Measuring and diagnosis solutions for inspecting building components

Deliverable report D1.5

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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.

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

INSITER INTUITIVE SELF-INSPECTION TECHNIQUES

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Publishable executive summary

Deliverable D1.5 *Measuring and diagnosis solution for inspecting building components* is a follow-up of D1.4 *Calculation and analytical methods for building components* within the framework of WP1 and under the umbrella of T1.2 *Self-inspection techniques and quantifying methods for building components*. T1.2 ends at M45 and D1.2 is the final deliverable of this task. D1.5 is focusing on practical techniques using hardware and software tools for self-inspection of building components. D1.6 *Calculation and analytical methods for MEP/HVAC components* -the final deliverable in T1.3 is focusing on MEP/HVAC components instead of building components.

The techniques applying hardware at experts´ level are evaluated and demonstrated at the laboratory, at demonstration sites and at the Dragados factory. Exhaustive documentations about these results are available and embedded in deliverables D5.1 *Lab test protocols and set-up*, D5.2 *Lab test report and recommendations*, D5.3 *Case study elaboration, field validation protocols, and equipment calibration*, D5.4 *Field validation report and recommendations*, D5.5 *Integrated field demonstration report and upcoming deliverable* D5.7 *Cross-case analysis and benchmarking*. Furthermore the testing equipment applied has been enhanced in terms of handling quality by extending their functionality in WP2.

D1.5 is focusing now on the practical application of handling the test equipment and methodologies assigning thresholds and KPIs to them in order to rate qualities and balance them against INSITER demands. Especially enhanced 3D measurement systems, infrared non-destructive testing, and acoustic imaging technologies have been surveyed and the practical use in self-inspection activities has been elaborated and documented. The chapters of D1.5 are representing the explicitly applied technologies in the above mentioned fields of action:

- 3D laser scanning
- Thermal measurement
- Air tightness
- Acoustic measurement.

The structure of each chapter is following a systemic approach in order to ease the application: The objective is to simplify the retrieval of information by the applicant:

- Devices and technologies
- Applied KPIs
- Procedure methodology and techniques
- Thresholds.

In the framework of WP1 *self-inspection techniques and process methodologies* the closing deliverables D1.5 and D1.7 are embedded following the demands of the methodology related content and timing of measurements to be performed and the related calculation of KPIs. D1.4 *Calculation and analytical methods for building components* is focusing on quantification of results related to building components while D1.6 is focusing on qualification of building components related to their performance quality.

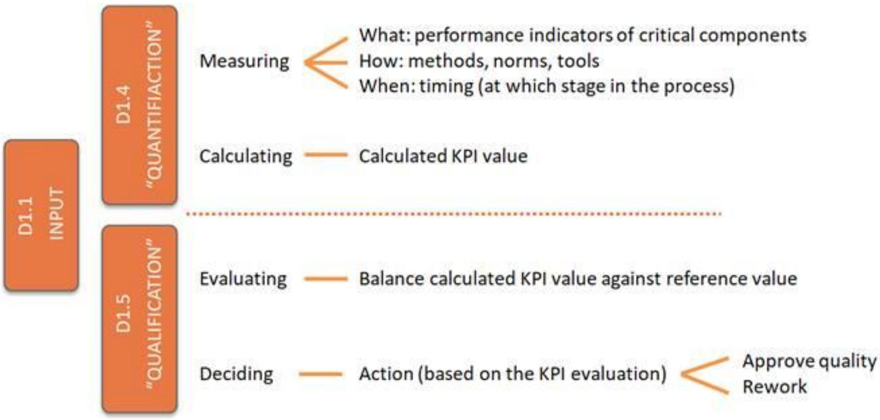

Fig. 1: Inspections of building components during different building phases based on quantification and qualification

Nevertheless there is a holistic focus on a total building quality especially related to energy performance and consumption issues as elaborated at D1.5 and D1.7 at building component and MEP/HVAC component level. The combination of the applied methodologies described in both deliverables insures the total building quality.

