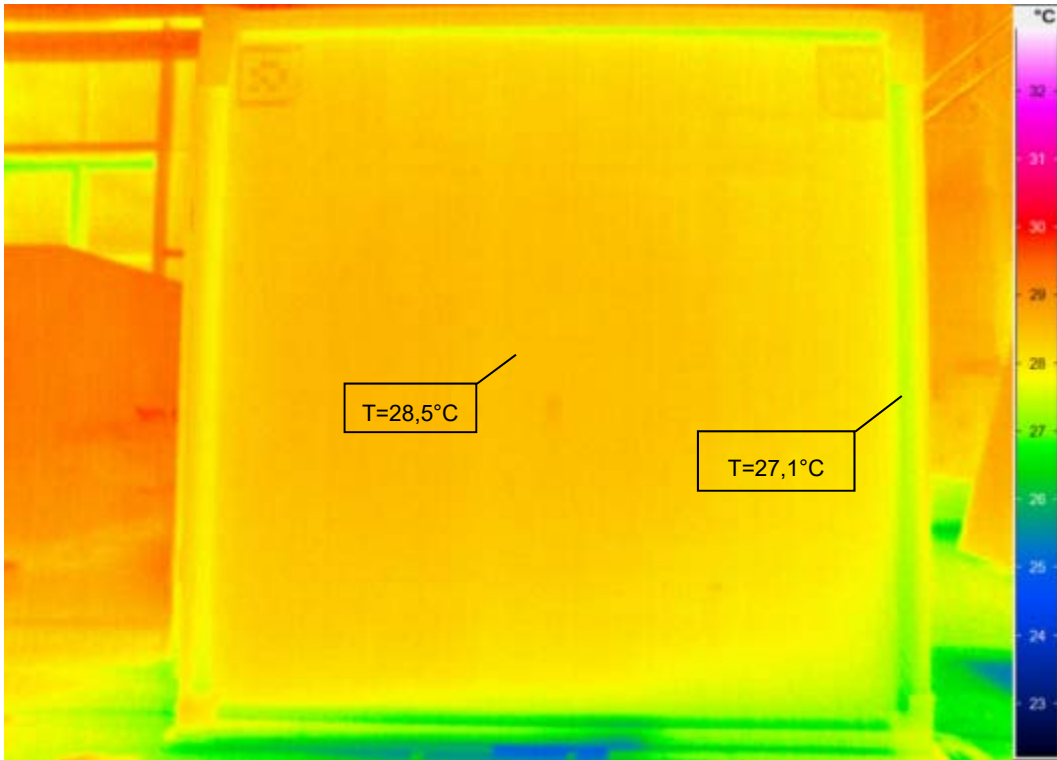


Figure 5: Wall C picture (top) and thermogram (bottom).

The thermogram acquired on the wall (called wall C) georeferenced by the QR with position (325.0;2225.0;1986.5) is illustrated in Figure 6. The string read on the QR is (325.00;0.00;1986.50).



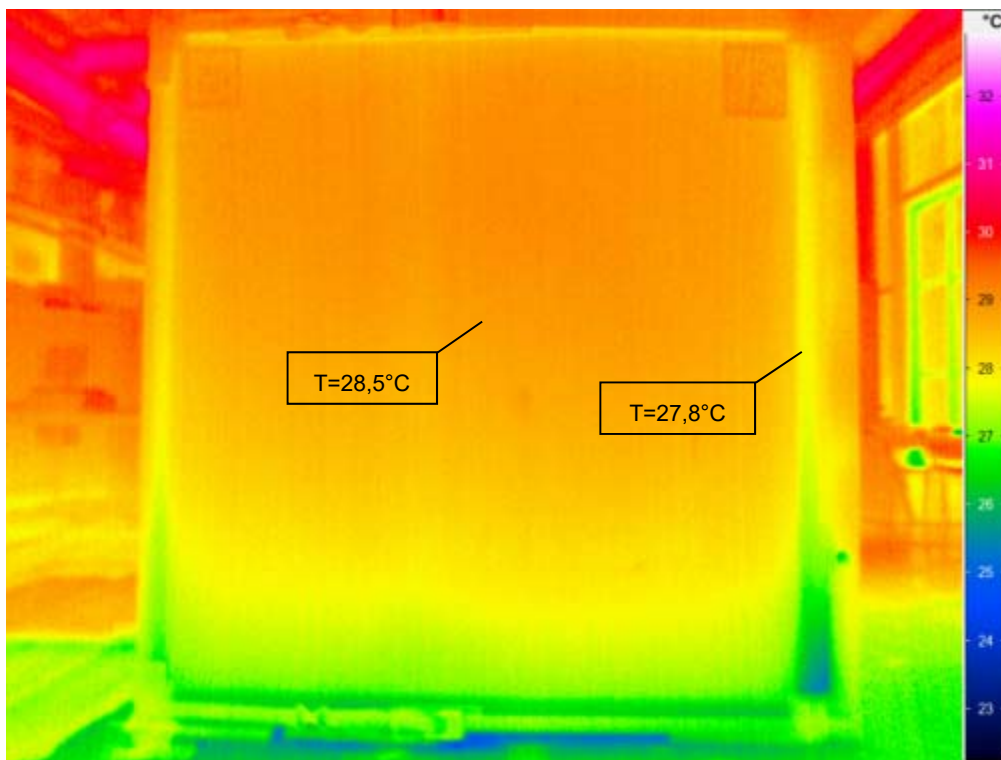


Figure 6: Wall D picture (top) and thermogram (bottom).

A thermal bridge is defined as an area of the building envelope where the uniform thermal resistance is significantly changed by:

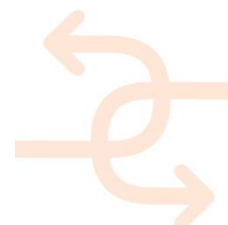
- full or partial penetration of the building envelope by materials with a higher thermal conductivity;
- the fabric degradation;
- a difference between internal and external surface area, such as occur at wall, floor and ceiling junctions.

The methodology to quantify the thermal bridge has been described in D2.3, together with the protocols based on soft sensing method for the evaluation of the thermal transmittance.

2.1.2 Image processing for SNR improvement

IR thermograms are usually affected by thermal noise and interfering inputs which spoil the thermal images and make difficult to identify clearly thermal bridges extension or potential damages location. Interfering inputs are often related to inhomogeneous thermal load and emissivity spatial unevenness. Specific image processing methods based on low pass filter in the frequency-domain can be applied to the thermograms to reduce the effect of noise and interference. Those methods have been described in the deliverable 2.3 chapter 2.3. Their application to the thermograms acquired in the DRAGADOS prefab panel is shown in this chapter.

The first step is the noise reduction by the application of a time domain denoising algorithm. Figure 7, right, shows the thermogram (top) and the thermal profile on the yellow line, after the application of the denoising algorithm. It is clear that the image is smoothed and the contrast increased.



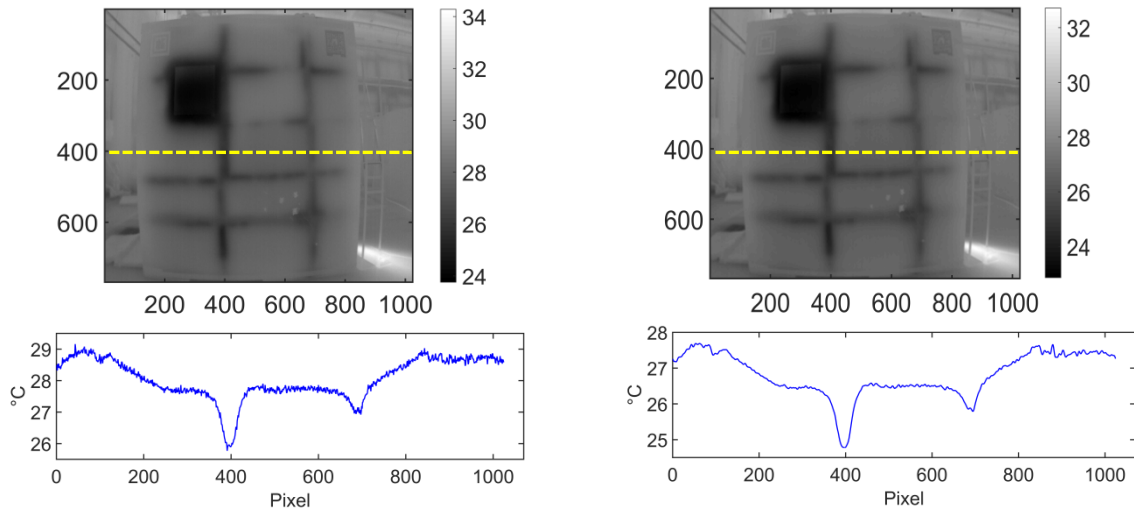


Figure 7: Left, original thermogram (top) and thermal profile on the yellow line (bottom); right, denoised thermogram (top) and denoised thermal profile on the yellow line (bottom)

To further improve the contrast between sound areas and thermal bridges the thermal contrast has been calculated as described in D2.3 chapter 2.3. The thermal contrast is the pixel by pixel maximum contrast with respect to the sound area evaluated in each thermal frame of the IR time history. The thermal contrast of the thermogram considered is shown in Figure 8: the thermal bridge profile has become more evident.

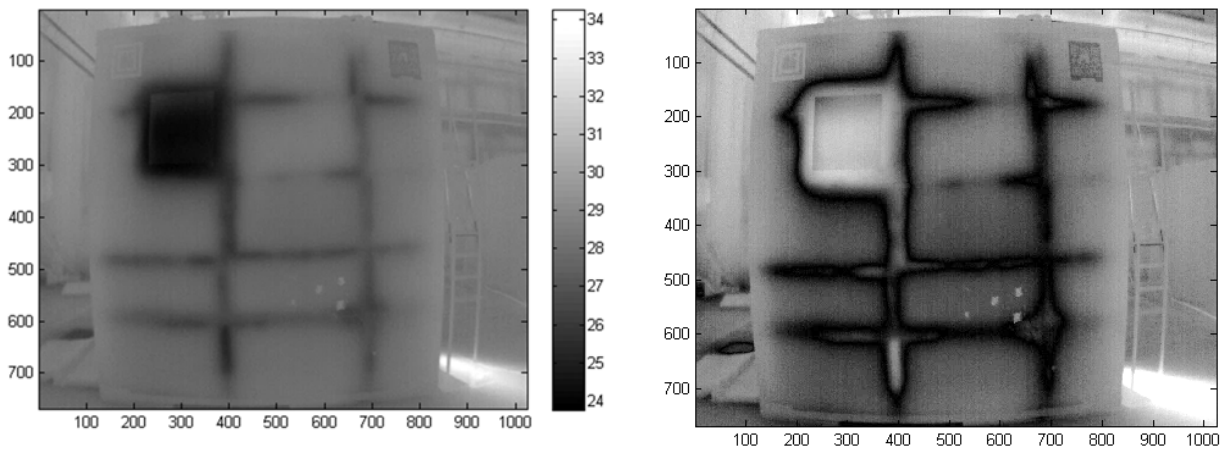
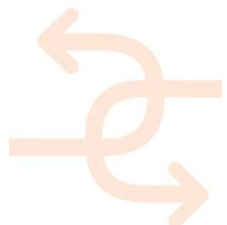


Figure 8: Left, denoised thermogram; right, thermal contrast map

2.2 3D Acoustic test

This chapter presents the acoustic tests performed on the Dragados-UNIVPM mock-up. As discussed previously, the mock-up consists of a prefabricated panel manufactured by Dragados, mounted against a mock-up room. The walls of the room itself are correctly sealed, however the Dragados panel is placed without any special sealing in order to replicate an incorrect installation such as that encountered in a real building scenario.

2.2.1 Experimental setup- sound intensity measurement – SoundBrush



The experimental setup for sound intensity measurements using the SoundBrush probe is composed of a calibration board, a tracking camera, as depicted in Figure 9. In order to characterise the sound transmission properties of the Dragados panel (in red on the figure) a spherical source is placed inside the mock-up room and measurements are performed at the vicinity of the panel both at its inner and outer sides.

The source is fed with a broadband random signal in the range 100 Hz – 6 kHz. Such frequency range is chosen so as to maximise the output power of the amplifier and the loudspeakers. Indeed, the maximum frequency of validity of the measurements performed using the SoundBrush intensity probe is 4 kHz. The further upper range of the frequency band of excitation ensures that the filter does not affect the frequency band of interest. The position calibration of the probe is performed by means of the chessboard panel and dock, located within the field of view of the tracking camera.



Figure 9: Experimental setup for sound intensity measurement at the inner side of the mock-up panel. From left to right: SoundBrush probe and calibration board, 12-speaker spherical source, tracking camera, control laptop running Siemens SoundBrush software with amplifier



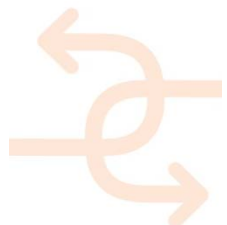


Figure 10: Experimental setup for sound intensity measurement at the outer side of the mock-up panel

2.2.2 Exporting SoundBrush data as a 3D model

A bash script was written in order to represent the data measured using the SoundBrush probe as a 3D model, readily compatible with software able to import STL (stereo lithography) or X3D files.

The script outputs a JSCAD model, which is a 3D model format for the free software OpenJSCAD, which can in turn output an STL or X3D model.



```

# 3D representation of SoundBrush measurement
# Project INSITER
#
# This program is free software and is distributed under the terms of
# the GNU General Public License, version 3 or any later version.
# A copy of the license can be found here: https://www.gnu.org/licenses/gpl-3.0.en.html
#
# usage:
# ./sb2jscad.sh <file>
# <file> is a text file containing the data from any generic table
# exported using the SoundBrush "Generate Report" tool
#
# J.Cuenca 2016

m=$(awk -v a=8 '{print $a}' i_side_nowool|sort|sed -n '1p;$p')
min=$(echo $m | awk -v a=1 '{print $a}')
max=$(echo $m | awk -v a=2 '{print $a}')

NI=$(more i_side_nowool|wc -l)
for I in $(seq 1 4 $NI)
do awk -v line=$I -v x=5 -v y=3 -v z=4 -v phi=6 -v rho=7 -v amp=8 'NR==line {print "arrow(lx-
"$x","$y","$z","$phi","$rho","$amp");}' $I >> out
done

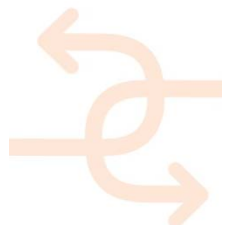
echo "function arrow(x,y,z,phi,rho,amp)
{
  var res=3
  var pi=3.141592
  var min="$min-1", max="$max"
  amp=(amp-min)/(max-min)
  return union(
    cylinder({start: [0,0,0], end: [amp/10,0,0], r: 0.01*amp, fn:res}),
    cylinder({start: [amp/10,0,0], end: [(amp+amp/3)/10,0,0], r1: 0.02*amp, r2: 0, fn:res})
  ).scale(1).rotateY(phi).rotateZ(180-rho).translate([x,y,z]).setColor([amp,1-amp,0])
}

function mockup(lx,ly,lz,lw,h)
{
  return union(
    cube({size: [lx,h,lz]}).setColor([.5,.5,.5]).translate([h,0,0]),
    cube({size: [lx,ly,h]}).setColor([.5,.5,.5]).translate([h,0,0]),
    cube({size: [lx,ly,h]}).setColor([.5,.5,.5]).translate([h,0,lz-h]),
    cube({size: [lx,h,lz]}).setColor([.5,.5,.5]).translate([h,ly-h,0]),
    cube({size: [h,ly,lz]}).setColor([.5,.5,.5]).translate([lx,0,0]),
    difference(
      cube({size: [h,ly,lz]}).setColor([1/2,0,0]),
      cube({size: [h,lw,lw]}).translate([0,ly-2*lw,lz-2*lw])
    )
  )
}

function main()
{
  var lx=2.53, ly= 2.38, lz=2.35, lw=.4, h=.1
  return union("$out"
    arrow(0,0,0,0,"$max").setColor([0,0,1]),
    arrow(0,0,0,90,"$max").setColor([1,0,0]),
    arrow(0,0,0,-90,"$max").setColor([0,1,0]),
    mockup(lx,ly,lz,lw,h).translate([2*h,-ly-h/2,0])
  )
}
" > out
mv out out.jscad

```

Bash script for the conversion raw SoundBrush measurement data into JSCAD models



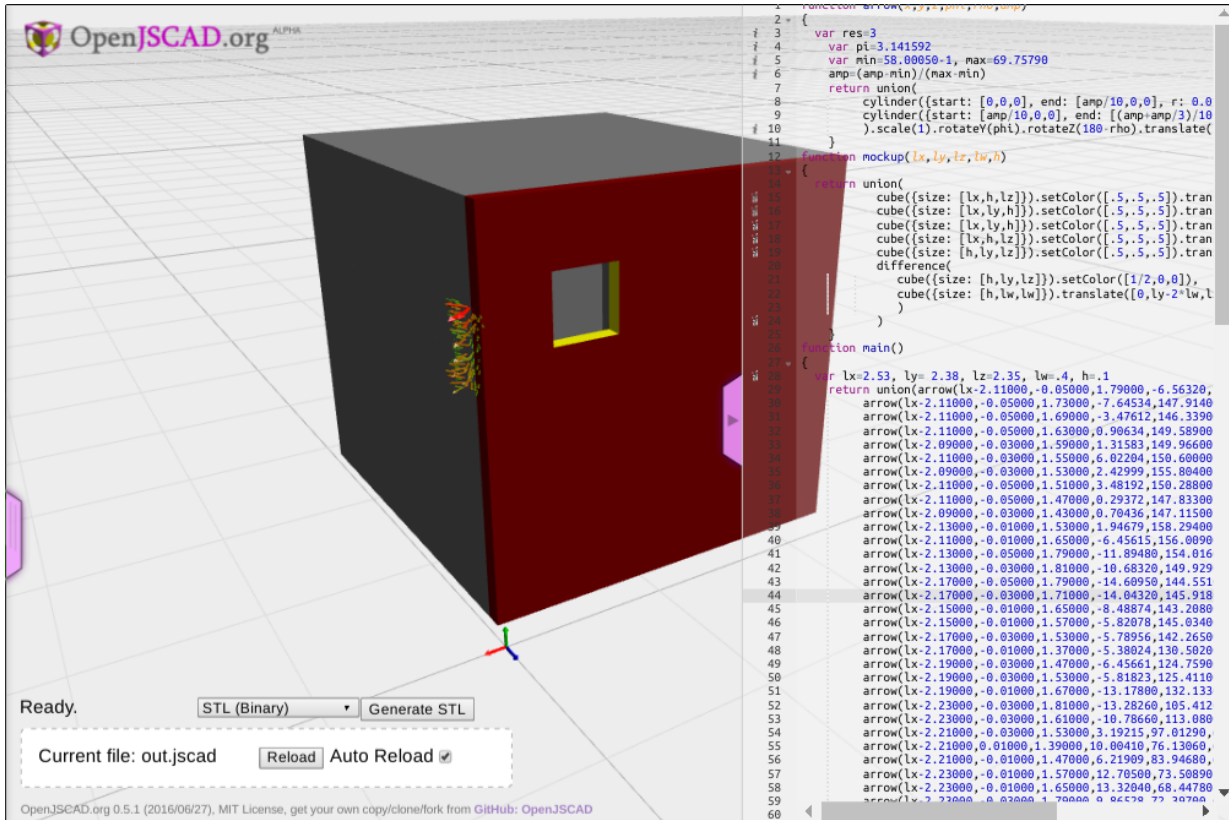


Figure 11: Screenshot of an example output model in OpenJSCAD, before being exported to x3d

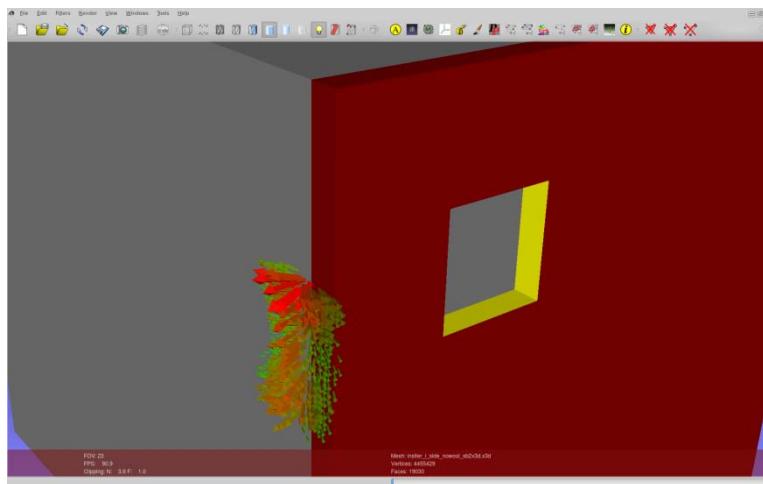
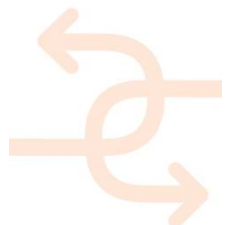


Figure 12: Resulting x3d model of measured data visualised in MeshLab

2.2.3 Sound source localisation – acoustic array

A microphone array is employed in order to identify the sources of noise on the exterior surface of the mock-up room. The experimental conditions are identical to those of the sound intensity measurements, allowing both acquisition systems to operate simultaneously. The microphone array used for this test is the Siemens 2Dcam45. It is



composed of 45 high-end microphones irregularly spaced within a circular plane, as depicted on Figure 13. In addition to the microphones, it features a camera located at its centre in order to superimpose the sound pressure map to an image of the analysed structure. The processing is done within the HDCAM application in Siemens Test.Lab 15A.

Note: The Siemens 2Dcam45 is used here as a demonstrator and proof of concept of the MEMS microphone array currently in development as of the writing of this deliverable. The specifications of the MEMS array are given in available detail in deliverable D2.3.



Figure 13: Microphone array measuring the sound pressure from the different panels of the Dragados-UNIVPM mock-up. Mineral wool panels were placed on the floor in order to suppress parasite reflections

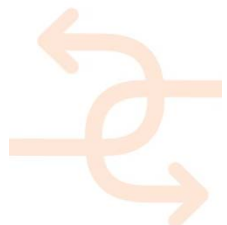
2.2.4 Sound source localisation results - leakage at the top of the panel side

This chapter presents the results of the sound source localisation by means of the microphone array in the case of the leakage from a defective sealing induced in a controlled manner at the side of the Dragados panel. The leakage was generated by placing the Dragados panel against the mock-up room without any sealing or bonding, which leaves an air gap at first sight difficult to notice. The inner side of the Dragados panel was treated with panels of 50mm thick mineral wool. In the present case the top half of the panel was left untreated in the vicinity of the junction with the mock-up room in order to favourise a controlled acoustic leakage. For this experiment, the microphone array was placed at 1.5 m, parallel to the side panel of the mock-up. Such distance was defined so as to entirely contain the full vertical span of the mock-up in the visualisation.

