INSITER INTUITIVE SELF-INSPECTION TECHNIQUES

Cross-case analysis and Benchmarking

Deliverable report D5.7

Deliverable Report D5.7, Issue date on 16 November 2018

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

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

Cross-case analysis and Benchmarking

Deliverable report D5.7

Issue Date	16 November 2018
Produced by	Work Package 5 Team (WP leader 3L)
Main authors	Carlos Bárcena (DRA) Klaus Luig / Dieter Jansen (3L) Günther Riexinger (FHGIPA) Giuseppe Pandarese (UNIVPM) Pedro Martin Lerones (CARTIF) Jacques Cuenca (SISW)
Co-authors	Jan-Derrick Braun (HVC)
Version:	Final
Reviewed by	Arjan Broers (ISSO) and Gian Marco Revel (UNIVPM)
Approved by	Rizal Sebastian – Technical Coordinator (DMO) Ton Damen – Project Coordinator (DMO)
Dissemination	Public

Colophon

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

List of acronyms and abbreviations

- AEC: Architecture, Engineering and Construction industry
- AR: Augmented Reality
- BIM: Building Information Modelling
- BLC: Building Life Cycle
- CAD: Computer Aided Design
- CNC Computerised Numerical Control
- DoA: Description of the Action
- EE: Energy Efficiency
- EeB: Energy Efficient Buildings
- GUI: Graphical User Interface
- GUID: Globally Unique Identifier
- HFM: Heat Flow Method
- HTML: Hypertext Markup Language
- HVAC: Heating, Ventilation, Air Conditioning
- ICT: Information and Communications Technology
- IFC: Industrial Foundation Classes
- ISO: International Organisation for Standardization
- KPI: Key Performance Indicator
- LCA: Life Cycle Assessment
- LCC: Life Cycle Cost
- M&E: Mechanical and Electrical services
- MEP: Mechanical, Electrical, Plumbing
- MTT: Methods, Tools and Techniques
- NDT: Non-destructive test
- nZEB: Nearly Zero Energy Building
- QC: Quality Control
- QR code: Quick Response Code
- SIG: Special interest group
- TCO: Total Cost of Ownership
- URL: Uniform Resource Locator
- VR: Virtual Reality
- WBS: Work Breakdown Structure
- ZEB: Zero-Energy Building

List of figures

Fulfilment of the Description of Action (DoA) in D5.7

Accessibility of this deliverable: public

Fulfilment of WP, Task and Deliverable scope and objectives

Summarised objectives as stated in DoA	Results presented in this deliverable
WP 5 scope and objectives: • To test, validate and demonstrate the holistic toolset for self-inspection for use by different stakeholders from architects to engineers, workers/craftsmen and end-users in order to ensure the realisation of the targeted building performance. • To involve the different groups of stakeholders in testing, validation and demonstrations –in conjunction with training, dissemination and exploitation activities in WP6. This is towards embedding validation and demonstration results into dissemination activities, and where possible using validation and demonstration for the start and as a catalyst of dissemination.	Addressed to the following extent: • Based on storyboards and the developed use cases for all 6 demonstrators the objective of D5.5 is to proof test the technologies developed in the project in the demonstration buildings. After the detailed description of the validation process in D5.4 Field validation report and recommendations, it is in this report where the outcomes of those tests are described. This report is the integrated report resulting from the merge of the old *D5.5 Field demonstration set-up* and *D5.6 Field demonstration report.* • Relevant stakeholders in each of the use cases have participated in the validation process, either being part of it or through the assessment of the results.

Task 5.3 scope and objectives:	Addressed:
• Show evidence of the final performance of the buildings, and the scale of improvements made by using the prototype INSITER Systems and Methodology. • Demonstrate at full scale and under real conditions, the INSITER technologies and approach. The approach, methodology, and global INSITER self-inspection methodology and tools will be validated by external stakeholders under real work conditions • Contractor's on-site technical staff, subcontractors and clients will be engaged before, during and after the demonstration, not only to witness INSITER technologies functionality but to use them and evaluate their performance.	• All the relevant technologies and methodologies developed in INSITER have been validated in real use cases. In most of the cases, the demonstration buildings were not finished when carrying out the tests. Therefore, the real performance of the building could not be assessed. However, it is the positive impact on the quality assurance of the construction processes and final (partial) products what is important for the demonstrations carried out. That positive impact subsequently improves qualitatively the building's energy efficiency. • External stakeholders such as technical staff, workers, quality managers, etc. have been involved in the demonstrations. In those cases where, due to delays or change of plans in the demonstration buildings, the demonstrations have not been carried out as planned, virtual demonstrations have been performed.
• D5.7 scope and objectives: • This deliverable describes the industry's views on practicality and affordability of INSITER tools and methods.	• Cross case analysis between different demonstrations within INISTER have been carried out for the case of thermal and laser scan techniques. • The use of INISTER technologies has been benchmarked against the use of those technologies in other sectors. • Relevant feedback (usability, applicability, etc.) from practitioners and other stakeholders participating in the demonstrations has been gathered and assessed.

Contents

1. Introduction

D5.7 Cross case analysis and benchmarking is the last deliverable within T5.3 Demonstration in new construction & refurbishment, due on M48.

WP5 has followed a use case based approach in order to fully validate the technologies and methodologies developed in the project. This use case approach was initially described in D5.3 *Case study elaboration, field validation protocols and equipment calibration*. Then D5.4 *Field validation report and recommendations r*eported the validation of these use cases against the INSITER methodology taking into account the specific testing needs and the equipment to be applied on site in future application. D5.5 (formerly split into D5.5 and D5.6) showed the results of the live (or virtual in some cases) demonstrations carried out.

In this report, chapter 2 describes a cross analysis of some of the technologies developed/used in INSITER across several demonstrations, such as the thermal and laser scan techniques and associated hardware/software.

The application of some of the INSITER technologies (acoustic and thermal scan techniques) in other industries such as the automotive or the aeronautic sector, compared to their application in the construction sector is as well discussed in chapter 3.

Finally, the results from the two main workshops organised within INSITER are presented in chapter 4. In these two workshops, celebrated in Enschede and in the DRAGADOS factory in Seville, allowed different stakeholders to be presented with the main outcomes of the project and to participate in live tests of the developed technologies. Very valuable feedback from the participants was gathered, and is presented in the report.

2. Lessons learned and best practises across INSITER on-site demo cases

2.1 Comparison of thermal scan techniques and results in Pisa and Enschede cases

The thermographic scanning system can measure temperature distribution based on IR radiations emitted from a heated surface of an object without physical contact between the measuring equipment and the surface investigated as long as the surface emissivity is known. The result of an IR scanning system is a thermogram, e.g. a two-dimensional map of the object´s surface temperature distribution, given in colour or grey scale representing the temperature level. The principle of the measuring test is based on the fact that any material continuously emits energy (electromagnetic radiation) proportional to their surface temperature. A thermographic scanning system based on IR thermal camera has been used in INSITER to study thermal performance and thermal anomalies in two demo cases: Hogekamp in Enschede and Concetto Marchesi in Pisa. At the beginning of the INSITER a deep renovation project was programmed for both demo cases. However, while in Hogekamp the retrofitting is now in an advanced phase, Concetto Marchesi´s renovation works could never start.

When the thermal measurements were performed in Hogekamp, in April 2018, most of the rooms were in the finishing phase and the conditioning system was already working. This allowed having a sufficiently large thermal gradient between indoor and outdoor environment to create a thermal flow through the building envelope. The temperature gradient was practically of about 10°C. These environmental conditions made it possible to identify and accurately localise thermal bridges in the building structure.

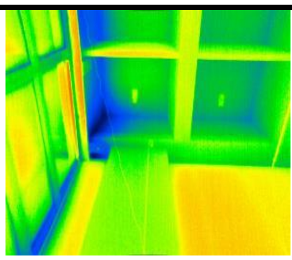
		
Structure under test	**Thermogram**	**Thermal bridge superimposed to the visible image of the structure**

Figure 1: Zoom on a thermal bridge in the right corner of the ceiling of a room

However, the Concetto Marchesi building was in poor maintenance condition and not conditioned. The thermal gradient detected between inside and outside was of about 2 °C. That gradient is not sufficient to generate a thermal flow through the building envelope and allow identifying clearly thermal anomalies. The measurements performed in August 2018 allowed to evidence the bad insulation of all opaque elements of the envelope but not to identify local thermal bridges (see Figure 2).

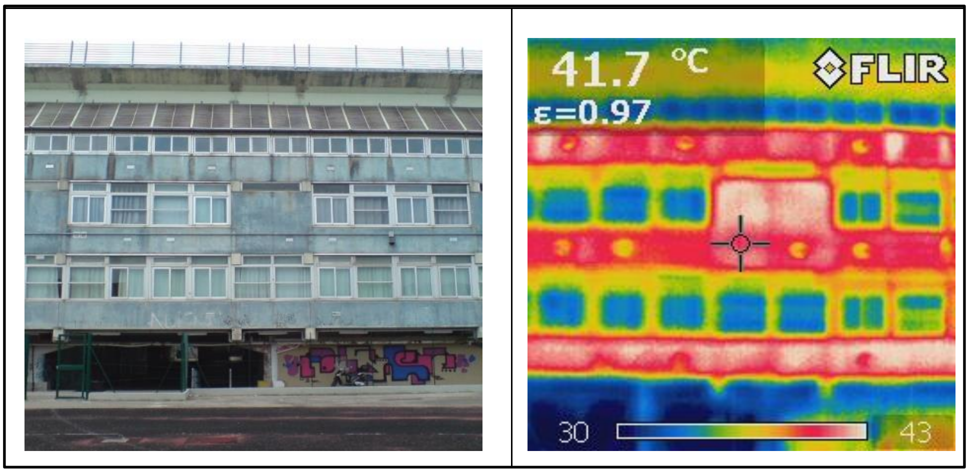


Figure 2: Example of a thermogram acquired in the East facade of the building

The Concetto Marchesi demonstrator proved that the environmental conditions are fundamental importance for reliable results in thermographic surveys. When a thermal gradient between the two surfaces of a building element (partition or external wall) does not exist, it must be artificially created, for instance through the use of a portable heater/conditioner. This was the case in the DRAGADOS demo case, and thanks to that an accurate localization of thermal bridges could be achieved (see Figure 3).

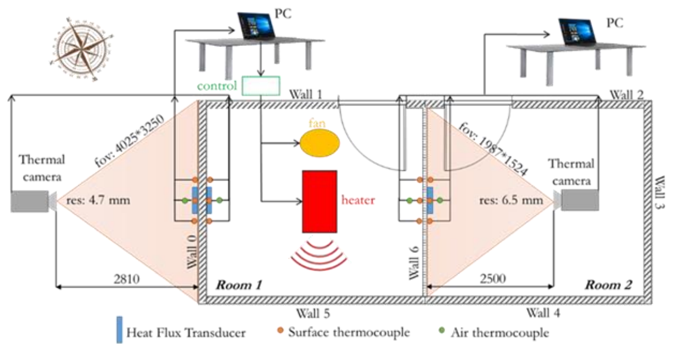
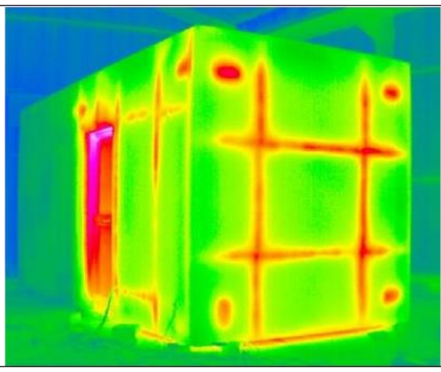
Thermal Measurement setup	
Thermal map View from the outside	

Figure 3: Thermal measurement setup and thermal results on the Dragados Factory demo case.

2.2 Comparison of laser scan techniques and results in Cologne and Valladolid cases

3D data is a precise and valuable technique to model or draft on point clouds. Since laser scanners capture reality with high efficiency, they are mostly used in applications where this capability provides added value. In the BIM market, these uses primarily fall into two categories (both addressed in INSITER):

- Renovations: demo site CARTIF-3, Boecillo (Valladolid), Spain.
- New construction: demo site HCC, Cologne, Germany.

The typology and deployment of self-inspection activities to be carried out in CARTIF-3 and HCC are very different and described in detail in *D2.4: Integrated site and indoor positioning systems for measurement and diagnostic instruments*.