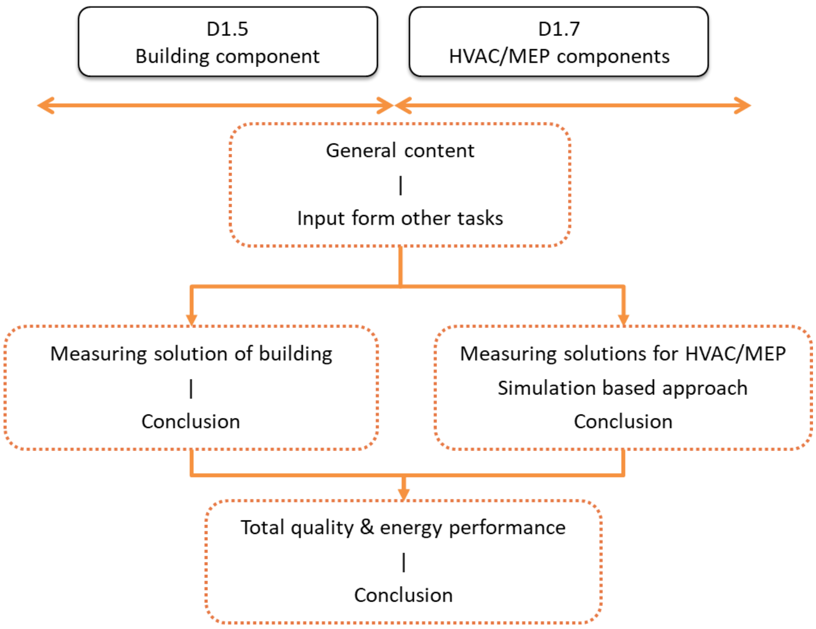

Fig. 2: Relation and difference between D1.5 and D1.7

In the INSITER project, experiments were carried out with various testing technologies and equipment -laser scanner, thermal scanner, air tightness, acoustic measurement- at building sites in Cologne, in Pisa, Italy and Valladolid, Spain. These experiments gave the following results:

- The crucial deviations being responsible for gaps and leakages at points of junction at building component level can be avoided by using enhanced measuring tools for dimensions and building physic performance;
- The scan time can be shortened;
- By using a linked tablet during the scanning, the results determine directly which parts should be scanned better;
- In terms of 3D laser scanning different pointclouds from the same equipment indicate that some pointclouds can be more easily translated to BIM than others;
- By using smaller parts, such as walls only, deviations between the BIM model and the pointclouds can be better mapped.
- Air leakages can be detected before closing the building envelope by enhanced acoustic measurement.

List of acronyms and abbreviations

- **AB:** As-Built
- **AD:** As-Designed
- **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 and 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
- **SPR:** Sound Prominence Ratio
- **STL:** Sound Transmission Loss
- **TCO:** Total Cost of Ownership
- **URL:** Uniform Resource Locator
- **VR:** Virtual Reality
- **WBS:** Work Breakdown Structure
- **ZEB:** Zero-Energy Building

Fulfilment of the Description of Action (DoA) in D1.5

Accessibility of this deliverable: Public

This deliverable is presented in 1 part:

- Report / documentation (this document)

D1.5 is delivered at M47. The reason of this slight delay is the integration of ongoing testing at the building site level and the important influence of these results on D1.5. Therefore, the original version has been continuously updated.

Fulfilment of WP, Task and Deliverable scope and objectives

Summarised objectives as stated in DoA	Results presented in this deliverable
WP 1 scope and objectives: WP1 - Self-inspection techniques and process methodologies Research in this WP will be carried out within the following areas: • Key performance indicators (KPIs) and parameters addressing quality and energy performance level, including the most effective quantitative methods to analyse them. The parameters are for instance: thermal bridges, air leakages, imaging of U-Value distribution, acoustic leakages, vibration transmissibility from MEP/HVAC. The measurement systems considered can be grouped in three main areas: thermal/imaging, acoustic/vibration, positioning/sensing. The data provided by the different sensing technologies will be then integrated to give combined 3D information. • Generic and particular techniques to: – perform self-inspection and to provide self-instruction in different types of projects –new construction, refurbishment, commissioning, and maintenance. – inspect critical building components (e.g. roof, façade, openings) and MEP/HVAC components (e.g. energy and comfort systems). – use hardware and software tools during off-site and on-site processes for self-inspection and self-instruction, depending the type and scale of projects and site circumstances	**Addressed:** • Self-inspection techniques and process methodologies are exhaustively covered in this deliverable at building component and MEP/HVAC level –see D1.7. The listed testing methodologies have been elaborated, enhanced and applied.