Figure 15 shows the averaged sound pressure spectrum of the back-propagated sound field on the mock-up. Acoustic beamforming provides sound pressure maps whose resolution increases with frequency, as the wavelength decreases. The frequency range 1950-2680 Hz (highlighted in green on the figure) presents significant variations of sound pressure amplitude and is therefore chosen as the frequency range of reference.

Figure 16 and Figure 17 show the back-propagated sound pressure at the surface of the mock-up at different frequency ranges, respectively reported in the figure legends. It can be observed from the figures that the analysis at the frequency range of reference provides a successful estimation of the global position of the sound source corresponding to the leakage from the imperfect junction.

However, due to the lack of resolution at the chosen frequency range because of the large wavelength (12 cm to 17 cm), higher frequency ranges provide a better localisation of the actual source. Indeed, by increasing the frequency range of



the analysis, it can be observed that the noise source related to the leakage is in fact composed of two main areas where the sealing is defective, radiating at different levels across the frequency range.



Figure 14: Microphone array at the side of the Dragados panel for acoustic leakage identification. Mineral wool panels were placed on the door and floor sealings in order to suppress the sources of noise originating thereupon, so as to correctly identify the noise source due to the imperfect sealing of the Dragados panel, introduced intentionally for this test. Note: the array position in the photograph does not correspond to the final configuration

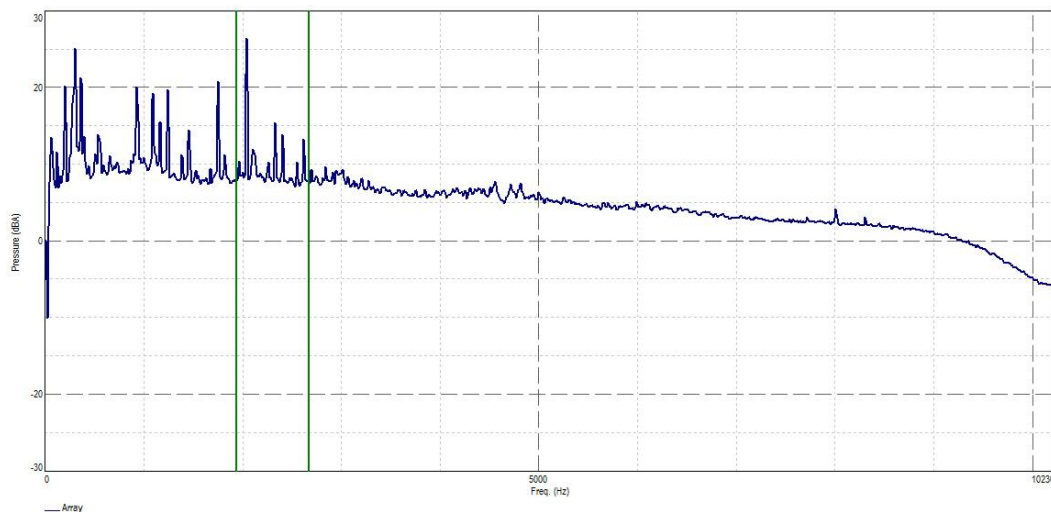
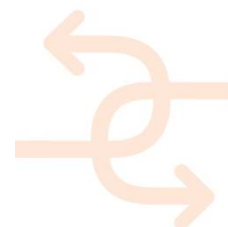


Figure 15: Averaged sound pressure spectrum on the back-propagated field at the surface of the mock-up side



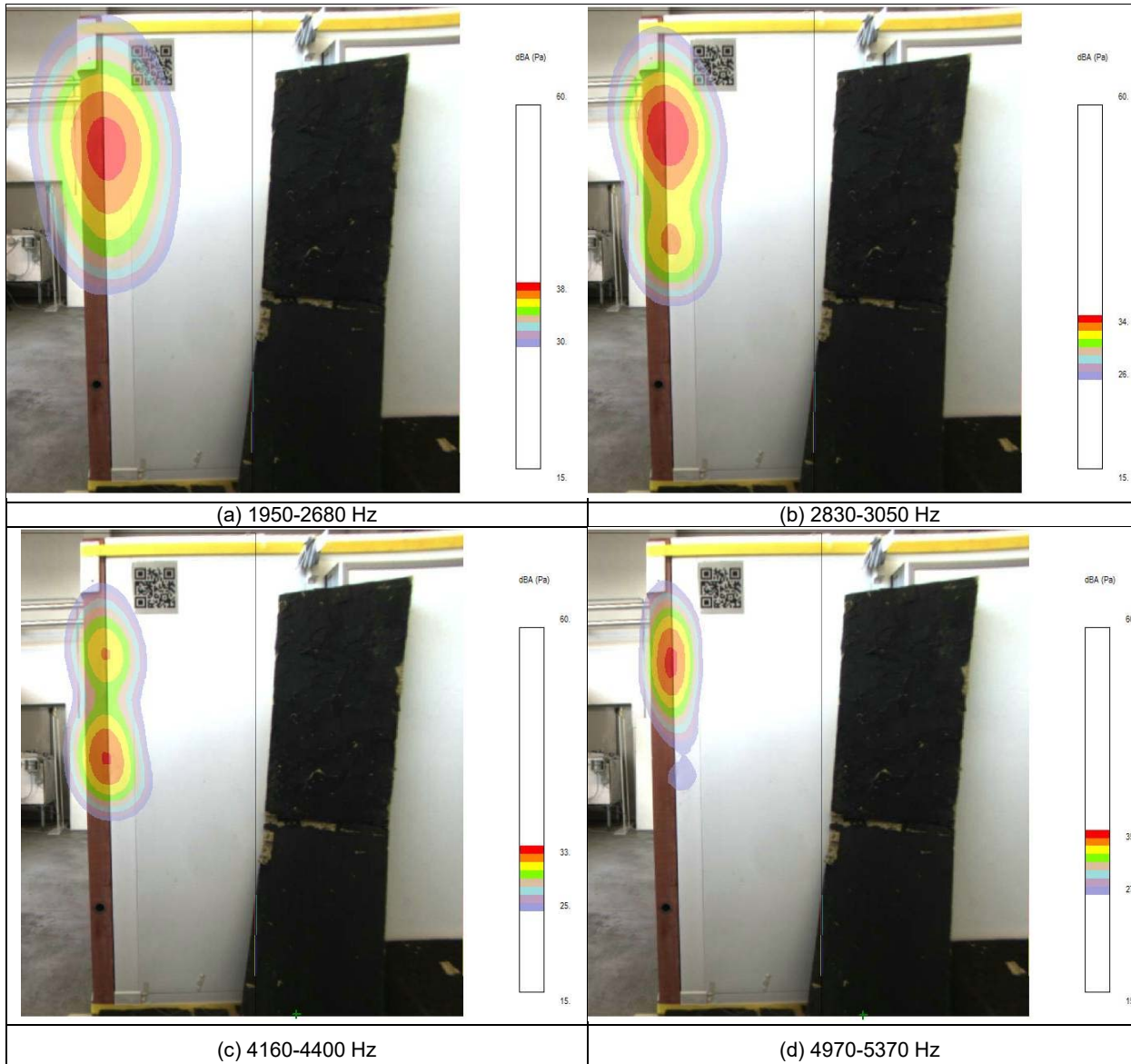


Figure 16: Back-propagated sound pressure at the surface of the Dragados-UNIVPM mock-up at different frequency ranges. Top of mineral wool treatment in the inside of the mock-up removed

2.2.5 Observation of leakage across the entire panel-room junction

A second experiment was carried in order to validate the identification approach. In this case, the mineral wool was removed from the entire vertical length of the panel's inner side. Figure 16 to Figure 17 depict the corresponding results at different frequency ranges. A leakage across the entire junction is identified, thus allowing for a direct correlation with the controlled defect.



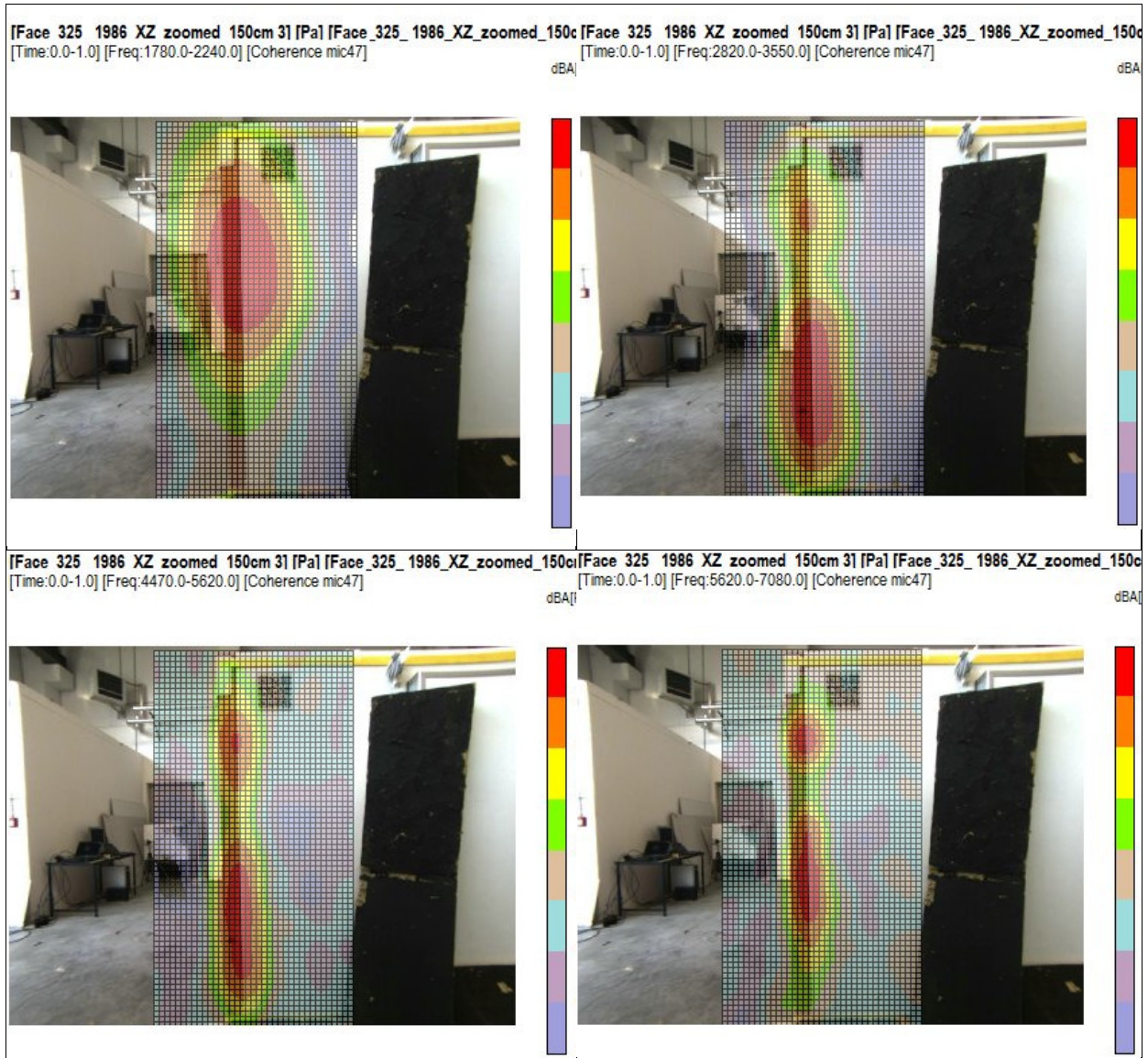


Figure 17: Back-propagated sound pressure at the surface of the Dragados-UNIVPM mockup at different frequency ranges. Top and bottom of mineral wool treatment in the inside of the mockup removed.

2.2.6 Sound intensity results - leakage from the panel-mock-up junction

This chapter presents the identification of acoustic leakage from the junction between the Dragados panel and the walls of the room mock-up.

The measurement was performed in stationary conditions using a random excitation signal in the range 100 Hz – 6 kHz, as detailed above. The frequency range of validity of the SoundBrush probe is 100 Hz – 4 kHz. The low-frequency limit is imposed by the sensitivity of the microphones themselves and the high-frequency limit is given by the distance between the microphones. Please refer to D2.3 for more details.

The sound pressure and particle velocity were recorded in the vicinity of the left junction of the Dragados panel with the rest of the mock-up, in the absence of mineral wool panels in the inner side. The resulting sound intensity vector field is represented in Figure 18. The physical gap materialises into a noticeable acoustic source, thus correctly identifying the installation error. The acoustic power of the sound source (located inside the mock-up) was not quantified. Therefore the



absolute level of the sound intensity is not relevant in this case as it is relative to the source. Nevertheless, it is worth noting that the amplitude range of the identified source is at least 12 dB above ambient noise.

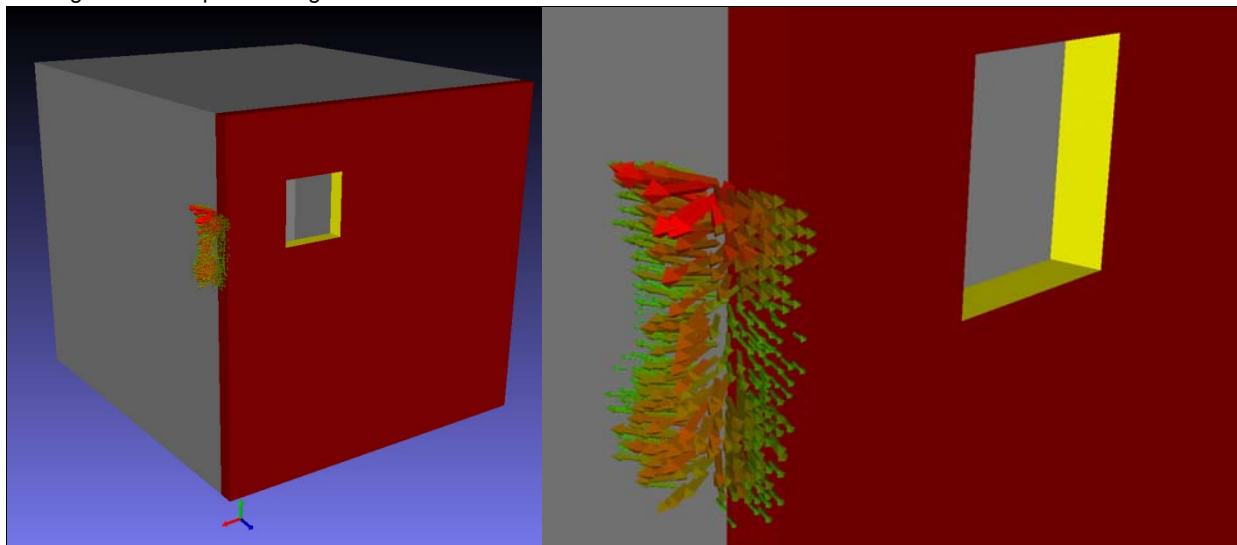


Figure 18: Averaged sound intensity vectors in the vicinity of the junction between the Dragados panel and the room mockup within the frequency range 100-4000 Hz. The sound intensity level is here represented as a linearly varying colour scale from green (57 dB) to red (70 dB).

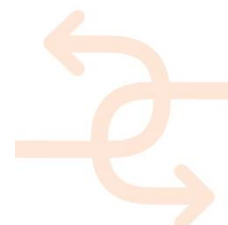
2.2.7 Determination of the sound transmission loss

Preliminary observations of the acoustic field were made. These include a complete mapping of the exterior walls of the mock-up using the acoustic array, as well as sound intensity maps.

The sound transmission loss is computed using the method described in deliverable D5.1. The reader is referred to that document for the details.

In the present case an estimation of the sound transmission loss is obtained as the difference, in decibels, between the exterior and interior levels of the normal component of the sound intensity vector in the vicinity of the Dragados panel. A region of 1m×1m was scanned at both sides.

Figure 19 shows the obtained sound transmission loss calculated from the measured sound intensity levels. The measurement is valid within frequencies 100 Hz to approximately 2.3 kHz. The reason for this in the present case is that the sound pressure level is below the ambient sound pressure level outside of the mock-up, determined at 35 dB SPL before the measurement campaign. At this point it is worth noting that the measurement could have been extended to higher frequencies by placing the source outside of the mock-up in order to take advantage of the lower sound pressure level inside it.



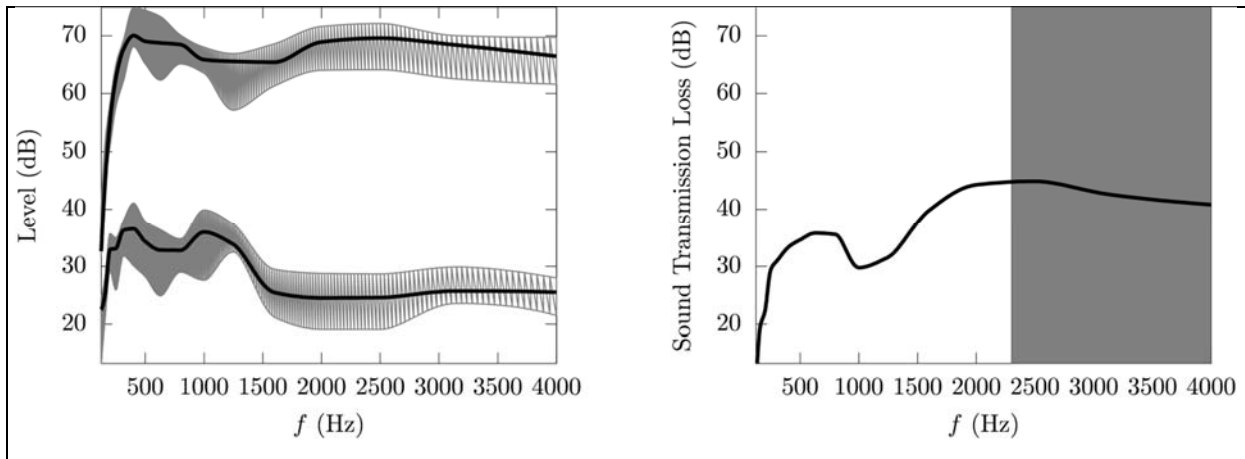


Figure 19: Estimation of the sound transmission loss using sound intensity measurements as described in D5.1. Left: sound intensity level at the inner (higher) and outer (lower) sides of the panel, with levels at the ensemble of measured points indicated in grey. Right: Sound transmission loss of the Dragados panel. The validity frequency range of this particular measurement is indicated with a white background.

2.3 3D air leakage test

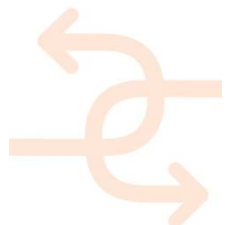
The air leakage detection by ultrasound system has been introduced in D5.1 chapter 10.2 as an alternative for the measurement of the air tightness performance of the building envelope. This is a very promising method to detect leak on open and close structures thanks to the small wavelength used. The theoretical aspects and protocols for calibration and testing have been detailed in the D2.3, chapter 7. In this chapter, the results of the inspection by ultrasound system on the cooling room where the DRAGADOS prefab panel is installed (Figure 3) are described. The air leakage detection requires the generation of ultrasound waves (frequency range between 30 and 50 kHz) inside the close envelope and the acquisition of the transmitted waves outside the envelop.

In this case the ultrasound waves have been generated by an air blow gun placed inside the cooling room and directed towards the prefab panel (Figure 20). The pressure level has been set at 2.5 bar.



Figure 20: air blow gun placed inside the cooling room.

The ultrasonic receiver (Ultrasonic Detector SDT 150) is placed outside the cooling room (Figure 21, left) and is connected to an digital acquisition board installed (acquisition board NI PXI- 5122) to a PC for recording data measured while the operator scans the area along the junction between the prefab panel and the cooling room structure. The ultrasonic receiver was kept about 2 cm away from the wall by the operator. The scanning spatial resolution was of 5 cm in the vertical direction. The acquisition rate has been set at 1 MHz and RMS (Root Mean Square) value of the time signal was calculated every 2 ms interval. The operator was scanning the junction at approximately 12 mm/s speed so that the acquisition system acquires more than 40 samples per mm, i.e. the probe moves of 1mm in 83 ms.



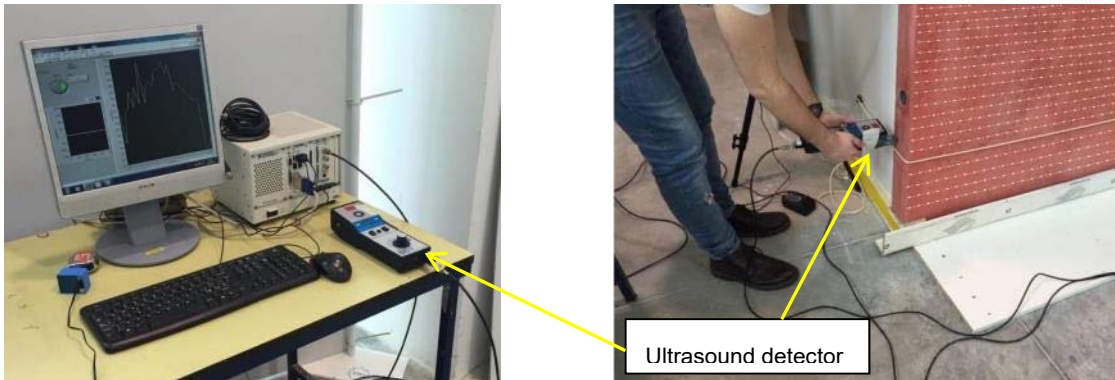


Figure 21: Ultrasound detector connected to pc (left), scanning area by operator (right).

The RMS ultrasonic level in Volts measured over the scanned area illustrated in the following figures for the different walls of the cooling room. Figure 22 (left) highlights a small leak on the window frame that is identified also by the ultrasonic level map, because the leak allows the ultrasonic waves to be transmitted to the exterior. An increase of the ultrasonic RMS level is evident in the ultrasonic map shown in Figure 22, right.