The application and validation of 3D laser surveying for geometrical deviation analysis, both in CARTIF-3 and HCC, is provided in particular use-cases within *D5.4: Field validation report and recommendations*. Their respective correspondences with the 8-step INSITER methodology and specific KPIs are reported in deliverable *D5.5: Integrated field demonstration report*.

2.2.1 Construction validation: CARTIF-3 example

The naked eye cannot detect certain construction issues. Laser scanning is the fastest and most accurate way to capture the complete building or relevant areas, so work can be evaluated on a weekly or daily basis to assure the best quality construction.

This process starts with scanning all parts of the construction site to be analysed. The point clouds are registered together and oriented to match reality. Depending on the available digital files, the point cloud data is then compared to: (1) the CAD/BIM model geometry (when available); (2) a previously existing point cloud. This evaluation is made with automated tools to identify clashes and deviations. When deviations or clashes are identified, professionals are ready to investigate the as-built point clouds to determine the source of the problem, trying to find a solution for **proper maintenance or renovation actions** according to schedule and budget.

3D laser surveying has been applied in CARTIF-3 to two aspects:

1. Study of geometric deviations between the initial construction project and the current situation, particularly in the South-East and South-West facades (where the greatest thermal variations may occur).
2. Early detection of humidity in HVAC elements in the workshop.

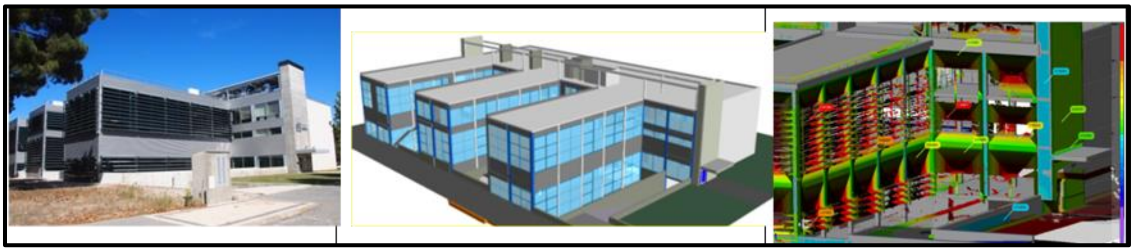


Figure 4: Different views of Cartif III building

As detailed in *D2.3: Toolset of capturing, measurement and diagnostic systems for self-inspection*, XYZ data (spatial coordinates) provided by the laser scanner were used for case 1, which is the one comparable to the laser surveying on the HCC of Cologne (In Cologne, the use of the scanner's reflectivity index to study humidity was not planned).

Project setting:

Building maintenance / renovation

Focus area:

Building envelopes

EeB-related KPIs:

Air-leakages (dimensional control deviation) → Thermal losses

Scope of inspection by referring to the 'most frequent errors':

- Alignment of insulation layer at building façade
- Incorrect assembling of the building components
- Installation of unsuitable material

Actors to perform the inspection:

Construction workers, operators

Inspection instrument and protocols:

Inspection on-site using laser scanner (XYZ)

Complemented by thermal images (when needed)

Actions to perform:

No actions needed (by the moment)

Deviations < Threshold (3 x Std)

Std: Standard deviation by modelled accuracy (plane featuring) = 1.2 mm

2.2.2 **New construction as-built scanning: HCC example**

Most as-built drawings are inaccurate and incomplete, leading to errors completely invisible until the construction phase, when they are very expensive and time consuming to resolve. The best way to avoid these unwanted surprises is to perform 3D as-built laser scanning to capture the complete information about the space to be newly constructed.

This requires first scanning all areas of the building involved in the project, then registering the point cloud data together. If drawings or models exist, the point cloud will need to be oriented to match the coordinate system of the drawing or model so both sets of data align. The models and drawings can be adjusted to match the scan data so the team can begin designing. If neither models nor drawings exist, the scan data can be utilized as a "template" to create the new documentation. It has to be mentioned that it is not recommended to create complete models merely based on point clouds, because this is highly resource consuming. The proposed way to work efficiently is to create models on base of available data like 2D drawings and to validate these draft models by performing a deviation analysis against point clouds with the aim to create verified as-built models.

The point cloud can be sliced vertically to expose elevation views for tracing, or it can be sliced horizontally (Z cross-sections) to expose a plan view that can be traced to create very accurate floor/roof plans.

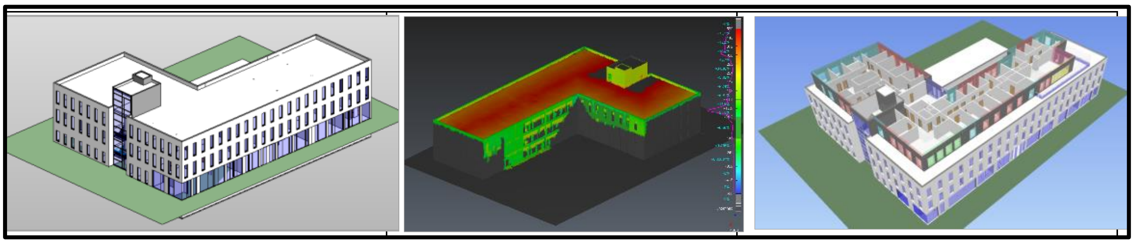


Figure 5: Different views of Cologne building

Project setting: Building construction
Focus area: Rooftop extension
EeB-related KPIs: Air leakage
Scope of inspection by referring to the 'most frequent errors': Dense joint of elements, deviation analysis
Actors to perform the inspection: Surveying department
Inspection instrument and protocols: Inspection on-site using laser scanner (XYZ)
Actions to perform: Adjust and correct 3D models where deviations have been identified in comparison to the point clouds

3. Comparison of innovative technologies between INSITER and similar research projects

3.1 Comparison of AR techniques between INSITER and ACCEPT and Built2spec

As described within the paper “Digital Tools for the Construction Site. A Case Study: ACCEPT” [1], the ACCEPT system consists of one major AR application: “CoOpApp” for android based smart glasses applied on the Epson Moverio BT-200. Planning data and additional information such as pictures, 3D models, technical documents drawings, etc. can be superimposed as AR or linked to AR codes (see Figure 6).

Figure 6: Example of ACCEPT “CoOpApp” features from paper “Digital Tools for the Construction Site. A Case Study: ACCEPT” see also reference [1]

The android based Epson Moverio BT-200 smart glasses from 2014 offers limited possibilities for AR applications, thus e.g. a spatial mapping of the environment is not possible due to the lack of computer vision-based sensors. INSITER on the other hand, by using the HoloLens for example, applies multiple cameras and a depth recognition system as well as inertial measurement units including an accelerometer, gyroscope, and a magnetometer, to enable e.g. advanced surface-based tracking methods. Moreover, the INSITER Hardware such as the HoloLens is capable of displaying detailed BIM models as it has an advanced graphical processing performance. With the INSITER solution, actors on-site are supported with gestures and speech recognition enabling intuitive interaction with the virtual objects and the real environment. This allows for several applications such as identification of BIM objects and construction elements, object placement, orientation, or perform an on-site visual comparison between virtual BIM model and real on-site situation, construction validation and compliance checking, etc. (see D2.2 and D5.5).

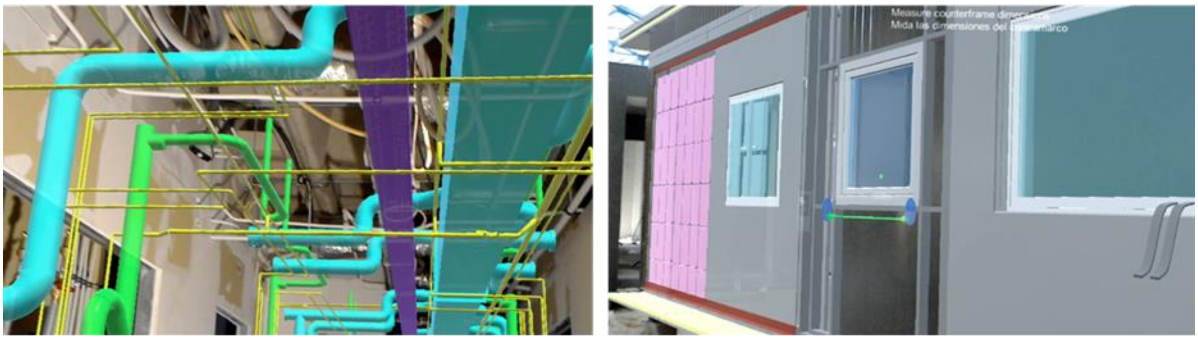


Figure 7: Example of INSITER HoloLens BIM-based Mixed Reality App screenshots see also D2.2 and D5.5

Due to hardware limitations, it is not possible to display 3D BIM models in direct computer vision based spatial relation with the real surroundings or on-site situation by using the android based Epson Moverio BT-200. Thus, the Moverio BT-200 smart glass device of the ACCEPT project is limited to display images, text or small 3D models within a floating screen, linked to markers or AR/QR-codes. A superimposition of BIM data such as MEP systems in direct relation with the real situation on-site, like INSITER did (see also use cases in D5.5), is not possible with this device. Until the end of the project, the Epson Moverio was the flagship device for “CoOpApp”. According to the latest information that INSITER has received by the ACCEPT consortium, they also started to adopt parts of their system for the MS HoloLens to overcome the described limitations of the Epson Moverio BT-200 in the future. The new main interface of CoOpApp applications will consist of a set of floating elements with interactive elements that, when they are focused with the gaze, trigger a function of the application see example in Figure 8.

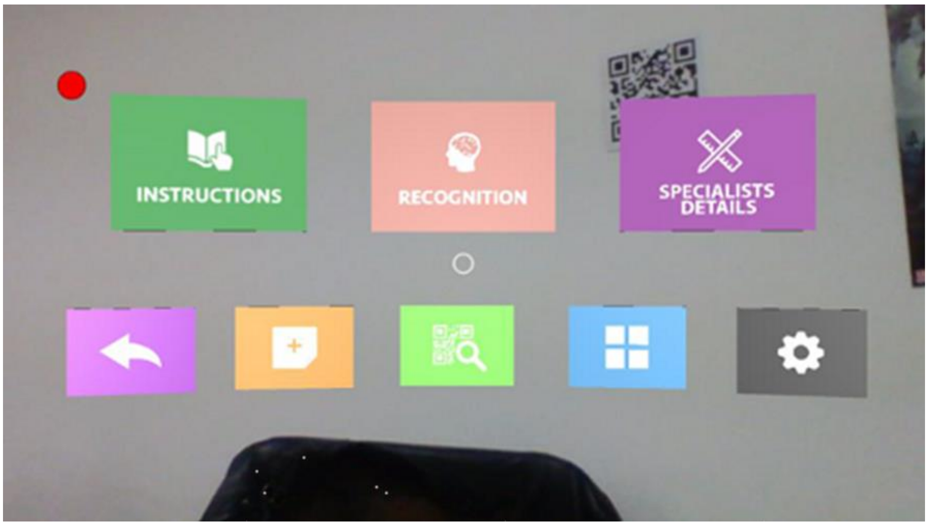


Figure 8: Example the new interface of “CoOpApp” with a set of floating elements

Additional information can be found within the paper "Digital Tools for the Construction Site. A Case Study: ACCEPT" see:
https://www.accept project.com/downloadFiles/digital_tools_for_the_construction_site_a_case_study_accept.pdf
The consortium of Built2Spec was using the android-based augmented reality computing platform Google Tango [2], which is deprecated and is not supported by Google any more since March 1st, 2018. Google instead introduced a new AR SDK (software development kit) "ARCore" as a replacement for Google Tango, which has new hardware and software requirements such as Android 7.0 or later. No announcement or publication was made by the Built2Spec consortium about any further intent to apply AR tools or to use an alternative AR SDK such as the "ARCore". The last information about the use of TANGO can be found here: https://www.bsria.co.uk/news/article/built2spec-vcmp-and-thermal-imaging/.

[1] J. Ratajczak, C. Marcher et al., "Digital Tools for the Construction Site. A case Study: Accept Project", *Proc. Lean & Computing in Construction Congress (LC3)*, vol. 1, 2017.

[2] Built2Spec - VCMP and Thermal Imaging. Available from https://www.bsria.co.uk/news/article/built2spec-vcmp-and-thermal-imaging/ , accessed 07.11.2018.