Summarised objectives as stated in DoA	Results presented in this deliverable
Task 1.2 scope and objectives: Task 1.2: Self-inspection techniques and quantifying methods for building components The main subjects / activities within this task are: • Self-inspection techniques using 3D laser measurement systems, infrared non-destructive testing, etc. • Multidisciplinary approach, including research on quantitative analysis, involving techniques from building physics, civil engineering and material engineering disciplines. • Integration of BIM in design, manufacturing and assembly process of building components. • Review of the software tools for building condition assessment including lifecycle cost validation. • User and process requirements for upgrading the hardware equipment, software tools and BIM capabilities for self-inspection and self-instruction. • Development of a defect inspection manual involving consultations group with all actors in the construction industry: architects, contractors, building component suppliers and consultants. • Acoustic imaging technologies will be proposed as troubleshooting tools able to precisely diagnostic and locate lack insulation areas and acoustic leaks. Some advanced technologies are already present in the market for the application in different sectors (such as the technologies for noise source localization in automotive/train/airplane interior cabins) and their exploitation in buildings acoustics will allow to speed up and simplify the self-inspection and the decision making process. An optimization of those tools is required to keep a moderate cost even though the advantages brought in terms of accuracy, 3D visualization and speeding-up of the measurement process will also be cost-effective.	**Addressed in D1.5:** • The application of 3D laser measurement systems are dealt with in D1.5 and applied at demonstrator level in WP5. The multidisciplinary approach is the basis of deep analysis procedures based on building physics, civil engineering and material engineering disciplines –see calculation methodologies foreseen in D1.5. BIM has been applied as an integrative communication and construction tool supporting the assembly process. In coordinated action with WP2, D5.1 and D5.2, and based on D1.2 and D1.3 user requirements for upgrading the hardware equipment and software tools and their BIM capabilities for self-inspection and self-instruction have been analysed and embedded. The defect inspection manual is integrated in the D1.2 and D1.3 guidelines for the application of the INSITER methodology. Acoustic imaging technologies have been treated in chapter 6 and 7 of D1.5
	• Additionally –not mentioned in the task description- air tightness and energy relevant leakage detection has been surveyed in chapter 5 of D1.5.

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1. Introduction

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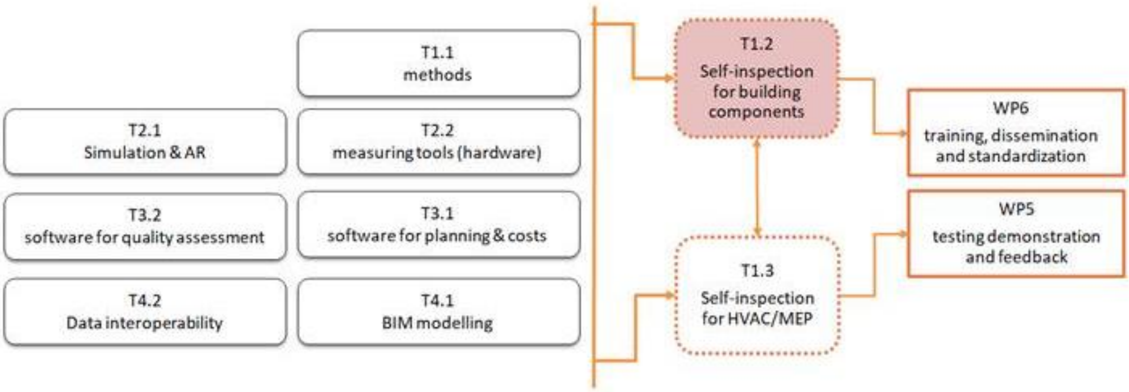

Fig. 3: Input and output of task 1.2

D1.5 is focusing now on the practical application of handling the test equipment and methodologies assigning thresholds and KPIs to them in order to rate qualities and balance them against demands. Especially enhanced 3D measurement systems, infrared non-destructive testing, and acoustic imaging technologies have been surveyed and the practical use in self-inspection activities has been elaborated and documented. The chapters of D1.5 are representing the explicitly applied technologies in the above mentioned fields of action:

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- Thresholds.