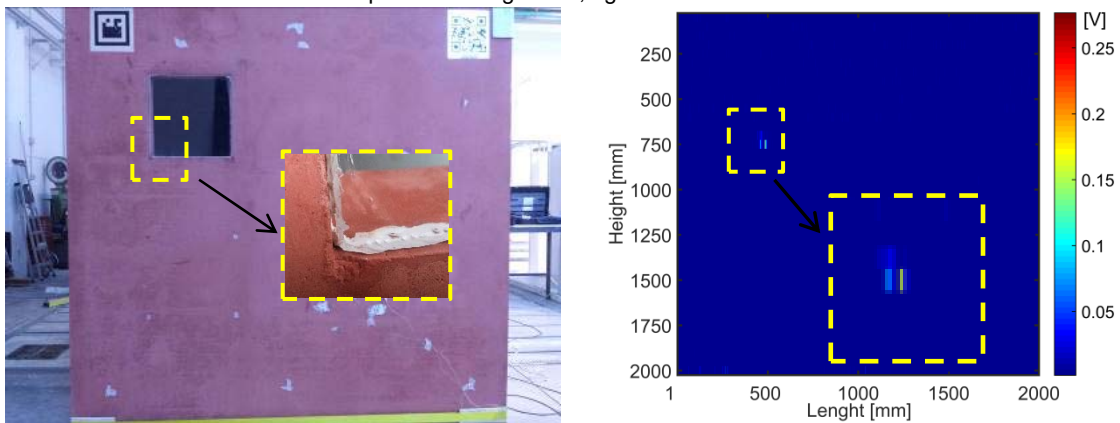


Figure 22: DRAGADOS panel (Wall A), left; Ultrasonic level map, right.

Figure 23 shows the scan area on the wall B and the map highlights a leak along the junction between the prefabricated panel and the cooling room structure. Moreover a small leak appears also on the bottom of the door probably due to a problem with the sealing.

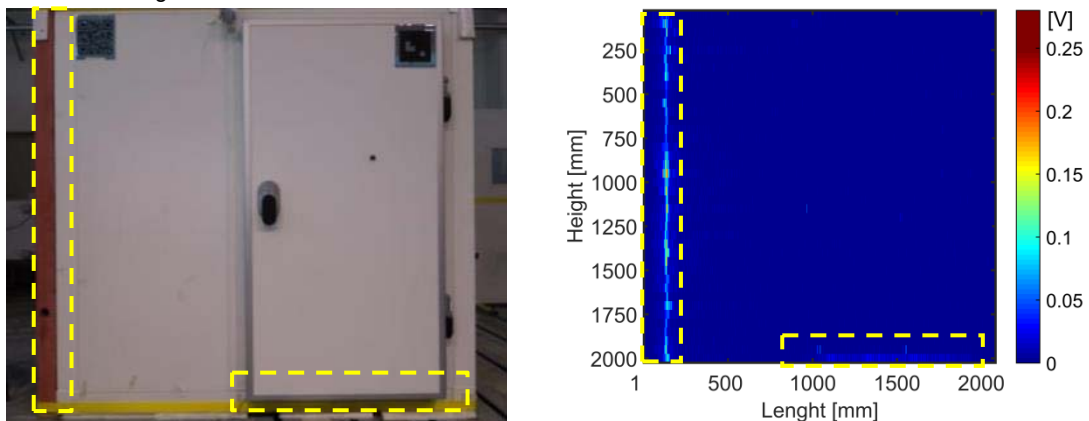


Figure 23: Wall B, left; Ultrasonic level map, right.



Figure 24 shows the scan area on the wall D, also in this case a leak has been highlighted corresponding to the junction between the prefab panel and the cooling room structure, as expected.

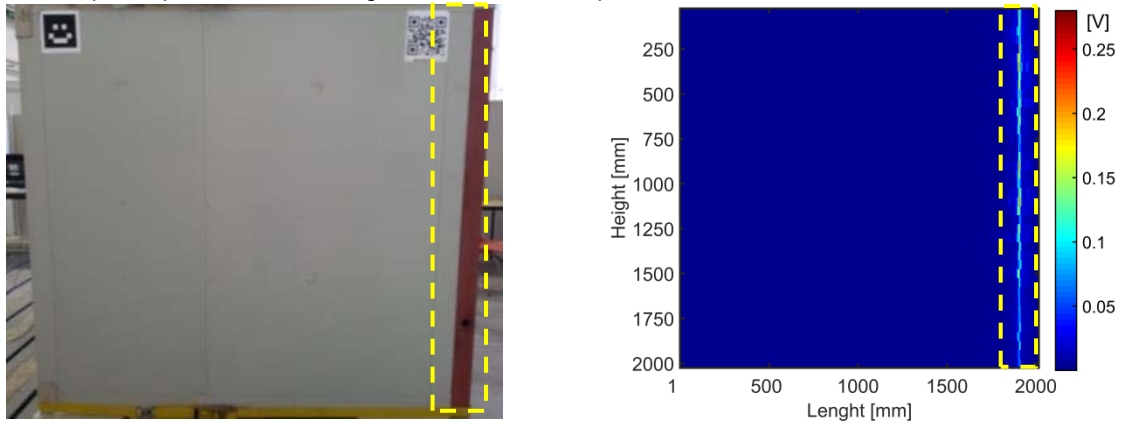


Figure 24 Wall D, left; Ultrasonic level map, right.

Figure 25 shows the scan area on the wall C, in this case any leak has been detected.

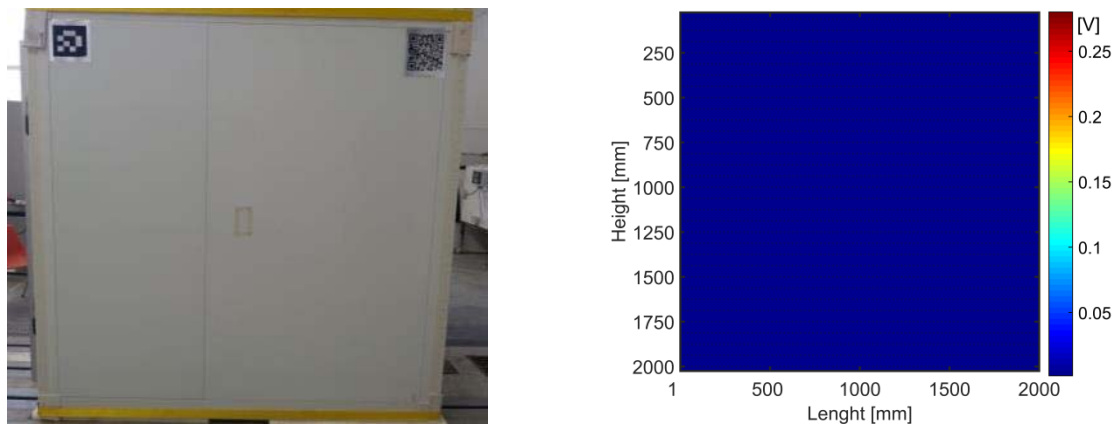
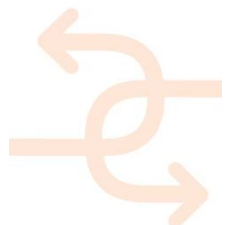


Figure 25 Wall C, left; Ultrasonic level map, right

2.4 Comparative overview of the achievements

Chapter 2.4 presented the applicability of the INSITER diagnostic tools for different measurement aspects assessment. Hereafter the main advantages/disadvantages of those techniques with respect to the currently available are summarised in terms of the measurement aspects addressed.

Concerning the thermal transmittance the IR camera based soft sensing procedure allows to reducing the testing time by keeping the same level of accuracy. The current standard for in-situ thermal transmittance measurement by means of heat flow meter (ISO 9869) states that the U-value can be evaluated with an accuracy of about 8%, depending on the environmental conditions. The inspection time is a function of the building element thermal phase (or time shift related to its thermal inertia) and is influenced by the stability of the natural day cycle. The standard, in fact, is based on natural day cycles for the generation of a gradient between the internal and external surface of the building element. The minimal inspection time declared is of 72 h but the test can be stopped only if the U-value do not change more than 5% for three consecutive nights. Standard testing time is between 7 and 15 days. The IR camera soft-sensing method proposed as INSITER thermal transmittance measurement system is based on forced thermal cycles and an



accompanying model which allows to decrease the testing time up to some cycles (between 20 and 60 hours) depending on the thermal phase of the building element (4 h for a concrete wall or 10 h for an high insulation wall, respectively). The cost of the equipment used in the current standard (ISO 9869) is of about 3000€ (cost of the heat flow meter) even though is strongly suggested to use an IR thermal camera to accurately position the heat flow meter on an region free of thermal bridges. The cost of the thermal transmittance tools proposed by INSITER is of about 5000€ (cost of the thermal camera). The same tool proposed by INSITER for the thermal transmittance evaluation (IR camera) is used for thermal bridge estimation and quantitative effect estimation on the global transmittance. The current standard ISO 14683 allow estimating the linear thermal transmittance of thermal bridges in building construction by numerical calculation. The INSITER procedure is based instead on real measurements.

Concerning the acoustic aspect the tools proposed by INSITER are the SoundBrush and the acoustic beamforming for acoustic leakages identification. The first has the main advantage of having installed a tracking device able to localize the measurement position in relation to the testing element. The positioning system has been interfaced with the BIM in order to easily superimpose the measurement data to the 3D model. Beamforming also called acoustic camera is powerful tool since, as the name states, allows visualising acoustic fields and therefore localising sound insulation losses or acoustic leaks, superimposing them onto the visual image of the building component.

Finally, the method proposed as INSITER tool for air leakages localisation is an improvement of the current standard based on blower door test (EN ISO 9972) which allows only to assess if air leakages are present but not to identify their spatial position. INSITER proposes to use ultrasound probes to localise in spade air leakages of approximately 3-20 mm width. Only with sensors working in the ultrasonic frequency range (20-100 kHz), it is possible to identify such tiny cracks thanks to the small wavelength of the ultrasonic waves. For bigger cracks or gaps between building elements the tools proposed by INISTER for acoustic aspects assessment can be applied indifferently. Since they are working on a frequency range up to 10 kHz they are suitable for the detection of gaps larger than about 30 mm.

Table 5 summarises the main characteristics and innovation of the INSITER tools for acoustic/thermal/air tightness aspects assessment.

Meas. Area	Main characteristics		Innovation for on-site self-inspection during construction and maintenance				Addressed challenges for on-site use
	Conventional procedures	INSITER procedures	Accuracy	Testing Time	Cost	User-friendliness	
Thermal transmittance	ISO 9869 In-situ measurement of thermal resistance and thermal transmittance - Part 1: Heat flow meter method	IR thermal camera measurement method accompanied by a numerical model of the building element (Soft Sensing based IR camera)	5% lower than current standard (8%)	Up to 50% of reduction with respect to the current standards depending on the thermal properties of the building elements and environment al stability	5000 € Higher than heat flow meter but IR camera is used also for thermal bridge assess-ment	IR camera is a non-contact measurement system, that simplify its application in field	Environmental conditions variation Thermal load application



Thermal bridge	ISO 14683 - Thermal bridges in building construction - Numerical calculation	IR thermal camera based method for the evaluation of thermal bridge influence on building element global transmittance	5% in line with the numerical model method	Increased time required for experimental data acquisition	5000 € The IR camera is used also for thermal transmittance assessment	IR camera is a non-contact measurement system, that simplify its application in field	Environmental conditions variation Thermal load application
Acoustic test	Sound level meter - ISO 16032:2004	Sound pressure level by Beamforming microphone array	Spatial leak detection in the order of 10 cm	Lower than 10 min for an area of 200 cm x 200 cm	Higher than a sound level meter	The acoustic field distribution is automatically superimposed to the visual image of the building component	Environmental conditions variation
	Intensity probe - ISO-9614 series	Sound intensity field by SoundBrush	Spatial leak detection in the order of 30 mm	About one hour for an area of 200 cm x 200 cm	Higher than a sound intensity probe	The position of the measurement point is automatically recorded by a tracking system	Environmental conditions variation
3D Air leakage test	EN ISO 9972 - Blower door test	Ultrasonic waves detection	Spatial leak detection in the order of 3-20 mm	About one hour for an area of 200 cm x 200 cm	3000 euro Similar to Blower door equipment	The ultrasonic probe is manually moved and its position tracked by automatic positioning system as the SoundBrush one	Noise in the ultrasound range

Table 5: Comparative overview of the achievements



3. Inspection & Instruction information for MEP/HVAC installations

MEP (Mechanical Electrical and Plumbing), in addition to HVAC (Heating, Ventilating, and Air Conditioning) equipment is often crammed into a much awarded shaped space in energy-efficient buildings made of prefab components. This is the case of CARTIF-3 Building (INSITER Spanish demonstrator), according to:

- Project setting: Building maintenance
- Test case 4: Humidity
- Test case 5: Geometry

Digital surveys carried out laser scanning and modelling of representative MEP/HVAC elements. A LEICA HDS-3000 was used, trying to evade voids (2cm @ 7m). Once X, Y, Z and L data were saved in *Cyclone*, they were registered together into *PolyWorks* universal reverse engineering and inspection software [<http://www.innovmetric.com>].

The automatic guidance for extracting the bulk of the piping and other interesting features was done in *PolyWorks* (cylinder, cones, planes, rectangles, circles) and transferred into CAD/BIM for manual completion and to clean up, adding elbows and fixing any areas the scanner could not pick up.

The final deliverable is a MEP/HVAC model with all elements correctly represented, useful to the MEP/HVAC engineers to identify the supply work, possible leakages and begin the maintenance actions with the aim of mitigating any clashes or nasty surprises on site.

3.1 Use of 3D reflectivity information for MEP/HVAC inspection and instruction

The index of reflectivity (L) was processed according to the protocol for humidity check related on D5.1. This protocol indicates the guidelines that an operator should follow for self-instruction on this purpose.

The practical demonstration of the utility of this type of data for the inspection & detection of moisture, with a real example in one HVAC system of the Spanish demonstrator (CARTIF-3 building), has already been made in the chapter 5 of the D2.3. Therefore the repetition of procedures here is avoided.

As additional application, now the technique is directed to a MEP system in CARTIF-3. After the digitization of the workshop area in that building (Figure 26) a higher resolution is just used on the MEP system (2mm @ 14m: Figure 27). The result is seen in Figure 28, where humidity is not evident, but the elements of the system and the types of material are distinguished.



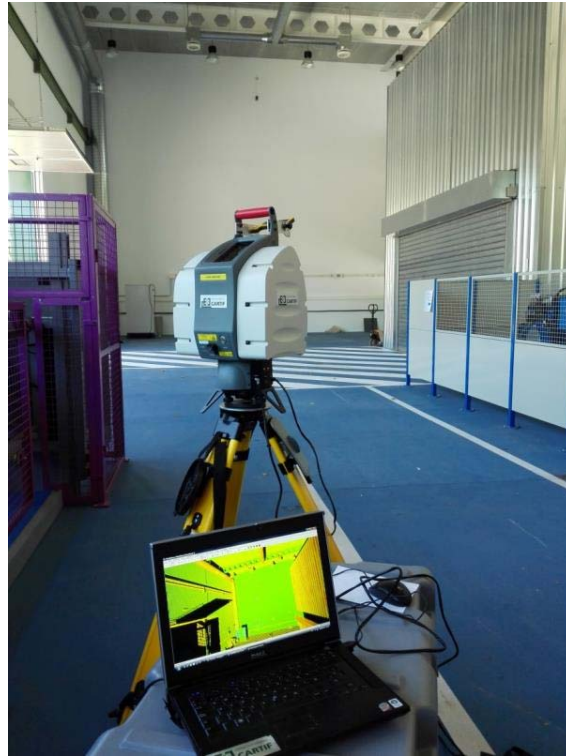


Figure 26: Recording of the index of reflectivity in the workshop area of CARTIF-3.



Figure 27: High-res 3D scanning (dotted square) of the MEP system example in the workshop area of CARTIF-3.



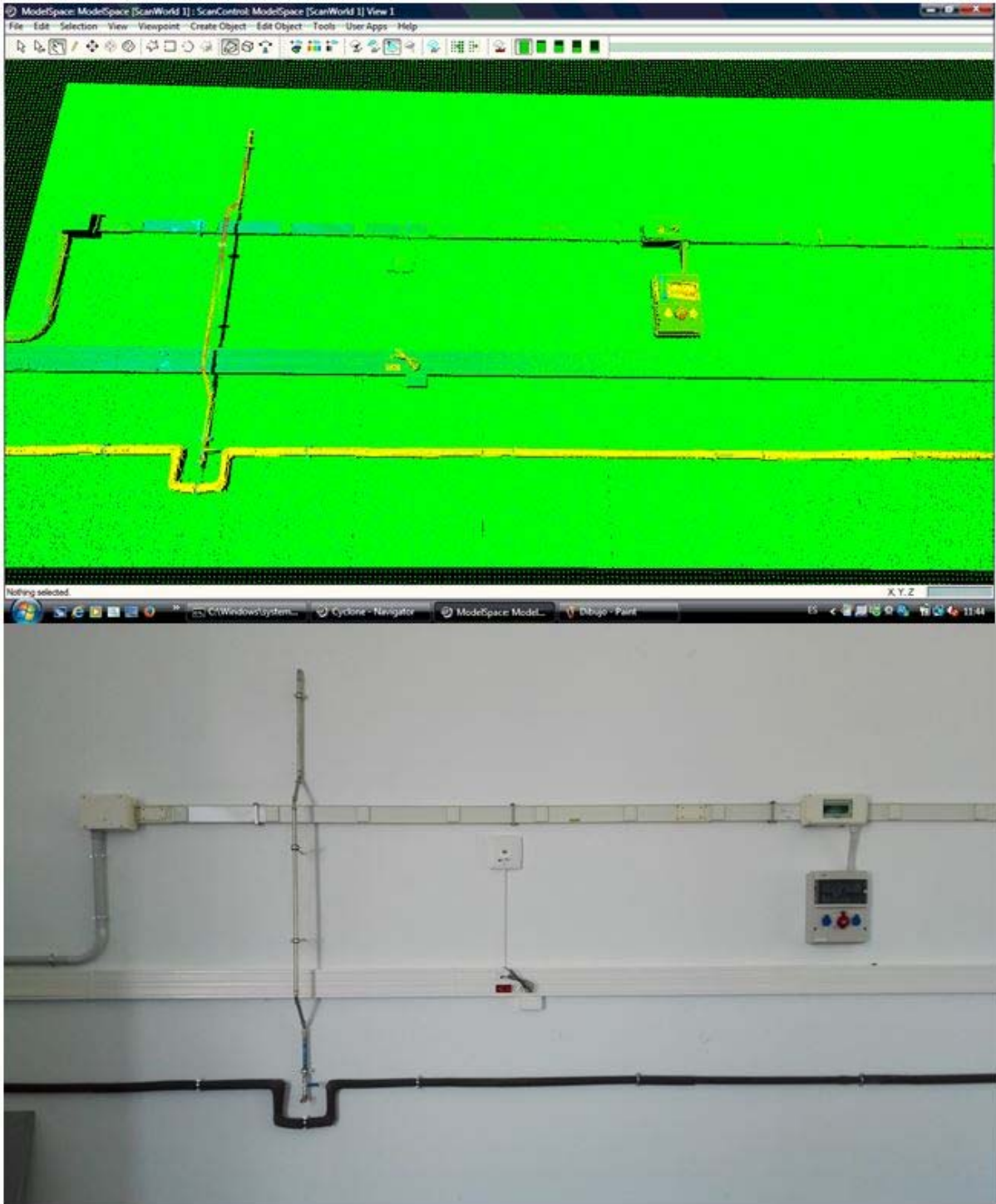
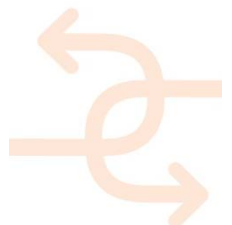


Figure 28: Dense point cloud (up) of digitized MEP system (down).



3.2 Use of 3D geometric information for MEP/HVAC inspection and instruction

Increasingly MEP/HVAC contractors involved in renovation and/or refit projects are looking for solutions that will enable them to quickly and effectively digitally represent the as-built environment as a 3D CAD/BIM model.

The emphasis with CAD/BIM is usually on the upstream activities: specification, design and build activities primarily for the construction of new buildings. More recently, MEP/HVAC contractors have begun to enthusiastically embrace the use of “Field to CAD/BIM” technologies like 3D scanning, seeing the benefits of using these tools in the design and modification of existing buildings. The goal is the transfer of as-built building information from point of source in the field directly into a CAD/BIM.

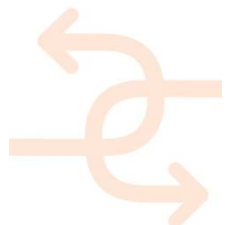
Using 3D scanners in combination with software to process and analyse the generated 3D point clouds and create a CAD/BIM is much faster and creates a better quality and accurate/precise solution than manual measurement and drawing techniques. 3D scanners are getting easier and easier to use, meaning inexperienced users can be trained to scan a site very quickly, avoiding experienced staff for days measuring and creating 2D drawings or 3D models. Moreover 3D scanners are currently relatively inexpensive given the quality of the data produced and the speed and ease of data capture. MEP/HVAC contractors are provided with a greater understanding of the as-built environment regarding the usual manual measuring procedures. This can lead to a reduction of clash and general errors caused by omissions and manual mistakes made during the measurement and drawing process. Hence, creating a 3D CAD/BIM model using scanning methods is a two stage process:

- Firstly scanning the site to create a point cloud (millimetrical accuracy).
- Secondly analysing and processing the point cloud and produce a 3D model.

Many contractors wrongly think that the majority of the work is done during the 3D scanning phase, but this is not the case. As we already know, 3D scanners create point clouds. These point clouds must be turned into the CAD/BIM models as output using processing software. The quality of the models and the speed to produce them will be dependent in part on the selection of high quality point cloud processing and analysis software. There are two ways of producing a useful CAD/BIM model from point clouds:

- Just directly modelling into the CAD/BIM tool by means of special plug-ins, as stated for the REVIT case in the D5.1, chapter 9.2.3.
- Just using specific software tools for 3D modelling that allow the creation of parametric elements to be exportable to CAD/BIM environments further on.

Let's focus on this last case since has not been contemplated in any other deliverable. Thus, some representative examples of MEP/HVAC modelling by means of *PolyWorks (MInspect module)* using CARTIF-3's workshop data are presented here. The model is built up manually by repeatedly selecting sets of points from the point cloud that correspond to individual 3D elements and then converting them to geometry (Figure 29). The selection needs to contain all the points that are relevant to the geometry that is going to be created (Cylinder: Figure 30; Cone: Figure 31; Circle: Figure 32; Plane: Figure 33).