3.2 Comparison of (self)-inspection thermal measurement techniques between INSITER and other areas of application

Infrared thermography is a non-destructive measuring method for the examination of thermal aspects related to the building physics, as insulation, thermal comfort and energy budget. Infrared cameras provide a means for temperature measurement in buildings even during construction and allow localising thermal anomalies as thermal bridges, heat loss sources, growing mould and moisture. In order to obtain measurable temperature differences on the surface of an observed element, a heat flow should persist through the element. This heat flow is usually generated by heating one of the two surfaces of the element itself. This heat flux can be induced in a passive or active way. The static (passive) thermography technique is achieved by exploiting natural solar radiation. The dynamic (active) thermography is achieved by using an artificial source of irradiation (in the IR range). The energy is delivered into the object in a dynamic periodic way (lock-in thermography) or in a dynamic single-shot way (pulse thermography). Heat penetrates the investigated object and the surface temperature distribution depends on the thermal properties of the material and its internal layers. Inhomogeneities as defects in the surface, or in inner layers, of the investigated object will be detected as measurable gradients of the surface temperature. Active thermography is applied for non-destructive inspection in many sectors like industry, aeronautics, cultural heritage etc. Although the measurement is in principle the same, the technique must be designed on the basis of the different applications because the principle of thermal propagation depends on the type of material, its thermal inertia and phase. Active thermography has been developed also in INSITER for thermal bridges detection and localisation and for thermal transmittance estimation of non-conditioned buildings.

In INSITER, in order to reduce the inspection time for thermal transmittance estimation of building envelopes, a simplified mono-dimensional numerical model has been developed and used in conjunction with the experimental data to estimate thermal transmittance by running an optimisation model. The method developed in the project has been called *Soft Sensing* because it couples numerical (soft) data with experimental (sensing) ones. While inspection time is of at least 3 days when using standard procedure, the new methodology, based on Soft Sensing and on an appropriately developed artificial thermal load, allows estimating the thermal transmittance of a building wall in a few hours.

Some examples of IR thermography for anomalies detection are reported hereafter.

In the cultural heritage field, active thermography has been exploited to monitor the health of different artworks like frescoes, icons, mosaics, paintings and bronzes. An example of damage detection on fresco paintings can be found in [1]. In Figure 9 the thermal experiment setup, the fresco photograph and the thermogram are shown. The fresco has been thermally stimulated (i.e. heated or cooled) to induce a temperature difference between undamaged areas, the so-called "sound" regions, and damaged ones. Therefore, the thermogram evidences cracks, flacking and regions where detachments between different layers occur.

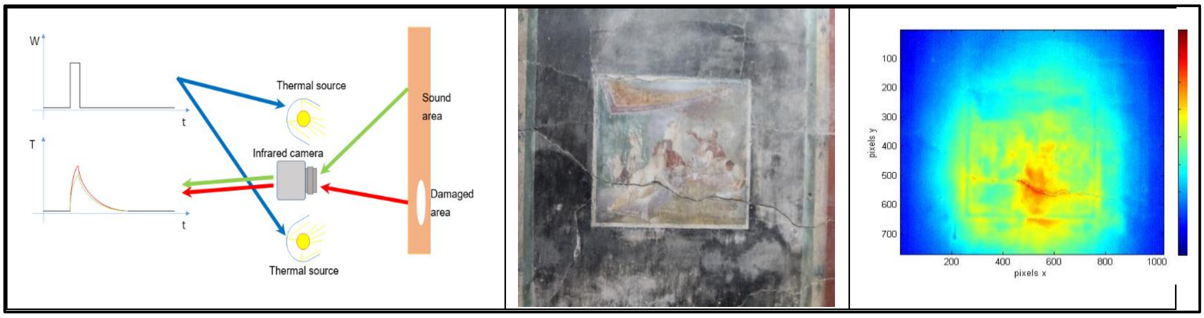


Figure 9: Left: thermal setup; centre: fresco photograph; Right: thermogram

In the industrial sector IR thermography is applied to several field, as for example to assess the health status of welding and soldering or to monitor the process of the welding. In [2] IR thermography was used to monitor a friction stir welding during the welding process, see Figure 10. Only a non-contact method could be able to follow the dynamics of the process. The IR thermography is a powerful real time diagnostic tool allowing monitoring the work piece temperature profiles and identify anomalous distributions, which could worsen the welded joint quality, during the process itself.

In aeronautics field non-destructive techniques like thermography are used in maintenance to inspect periodically the structures in order to maximize the structure life. A lot of parts of the aerospace structures are in Carbon Fiber Reinforced Polymer (CFRP) and defects like inclusions, loss of material, delamination or impact damages can be detected by active thermography inspection. In [3] internal defects in the panel with Teflon® insertions have been carried out at different sizes (from 5 to 15 mm) and depths (from 0.3 to 2.0 mm). The CFRP panel was excited with a pulsed heat load of 6 kJ provided on a 700 μs time interval, using two flash lamps and the temperature of the surface was monitored by thermal camera with an acquisition rate of 30 Hz and acquisition period of 40 s. In Figure 11 thermal results highlight the possibility to detect defects until 2 mm in depth per 15 mm in size and 1 mm in depth per 5 mm in size.

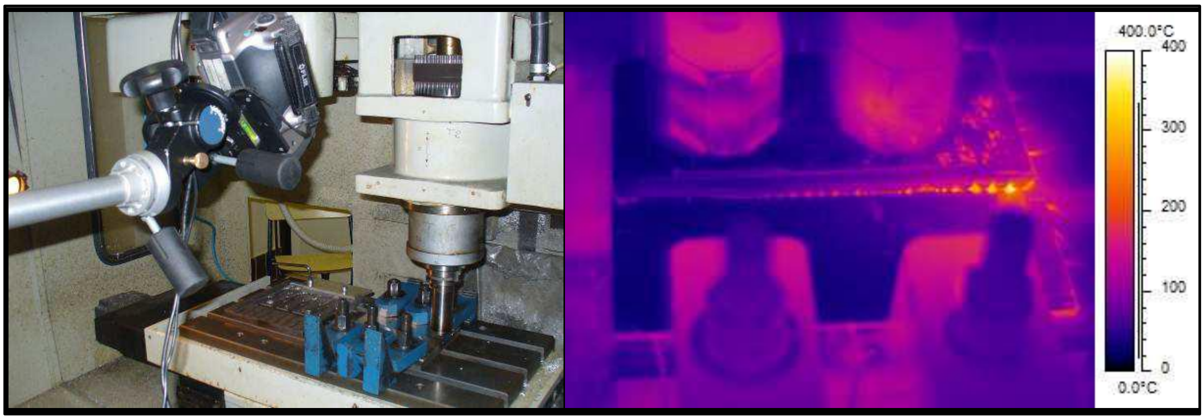


Figure 10: left: thermal setup; right: thermogram

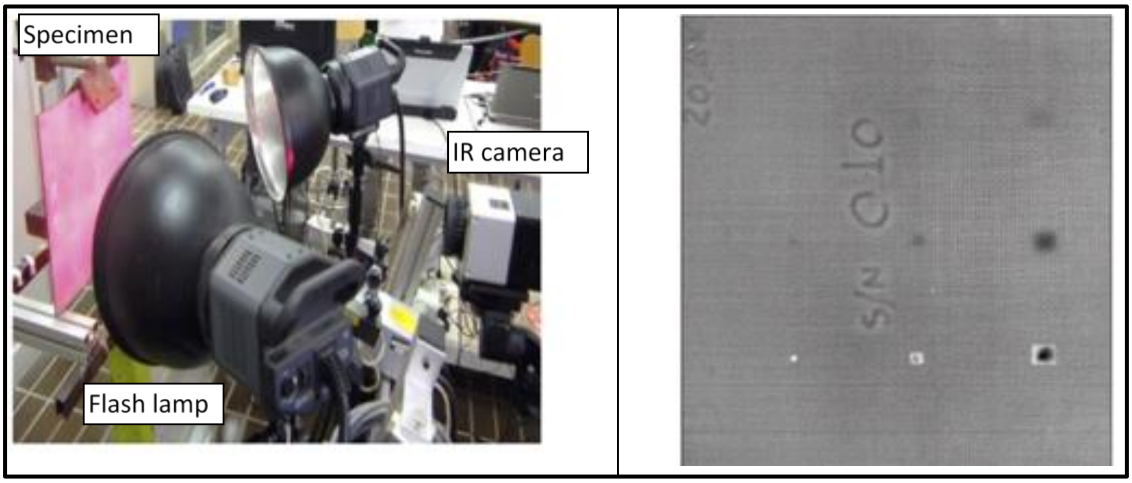


Figure 11 left: measurement setup; right: thermogram

[1] Castellini P., Martarelli M., Lenci S., Quagliarini E., Silani M., *“Diagnostic Survey on Frescoes Paintings in Pompeii by Active IR-Thermography”*, IMEKO INTERNATIONAL CONFERENCE ON Metrology for Archaeology and Cultural Heritage, Lecce, Italy, 23-25 October 2017

[2] Forcellese A., Martarelli M., Pandarese G. and Simoncini M., “*Similar and dissimilar FSWed joints in lightweight alloys: heating distribution assessment and IR thermography monitoring for on-line quality control*”, Key Engineering Materials Vols. 554-557 (2013) pp 1055-1064 © (2013) Trans Tech Publications, Switzerland doi:10.4028/www.scientific.net/KEM.554-557.1055

[3] Revel G. M., Chiariotti P., Copertaro E., Pandarese G., “*Stationary Wavelet Transform in Pulsed Thermography: influence of camera resolution on defect detection*”, Proceedings of 13th Advanced Infrared Technology and Application conference, Pisa, Italy, 2015

3.3 Comparison of (self)-inspection acoustic measurement techniques between INSITER and other areas of application

3.3.1 Context

This section aims at placing the acoustical self-inspection techniques proposed in INSITER into perspective, in particular with regard to other existing acoustical inspection techniques of relevance, for instance as used in the automotive and aeronautical fields. Owing to the overwhelming amount of specific techniques and inspection procedures, an overview of applications is given for the measurement methods used in INSITER, namely acoustic inspection using sound intensity measurements and using sound source localisation based on microphone arrays.

Common applications include the inspection of vehicle components and structural members, both in operational conditions and in laboratory conditions. These include testing of door and window junction quality, sound transmission by the different panels (e g. outer vehicle shell, engine compartment shield, etc.). However, there exist significant differences in the production cycle in the vehicle industry and the building industry which in turn have an impact on the implementation of the inspection methodologies. For instance, detailed acoustic inspection tools are systematically used in the prototyping and validation phases of vehicle manufacturing, rather than on individual assembled vehicles.

As a matter of fact, a large part of the market for acoustical solutions for SISW consists of B2B in the vehicle manufacturing sector.

3.3.2 Acoustic inspection using sound intensity measurements

Throughout the INSITER project, the LMS SoundBrush 3D sound intensity probe has been used.

Standard sound intensity probes provide the advantage of a higher upper frequency limit than the GRAS® 4-microphone sphere used in the SoundBrush probe. This is allowed by the one-dimensional 2-microphone configuration with a calibrated microphone spacer. Conversely, the 4-microphone sphere allows for three-dimensional measurements. The standard sound intensity probe allows for interchangeable microphone spacers and therefore measurements can effectively be performed on a wide frequency band. In contrast, the spherical probe tip is shaped to a frequency range suitable for applications in the frequency range where human sensitivity is high.

This is summarised in

Figure **12** below.

High precision standard sound intensity probe
Frequency band: 50Hz-10kHz
Point (or averaged) measurement

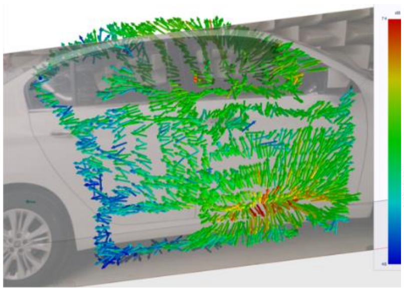
SoundBrush intensity probe
Frequency band: 50Hz-5kHz
3D measurement with spatial tracking

Figure 12: Comparison between sound intensity probes

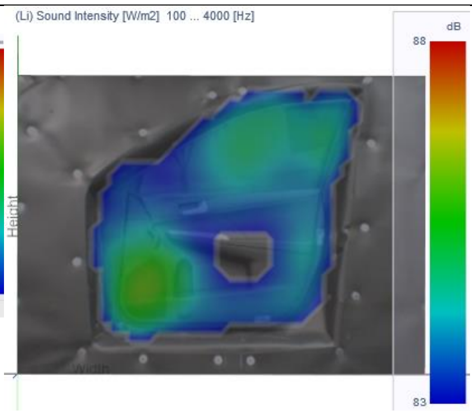
As detailed in previous deliverables, the choice of sound intensity device has been motivated by the three-dimensional capabilities of the LMS SoundBrush probe and the integrated augmented reality software.