The INSITER project aims to increase building quality and optimizes energy performance in buildings. This optimisation is achieved by eliminating the gaps between design and realisation based on prefabricated components. The final INSITER solution includes:

- a new self-instruction process
- a new self-inspection process
- both processes supported by intuitive and cost-effective tools (Augmented Reality)
- all connected through the BIM process and empowered by simulation and monitoring software

1.1 Objectives and structure of this deliverable

The main objectives of this deliverable are:

- to implement calculation and simulation and diagnosis methods and monitoring techniques in the self-inspection process
- to estimate the uncertainty of each key performance parameter measured on the global building performance
- to extract self-instruction information as guidelines for the applying experts and the integrated construction workers
- to embed the new self-inspection processes in the quality assurance systems and standardization

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

This deliverable presents the main results of the research for integration of calculation and simulation techniques to support the self-inspection process including the related decision support process.

The R&D methodology is based on the following:

- experience of the consortium partners and especially of Task 1.2
- new processes in the field of commissioning
- new possibilities in the world of digital construction (using BIM and simulation techniques)
- new developments in the field of quality control software (such as BIM Field360 and ED-Controls)

The development of the calculation solutions and diagnosis approach has been done through answering the following questions:

- What is the current practice of an inspection process?
- Which part of the inspection process is relevant and can be transferred to the workers themselves?
- Which information does the worker need to perform the inspection process?
- Which tools can support the worker performing the inspection?

The global planning and process that is followed, is shown below:

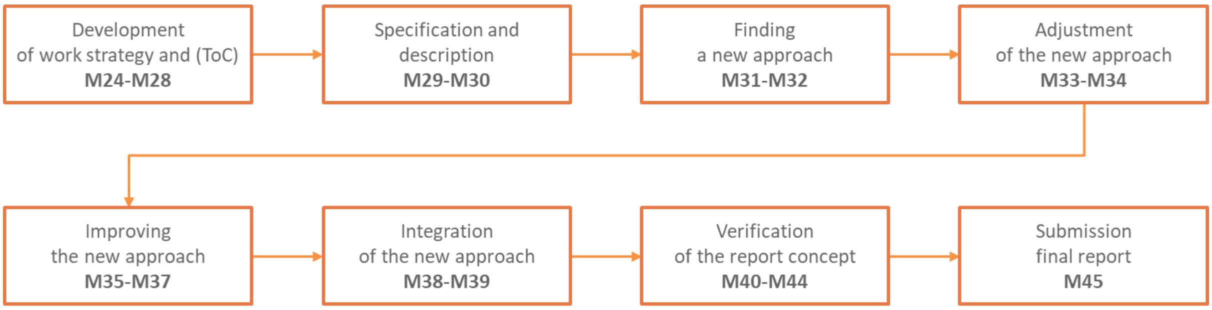

Fig. 4: Project planning T1.2 / D1.5

1.3 Main achievements and limitations

The deliverable presents the results achieved in T1.2 during the third and fourth year of the INSITER project that can be summarized as follows:

- **Explaining the complexity** of the interaction between the building component systems in relation to the total building performance
- **Extending the self-inspection process** by introducing measuring and calculation solutions to the process developed in D1.4
- Introducing a new simulation based self-inspection approach to support self-inspection methodology
- Specifying the new solutions and approach for the major applications

The T1.2 team was able to cover all D1.4 objectives as required in the Description of Action. However, some difficulties were also faced during the project resulting in some limitations.