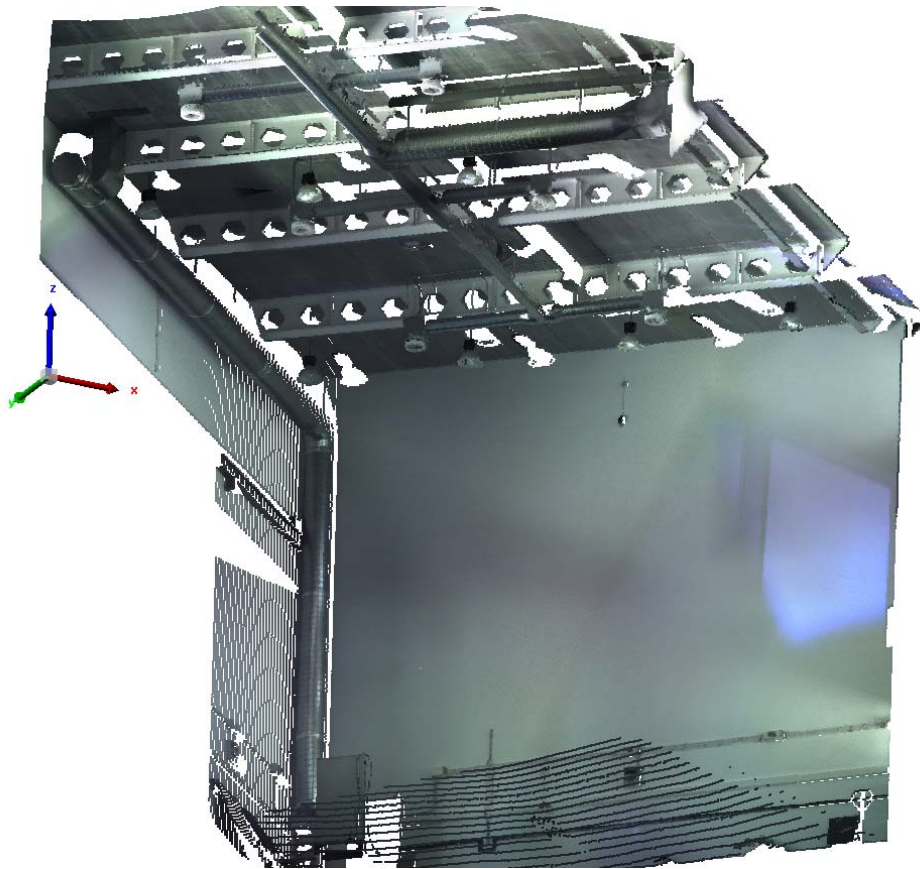


Figure 29: Point cloud of the CARTIF-3 building warehouse for 3D modelling of MEP/HVAC elements.

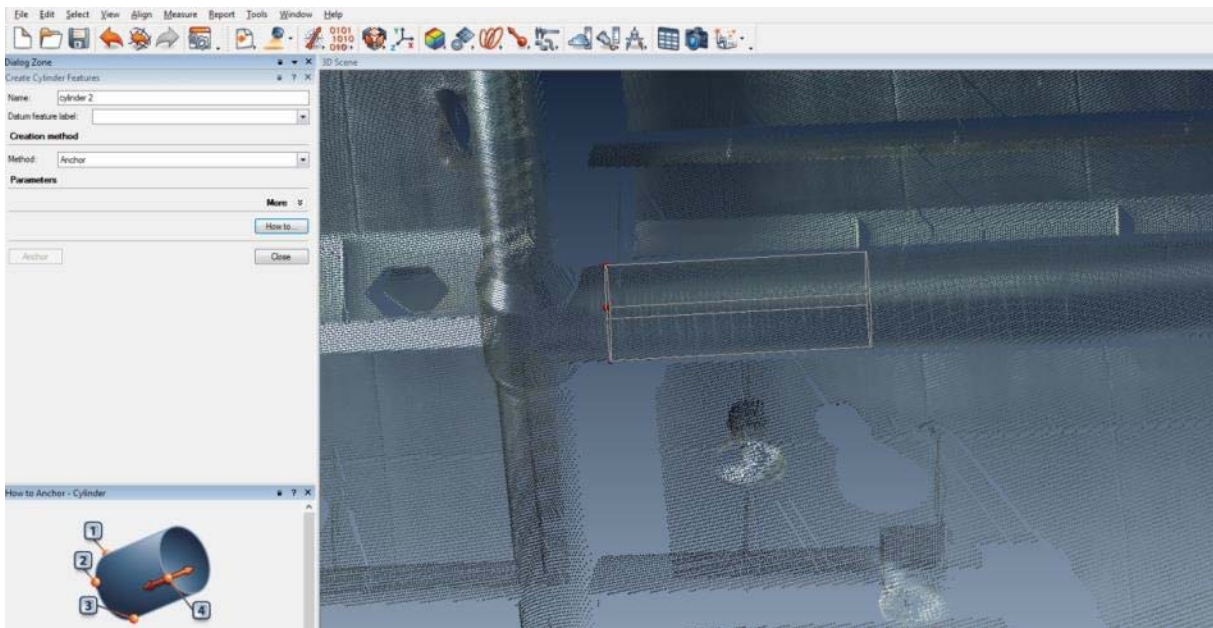


Figure 30: Cylinder adjusting for HVAC pipeline 3D modelling.

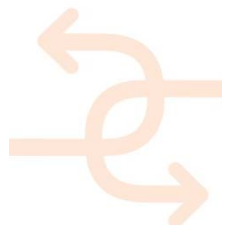




Figure 31: Cone adjusting for lamp 3D modelling.

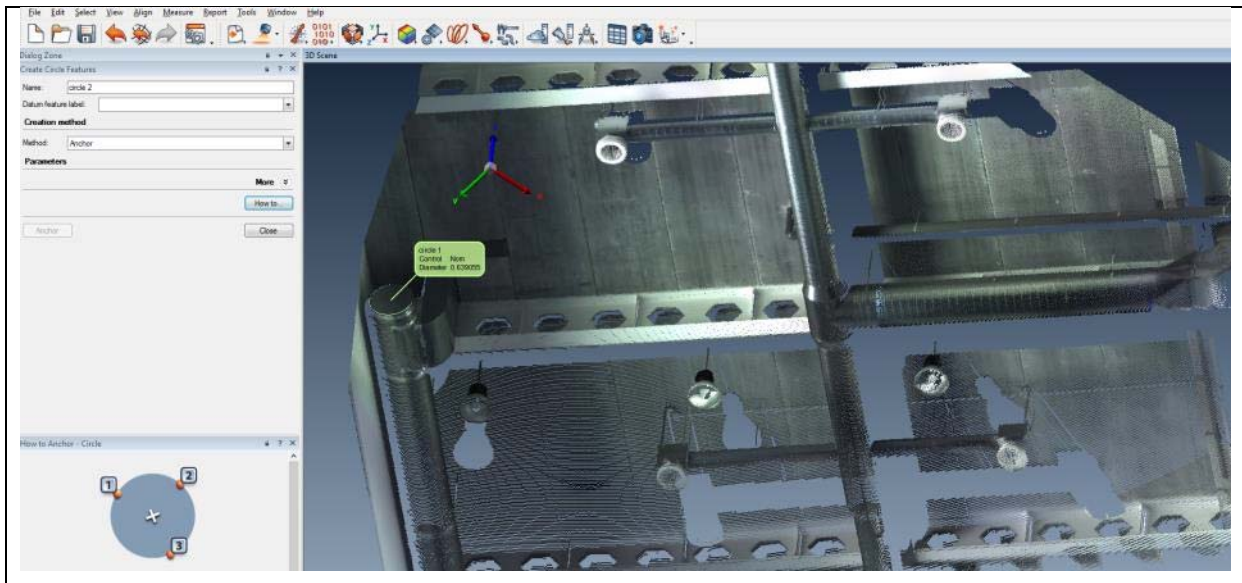


Figure 32: Circle adjusting for HVAC stopper 3D modelling.



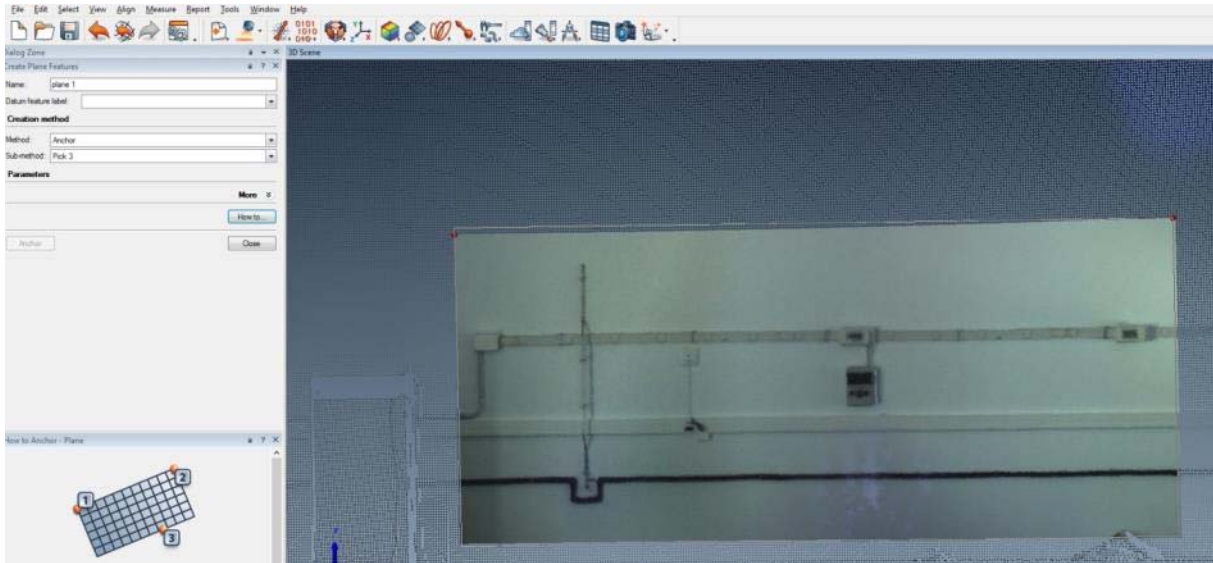
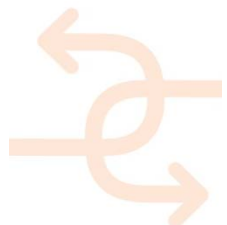


Figure 33: Plane adjusting for MEP wireway 3D modelling.

The tools within the point cloud modelling software allow building up the geometry for each item as much as automatically as possible. This activity is repeated until all required elements of the building are modelled (Figure 34). In addition any kind of measuring verification and dimensioning can be carried out on the point cloud and on the obtained parametric features (Figure 35).



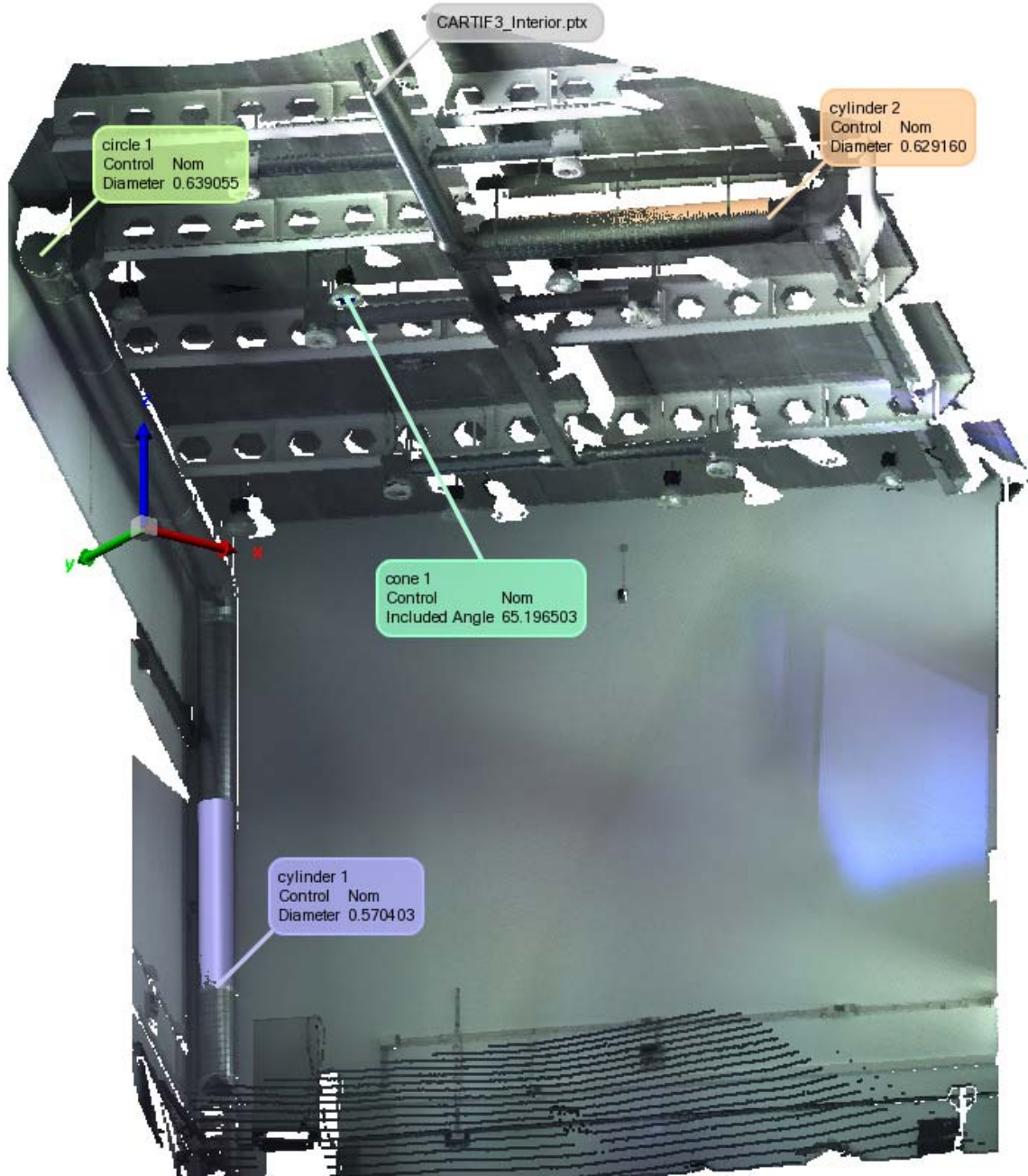
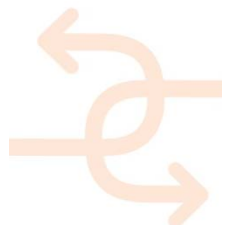


Figure 34: Basic modelling of MEP / HVAC representative elements.



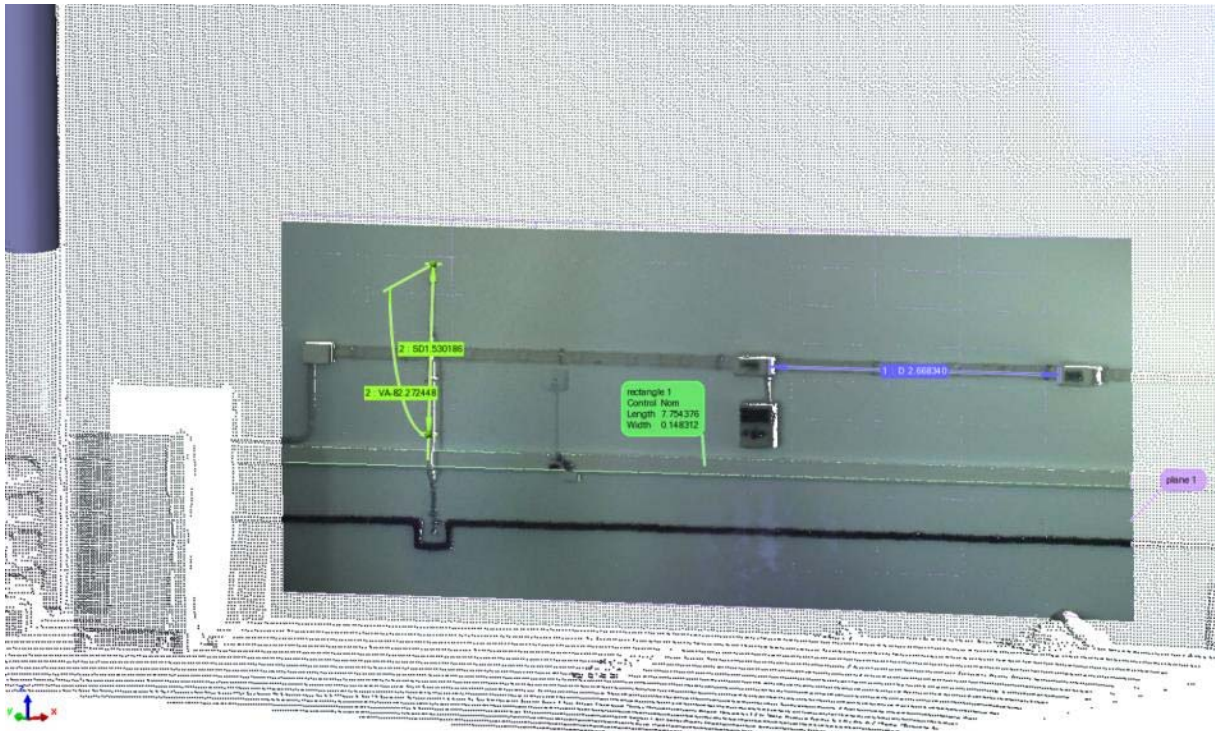


Figure 35: Distance and angle measuring on the MEP point cloud.

Good point cloud modelling software will contain functionality that allows duplicating geometry across the model, meaning that is only needed to model repeated items once. Additionally, it could also contain tools that speed up the creation of common MEP/HVAC items (this is the case of well-known software such as: *TRIMBLE RealWorks* [<http://www.trimble.com/3d-laser-scanning/realworks.aspx>] or the *LEICA CloudWorx* family [<http://leica-geosystems.com/products/laser-scanners/software/leica-cloudworx>] that allows you to automatically model a pipe by selecting a section of the pipe data in the point cloud and then extrude the section along the point cloud. The extract function will create a pipe that follows bends in the point cloud (Figure 36).



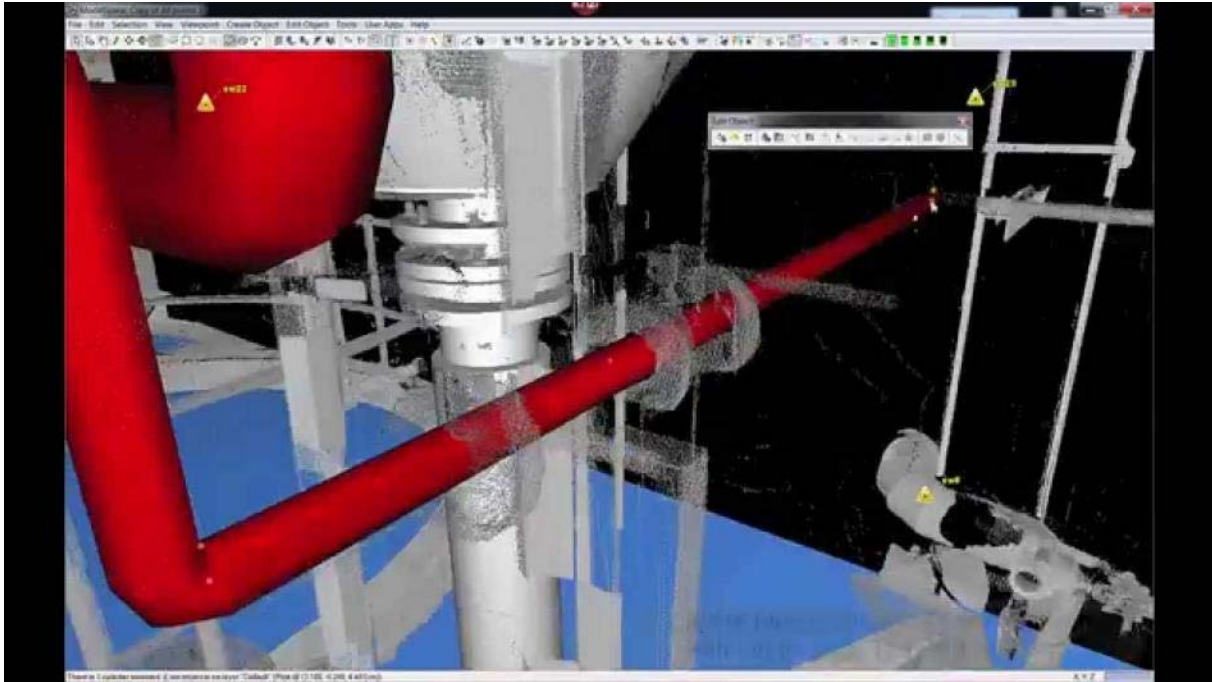


Figure 36: Plant modelling using LEICA Cyclone 9 [Source: C.R.Kennedy & Company].

As final step, CAD/BIM models are generated from 3D scanning by exporting the modelled features to useful formats (Figure 37). Hence the global described process implies reduction of cost of model creation, deskilling of model generation activities, budget reduction and quality improvements.

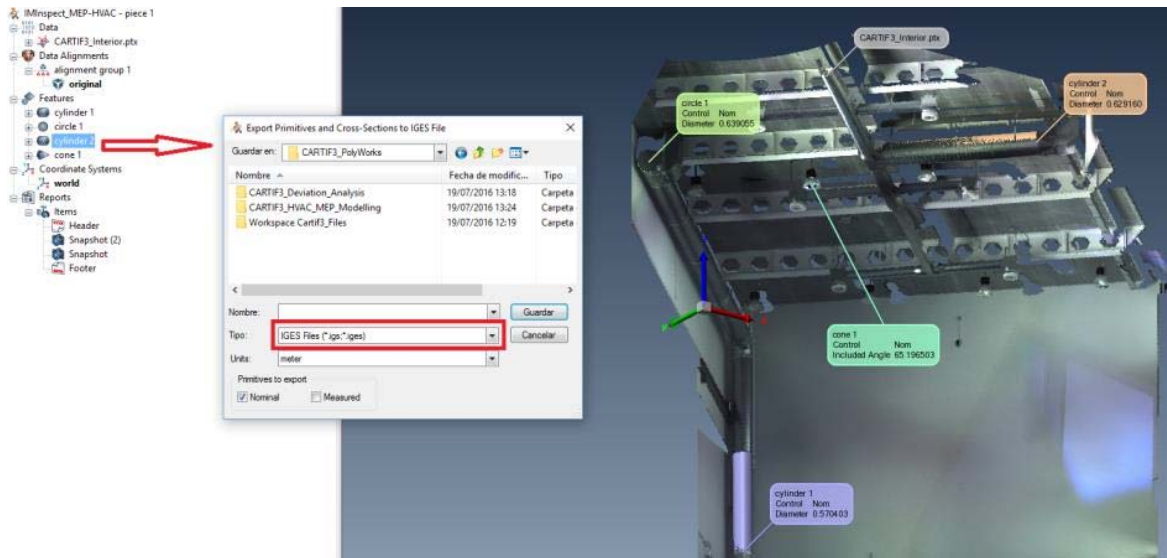


Figure 37: Exporting to IGES format of a modelled pipeline (valid for CAD and BIM).