The table below illustrates the use of the above in the context of vehicle components inspection. The examples chosen (see

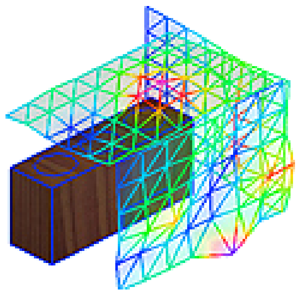
Figure **13**) for illustrating the present discussion give comparable information to that provided by the INSITER methodologies. For instance, car door sealing and its acoustic performance is analysed by means of 3D acoustic intensimetry, as well as sound transmission through car doors and windows. A major area of research is the inspection of the acoustically active components of vehicles, e.g. engine compartment components or exhaust, where the measurement results are critical for designing and optimising engine mounts, tailpipe geometry and materials. In addition, although on average general consumer vehicles have presented an increase in weight in the last decades, knowledge of their vibrational and acoustical behaviour provides the means to replace materials and components with lighter alternatives, with the potential of lowering the energy consumption footprint.



Augmented reality representation of the transmitted sound intensity in the vicinity of a vehicle door. (LMS SoundBrush measurement and software)



Augmented reality representation of the transmitted sound intensity magnitude into the interior of a vehicle door. (LMS SoundBrush measurement and software)



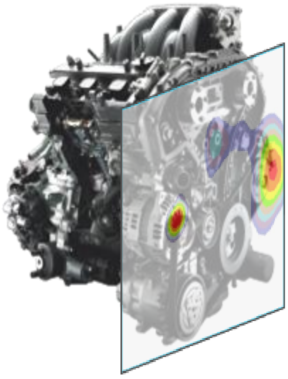
Post-processing of sound intensity measurement around an acoustic component. (Standard sound intensity probe)

Figure 13: Example of 3D capabilities of the LMS SoundBrush probe and the integrated AR software.

3.3.3 Sound source localisation using microphone arrays

Sound source identification provides a means to localise sources of noise in a precise manner, without the need for a manual detailed scan, as in the case of sound intensimetry. This is achieved by means of a large number of microphones feeding signal processing algorithms that reconstruct the acoustic field on the surface of the scanned object. Commercially available devices generally provide sound pressure levels, although sound intensity microphone arrays are also produced, albeit at a slower demand.

Figure 14 below illustrates the application of acoustic imaging to components and vehicles. For instance, simultaneous and synchronous measurement of the sound pressure at the vicinity of combustion engines allow for the identification of potentially problematic sources of noise. Sound source localisation is also used in the case of moving vehicles. For instance, noise sources may be identified on land vehicles during pass-by tests or on aeroplanes during flyover tests, the purpose being to characterise aerodynamic sources of noise in addition to those originating from combustion processes in the engine, for instance.



Augmented reality visualization of the sound pressure map of a vehicle engine.

Sound source localisation on the engine of an aerobatic electric plane. (Ground setup using Sound Camera)

Sound source localisation on an aerobatic electric plane. (Fly-over setup using a purposely-built 100-microphone ground array)

Figure 14: Example of application of acoustic imaging to components and vehicles

4. Impact assessment on practice / market based on industrial stakeholders

4.1 Survey among stakeholders present in Seville / Enschede

The meeting in Seville leads to a positive feedback. Several stakeholders and employees participated at the meeting and applied new and unknown methodologies, including the acoustic scanning devices and the use of AR hardware and software. The involved stakeholders included MEP specialised subcontractors, permanent and temporary factory white and blue collar staff, quality managers, the Factory Director and even DRAGADOS Director of the Prefabrication Division attended some of the demonstrations.

The workshop included detailed presentations of the different demo cases carried out throughout the project and hands on trials where the different technologies were experienced by the workshop participants. The handling of the devices was simple after a short introductive training. Feedback was then gathered.

Figure 15: demonstration of use of self-inspection acoustic technologies at Dragados factory

Figure 16: Factory workers trying the AR self-inspection and self-instrution technology

The feedback and suggestions from the stakeholders showed generally high appreciation. The imagination of integrating this working method through new, modern and connected devices which facilitate the working process was strong.
It turned out that the multiple advantages can as well be transmitted on the part of the contractor. Customers can utilise the techniques as easily as the employees for self-coordinative process steps. A holistic app which includes the needed information would change the relation between contractor and executor. Long term relationships could be established in single steps to push the efficient workflow of all participants. Especially with regards to apps there is a huge desire to compress sophisticated processes in simple and manageable sequences from both sides. Integrating every day used devices for exact planning and consultation facilitate the way companies are represented and seen through the customers´ eye. This allows the method of individual customized packages for every desire concerning construction projects.
The opinion of the participants rendered strength of the tools and devices related to easy application and functionalities. The results of this meeting delivered a clear vision of damages or could enable exact reassuring methods which are better than the nowadays utilised tools. Obviously the processes can be improved and used or desired gadgets can be individually optimized, but the core essence of the valuable process optimisation was astonishing.
Another well discussed issue was the necessity for wireless systems. Wires represent a potential hazard and reduce productivity so they should be eliminated whenever possible.
The opportunity of saving energy, time and resources thanks to these technologies was as well highly regarded. Through simple working steps being well coordinated the process becomes effective and fast. The risks of complications, damages and stress on site are reduced to a minimum.
Summarising, the feedback provided by the attendees showed high appreciation of the developed technologies and methodologies.

In the workshop celebrated in Enschede on May 28th, 4 groups consisting of a mix of external stakeholders with INSITER partners drafted Value Propositions (VP) around INSITER for four different target groups:

- General contractor/Investor;
- Mechanical workers/engineers (HVAC / building);
- Operator of the property;
- Asset manager of the property.

The main value propositions agreed during the workshop are enumerated below and can be used to further elaborate exploitation strategies and to strengthen communication about the project results.

1. Value Proposition 1 for General contractor/Investor.
   Our AR-based self-inspection procedures helps workers and supervisors who want to prevent and detect potential quality loss by anticipating the failure identification and speeding up the correct information flow between different actors.

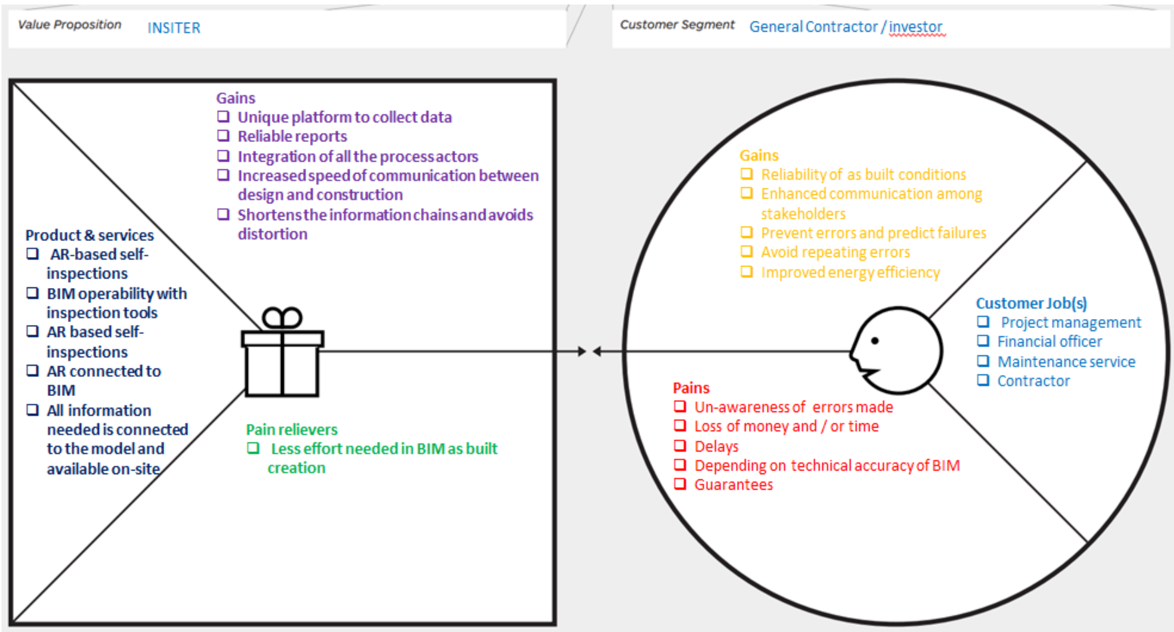


Figure 17: Enschede Workshop's Value Proposition 1

2. Value Proposition 2 for Mechanical workers/engineers (HVAC / building)

   Our self-instruction / inspection tool helps installation companies who want to perform proper realization by avoiding known mistakes and errors, thus enabling correct delivery

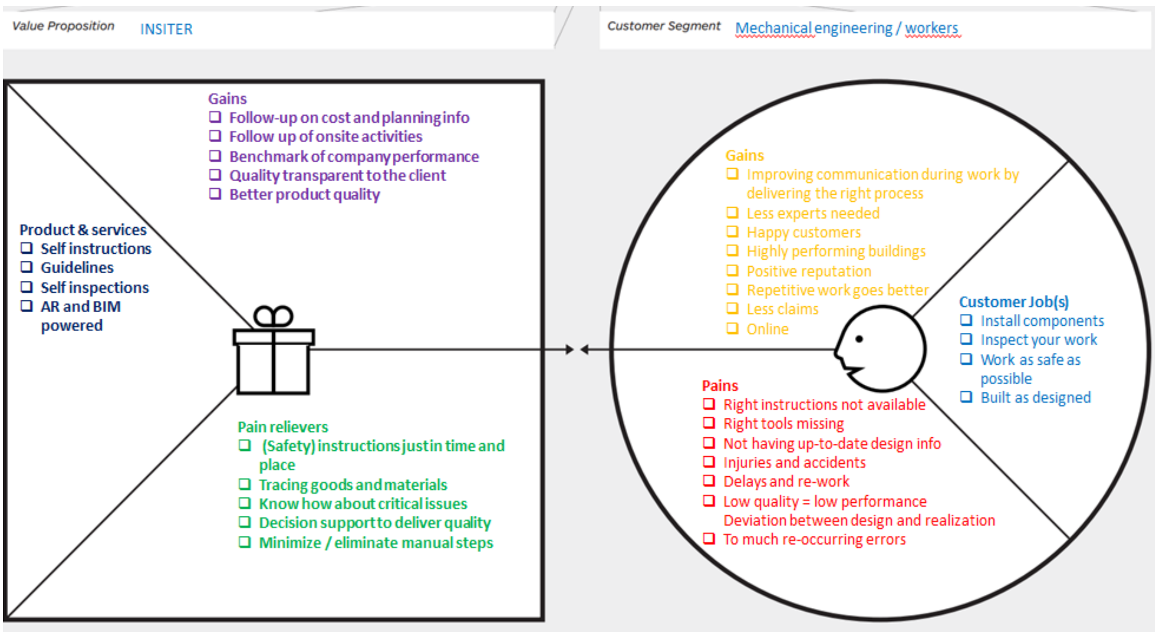


Figure 18: Enschede Workshop's Value Proposition 2

3. Value Proposition 3 for Operator of the property
   Our self-instruction and self-inspection tools combined with QR scanning helps the operator of the property who want to have traceable quality by less deviations and better accessible documentation