TOPIC	LIMIT
1. Actual total building performance	Actual performance of the building depends on several factors including: design & building elements, HVAC/MEP systems, use & users and finally weather conditions. The INSITER methodology contributes to increase the total building quality and energy efficiency by providing measuring and diagnosis solutions for inspecting building elements and HVAC/MEP systems. However, the INSITER self-inspection process is not able to indicate the actual performance of the building during the construction stage (scope of the INSITER project). Only monitoring techniques (using actual data from the building, the HVAC/MEP system and the weather condition) are able to provide insights about the whole performance, at least after one year (four seasons) of data collection and analysis. The monitoring stage and the required data collection during one year or four seasons are outside the scope of the INSITER project.
2. Preventing common errors and increasing building quality	It is very clear that preventing (common) errors during the construction is resulting in higher building quality and lower rework cost. D1.6 is also able to quantify the impact of the (to be avoided) errors. But it is impracticable to quantify the performance increase created by the INSITER method during the period of the INSITER project. To do that you have to execute the project twice using two processes: the traditional one and the INSITER one.
3. Full self-inspection process	It is very desirable to transfer the quality issues and inspection processes to the workers. However, from a practical point of view there is still a need to have overall control on the inspected/controlled work. The role of the commissioning manager is, practically, irreplaceable.
4. Aggregation of performance deviations	It is very feasible to estimate the impact of a performance deviation on the whole performance of the building theoretically. We use the new approach based on simulation. This is only possible, if we consider that all building components are performing as designed. From practical point of view that is unrealistic. In practice, it is unimaginable that only one deviation will occur.

Table 1: research and result limitations of D1.5

1.4 Positioning of this deliverable

This document, D1.5, is the second deliverable of task 1.2. For development, it relies on the input from some of the deliverables from other tasks, and consequently, its output will be used again in WP6 (for training purposes). This is shown in Figure 5. Generally, task 1.2 will develop the methods for MEP/HVAC components as task 1.2 is doing the same for building components. The input includes the generic methods, software and hardware development and the research done on simulation and BIM. The developed methods will be tested and demonstrated in WP5, and feedback will be provided. The development of training material and standardization will be based on the input from T1.2 and T1.3.

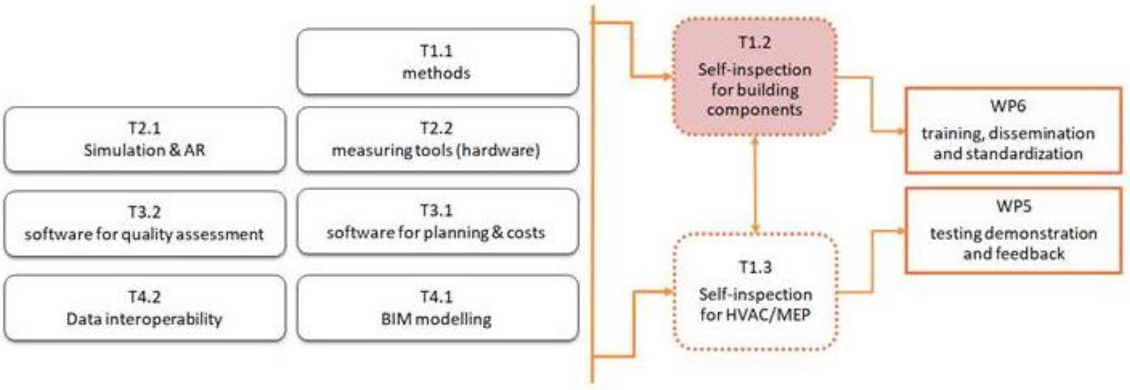

Figure 5: Input and output of task 1.2

As D1.5 is developed in T1.2, D1.7 is synchronically developed in T1.3. Because of the similarities, the approach is equal. The content differs though, because of the differences between MEP/HVAC systems and building elements. In Figure 6 the difference between D1.5 and D1.7 is shown, mainly concerning the 'simulation based approach for the measuring and diagnostic solution for the HVAC/MEP systems.