4. Virtual/Real testing of quality and performance levels based on BIM

4.1 Prove models to guarantee smooth BIM processes

Since the BIM model represents a crucial part of INSITER project regarding information and documents provided via 3d elements, it is essential to guarantee proper workflows based on BIM. The most common errors occur due to misspelled attribute namings and wrong formats of entered values. To prevent those errors the BIM model has to be evaluated regarding specific rules depending on the processes they are used for.

This chapter is referring to test case 6: BIM. The test case is for validating the consistency of the BIM models considering the aimed processes.

4.1.1 Model checks -> processes (naming conventions, data availability, attributes)

To guarantee smooth processes related to the BIM models it is important to use naming conventions. This will assure that the BIM models and connected information can be addressed in an automated way. Testing the functionality of automated model checks is the key to setup stable workflows and processes.

4.1.2 Deviation analysis -> Augmented Reality (geometrical exactness)

For using the technology of Augmented Reality it is most important to use BIM models consisting of very exact geometrical data. Therefore, techniques have to be validated to guarantee that the created BIM models match the reality even if available 2D drawings (input information) are very poor quality. Deviation analysis between created models and available laser scan information is the key to validate the BIM models regarding geometrical correctness.

4.1.3 4D checks -> sequences (logical correctness of time schedules)

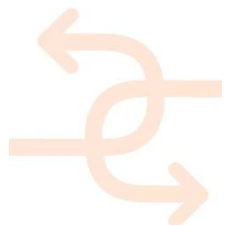
Using 4D simulations will offer the users a great opportunity to check the construction sequence for logical errors (e.g. columns will be created prior to the pouring of the below slab is finished). Therefore, it has to be tested how to communicate detected issues which are 4D related.

4.2 Validate the representation of results created by the other test cases

This part of the BIM test case is for approving the ability to provide results from the measurement devices to the project team.

4.2.1 Provide data via BIM ->(additional documents, attribute values, links)

To prove that results coming from several measurement devices may be attached to a BIM model in a suitable way the functionality of providing the information has to be tested. It has to be validated that external data (like documents and drawings), external links (to several internet sites) and values of BIM attributes (e.g. specific



value added to an attribute) can be provided to the project team.

4.2.2 **Provide model check results → (Feedback on model analysis)**

In case model checks can be performed in a feasible way the results of such an analysis must be provided to the project team. This part of the test case investigates the possibilities on how to forward the identified issues of model checks.

4.2.3 **Results of a deviation analysis→(Feedback on geometrical exactness)**

Results of a deviation analysis must be provided to the creator of 3D models to enable them to update their models if necessary. This part of the BIM test case refers to providing results of a deviation analysis.

4.3 Use Case Scenario Examples

Since currently the necessary requirements are not finally decided yet a fictional project has been used to approach the model checking. Several common checks have been setup and tested to easily transfer them later on to the INSITER use cases.

4.3.1 **Model Checks**

Model Checks are relevant if it comes to quality management regarding BIM models and related processes. To be able to ensure the correctness of the used models regarding available attributes, geometrical consistence and included information is the key to guarantee that no errors occur in further processing or at least keep them at a very low level.

To keep the model checking system open to be able to enhance the INSITER toolset by adding additional and more complex checking rules the decision was to use Desite MD for model checking. This software provides an API which gives the possibility to address the BIM models from outside of the checking software as well as to export information for further processing.

The screenshot displays the API interface for Desite MD. On the left, a class hierarchy shows 'QObject' at the top, followed by 'desiteCore::CoreAPI', 'desiteCore::ProjectAPI', and 'desiteCore::NavigatorProjectAPI'. A text box explains that scripting is provided by three levels: Level 1 (User Defined Properties), Level 2 (Scripts to automate actions), and Level 3 (Scripts embedded in the 'Input Forms'). Below this, a 'Properties' section lists methods like 'getPropertyValue', 'isPropertyInherited', 'getPropertyValueRange', 'getPropertyValueList', and 'getPropertyValueAsString'. The main area shows a function definition: 'QString desiteCore::ProjectAPI::createMaterial (QString xmlMat, QString modelID = QString ())'. Below the function is a description: 'Create a new material for visualisation. If the material already exists the existing material is not changed.' It lists parameters 'xmlMat' and 'modelID', and returns the 'ID of new material' or an empty string if not created. A code editor shows XML for a material: '<default-mat-11 name=default-mat-11>
<Q b=40 g=150 a=1 />
P b=40 g=150 a=1 />
S b=255 g=255 a=1 />
/></>'. A date '2013-01-14' is visible at the bottom.

Figure 38: API (application programming interface) of Desite MD to setup model checking system.



Additionally, it is possible to enhance the functions of the software by including user-defined properties (to have the possibility to enhance queries) and to include scripting functionalities in case more complex model checks have to be setup.

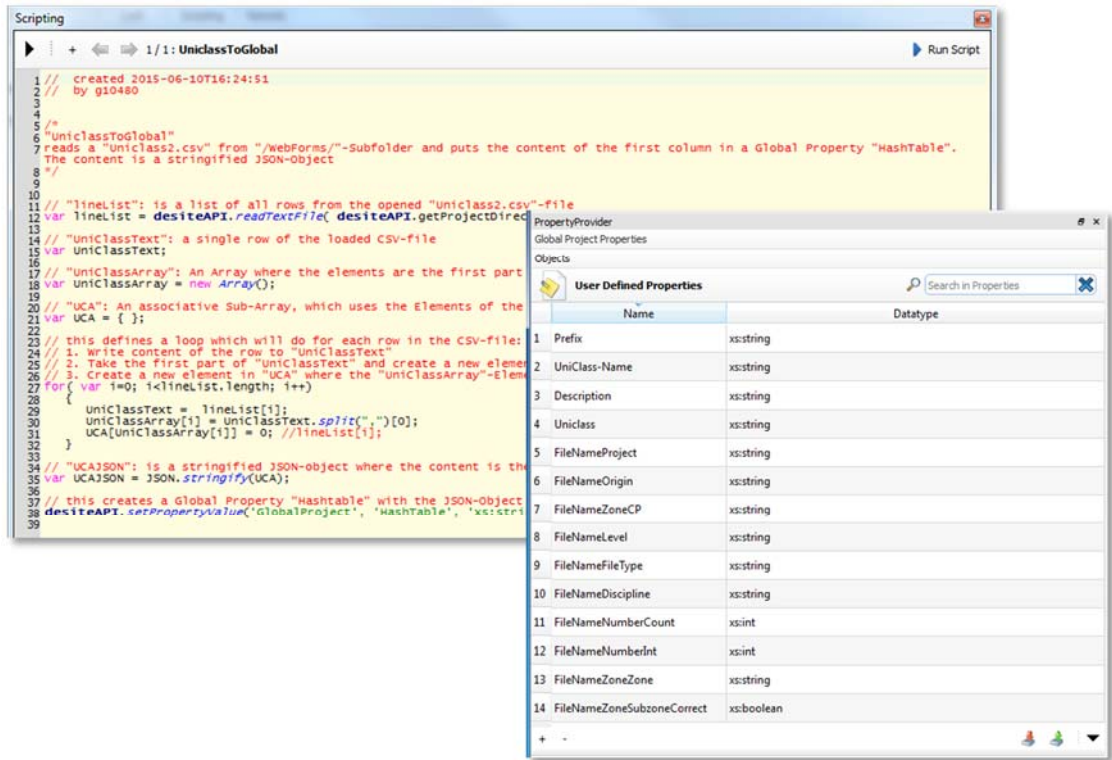
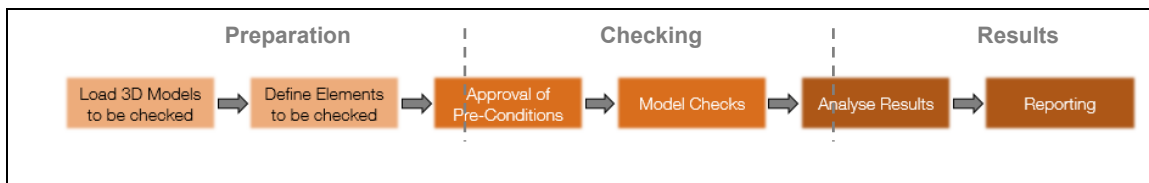
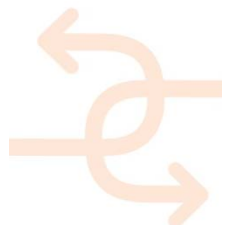


Figure 39: user-defined properties in Desite MD

Even if there are several kinds of Model Checks available all of them are going through the same process.



Preparation First, the models to be checked have to be loaded to a model checking software and all objects which should be analysed have to be selected for performing a specific check. This definition of to be checked elements might become relevant if only a specific area should be analysed.



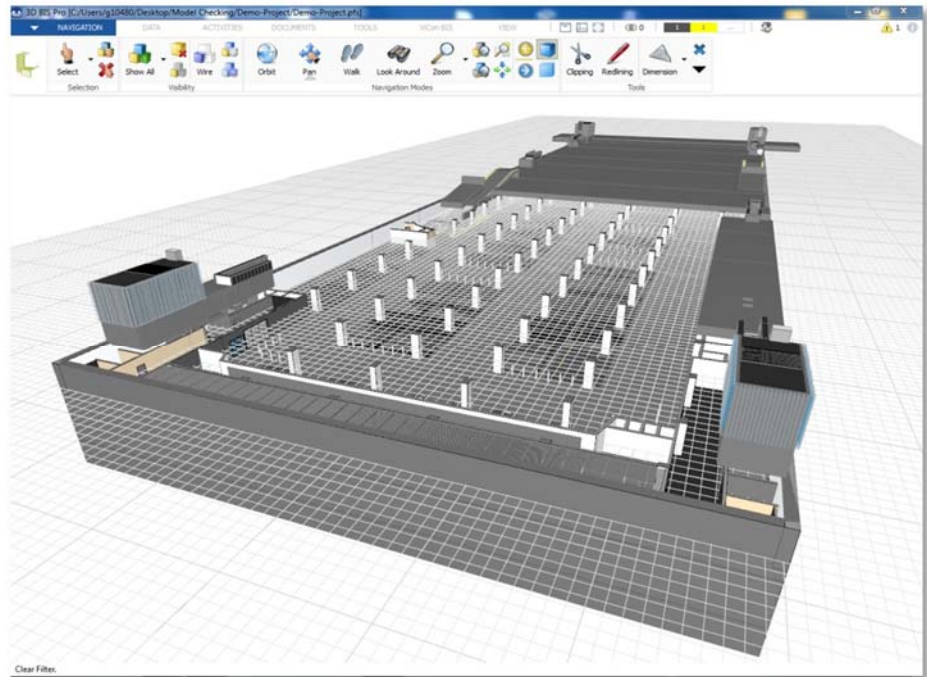


Figure 40: The GUI (graphical user interface) of Desite MD

Checking

Before starting the model check itself pre-conditions have to match. Defining pre-conditions enable the model checker to reduce the selected objects to just the relevant objects for a specific check. For example, a check about “used concrete” is irrelevant for door objects.

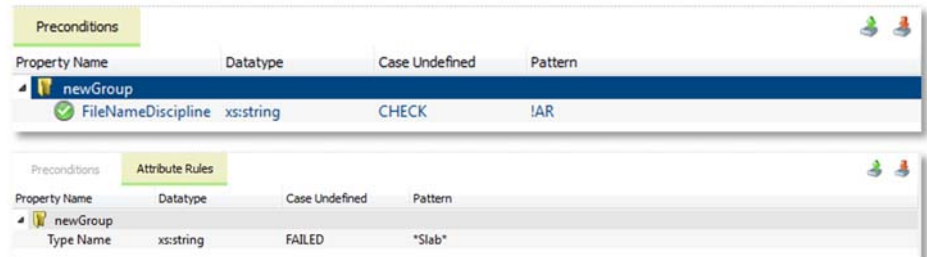
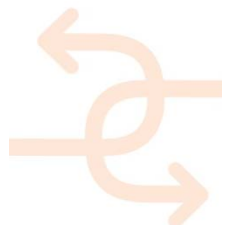


Figure 41: Preconditions and Attribute Rules

Pre-conditions and model checks are defined in the same way. It has to be defined which attribute of the selected 3D models has to be addressed and of which type this specific attribute has been declared (e.g. string, number, link). This guarantees that the check is referring to the correct value. In case the given value of an attribute does not match the named type or the attribute is not available for the 3D element the check would give a “warning”. Therefore, it has to be defined how this case has to be interpreted (failed or correct). The checking rule itself concludes the main process of checking where it is stated which statement has to be true to fulfil the model check.

Depending of the allowed values for a model check and the type of the attribute the checking rule will be setup differently. It is possible to use logical operators directly in the definition of the allowed values (e.g. “>” value must be larger than) or to include several



different allowed values “e.g. value must be “RL” or “TL” or “SL” or “ZZ”). In case the allowed values are a list of many entries it is possible to list them in an Excel-sheet. This list may be referenced to check the attributes against lots of values as well.

Some examples for possible model checks are listed in the following image:

Property Name	Datatype	Case Undefined	Pattern
FileNaming			
FileNameProject	xs:string	FAILED	LUS
FileNameOrigin	xs:string	FAILED	WAA
FileNameZoneCP	xs:string	FAILED	CP07C1B
FileNameZoneZone	xs:string	FAILED	Z0 Z1 Z2 Z3 Z4 Z5 Z6
FileNameZoneSubzoneCorrect	xs:boolean	FAILED	true
FileNameLevel	xs:string	FAILED	RL TL SL B1 B2 FN PL GL M1 01 02 RF XX ZZ
FileNameFileType	xs:string	FAILED	DB M3 MR RP
FileNameDiscipline	xs:string	FAILED	66 DC EL EN FF FI FS FW HV IR LV PN PW RD SL SS ST SW TE TM TS XX
FileNameNumberCount	xs:int	FAILED	5
FileNameNumberInt	xs:int	FAILED	<7000
FileNameNumberInt	xs:int	FAILED	>1000

Figure 42: Model checks examples

Results

After performing the model checks, the results will be analysed and reports will be created for further processing.

Name	State	Date	Comment
Basic Wall [222980]	OK		
Basic Wall [222981]	FAILED		No contact at top
Basic Wall [223065]	FAILED		No contact at sides
Basic Wall [223066]	FAILED		No contact at top/bottom
Basic Wall [223067]	OK		
Basic Wall [223075]	FAILED		No contact at top/bottom
Basic Wall [223076]	OK		
Basic Wall [223153]	OK		
Basic Wall [223161]	FAILED		No contact at top/bottom
Basic Wall [223162]	FAILED		No contact at top
Basic Wall [223163]	FAILED		No contact at top
Basic Wall [223165]	FAILED		No contact at top
Basic Wall [223166]	OK		

Figure 43: Model checks report

On one hand the results will be listed in the checks themselves, on the other hand the 3D component also provides the possibility to analyse the results.

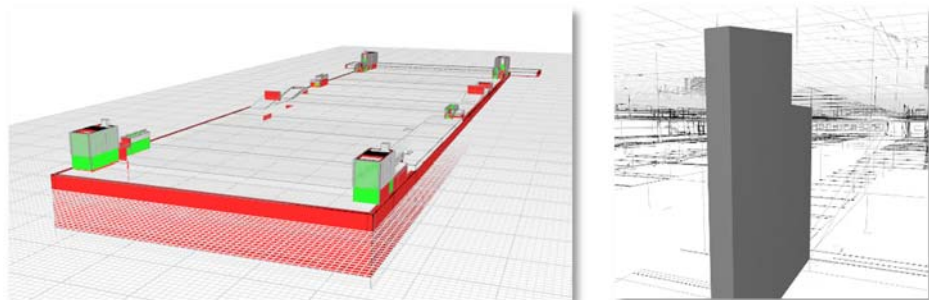
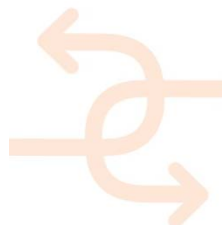


Figure 44: Highlighting the model check results in 3D



The colour coding enables the model checker to highlight all correct and wrong elements as well as those with a warning (e.g. the 3D element contains not the referenced attribute and therefore the specific check might not be performed).

To provide the evaluated results to the project team there are several options for transferring the findings. Beside analysing directly in the model checking tool there are the options to forward the results to a connected database or the export them into an Excel-sheet for further processing.

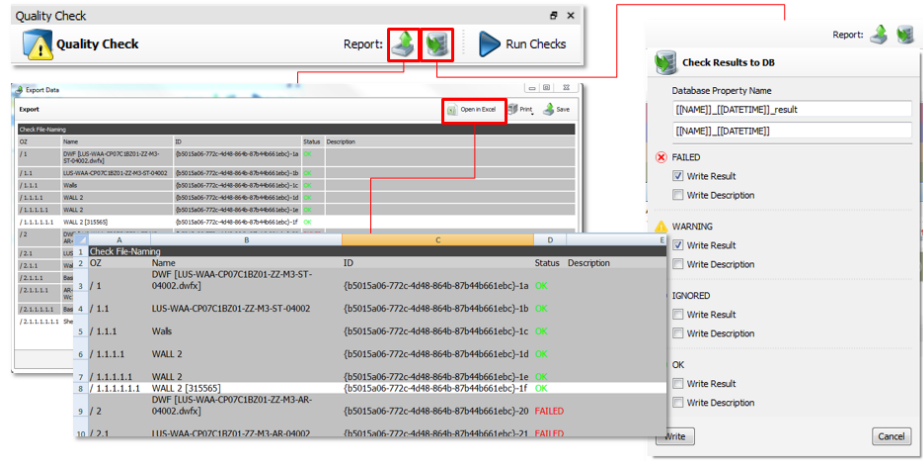


Figure 45: Report alternatives: Database & Excel

All of the available types of model checks follow the above mentioned process: attribute-checks, contact-checks, geometry-checks and ID-checks as well as the comparison of the different versions of models. All those mentioned kinds of checks will be explained below.

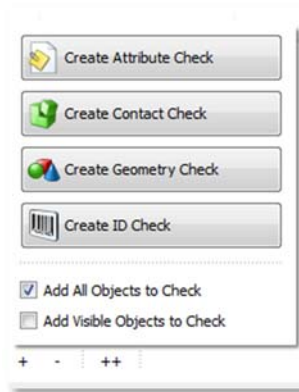
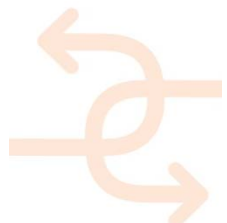


Figure 46: Types of model checks.

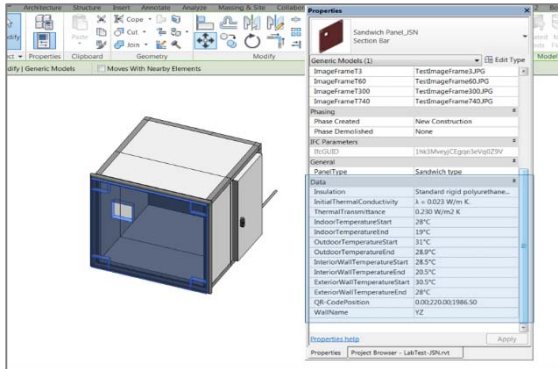
Attributes Check



The most complex check is the attribute check which gives the model checker the most options due to the fact that available attributes may be enhanced by scripts and user defined properties can be added.



For setting up the model checks it is essential that all 3D elements in the model have all necessary attributes. Creating a list of attributes is a helpful way to enable the modelling team to prove if all necessary data is included in the 3d model (right side image). All those attribute should be accessible in the 3D model as well.



List of Attributes	
Name of Attribute	example
Materials and Finishes	
Coating	White pre-painted hot galvanized steel sheet
Material	
Identity Data	
LinkToReport	http://www.test.com
Images	Image.jpg
ImageFrame3	TestImageFrame3.JPG
etc.	
General	
PanelType	Sandwich type
Data	
ExteriorWallTemperatureEnd	28°C
ExteriorWallTemperatureStart	30.5°C
IndoorTemperatureEnd	19°C
IndoorTemperatureStart	28°C
InitialThermalConductivity	$\lambda = 0.023 \text{ W/m K}$
Insulation	standard rigid polyurethane foam
Insulation Density	41.00 kg/m ³
InteriorWallTemperatureEnd	20.5°C
InteriorWallTemperatureStart	28.5°C
OutdoorTemperatureEnd	28.9°C
OutdoorTemperatureStart	31°C
QR-CodePosition	0.00;220.00;1986.50
Thermal Conductivity	0.0230 W/(m-K)

Figure 47: 3D elements and attributes

All these parameters will also be transferred by exporting the IFC file from the CAD system.

On the other side it is most important to know exactly the allowed values for a specific check. All kinds of input values may be checked, but must be considered while setting up the different model checks. This might be an Excel sheet with listings of allowed values as well as a table in a database. While setting up the different model checks information about the way how the allowed values are given is essential.

To summarize the findings regarding model checks, there are two important issues which must be covered before starting to create model checks and analyse their results. On one hand the range of allowed values must be considered (must be provided via lists or database entries) and on the other hand there must be information about the current situation available which should be evaluated (e.g. measurement results of inspections, attributes of 3D elements).

Bringing both sides together enables the model checker to validate the BIM models and forward results to the project team for further processing.

Example: Approval of Name Definitions

To standardize the modelling process, it is important to define a naming convention, which clearly defines the naming of files and elements (families/types/layers/elements itself/attributes) as explained by Work Package 4. Creating attribute checks may be used for the approval of the correct naming convention used for a 3D model. It is possible to evaluate the complete naming or just specific parts of the naming (this might be necessary if a defined substructure is defined within the naming convention).

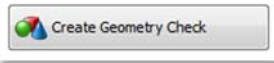
Example: Links and additional data checks

Due to the fact that there is a lot of additional information which needs to be added to a 3D model element,



(e.g. test results, pictures, links, additional data) it is necessary to approve the given links. It is possible to evaluate if a specific data is correctly attached to the model and additionally it can be checked if the value given in the model matches with given values in a test report for example. Data consistency may be approved this way.