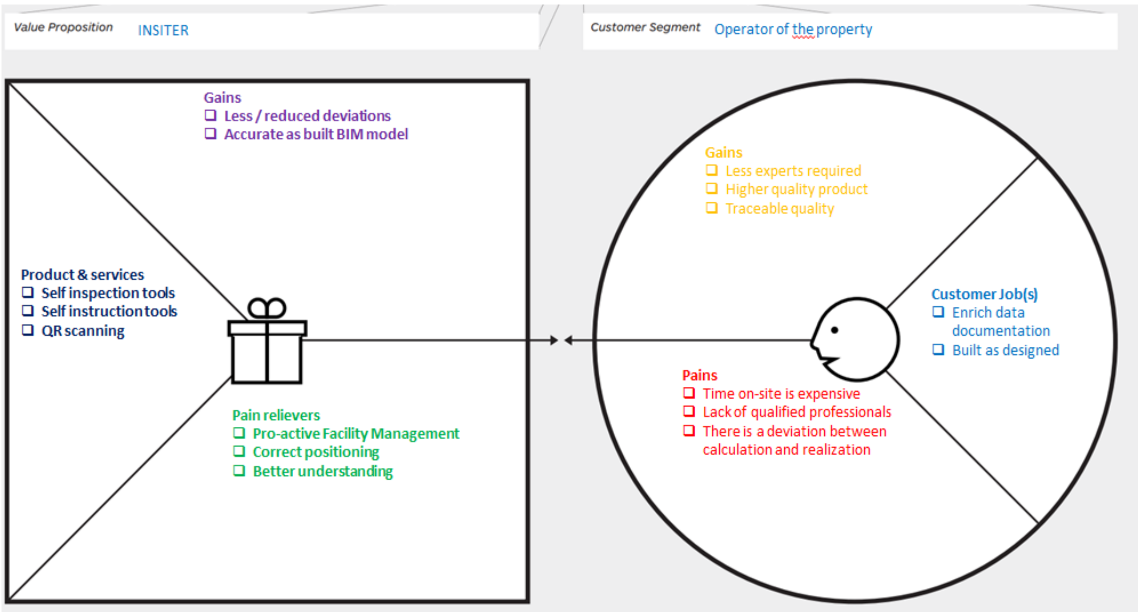


Figure 19: Enschede Workshop's Value Proposition 3

4. Value Proposition 4 for Asset Managers
   Our BIM based Quality assurance helps asset managers who want to have complete as built BIM models by effective validation and documentation of realized quality.

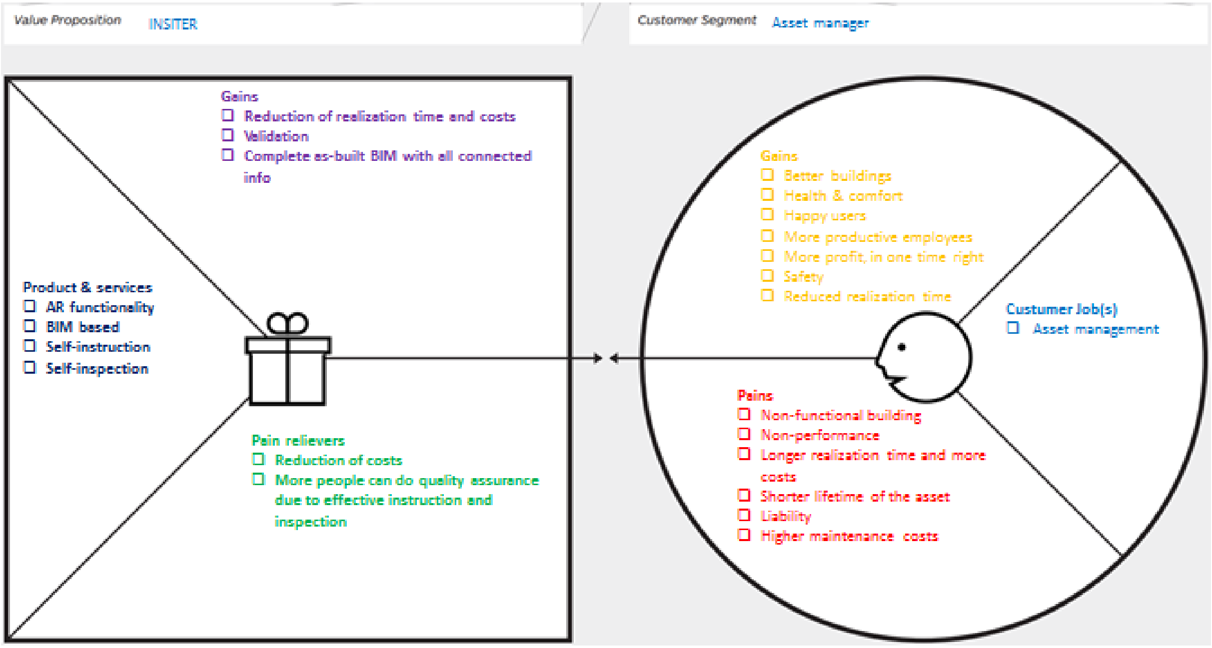


Figure 20: Enschede Workshop's Value Proposition 4

Both meetings in Enschede (in May 2018) and in Seville (in September 2018) reflect the same opinions of the majority of the participating stakeholders.

The key message consists of an indescribable desire of simplifying processes through known and often utilised devices. Also the desire for energy and time saving dominates as well as the aspect of one-self's participation. Customer relationships can be tremendously improved by connecting and establishing transparent work processes. Working efficiently and customer optimized due to specific techniques in the construction industry leads to customer satisfaction. Through the implication of customer-reviews and rating on the platform clients can obtain reliance to the company to be commissioned.

4.2 In-factory and on-site workshop in Seville & feedback from practitioners

"Customer Satisfaction" is an issue which gained a lot of importance in theory and practice in the last few years. High fulfilment levels of individual product specifications doesn´t necessarily imply customer satisfaction. The nature of requirements defines how products are seen and how their qualities are perceived on the customer´s side.
The Kano – Model, applied for the INSITER stakeholder survey of customer satisfaction, developed by Prof. Noriaki Kano from the Science University of Tokyo, involves a methodology of classifying product characteristics which have different influences regarding fulfilment / non-fulfilment. The categorisation, based on the idea of a multi-factorial model structure for customer satisfaction, is divided into 3 different groups: basic, performance and delighting demands.
By utilising a specific questioning technique, composed of a functional and dysfunctional question, one can get the requirement classification. The first question (functional) regards the reaction of the customer if the product contains the desired attribute; the second question (dysfunctional) refers also on customer reaction but without the desired product attribute. The response possibilities are restricted to 5 options:

- I like it this way
- I expect it this way
- I´m neutral
- I can accept to be this way
- I don't like it this way

Customer requirements		dysfunctional				
		like	expect	neutral	live with	dislike
functional	like	Q	E	E	E	L
	expect	R	I	I	I	M
	neutral	R	I	I	I	M
	live with	R	I	I	I	M
	dislike	R	R	R	R	Q

M Must have, R Reverse, L Linear, Q Questionable, E Exciter, I Indifferent

Figure 21: Customer requirements classification

The combination of the chosen responses leads to the classification which allows multiple methods of evaluation. The deeper the analysis becomes the more efficient the development gets and the resulting leads to customer-oriented and optimized product development. As the graphic below, the classification is partitioned in 6 categories: Must have, Linear, Exciter, Reverse, Questionable, Indifferent.

After the classification of answers follow the first evaluation filtered by frequency. The analysis of the results creates a satisfaction portfolio (Boston Window) to identify in which sector the classification belongs to interpret the value of it.

For the conclusive evaluation all answers are projected in a graph of an exponential function with subdivided sectors belonging to different categories of the classification done before. Recording to this evaluation the result is shown in a holistic diagram for estimating the opinion of the customer referring on the asked attribute.
For the stakeholder meeting in Seville – and simultaneously organised for the stakeholder survey focusing on participants of the Enschede meeting in May 2018- the survey was build out of 14 question packages. A holistic and representative output was delivered by the evaluation which substantiates the success of the survey.
The key statement of the meeting reflects the advantages of simplifying processes through utilising multiple devices to digitalise information that are collected and saved in clouds for continuous availability. Making these processes working more fluently leads to higher efficiency. Through simple courses for employees, everybody is capable of learning and using the developed technologies and methodologies.
The permanent connection with projects throughout daily life devices shows a revolutionise impact on work attitude and motivation on the part of the employees.

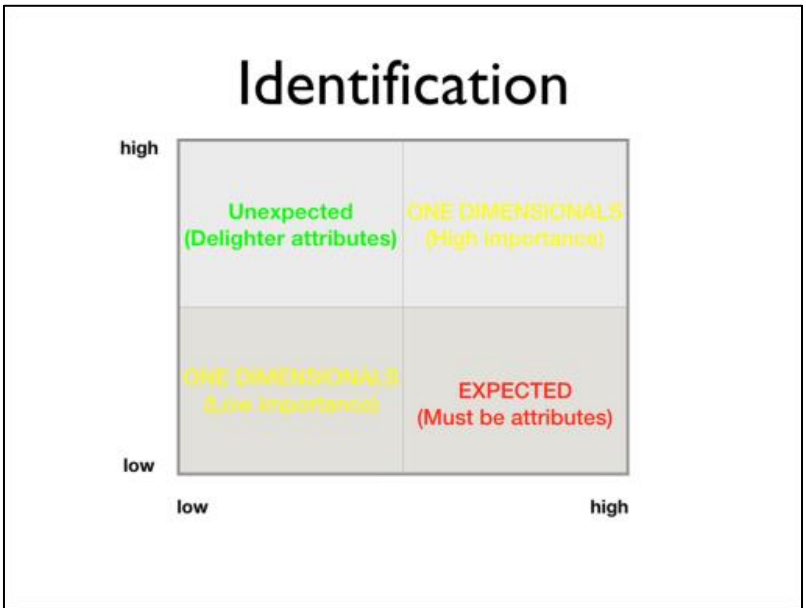


Figure 22: Customer requirements portfolio

The feedback summary for the different questions is presented hereafter:

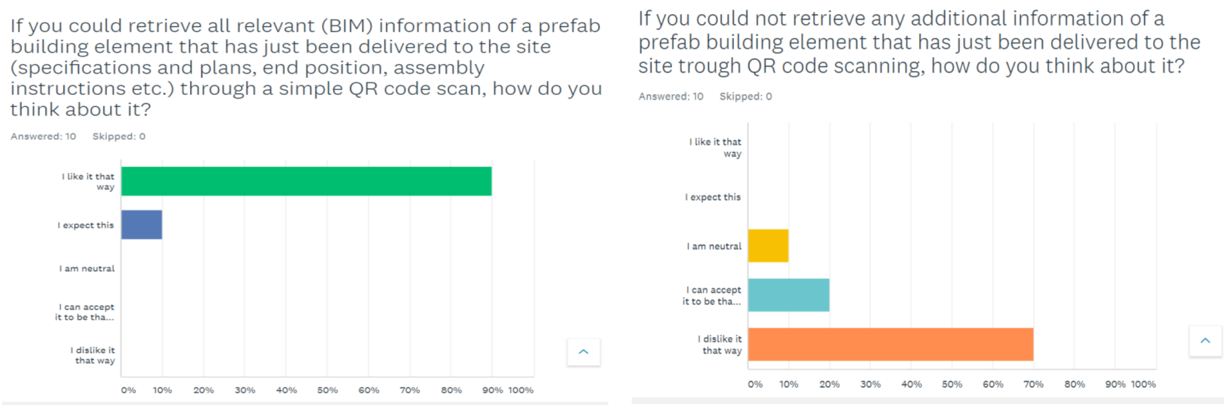


Figure 23: Q1: QR Code application

The first question (Figure 23: Q1: QR Code application) focuses on the methodology retrieving all relevant Information on prefab building elements immediately on your mobile device. The methodology consists of the simple process of recalling cloud saved data regarding the building component. Being able to see all relevant data through scanning an QR-Code enhances the construction process when the element is simultaneously being delivered or discussed. After collecting the needed information there are several opportunities to work with so that adjusting and provident planning is done with minimal expenditure of time.