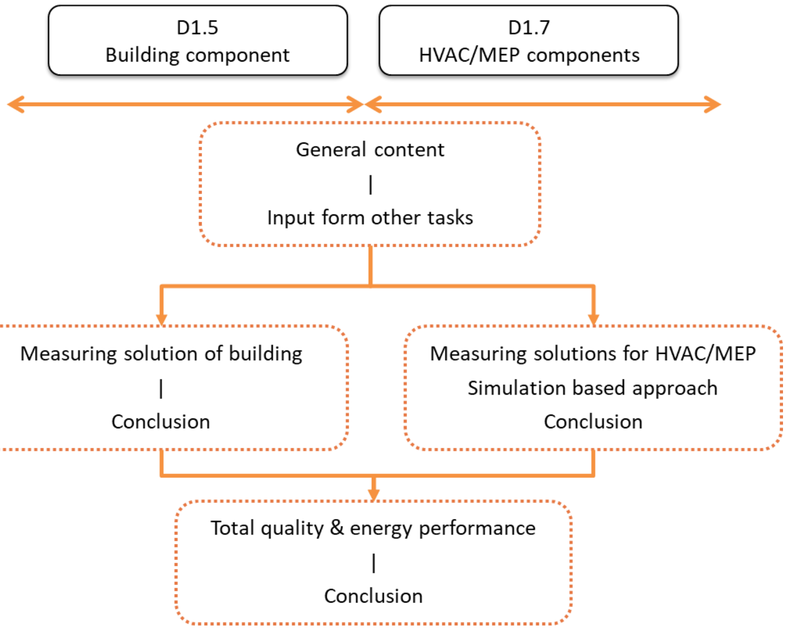

Figure 6: development of and difference between D1.5 and D1.7

Finally, within T1.2 two deliverables are developed: the present D1.4 and D1.5. Where D1.4 ended D1.5 began focussing on new approach for calculation and diagnostic solutions for building components. See Figure 7 for a visual explanation.

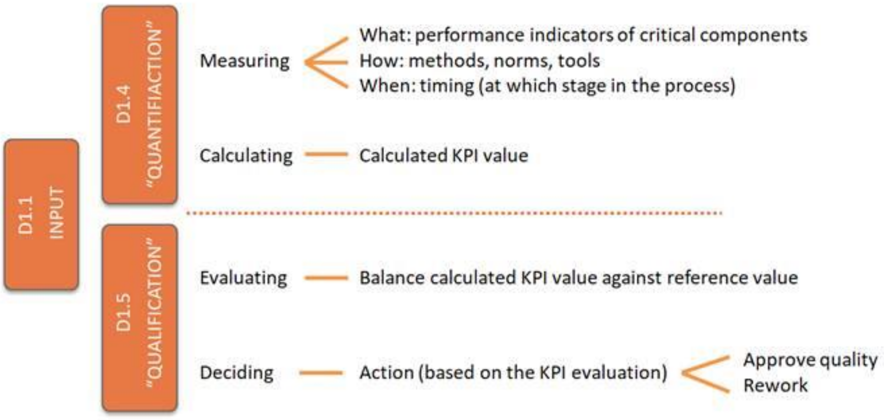

Figure 7: Inspections for building components during the different building phases

2. Dimensional and geometric quality

2.1 Introduction

Prefab components analyzed by the INSITER project (see also D1.4 and D1.5) can offer faster production and lower cost compared to typical cast-in-place construction. As prefab components gain prominence, there is increasing demand to control their dimensional quality during the fabrication (on-factory) and assembly stages (on-site). In fact, the use of prefab components, however, can suffer from system failures due to dimensional mismatches of prefab products with other prefab components, or the rest of the structure, during assembly.

In consideration of the problem introduced, construction industry interests for “timely” and “accurate quality information” on the progress of the construction project are increasing. Unfortunately, continuous monitoring and control (inspection) in all phases of the project are one of the most difficult tasks in construction project management. This includes the measurement of the progress through site inspections and comparison with the project plan, while the quality of progress data highly depends on the surveyor’s experience and the quality of measurements. Manual visual observations and traditional progress monitoring help to obtain feedback about progress measurement, equipment and material tracking, safety planning, productivity tracking, and causes of schedule and cost overruns.

Effective project management requires timely and accurate information about construction progress regarding the status and the quality of the work in comparison to the design. To get useful progress information, two characteristics of a specific design are important for the project manager: 1) An optimal level of project activity granulation, and 2) An object-oriented activity structure, where each activity is associated with clearly distinguishable building elements/components that can be identified on site. Due to the significant required workload of experts, manual progress monitoring represents disproportionately high costs, or may be in-effective, or even both.