Geometrical consistency check



Another important check, especially if quantity take-off is needed in the project, is to analyse if the 3D elements are closed solids. Unfortunately it often happens that some elements are not properly exported from CAD system to IFC format. This may result in that those mismatched elements have no volume due to the fact that the elements are not closed solids. Therefore, those elements cannot be used for meaningful quantity take-off anymore. A check run which shows results of the consistence of the 3D elements is a very helpful tool to avoid such corrupt data.

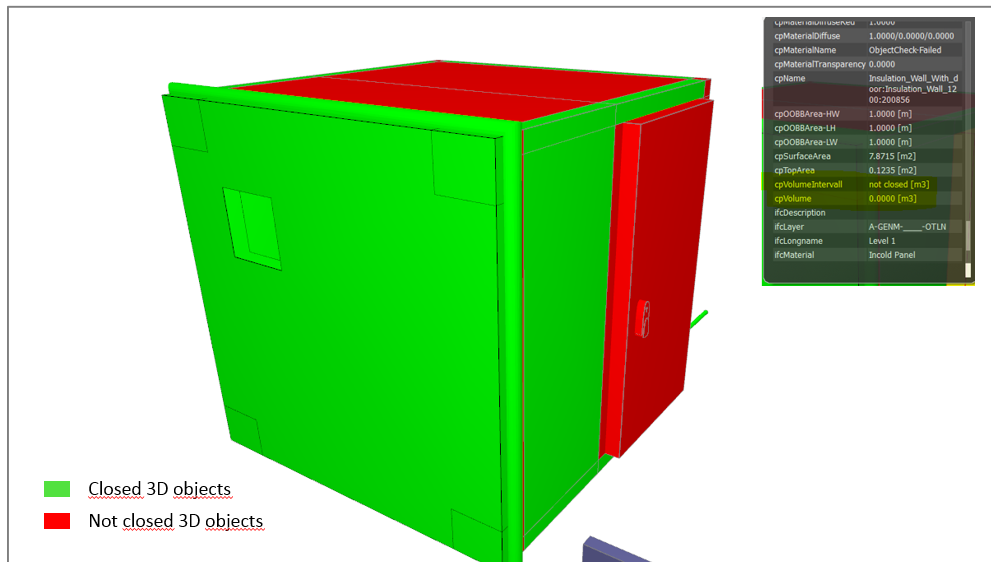
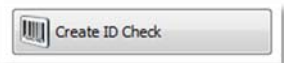


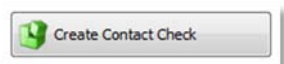
Figure 48: Example for a Geometrical Consistency Check

Unique ID Check



Having a unique ID for each model element is crucial to avoid any kind of mismatch in the evaluation of all data. Therefore, a check may be setup to evaluate whether all used IDs of all 3D elements are unique to avoid wrong addressing. Otherwise wrong addressing could lead to corrupt BIM processes.

Contact Check



The contact check verifies contact of adjacent elements (for example: are structural walls directly connected to the slab below?). This kind of model check is also very important for checking the correctness of room models which are the required input data for energy simulations via VABI element



(see 4.5). In case that the given room elements do not fit to the existing walls it is not possible to perform a meaningful energy calculation.

Version checking

The comparison between different versions of BIM models is slightly different to the other model checks due to the fact that two models have to be loaded previously before performing this check. The version checking will be used to identify all changes between model updates (deleted, changed and new 3D objects as well as attributes). The most important aim of this check is to keep track of the design changes and to verify model revisions.

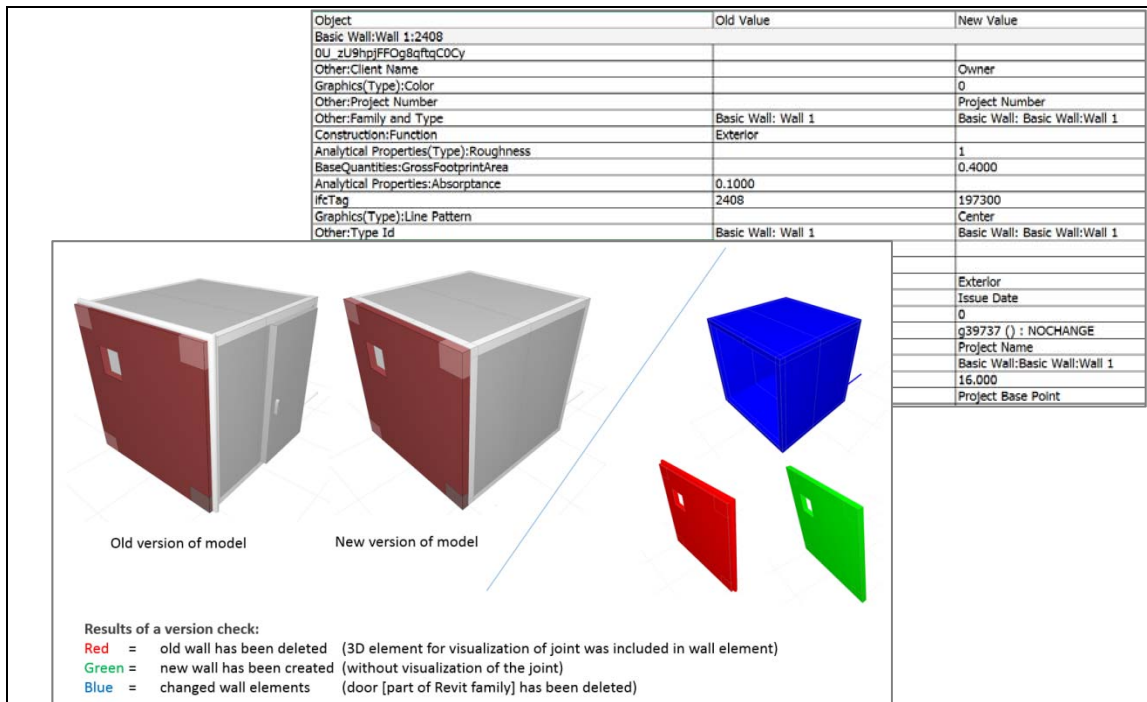


Figure 49:Version checking

4.3.2 **Deviation analysis**

To be able to use the BIM models for augmented reality it is most important to match the given construction situation on site with the BIM models appearance. To get reliable results with the BIM models even if only poor 2D data is available to create 3D models deviation analysis will be performed to compare laser scanning point clouds with created BIM models.

To test the deviation analysis, the project of the Pisa school complex has been used. Starting point were several 2D drawings with only some information for creating BIM models on one hand and on the other hand there were 26 point clouds of performed laser scans.

The deviation analysis was tested with the software “Scan to BIM”. For the test the 3D-model of the School Complex Pisa provided by Work Package 4 was used. “Scan to BIM” was chosen for the deviation analysis, because the 3D model is a Revit model and the point clouds were submitted in the ReCap format.



“Scan to BIM” is a plug-in for Revit. This software has the following functionalities:

- Assist the creation of Revit objects
 - Automated creation of Walls, Topology, Curtain Walls, Pipe, Duct, Conduit and more.
 - Construction geometry to assist with placement and creation for other object types
- Workflow-based tools to help set up and work on your model with the point cloud
- Measure points within your scan to quickly find true dimensions
- Tools to compare what was modelled against the point cloud for visualizing and documenting deviations.

At the beginning of the test there was the problem that the point cloud and the 3D model had different coordinates. So that the point cloud and the 3D model did not have the same location. There are three different options to load the point cloud in Revit, but in every option the result was that the location does not match between point cloud and 3D model.

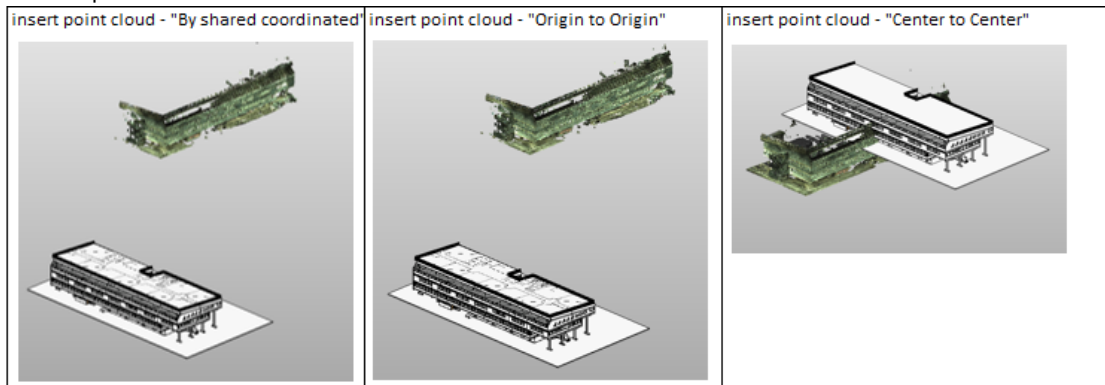


Figure 50: Coordinates of point cloud and 3D-model doesn't match

After the import the point cloud needs to be aligned manually to the 3D model by moving and rotation.

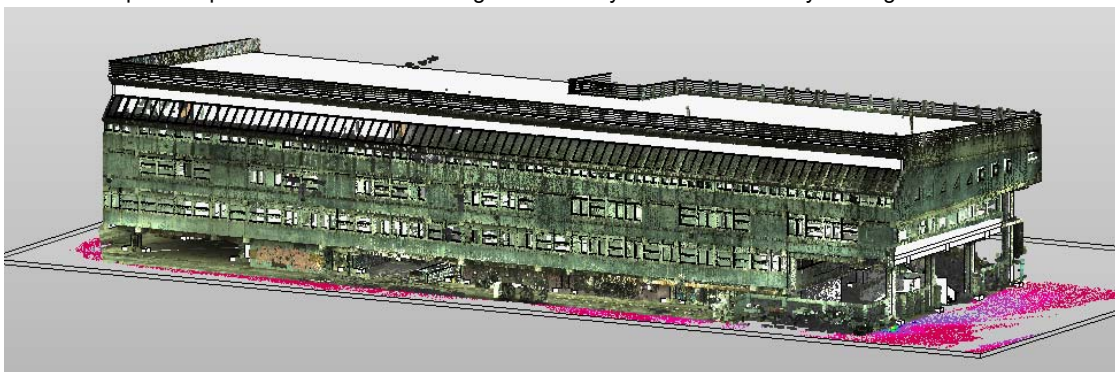


Figure 51: Aligned point cloud

The deviation tool in “Scan to BIM” is a visual inspection tool. It should show the deviation/difference between the point cloud and the 3D model. The tool uses planar and curved surfaces for the analysis. Points will be coloured based on their distance to the geometry. Colours and distances are defined on the “Point Cloud Distance Style”. The style can be adjusted according to the project relevant settings.



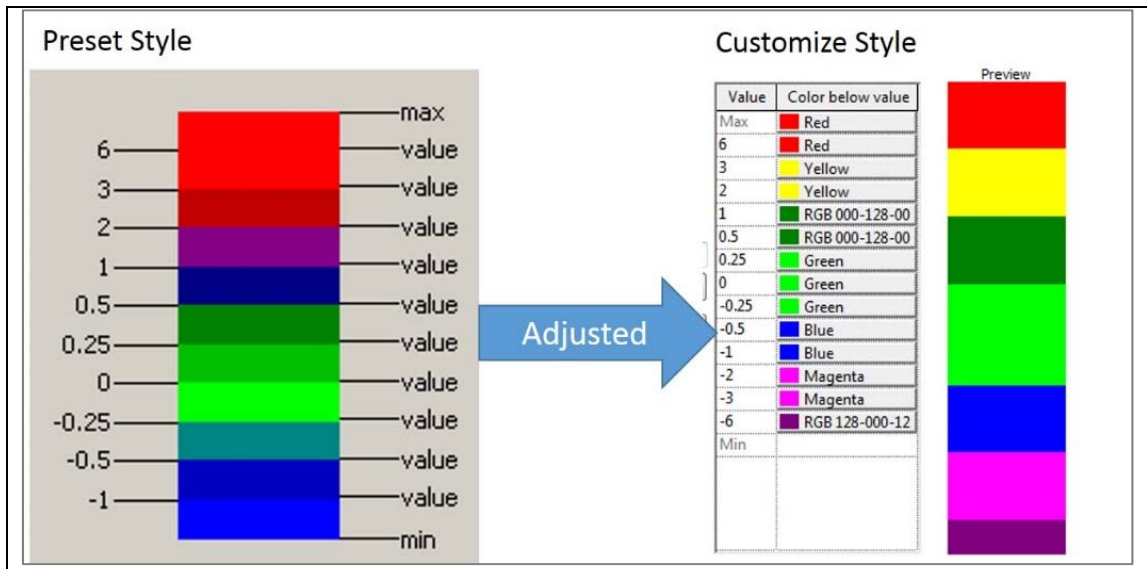


Figure 52: Adjustment of deviation style

There are two different ways of how to do the deviation analysis in “Scan to BIM”:

- Pick faces

That means that only one face of an element can be checked. In the demo project one face of the facade was checked. In the result only the points which are located directly at the face will be coloured with the defined style. There is a distance of max. 2 cm in the result.



Figure 53: Result of deviation analysis by "pick face" method

- Element based

In this case the elements that should be checked have to be selected. With this method it is possible to check more than a single element.

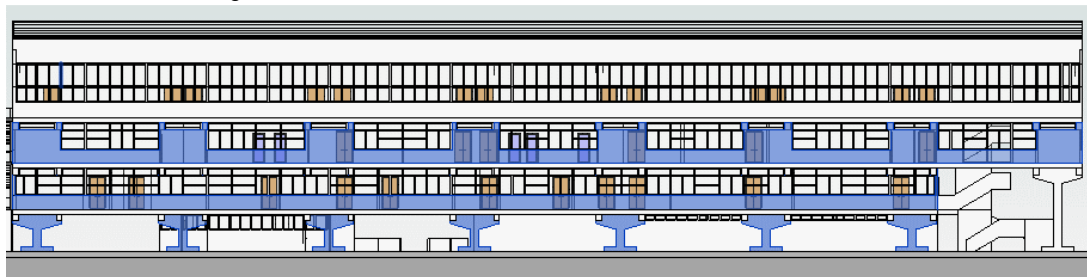


Figure 54: Elements shown in blue are selected for the deviation analysis.

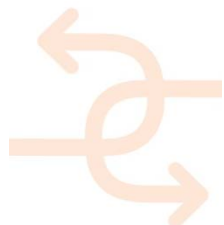




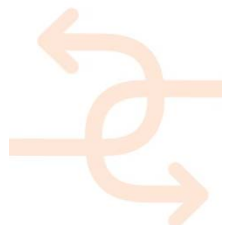
Figure 55: Result of the deviation with the Element-Based method

Reporting of results:

There is the possibility to save views with deviation results. With the option "File + Export + Image" it is possible to export the result to an external file or just only do a right click in the current view and choose "Save Project As Image" - this will put the image in a rendering view type.

Findings about deviation analysis

- It is necessary that the point cloud and the 3D model are having the same coordinates, because to align the point cloud to the model will bring errors in the results. Obviously in the first deviation picture (Pick Face Method) there is a negative and positive value of coloured points. This might be, because of the manual rotation of the point cloud to the model.
- The "Scan to BIM" tool is good when working with Revit, because it is possible to save views with marked errors. The advantage of saving the view in Revit with marked errors are:
 - it allows the team to quickly identify where the error is,
 - it saves time in creating the views required for updating the error,
 - it enables easy comparison of revised updates of the models by overlapping the views in Revit,
- Deviation analysis will be carried out selectively – either by zones, rooms or by element types depending on the project requirements.
- For elements whose geometry is directly in contact with laser scan (which are not hidden by finishes/insulation/other elements), deviation analysis will be done using "Scan to BIM" plug-in for Revit and the errors will be marked in saved Revit views. The colours of the points in the view will indicate the deviations along the element being inspected.
- Some elements may have finishes such plaster, cladding. If these finishes are not modelled there may be false deviations with laser scans. If the tolerance cannot be generalized sections in Revit will be produced that will be analysed manually through visual checks by a BIM specialist. The deviations will be marked with revision clouds and saved as Revit views.
- In the case of using the face-based comparison negative values will indicate that the distance is behind the face (rather than in front of it). In both cases the application will determine the bounding box of the geometry and query the points from the point cloud that surround this data.
- For working with "Scan to BIM" it is necessary to convert the point cloud in the ReCap format, because Revit can only load these kind of files. The process of the transformation needs a long time (depends also on the size of the project, but this process might take some hours).
- The results of the two mechanism to generate the deviation analysis are different, because:
 - Deviation Analysis by picking faces: All points behind and in front of the face will be coloured. Therefore,



negative values are possible as well. This method is only suitable for small projects (or if a single surface should be evaluated).

For example: to check one rectangular column four analyses are required to proof the outer surfaces. For bigger projects this way of checking is too time consuming to be suitable.

- Deviation analysis by selecting model elements: In this case only positive values will be coloured in the point cloud. With this method it has to be considered in advance precisely what is tested. When selecting many 3D elements of a project at once the process of the analysis may endure a long time due to many calculations. For this reason, it is recommended to divide the model for analysis – either according to specific areas or element types.
For this test case just nine elements were selected and the tool needed for the deviation analysis about 5 minutes.
- For the reporting there is only the possibility to save views and export them as an image.
- Additional software packages for performing deviation analysis are Polyworks, 3Dresaper and CloudWorx. Further investigations have to be performed to give reliable recommendations.

4.3.3 4D Checks

Using 4D simulations will offer the project team the opportunity to check the construction sequence for logical errors (e.g. columns will be created prior to the pouring of the below slab is finished). Therefore, it has to be tested how to communicate detected issues which are 4D related.

Compatibility check:

This check validates the structure of the 3D model against the given project WBS (Work Breakdown Structure). It has to be checked if it is possible to link all 3D CAD objects to the given tasks in the time schedule. In the example below the breakdown of the time schedule for wall No. II does not match the breakdown of the given building structure. According to the given building structure it is necessary to change the schedule, because it is not possible to start the construction of wall No. II before slab C is finished.

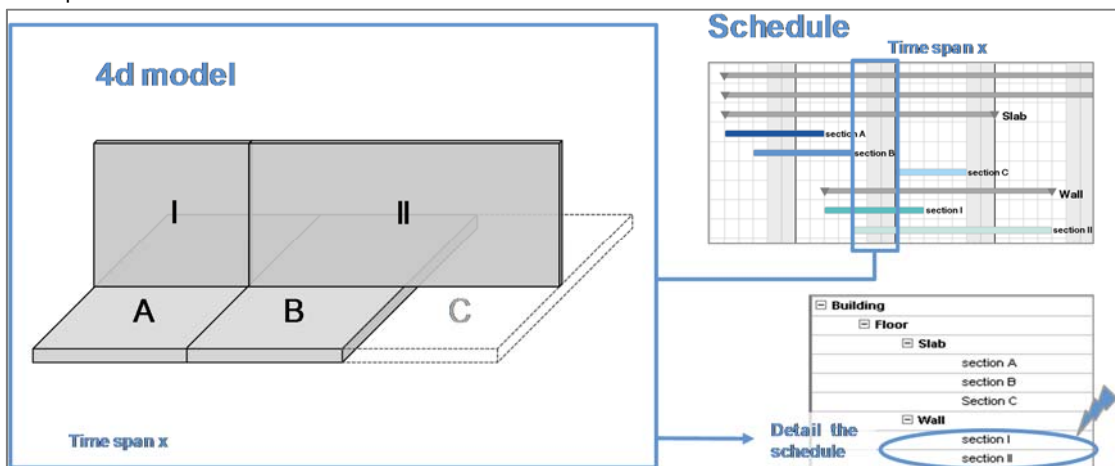
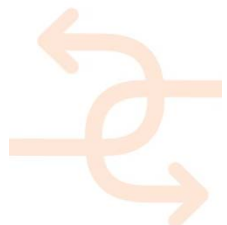


Figure 56: Example for a compatibility check of PBS and WBS.



Completeness check:

This verifies if all structure elements are assigned to activities and all required activities are assigned to structure elements or even exist. In the example below the link between CAD object B and the corresponding task in the time schedule is missing.

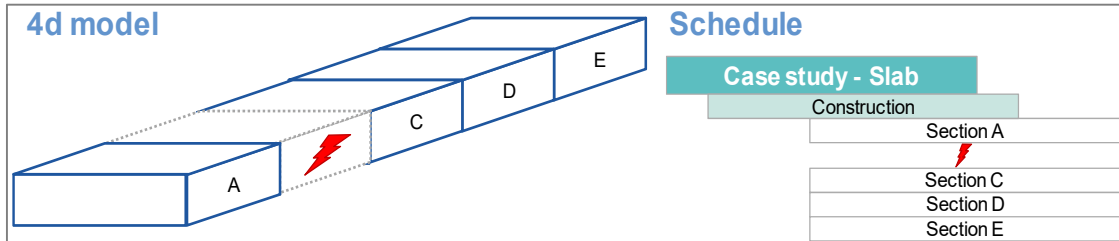


Figure 57: Example for completeness check of project schedule.

Sequencing check:

This check validates tasks relationships based on defined project construction methods. In the example below the task for wall No. III starts before the slab C is finished.

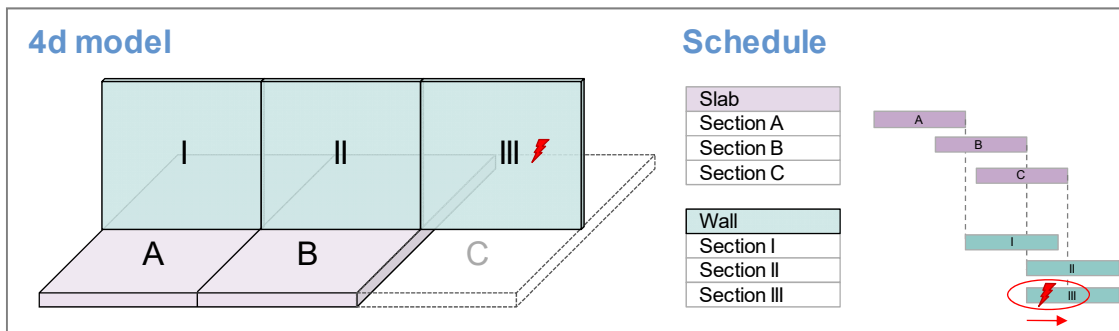
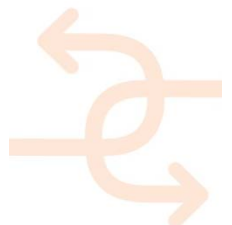


Figure 58: Example for sequencing check of project schedule

Reporting

The following screenshots are showing how a 4D check report might look like.