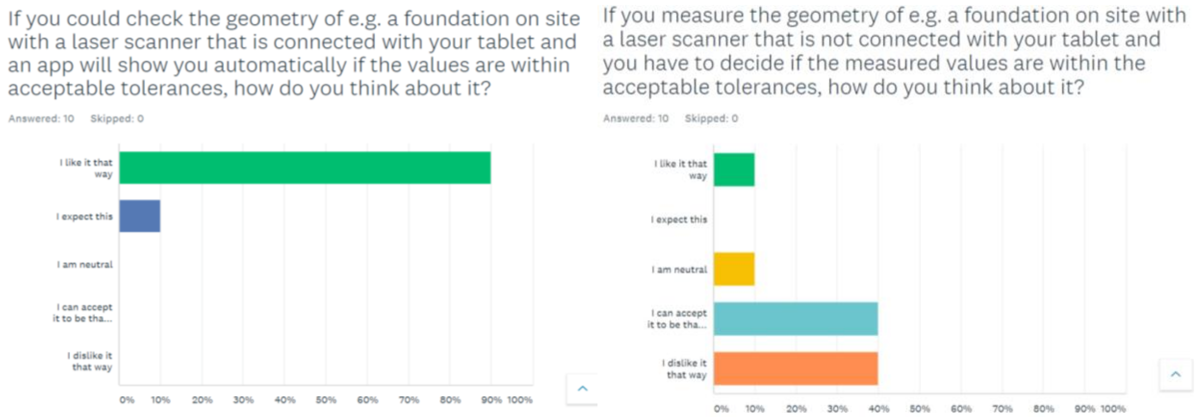


Figure 24: Q2: Geometry check of foundation

Construction at the side of existing unities has a rising value. Renovation has proved to be more efficient and time saving whereas the demolition and construction of a new building its more profitable on the financial side. Having the opportunity to use inter-connected devices (Figure 24: Q2: Geometry check of foundation) on site to help on the reliably estimating accurate values for concerning unities, saves time in planning and development. The process is simplified through methodologies which are improving the consideration of existing unities on site. Throughout these specific techniques new constructions (e.g. with prefabricated elements) could become a standardised and alternative way for energy saving constructions.

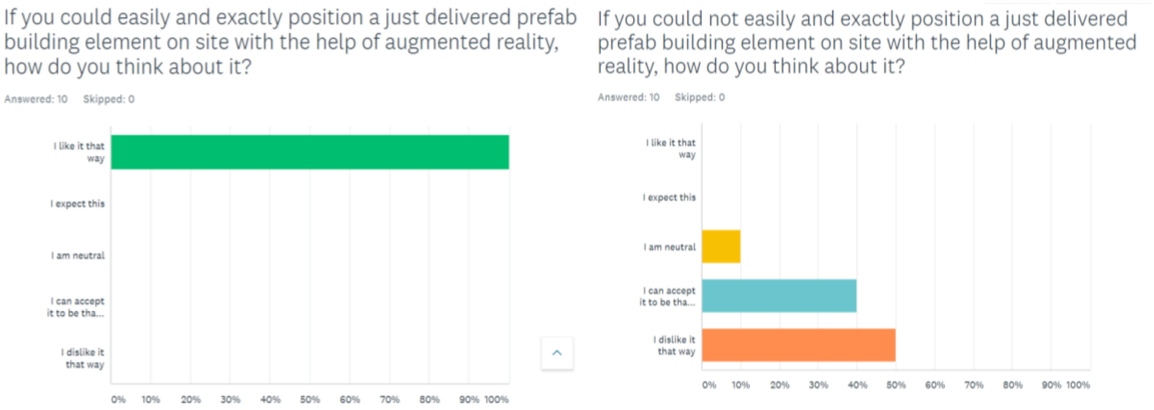


Figure 25: Q3: AR application

Augmented Reality (see Figure 25: Q3: AR application) develops to a feature which will be used permanently. Thanks to being able to access programmed reality in front of you shown by any mobile device, it gets easier to imagine, plan and discuss several aspects concerning construction, structure and time management as well as financial management. Using this technology on prefab elements on site could prevent unspotted damages through delivery and insecurity about the purchased element. Additionally, AR will help to save time in the phase of assembling the prefab elements on site. Preventing inaccurate fitting of the elements reduces the possibilities of mistakes, assures unproblematic termination and indirectly will have a positive impact on the building's EE.

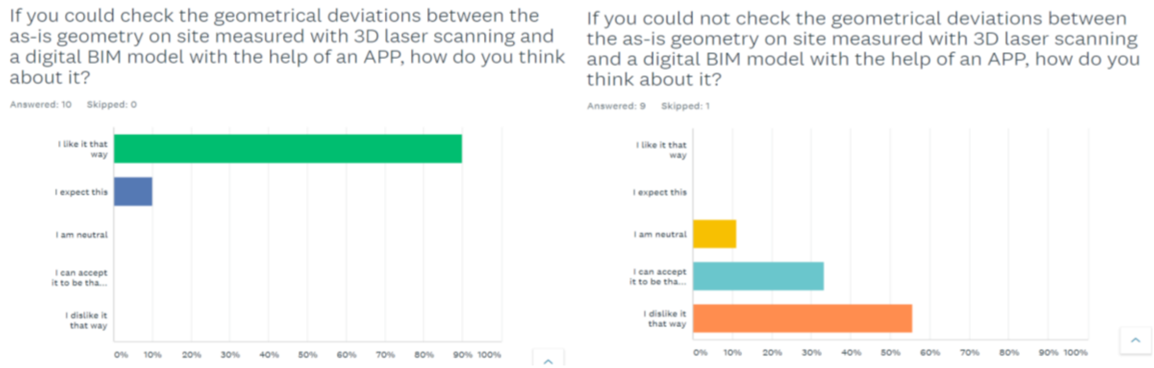


Figure 26: Q4: 3D Laser scan and BIM

Being able to carry on a holistic data cloud like a BIM model for reliable information (Figure 26: Q4: 3D Laser scan and BIM) makes methods of measuring more precise. Compressing these characteristics within an app (Figure 27: Q5: 2D/3D data combination) enables accessibility for more employees. Simplified working processes, which would be easily assimilated through proper training, will facilitate the working on-site while receiving real time support from colleagues in other locations. The connection shown in the BIM model is the demonstration of a coherent process followed by all participants guided by an app which works on any mobile device. Procedures and sequences are combined with direct exchange of information which leads to reduced costs and in time savings.

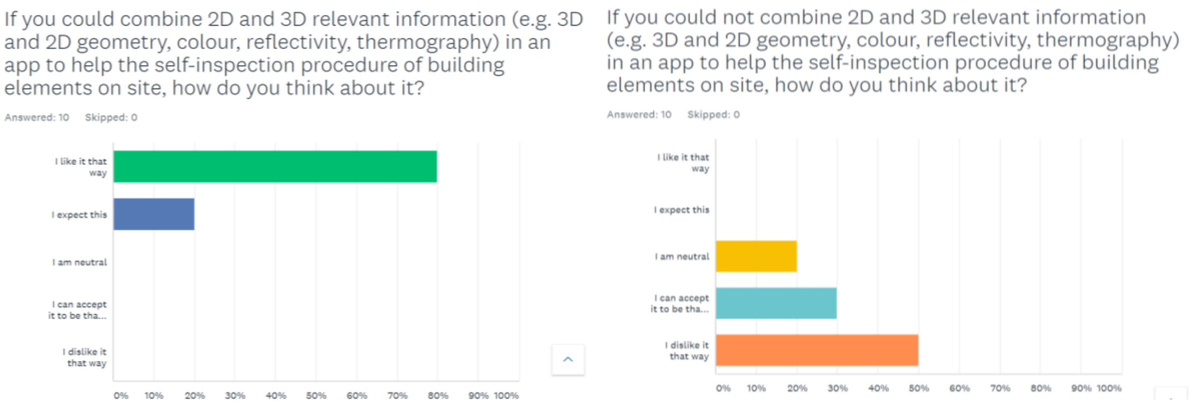


Figure 27: Q5: 2D/3D data combination

Self-inspection procedures are customer orientated and don't require extensive learning. Knowledge is shared through learning to understand multiple processes of Construction by personal initiative. The possibility of self-inspection allows the identification of problematic or damaged elements in the construction. By compressing all information and tools needed in an app, the operational maintenance is simplified thanks to the possibility of individual response in real time.

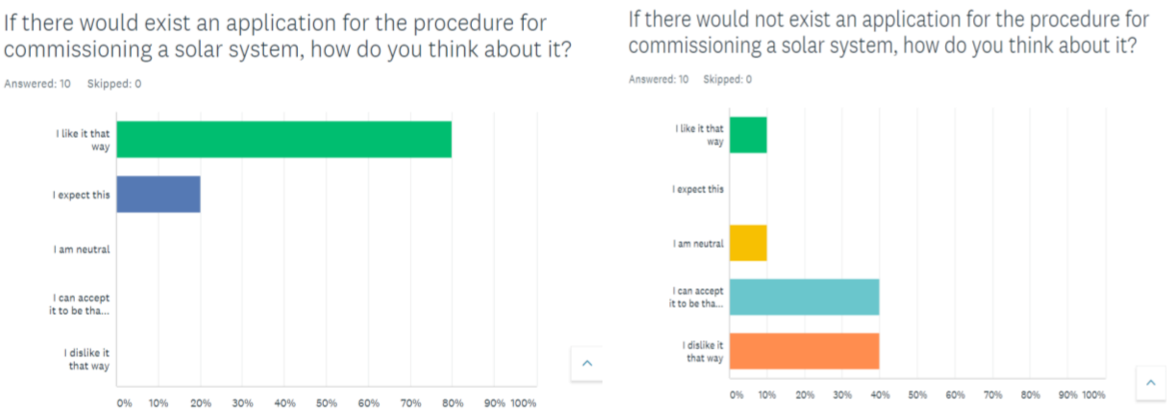


Figure 28: Q6: Solar system commissioning

Renewable energies like solar systems dominate the market. But the process of purchasing these energy saving systems is rather difficult. An app which allows market comparison could lead to financial savings and a more expanded market. Additionally it has an advisory component. Simplified user interfaces could emphasize the attractiveness of such systems (Figure 28: Q6: Solar system commissioning). The easy way to purchase these individually optimized systems will attract more stakeholders that simultaneously increase the value of and the investigations in the market of renewable energies.

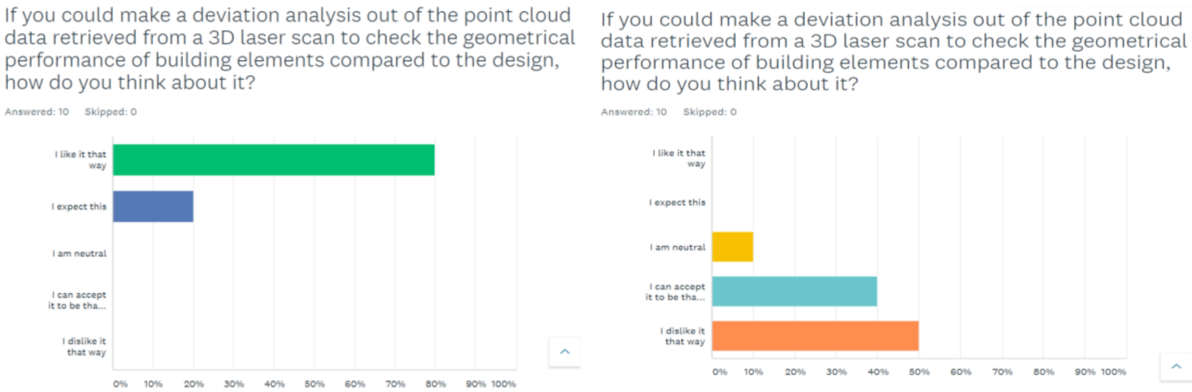


Figure 29: Q7: 3D Laser scan and component check

An important part of prefab element application is the facade construction. The process mentioned in *Figure 29: Q7: 3D Laser scan and component* check facilitates façade renovation works through the use of prefabricated building elements which are customized to each particular construction project. Retrieving point cloud data from 3D laser scans to check components and façade's geometry drastically improves the assembly process. In the case of old buildings, one cannot safely confirm that the whole building complies with the blueprints. This method facilitates accurate checks of the fitting of the façade elements without disturbing the building users and wasting time on on-site inspections.

Building physics have a large impact in architectural design and building construction, and most importantly, operation. Constantly changing guidelines and norms sometimes hamper building execution exactly as per initial design.