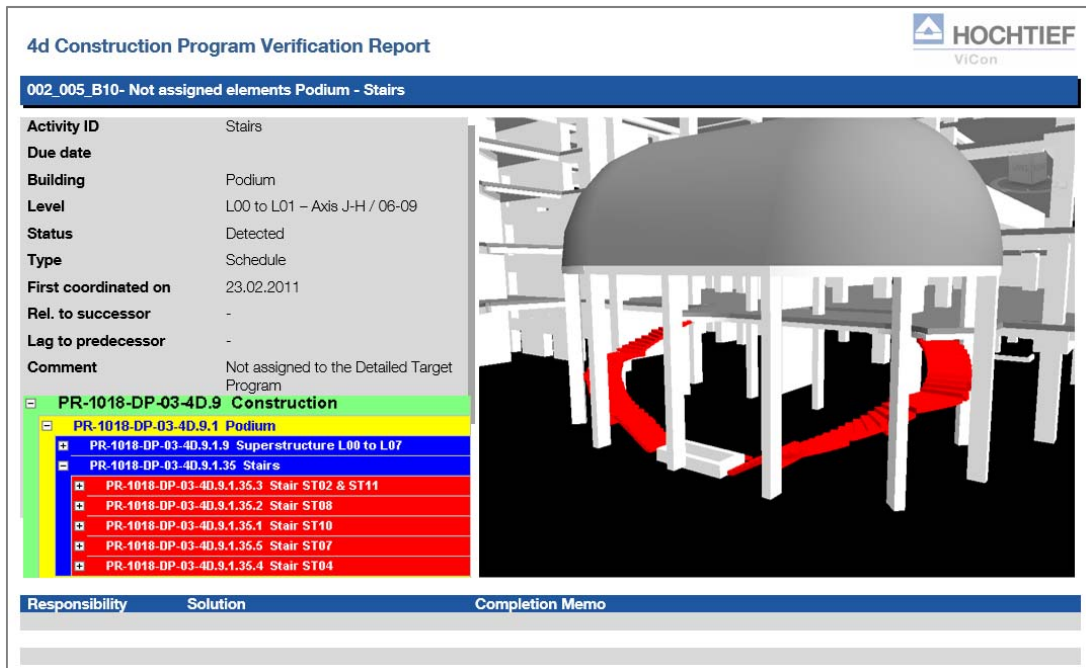


Figure 59: Example of a 4D check report

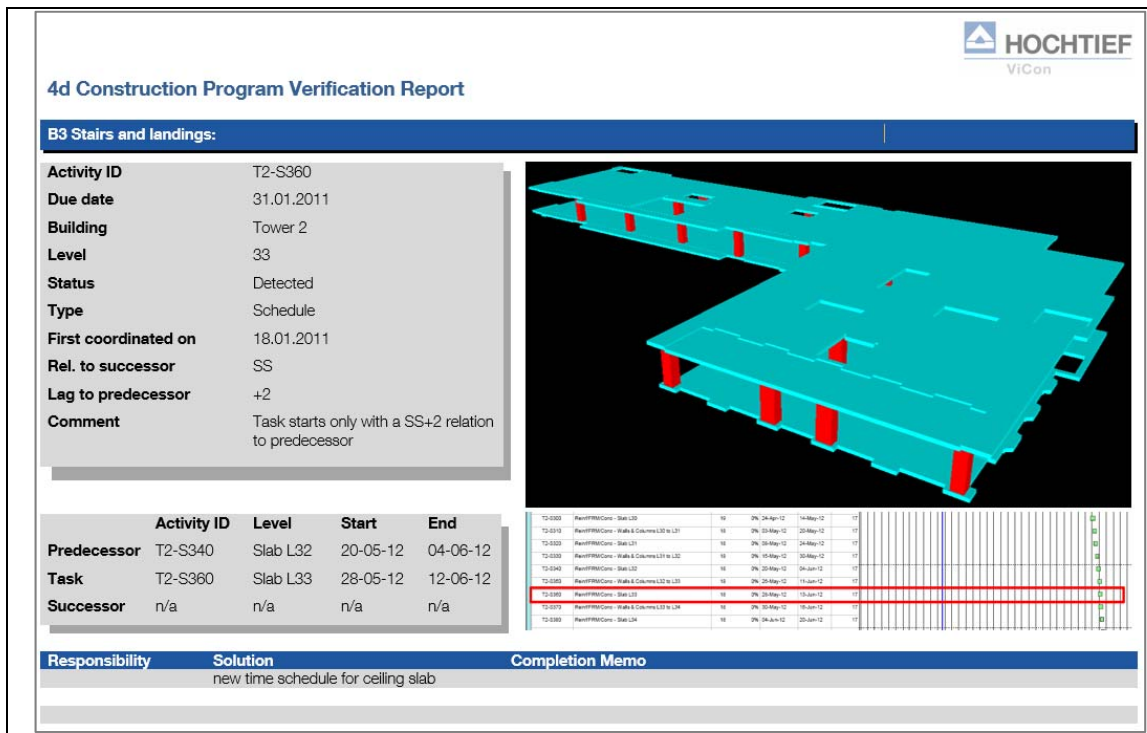
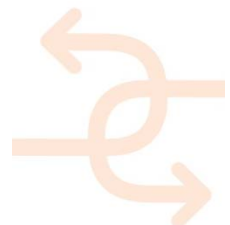


Figure 60: Example of a 4D check report



4.4 Applying the results to BIM

The second part of the BIM test case refers to the suitable representation of the results coming from either the above listed BIM internal checks or coming from the other test cases.

As declared in the previous test case images are commonly used for providing the results of the measurement devices (e.g. thermal image as a result of a thermal inspection provided by Work Package 2). Therefore, it is most important to provide images related to specific BIM objects in a suitable way.

4.4.1 Direct integration of images within the model

Referring to Work Package 4 the BIM models used within INSITER project will be created using Revit as CAD software and afterwards exported to IFC file format. Therefore, two possible options are relevant for mapping images onto a 3D object (e.g. a thermal scan will be laid onto the surface of a wall):

- Connection will be established in native CAD software (e.g. Revit)
- Connection will be established later on in the IFC export file

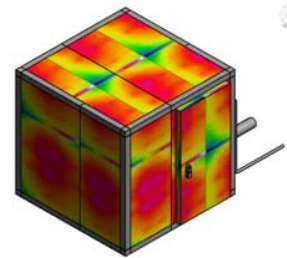


Figure 61: Mapping images on 3D object

Requirements towards images:

To apply the images of measurements onto CAD objects in a useful way the images have to match exactly the size of the 3d element to avoid distortions. Following requirements are derived from the finding that the adjustment of the images which should be mapped is very sensitive (perspective of images, orientation, scaling):

- Images have to be cropped exactly
- Images have to be taken preferably in a 90° angle (front view)
- Exact measurements of the 3D element/construction element must be known

Benefits:

By directly mapping prepared images onto 3D objects of the BIM model the following benefits may be generated:

- Very intuitive to read and to get a first impression of the measurement results
- Measurements for specific locations might be taken directly from BIM models

Drawbacks:

Even if the benefits which might be created are useful this process of mapping the images are connected to high efforts of manually work to prepare the images (cropping, normalizing). Additionally, several more drawbacks are linked to this way of providing the images:

- just working for simple walls
(rounded walls and elements with included edges are excluded due to more complex distortions)
- IFC files are growing due to included additional image information (loss of performance)
- High effort for preparation of the images to be used



4.4.2 Findings about mapping images onto 3D objects:

- Preparation of the images:

If the test result pictures are not cut exactly (meaning: if they show the analysed element and the surrounding), it is not possible to map it onto a 3D element in a correct way. The left side image shows an example for this issue.

Following adjustments have to be performed to adjust the image in a suitable way:

- Crop the image (surrounding, scale reading and frame construction) to focus just on the relevant part
- Image has to be adjusted to match exactly measurements of the building component.

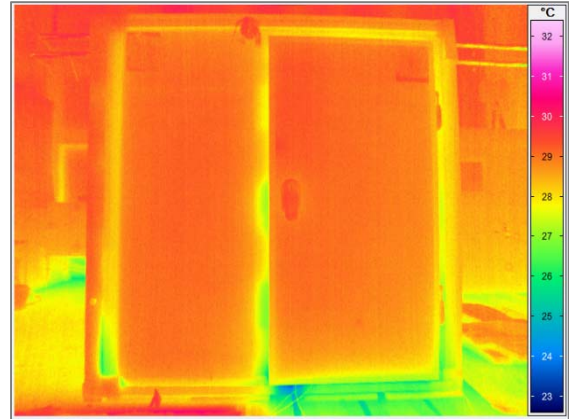


Figure 62: Thermal map

Another example image shows an additional issue. Even if the prepared image on the right side nearly matches the named requirements the scale reading has to be cropped. While doing so would adjust the image in a suitable way, but information about the colour coding would be lost and the colours could not be read in a useful way anymore.

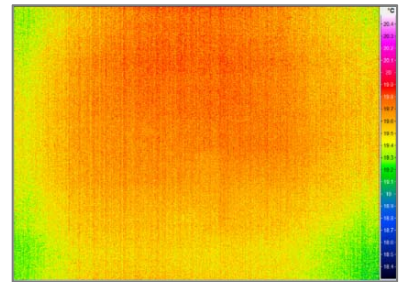


Figure 63: Thermal image cropped

- Mapping of the images in Revit:

Scaling and positioning of the picture to match with the 3D element is also a high effort. It needs to be done manually for each 3D element (right side image).

Several settings have to be adjusted to match the image and the size of the 3D element. Types of adjustments which have to be set are:

- General Image definitions
- Transformations
- Definition of the Position
- Scaling
- Repeat (use image as tiles)

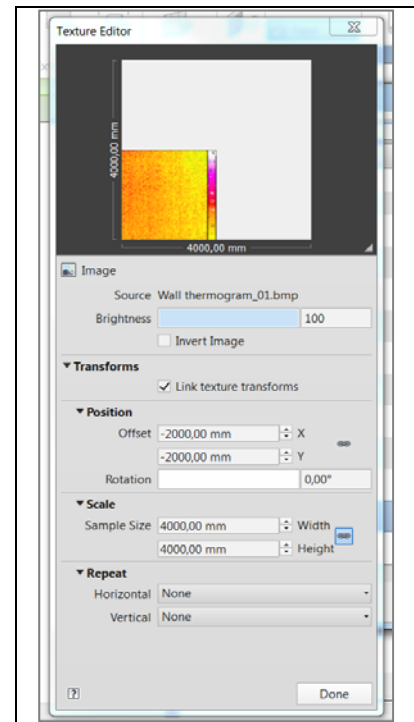
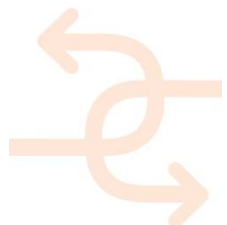


Figure 64: Image mapping via Revit



Mapping the picture to a 3D element also means that this material appears for the complete 3D element. This affects each side of the 3d element and not only the relevant surface of the element:

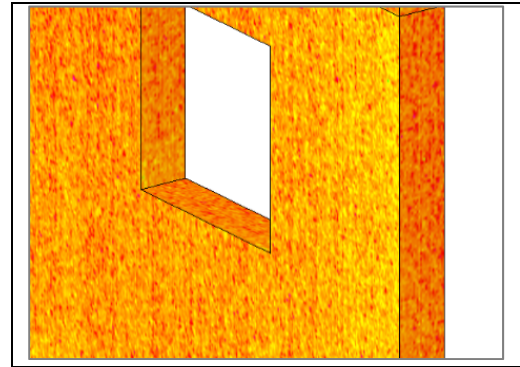
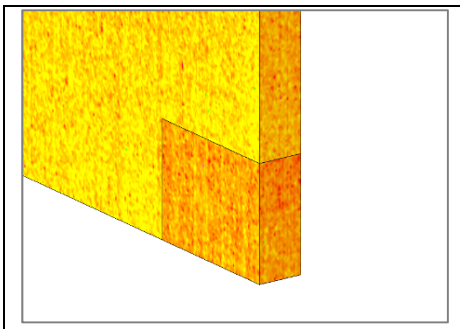


Figure 65: Mapping will be applied to all sides of a 3D element



If the element consists of more than a single element (e.g. because in the corner of a panel another material is used) the mapped pictures is calculated for each element separately and therefore not consistent.

Figure 66: Mapping onto combined 3D elements

A possible option to avoid this would be to have an additional layer modelled as surface of the wall and map the picture only to this surface layer. This needs to be done for each side of the element and afterwards all elements have to be grouped. The result would be a surface object which is totally covering the origin wall element. On the other hand, this solution comes with several additional drawbacks:

- Selection of the original objects would not be possible anymore (for other use cases)
- Increasing file size and slow down the performance
- High additional modelling effort

Mapping a picture onto a curved wall will also be difficult, because the picture of the testing program or of the camera which took the test result picture will not be curved. An exact matching would not be possible in this case.

In general it must be guaranteed that the camera took the picture exactly from in front of the wall to avoid distortions.

4.4.3 Linking of images

Another technique to transfer visual data (like images) is to provide links to the positions where the data is externally (not directly included in the 3D model) stored. An advantage of adding images this way is that not only images may be provided in this way, but all other data as well (for example: videos, documents, drawings).

- Direct link to the location where the image is stored
- Link to a database entry where the image location is given



Requirements towards images:

Due to the fact that the images will not be mapped onto the surfaces of 3D objects the measurements and also the content of the pictures are not relevant. Of course the given information of the image should be self-explaining for the purpose of information delivery. To attach an image via a link given in an attribute of a 3D object just the position has to be known where the picture is stored:

- File formats of images are just depending from the used system
- Exact position of image must be known

Benefits:

Beside the non-existence of requirements towards the used images there are some additional benefits when using the technique to attach images via links to 3D elements:

- Very easy to integrate into BIM models
- Identical procedure to add images as used for additional documents and video-files (standardization)
- All geometrical situations are possible to be handled, because images are separated
- Possible to include a scale for the used colour coding (measurements of image not that important)

Drawbacks:

While benefits are very representative for this technique the drawback must be considered as well. It is not possible to get the position of a specific value of a map (e.g. temperature value of a thermal map) directly of the 3D model. Image an 3D model will be shown separately.

- Direct measuring within BIM model is not possible

Findings about linking images to 3D objects:

- Requirement: Attribute with position of image to be used

For linking test results to elements in the 3D model those elements need to have attributes which define these documents or the link to these documents. It is possible to attach a picture directly to an element as well as defining the path to a folder (local directories) or a link to a website where the necessary information is stored.

Information added by using attributes is also transferred when exporting the model to IFC format. That means defining as much links as necessary is no problem. By adding more attributes, labelled according to time information from the report it is possible to add several pictures to a 3D element (e.g. "Thermal-Minute00", "Thermal-Minute15", "Thermal-Minute30", "Thermal-Minute60").



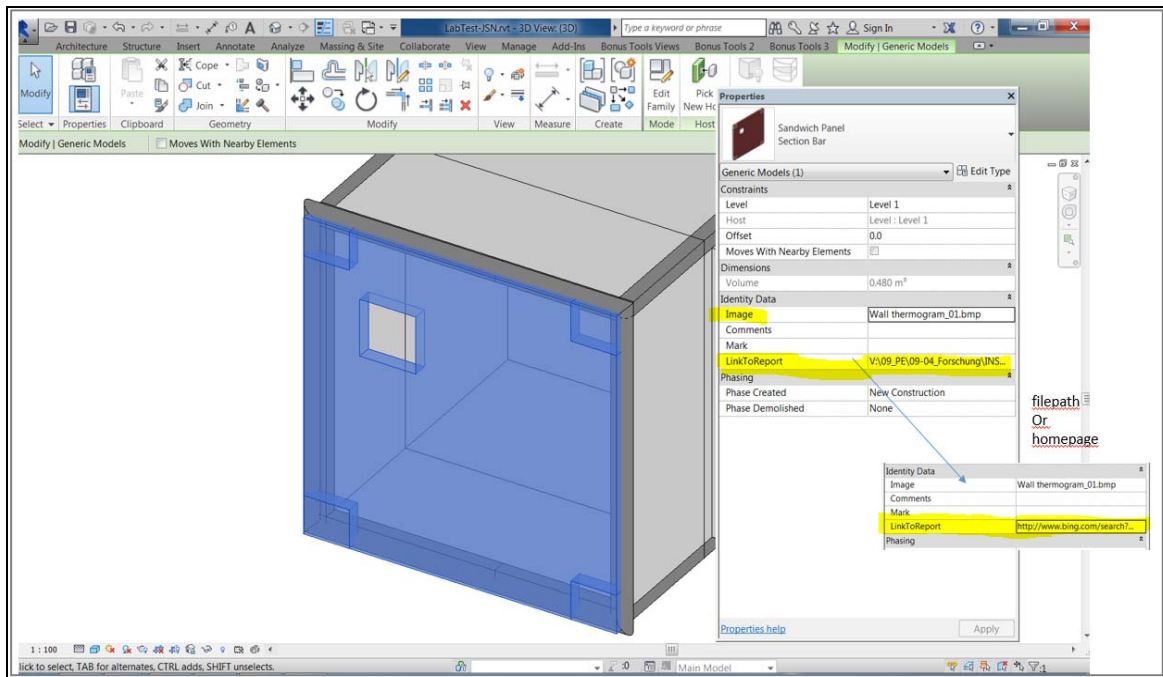


Figure 67:

- Link to database:

Additionally, it is possible to link a database (either access, excel or ODCB) to Revit. This is the easiest way to ensure the linking of current report data files to the 3D model elements. Revising data in the database is given back directly to the model and the other way round, so no information is lost and the model is always up to date with current report data. A big advantage of the working with a database is that also external parties can update/revise the database with report data if necessary. A Revit license is not required for these parties. They can simply update the database and after doing this, the modeller can reimport the revised database to the model. All required data is automatically transferred to the model. In the end the viewer can also access this database and so all data is combined.

All those findings lead to the decision that linking the test result picture to an element and not mapping it onto the element will be the most effective way for adding test result data. While direct linking is possible the usage of a database is strongly recommended.

4.4.4 Colouring the model elements according to a specific value (e.g. temperature)

Beside adding additional information like images to a specific BIM element it is also possible to directly integrate further information to an 3D element. Fixed values like “poured concrete” for example can be stored in an attribute of an CAD element. An alternative solution would be to specify an attribute which links to a database where the requested information is stored (e.g. measurements of a sensor).

To provide information via an attribute is theoretically possible in different ways:

- Exact temperature map (a single wall has to be split into thousands of sub-elements)
- Colouring whole elements according to average value (to be used in overview models)



Requirements:

As there are no images used for adding information this way there is no requirement for the images, but additional requirements are referring towards the 3D models:

- Models have to be cut according to the amount of values which are available
- Amount of given elements and exact position of given value must be known
- Attributes must be prepared
- Attribute type must be defined
- Naming Convention must be defined and match the definitions
- Shared attributes, which are valid for several elements and also might be important for other modelling teams must be defined with naming convention and be stored on a file-system which is accessible for everyone.

Benefits:

The benefit of using attributes for information transfer is the direct availability of information. No further data (like images) are required to provide additional information.

- Findings are directly incorporated into BIM models
- Each sub-element might be selected and position could be extracted according coordination system

Drawbacks:

On the other hand, all used 3D elements must be split according to the information which should be provided. In case a complex map of temperature values should be connected to a BIM object would mean that the specific wall has to be divided into many sub-elements representing the area of a specific temperature value. Beside the effect that the performance of the models would slow down this way of information transfer would create a huge effort of preparing the 3D elements.

- A single wall would be split into many sub-elements
- Very high effort while modelling
- (modelling of a single wall, reviewing the test results to know where to cut, add different data to each element)
- Performance of models would be extremely decreased
- File size would become very huge (due to thousands of elements)
- Very complicated modelling process
- This results in the fact that a single wall has several IDs. This makes it hard to add additional data to a 3D element.
- The uniqueness of the ID has to be guaranteed

Suggestion:

On the other hand, this way of providing information is very suitable for average values. This technique enables to possibility to provide a general overview about specific information for a whole project to be shown in an overview model:

- This approach is useful if the values of a single wall will be averaged and to colour the whole wall in a single colour within an overview model (table of content model)
- information provided and/or visualized example colouring 3D objects (e.g. objects which fail a specific test will be coloured red),

Additionally, this technique can be used for highlighting 3D elements according to a specific status (e.g. status of



inspections). For doing so it must be clearly defined how to visualize all possible values of a status (verified, failed, not defined (attribute not available), not defined (out of range), not defined (check not matching specific element)).

This can be done by using the phases in Revit. By giving each element a phase, it is easy to get e.g. a report of each phase (show only elements of phase “failed” (inspection) for example). Each phase can also be defined with a specific colour to highlight the issue within an overview BIM model.

4.5 Energy Performance

To perform energy calculations there are two different approaches: simulations (BIM based) and observations (sensor based). According to WP3 the BIM based simulations will be done with VABI elements. For the usage of VABI elements IFC models are required. VABI elements offers clear requirements to the IFC models to be used on their support web site:

<http://help.vabi.nl/elements/en/index.html#!Documents/bimconnect.htm>

Summarizing the most important findings regarding the input data:

- Walls with different layers need to be modelled as a single element, otherwise the definition for the rooms is not clear.
- Walls, Slabs, Columns need to be defined as room bounding.
- Windows/doors have to be linked to an opening in the wall.
- Rooms need to be defined correct in height (ignoring compound ceilings and follow angle of roofs).
- No double rooms, no overlapping rooms.
- All rooms need to be enclosed, otherwise they will be ignored by VABI.
- In the export options for the IFC export, the IFC classes need to be reviewed and if necessary be revised.