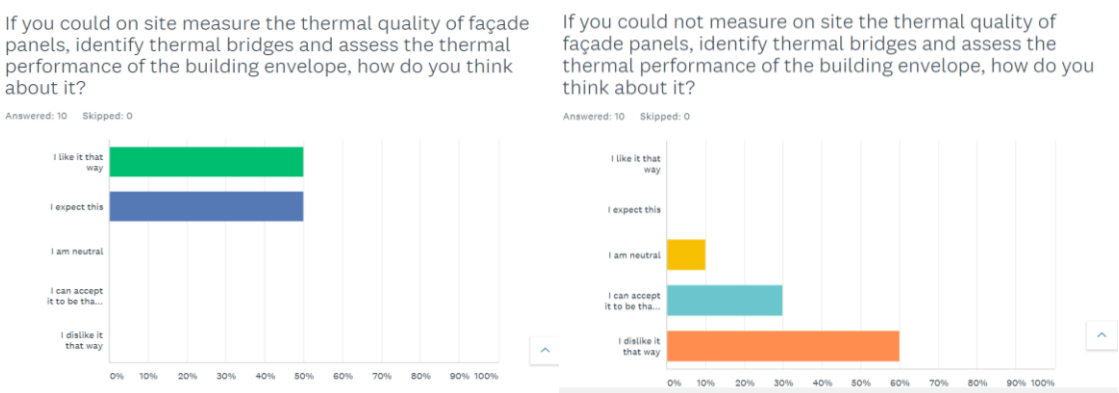


Figure 30: Q8: Thermal measurement

Before the element is fixed, there´s no possibility to assure that the delivered version of the element is completely compliant with the latest standard. Using several options to validate every aspect of an element's thermal performance results in higher quality and minimises constructional damages (Figure 30: Q8: Thermal measurement). This leads to efficient production, meaning time and financial savings at the same time. Thanks to augmented reality based apps it could be also possible to validate the quality and performance of the element during production and assembly.

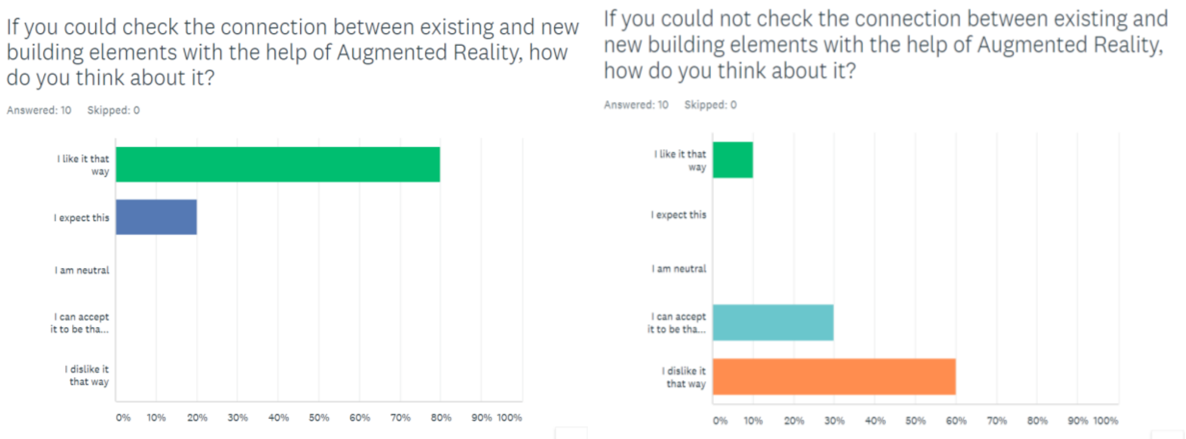


Figure 31: Q9: AR connection check

Mostly the new established buildings have either no or negligible connection to other existing units. Instead of wasting time by making vague evaluations and on-site experiments, one could simply look at the projected augmented reality and take a step to step virtual planning without the need of elaborated measurements. By simplifying the process with data-based virtual models the work on site is minimized. The intense planning with the client can as well be a modern solution of discussing next steps and interests. The construction itself can be optimized and at the request of the contracting entity. Unseen problems on-site can be discussed and avoided in an early status of the planning period.

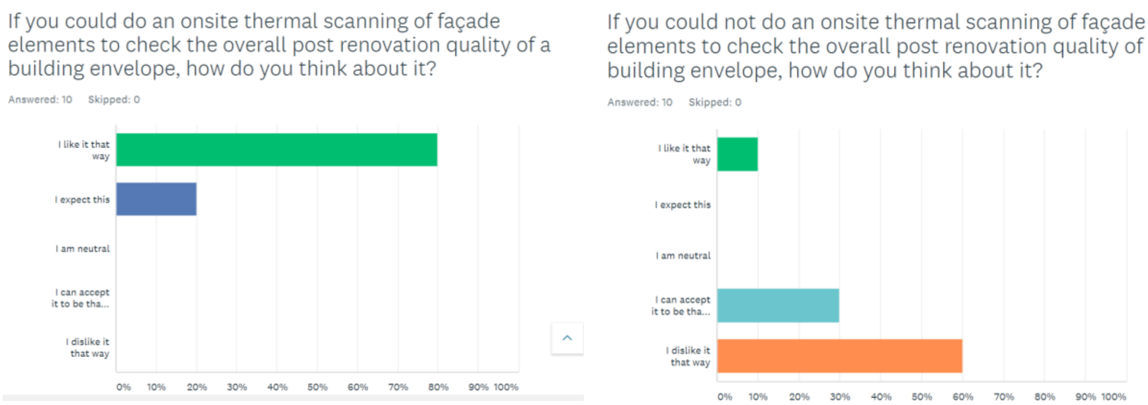


Figure 32: Q10: Onsite thermal scanning

Post renovation inspections (Figure 33: Q11: Clash detection and AR) with on-site thermal scanning can show directly how efficiently the new construction measures are working. It can be utilised to validate the actual standards of construction. The result of this after-renovation process are a fundamental intervention to see if there are any damages originated on the assembly process or to explain the energy savings to be achieved. As well performing better than norms raises the value of the building. The inspection of the status of the facade allows the contractor to certify a flawless condition of the facade. The rate of damages could be minimized through systematic checks by the contractor.

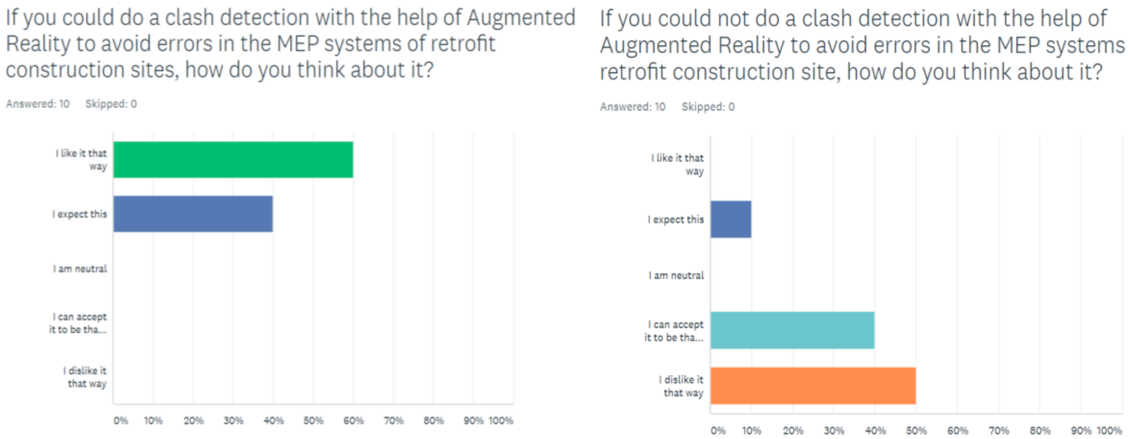


Figure 33: Q11: Clash detection and AR

The AR application at MEP/HVAC level was demonstrated at the Enschede stakeholder meeting in May 2018. Especially the clash detection demonstrated on site with the help of the HoloLens strongly impressed on site specialists and workers. The BIM based clash detection enables the identification of construction errors and clashes. Value added consists of, among other things, reduction of repair efforts and easier maintenance of hidden installation components.

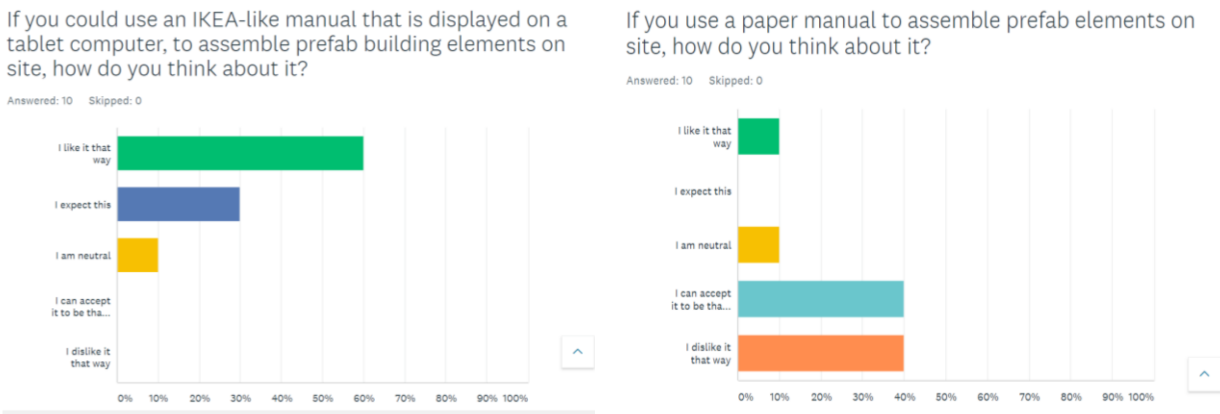


Figure 34: Q12: IKEA manual application

The difference between presenting information or valuable information for self-inspection and self-instruction is how this information is presented. The easier way this information is presented, the better. A comprehensive manual could be a suitable approach. Making it accessible on any mobile device allows anyone dealing with the assembling process to consult it. This solution could also be extremely useful for employees since allowing them to observe and control the process through a tablet with access to all relevant information would result in less work. Reducing construction on-site supervision due to process systematization implies having fewer workers in a particular project, so staff can be distributed to other sites.

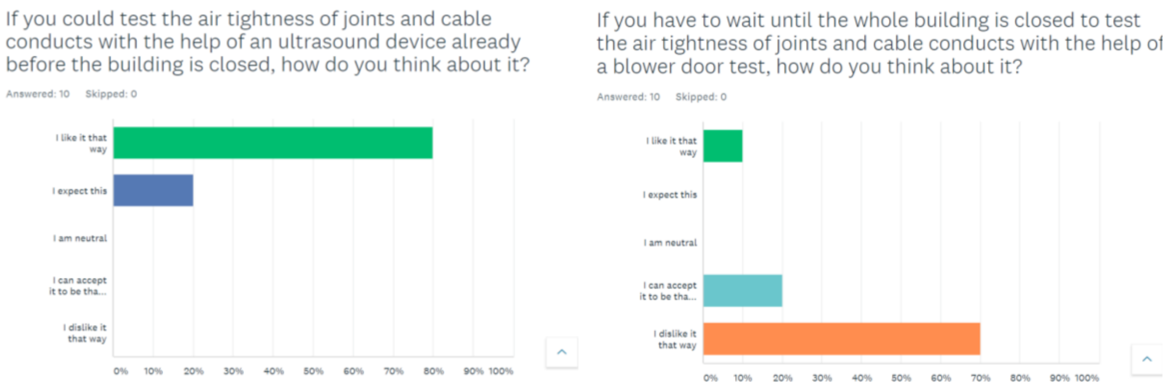


Figure 35: Q13: Air tightness

Joints and cable conducts are a sensitive part of every construction (Figure 35: Q13: Air tightness) and it is difficult to prevent damages due to incorrectly installed or defective ducts. With the chance of an ultrasound device system one can efficiently guarantee their safety and functionality, resulting in time and cost savings on the side of the contractor. Being able to validate the quality of every joint or conduct would result in a better perception by the client of the construction company's quality, allowing fruitful long-term relations with the client. Contractor's time management would become as well more efficient thanks to these techniques, allowing more production and installation with less re-work.