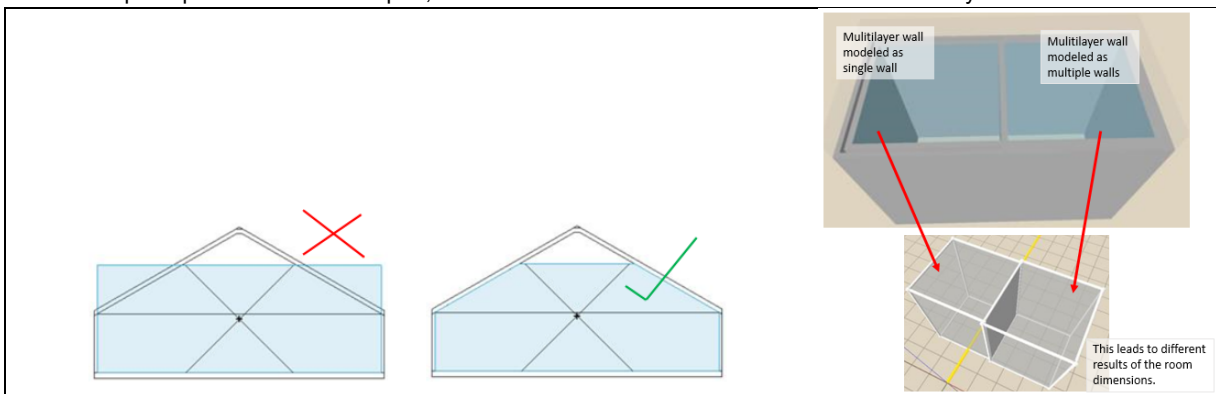
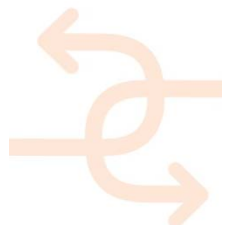


Figure 68: Definition of correct room height (left side); differing results using multilayer walls (right side)

Since several rooms are required to create a meaningful energy simulation it is obvious that the cooling room cannot be used as a test environment. There was the decision to use the first demonstrator project “Health Care Centre, Cologne” to create a test model to validate the functionality of VABI elements. The draft model of this project was created by Work Package 4:



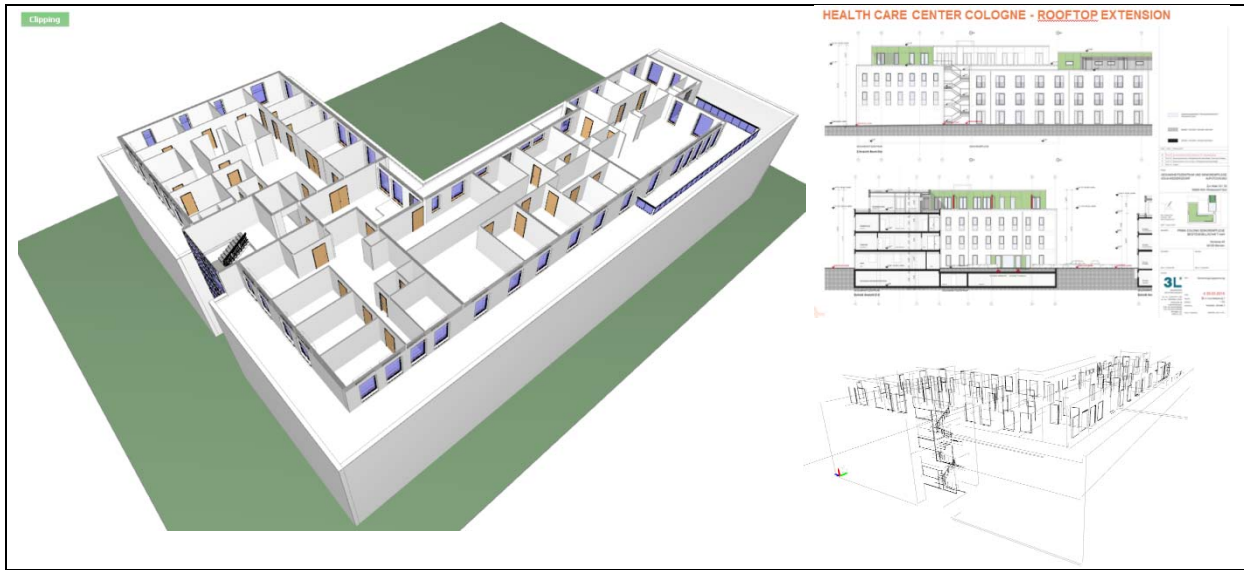


Figure 69: Preparation of BIM model for performing energy simulation

To prepare the already available draft version of this BIM model for performing the energy simulation with VABI elements the model was revised and the required room elements have been incorporated. The following image shows the created room object coloured in blue transparency:

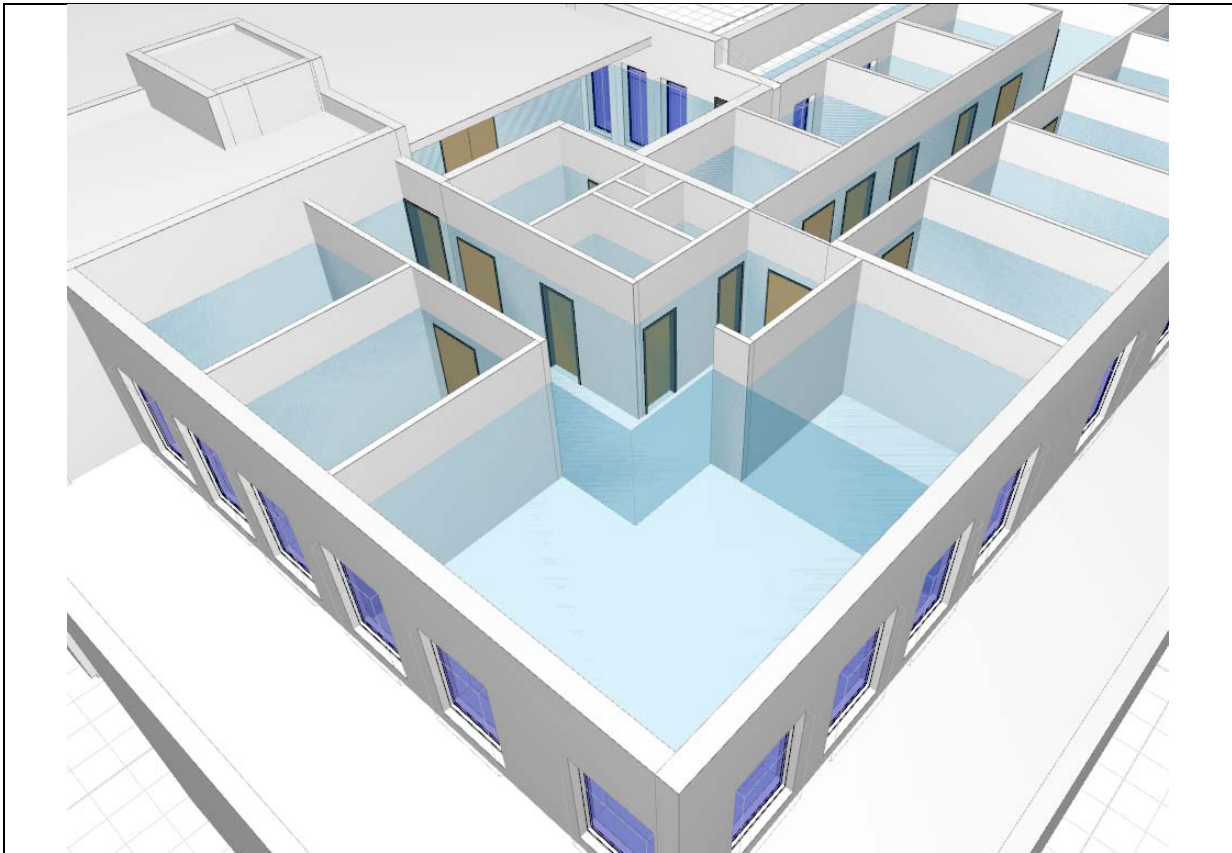
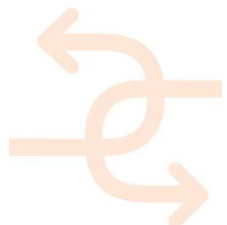


Figure 70: Included room elements (blue transparency) required for energy simulation



5. Test plan and recommendation for Factory application

In the lab-testing phase several measurements have been carried out, according to the relevant parameters identified in WP1 to evaluate the quality and energy performance of a building. For those measurements, described in D5.1, different tools and sensors have been used and the necessary procedures to carry out the tests have been defined. The table below, extracted from D5.1, summarizes all this:

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 6 List of sensors and parameters for each measurement to be carried out

As described in D5.1, these tests/measurements require a previous evaluation of the environmental conditions and the calibration of the tools. Those procedures are delicate in a laboratory but are even more critical in a non-controlled environment such as the one present in the factory where the same tests will be performed, within T5.2.

For that reason, the most critical issues are analysed below, trying to identify how the uncontrolled conditions of the factory can affect each test or calibration process and offering a solution to ensure the success of the test when performed in the factory.

5.1 Description of Factory conditions

The factory of prefabricated components where the tests are going to be performed is a large roofed space where different prefabricated construction components are manufactured by following a sequence of tasks based on rather manual techniques. Since the components (façade concrete panels, prefabricated bathroom units, 3D modules) need to be continuously taken out of the factory to allow for space to produce new ones, and since materials need to be continuously entering the facilities, the factory is never totally closed.

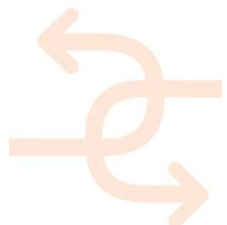




Figure 71 Factory of Las Cabezas working environment

This means that the factory conditions are not easily controllable, and are always dependent of the environment conditions. Variables like the indoor air humidity, CO₂ levels, are totally weather dependent. Other variables like luminosity can be influenced by the lighting systems. In the case of the indoor air temperature, despite the presence of cooling/heating systems, the huge dimensions of the factory really hampers any real control.

Variable	Control capability	Comment
Light	Medium	Lighting systems present. But natural light present too.
Indoor air temperature	Low	Factory not insulated. Normally access doors are open.
Indoor air quality	Low	Normally accesses are open. No air quality control system
Sound conditions	Medium	Not sound proof. Production process generates noise (that can be controlled to some extent)

Table 7 Variables and control over them in the factory's working area



5.2 Identification of main critical issues for each test

The main variables to be controlled have been identified for each main test to perform in the factory.

5.2.1 Thermal transmittance test

Description

Based on infrared (IR) thermographic techniques. IR thermography is a process in which heat at any temperature can be converted into a thermal image using specialised scanning cameras.

Variables and sensors

- 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

The following sensors are required:

- Infrared radiation detector: able to measure in the range between 2m and 12m 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 processes

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.

Considerations

Control of the outdoor temperatures mentioned above is not possible, so they will depend of and vary with the environment conditions. Internal temperature and humidity inside a prefabricated module are controllable to some extent.

IR can be influenced by light variations. The factory, although roofed, is affected by the variations of natural light.

Suitable working conditions are always kept but the indoor luminosity is not always constant.

Besides, as described in D5.1, since ambient radiation influences the IR sensor and the measured temperature, the thermal camera must be not shaded from external radiative sources. There are no major radiative sources in the factory. If there was any during the test campaign, we will make sure the tests are performed far enough to avoid its influence.

5.2.2 Thermal bridge test

Description



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.

Variables and sensors

Same as in Transmittance test

Calibration processes

Same as in Transmittance test

Considerations

Same as in Transmittance test

5.2.3 Structural integrity

Description

The structural integrity of a component can be monitored by IR thermography technique. The IR camera can identify the presence of cracks, delamination since those areas heat up faster under solar radiation. Only qualitative results can be presented. Besides, defects in the construction elements that are not exposed to direct sunlight cannot be located.

Variables and sensors

Uniform illumination is needed.

Calibration processes

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.

Considerations

This test has proven useful 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. The test could be performed on new GRC panels with different concrete mixes.

Internal temperature and humidity can be monitored but not controlled for a single panel. Those could be controllable to some extent if the panel was part of a prefab module.

Since uniform illumination is needed, a suitable location will have to be selected/adapted. There is always the possibility to perform the tests at night and use artificial light.

5.2.4 General comments for this set of tests

According to D5.1, main factors to be kept under control while performing tests based on the use of IR cameras are:

- reflection
- air flows



- wall thermal gradients
- influence from the external environment

Besides, some external factors affecting the building physics and therefore the tests to carry out:

- The sunlight 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.

Comment: As said before, direct sun light should not be a problem inside the factory. Indirect light influence can be managed by selecting a suitable location and time to carry out the tests

- The wind and air flows cool the outer surfaces of the walls, reducing the temperature differences between hot and cold areas.

Comment: Wind flows can be fairly controlled inside the factory by choosing a suitable location.

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.

Comment: Rain is not a problem inside the factory. Snow is not a problem in the south of Spain.

5.2.5 Acoustic tests

Description

Quantification of three acoustic key performance indicators to evaluate building components acoustic properties, these indicators are sound pressure spatial distribution, sound intensity vector field and sound transmission loss through simplified measurement methods.

5.2.5.1 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. 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.

Variables and sensors

Environmental noise must be controlled.

Calibration processes

Calibration of the microphone array is not required for every measurement case. However, a laboratory calibration is required on a periodic basis. Specific calibration details will be specified in a further deliverable.

Considerations

An acoustic source, preferably, an omnidirectional broadband source, is needed and placed at one side of the panel. This source must be provided by the partners performing the tests.



The noise can be controlled by choosing a suitable location or performing the tests after the working hours. So, no major issues are foreseen.

However, it is important to define the calibration process to find out if we will need to take any specific actions in the factory

5.2.5.2 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.

Variables and sensors

Environmental noise must be controlled.

Calibration processes

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.

Considerations

An acoustic source, preferably, an omnidirectional broadband source, is needed and placed at one side of the panel.

This source must be provided by the partners performing the tests.

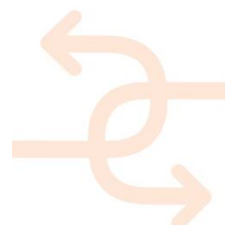
The noise can be controlled by choosing a suitable location or performing the tests after the working hours. So, no major issues are foreseen.



Figure 72 Working conditions in the factory. Sound control is hard.

5.2.5.3 Sound transmission loss

The sound transmission loss characterises the sound insulation efficiency of the object. The method proposed is for in-situ estimation of the sound transmission loss of a building panel.



Variables and sensors

Environmental noise must be controlled.

Calibration processes

As in previous test.

Considerations

The test requires the availability of reverberation rooms and for the sample to be uncoupled from any other building component.

5.2.6 Geometric discrepancy

5.2.6.1 3D laser scanner

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.

Variables and sensors

No additional sensors needed.

Calibration processes

There is no specific need of a periodic calibration (as customary in other measuring equipment).

Considerations

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. Both things can be done so no major problems are foreseen.

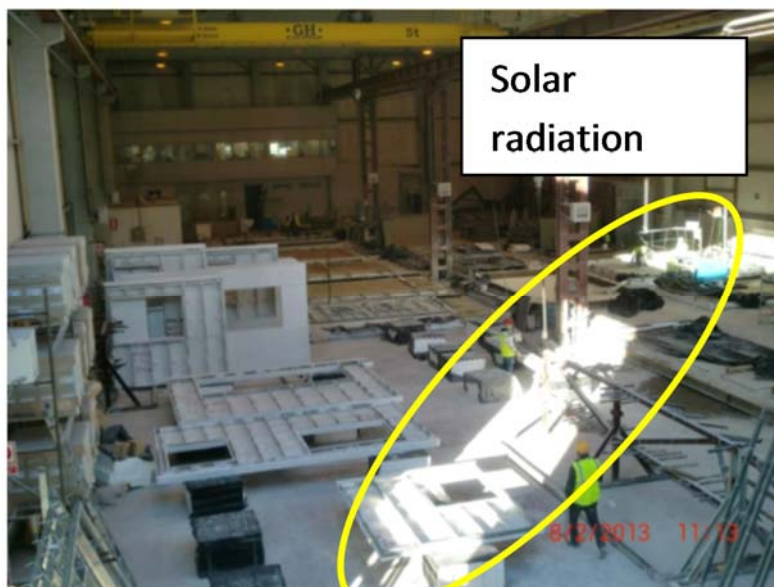
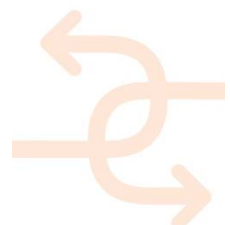


Figure 73: Solar Radiation in the Factory.



5.2.7 Humidity

5.2.7.1 3D laser 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.

Variables and sensors

No additional sensors needed.

Calibration processes

There is no specific need of a periodic calibration (as customary in other measuring equipment).

Considerations

Same as in Geometric discrepancy test.

5.2.8 Positioning system

Carrying tests in the factory should not bring any additional issues related to the use of GPS + RTK.

It is possible to carry out tests indoors or outdoors.

5.2.9 Data integration to BIM and AR

Carrying tests in the factory should not bring any additional issues related to integration of data into a BIM model or an AR application.

5.3 Recommendations for the tests in the factory.

Once analysed the main requirements that need to be met in order to be able to successfully perform the test in the factory environment, the following agreements have been reached:

1. A specific location within the factory where the presence of workers is limited has been selected. Besides, this new location allows a better control of natural light and wind, (It is not totally closed but quite closed).

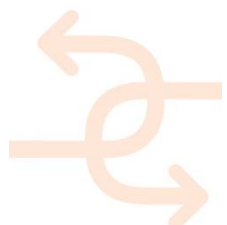




Figure 74 Location for the tests

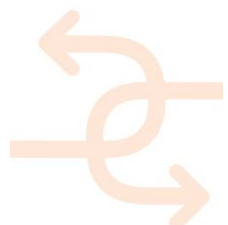
2. Perform measurements at night if necessary, for better control of natural light. Additionally at midday there is no direct solar light since there are no windows on the roof.
The area is secure to leave the instrumentation to acquire during the night since there are locked areas to leave equipment. In any case, specific actions can be taken in order to ensure the security of the equipment.
3. A complete prefabricated module with partition walls, doors and windows will be used for the tests
The plan is to use a full module 10.80 x 2.70m to which we can incorporate panels like the ones produced for the tests in Ancona or different ones. The module will be totally closed including door and windows.



Figure 75 Examples of some of the 3D modules produced in the factory

Once the module is defined, pictures and 2D drawings with all constructive details will be provided to the partners to facilitate planning the tests carefully.

Considerations regarding specific tests:



Thermal tests:

The IR sensors (provided by UNIVPM) will be put inside the module, where the environment is not influenced by the external conditions (wind, light). This solution is compulsory because a thermal gradient has to be generated between interior and exterior (10/15 °C between the different spaces). No openings must exist.

The different spaces/rooms of the modules must be closed to allow generating a thermal gradient of 10/15 °C. Since the modules normally don't have AC system, we will acquire a portable heating/cooling system to ensure that gradient.

Field of view must guarantee the inspection of the total wall area. The free space in the selected area allows for the camera to be sufficiently separated from the module, so the field of view is guaranteed.

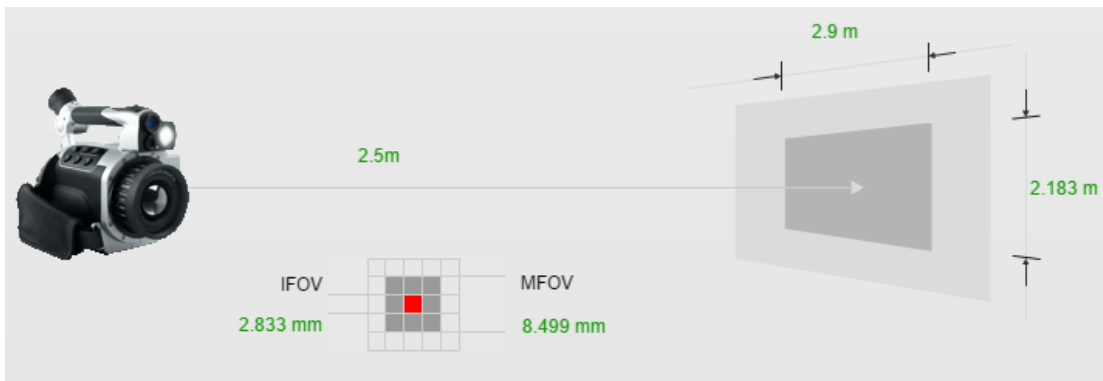


Figure 76: Field of view of the thermal camera

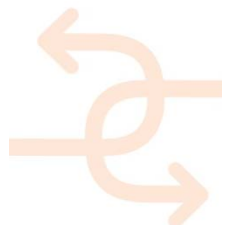
In addition to thermal camera for the thermal transmittance measurement is necessary the installation, on the inspection wall, of some thermocouples and a heat flux meter. Usually the installation is done with tape and thermal conductive paste. It is possible apply these on the module's façade. Internal and external wall surface details will be provided.

Air leakage test:

The air leakage detection uses a 40 kHz ultrasonic receiver probe, the noise in this band (compressed air flow, hammer blows, knock) generate disturbances. Disturbances could be produced due to the nature of these tests due to the noisy production process in the factory.

Two solutions are offered: The selected location for the tests is far from the production area so there should be no noise. In case there was some, we could always perform measurements after the production shift has ended (17:30).

The air leakage test detects leak on the windows, doors or in the joint between the prefabricated panels. It is necessary to use ultrasonic field generator, outdoor, and a receiver probe that scans the area indoor (or vice versa). The factory will provide an air compression system. In order to avoid the noise produced by the compressor, a long hose will be used so that the engine can be far away from the module.



6. Conclusions

The results of the lab test performed to validate the INSITER diagnostic tools, whose protocols have been described in D2.3, have been reported in this deliverable. The KPI addressed are:

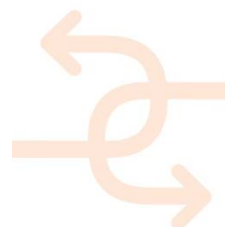
- Insulation quality by considering as measurement aspects thermal transmittance and thermal bridge
- Indoor comfort by considering as measurement aspects humidity, air leakage, sound pressure level, sound intensity field and transmission loss
- Design-construction consistency by considering as measurement aspects geometric discrepancy.

The lab tests based on thermal transmittance, thermal bridge, acoustic insulation and air leakage have been performed on a building room mock-up available at the UNIVPM. The tests for the evaluation of humidity and geometric discrepancy have been done on MEP/HVAC systems installed in the CARTIF3 Building at CARTIF where the main goal was to identify possible leakages and clashes of systems components.

In addition to the lab tests this deliverable illustrated in practice how to connect experimental data to the BIM in order to guarantee smooth BIM processes and presented some use cases scenario examples.

Finally the main recommendations for the use of the INSITER protocols in factory tests have been reported for the next testing campaign in DRAGADOS.

This deliverable puts the basis for the applications on-site (D5.4) and also for many deliverables of WP1 where the guidelines of self-inspection techniques will be detailed (D1.2 and D1.3) and calculation and analytical methods for building components will be defined (D1.4).



7. References

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- [7-6] M. Oraee, M.B. Luther, The next step in energy rating: the international ETTV method vs. BCA Section-J Glazing Calculator, Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association 2015, Melbourne.