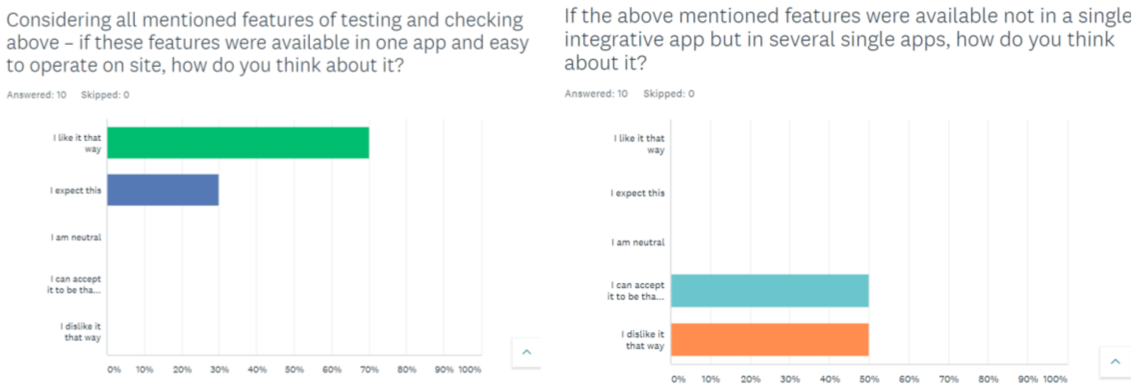


Figure 36: Q14: Integrated features in one app

One common user interface within all participants and parties would revolutionise the whole working process (Figure 36: Q14: Integrated features in one app). Comparable with social media, one app that everybody is familiar with and know under which rubrics they can find the needed information. Besides allowing for information upload and download counselling talks could be managed through the app, helping to improve relationships between customer and contractor. A holistic overview of every interaction, a shared clear course and a strengthened communication would result in an accelerated process on- and off-site. Customized and personalised designs could be done in an easier way and, that together with simpler and effortless control and coordination of construction projects due to digitalisation, would lead to more attractiveness on the construction sector.

Summarising the whole valuations from the survey, one can see through this graph with exponential functions how the results are classified. Product development and customer satisfaction are shown in a holistic and representative manner. As well improvements on different sections and parts of the achieved developments become clearly visible. Through this opportunity customer orientated products increase the satisfaction on both sites. Due to modern technologies and methods with everyday life devices and slight instructions employees are able to work more efficiently than ever. Increasing the financial earnings of companies due to time saving methodologies sustains the reputational quality of the company as well as the quality of the company's work. Ending up in generating more contractors with possible long term relations develops a new era for facility management. Contractors can be convinced and shown on-site how efficiently the renewed elements are working and fitting. This would increase the value of multiple buildings and make new constructions with prefabricated elements more attractive. Also existing buildings could be, rather than demolished and rebuilt, renovated using energy saving construction elements which are immediately proofed on-site and in the planning phase. Using new methods which are generally not in use like connection of huge databases and cloud based projects enhances a permanent and coherent work flow in projects. Combining and compressing every advantage described before in an app could lead to world changing perspectives. Customers´ satisfaction would become the rating of a company´s quality so the contractors could assure an optimized tailored offer. Due to a higher efficiency rate leading to financial and energy savings within short execution time people will be willing to invest in such tools and their application for new construction, retrofitting and maintenance.

4.3 Customer satisfaction portfolio

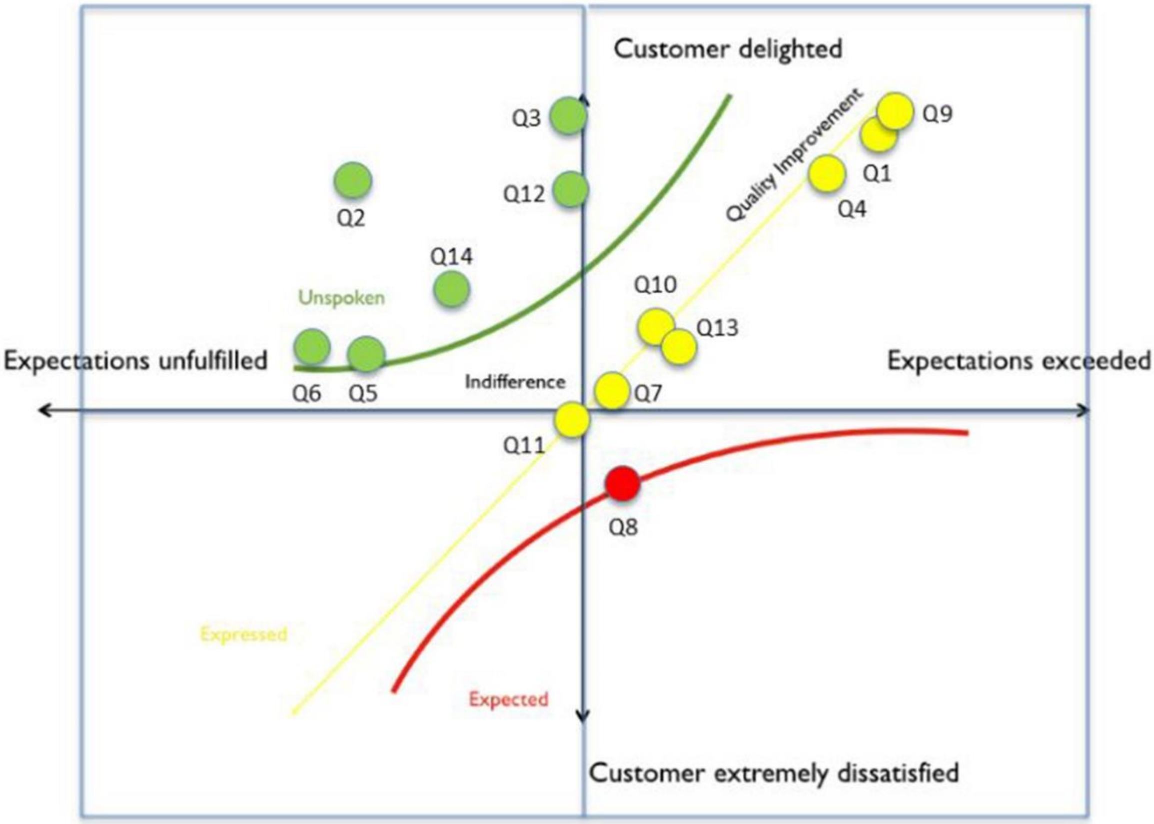


Figure 37: Customer satisfaction portfolio

The three categories and assigned question areas proof the high value and impact of the INSITER features (see Fig.37). Just *Q8 Thermal measurement* was identified as a basic feature -red colour- and expected by the customer as a must-have criterion. Nevertheless the category gives a hint that it is highly demanded as a part of the INSITER toolset as the missing would cause extreme customer dissatisfaction.

Within category 2 -yellow colour- related to value oriented quality impact, 7 of 14 features surveyed have been listed. The qualification of these features is at customer delight level causing the feeling at the customer to receive additional value exceeding the level of expectations. The following features are highly appreciated:

- Q1: QR code application;
- Q4: 3D Laser scan and BIM;
- Q7: 3D Laser scan and component check;
- Q9: AR connection check;
- Q10: Onsite thermal scanning;
- Q11: Clash detection and AR;
- Q13: Air tightness.

The unspoken category -green colour - represents the highest innovation rating from the perspective of the client combined with the highest added value expectation:

- Q2: Geometry check of foundation;
- Q3: AR application;
- Q5: 2D/3D data combination;
- Q6: Solar system commissioning;
- Q12: IKEA manual application;
- Q14: Integrated features in one app.

Especially in R&D projects the Kano methodology is not applied to rate features and qualities against expectations. There is a prejudice that not existing products and services can be analysed related to their probable upcoming impact. The scientifically developed Kano survey and analysis closes this gap. The results of the analysis for the INSITER toolset gives evidence on the extraordinary impact and development chances in terms of a successful exploitation of the results.

5. Conclusions

Thermographic scanning techniques developed in the project allow measuring temperature distribution of construction objects to, for instance, detecting thermal bridges, without physical contact between the measuring equipment and the object. Additionally, while inspection time is of at least 3 days when using standard procedure, this new methodology, based on Soft Sensing and on an appropriately developed artificial thermal load, allows estimating the thermal transmittance of a building object in a few hours. This combination of advantages extremely increase the applicability of these techniques in the construction sector, where, due to the unstructured and constantly changing environment (construction site) in which most of the processes take place, sufficient time for appropriate quality assessment and close access to the building components are not always available.

Laser scan techniques have the potential to help us detect construction problems that scope the eye thanks to the accurate 3D data they can provide. This represents a huge step forward in comparison with more traditional techniques. However, the building construction industry is just in the beginning of adopting 3D laser surveying as an integral part of a BIM process from as-built data and derived information. The work in INSITER has allowed providing reliable examples upon CARTIF-3 and HCC demonstrators as replicable case studies on the two main construction categories: building construction and building renovation.

Augmented Reality solutions merge virtual building models and planning data with real construction objects, thus connecting BIM data with the on-site real work environment. Developments in this field have been achieved by, besides INSITER and among others, different R&D initiatives such as ACCEPT and Built2spec. In order to successfully apply these technologies in the sector the selected software development platform and applied hardware plays a critical role. Limitations concerning the select the hardware devices or a demises of an utilized AR development platform, as happened in the assessed projects, can actually be a challenge for the operative application or further exploitation of the achieved software developments and AR solutions. In the case of INSITER, the world's rapid pace of technological evolution allowed us to access hardware which was not available at the beginning of the project (i.e. HoloLens), resulting in a better functionally and usability of the developed software.

The acoustic scanning techniques used in INSITER allow for sound sources identification and localisation in a precise manner, without the need for a manual detailed scan. The comparison of the applicability of acoustic scanning techniques in the building and the automotive industry has allowed to understand that energy performance aspects encountered in the building industry (i.e. identification of potentially problematic sources of noise in MEP components which could affect the system's energy efficiency), as investigated within INSITER, are absent in the vehicle industry. Conversely, safety and comfort are the main drivers for structural optimisation aided by inspection tools. Despite these differences, the procedure leading to a final product is equivalent, and the existing and evolving experience in the fields of automotive and aeronautical acoustics research is crucial in order to deliver state-of-the-art building inspection tools.

Trials on R&D project's developments by the intended users, even if the technologies are not 100% finished, always provide relevant and useful feedback to detect flaws and needed improvements. Finding the right moment to carry out those trials is never easy, since users will be expecting highly developed products they can go hands on and at the same time there has to be room for modifications and improvements after assessing the gathered feedback. In INSITER, continuous feedback to focus the developments has been provided by stakeholders in managerial positions (i.e. Quality Managers) and it has been once the technologies/devices where in an advanced stage of development when the *blue collars* have been involved, facilitating their understanding of the expected functionalities and usability.

Based on the cross-case analysis of the lab, factory and on-site validation and demonstration, the following conclusion can be drawn regarding the real development realised in INSITER and the outlook towards market implementation.

Technology innovation in INSITER for on-site construction	Starting TRL at the beginning of the project in 2014	Achieved TRL as demonstrated and validated until the end of the project	Brief recommendations for further steps towards real market implementation
Augmented Reality	TRL 5 AR validation in relevant environments with prototype implementations.	TRL 7 AR solution demonstration in an operational environment (UNIVPM lab, Enschede and Seville cases).	• Adjusting existing or establishing new regulations concerning on-site use of AR devices • Further elaboration of health and safety issues. For example to avoid distraction and risk of accident by the use of AR due to augmented content
Laser measurement	TRL 5: Validation in a controlled environment.	TRL 7: Demonstration and validation in a real environment (Cologne and Valladolid cases).	Construction companies are encouraged to support the developments that allows linking the different imaging (2D) and surveying (3D) instruments to BIM
Thermal measurement	TRL 5: Validation in a controlled environment (lab at UNIVPM)	TRL 7: Demonstration in an operational environment (Enschede and Pisa cases).	Thermal bridges localization: implementation of image processing developed in INISITER into commercial IR camera software Thermal transmittance assessment: development of a dedicated app for acquisition and data processing
Acoustic measurement	TRL 4: • Pre-existing sound intensity hardware. • Digital microphone array at early design stages. • Application to inspection in the building industry not part of portfolio as of 2014.	TRL 6: • Measurement procedure prototypes (both sound intensity probe and digital microphone array), tested in representative environment (UNIVPM lab, Delft and Seville case) • Quantitative evaluation tools for analysis and inspection tested in representative environment.	• Hardware compaction and ruggedisation. • Development of dedicated software for building self-inspection integrating INSITER self-inspection procedures.

Table 1: the real development realised in INSITER and the outlook towards market implementation