Construction site information has generally been organized into three main categories: 1) finance; 2) quality; 3) progress. One example of necessary action in construction management systems is to “mitigate defects” and “imperfections” that could have time and cost consequences but also could change the expected building performance (structural and energy). Late detection of such defects is problematic and allows only minimal time to mitigate the associated detrimental cost and schedule implications. In this task the INSITER project will propose an important technical and scientific advancement.

According to *Nahangi and Haas (2014),* about 10% of construction budgets associated with industrial projects are attributable to rework due to late detection of deficiencies in construction sites. Approximately 50% of the associated rework costs of defective components arise from human errors and 10% is attributable to material defects. Early assessment of the as-built status during construction is also essential for effective and efficient corrective action planning.

Progress monitoring activities are recently becoming more automated and integrated. Automated approaches have emerged as advantageous tools for quality management and as-built tracking purposes and is also important in improving productivity, which is paramount in construction management systems.

In consideration to the fact that The Construction Industry Institute (CII) revealed that the average cost of rework caused by construction defects is 5% of the total construction costs, several studies has been conducted in the last years on quality assessment of the construction realized with prefab components.

M.-K. Kim et al. (2016) presents an automated dimensional quality assurance (DQA) technique and its data management system for full-scale precast concrete elements using 3D laser scanning and BIM technology.
A number of advanced automated data collection technologies are used today for “real-time on-site progress tracking”. Information technology tools have been supported by a number of research studies to improve communication on construction sites and enable daily automated progress tracking of construction activities.
Most research on automated project progress tracking, in contrast to manually based quantity collection efforts, aims to automate the measurement of physical quantities in-place by using spatial sensing technologies. An intuitive way to assess the progress would be to geometrically compare the as-built condition with the planned condition.
Due to its accuracy, laser scanning is becoming an increasingly applied data acquisition method. It has been used for either As-Built (AB) reconstruction or As-Designed (AD) - As-Built comparison. Primary objective is to develop a continuous Scan-vs-BIM method that will support “automated construction progress monitoring”. The abbreviation "Scan-vs-BIM" represents a method where an AB point cloud model is compared with an AD BIM model.

2.2 Devices and technologies

INSITER uses 3D laser scanning tools that are currently provided by the industry. The harvested data is used for e.g. deviation analysis – see use case description in D5.3, D5.4, D5.d and D5.7.
Laser scanners have been one of the most popular recent measurement tools in the construction industry, and many applications using laser scanners have been proposed.
3D laser scanning is the most common technology to acquire 3D point clouds in engineering practice because of its accuracy and range. It enhances the speed and accuracy of data collection from construction sites. Laser scanning directly acquires 3D data with good accuracy (typically 2–6 mm at 50 m) and high measurement rate (up to 960,000 points/s). It can be used to track the progress of a construction site by recognizing existing built components and comparing them with the corresponding 3D CAD model. The benefits of using 3D As-Built BIM have been well acknowledged in the architecture, engineering and construction (AEC) industry. The process starts with the collection of AB building conditions using remote sensing devices, such as laser scanners or digital cameras. Then, the sensing data collected from multiple locations are registered, and building elements in the sensing data are recognized.
Compared to conventional contact-type sensors used in the AEC industry, a 3D laser scanner provides the following advantages: 1) It allows scanning of a large structure and measurement of a surface profile in a speedy manner; 2) It can yield ‘point cloud’ data of a scanned target surface with millimeter-level accuracy and spatial resolution; and 3) It can offer long-range measurement up to 6000 m. With these features, laser scanning has been successfully employed for a wide variety of applications, including 3D modelling of structures, deflection and deformation monitoring, construction progress monitoring and geometric or topographical surveys.

Terrestrial Laser Scanner (TLS) measures the distance to a target by emitting laser beams and detecting the reflected signals from the target. When TLS is in operation, the scanner head keeps rotating vertically and horizontally so that TLS can measure the distances of different measurement points. The scan data obtained from each measurement point contain a set of three-dimensional X, Y, and Z coordinates, a row index (corresponding to the scanner head's vertical rotation), and a column index (corresponding to the scanner head's horizontal rotation).
TLS mainly adopts two different techniques for distance measurement: 1) “time-of-flight”, and 2) “phase-shift”. TLS using

the “time-of-flight” technique emits a laser pulse and measures the travelling time of the reflected pulse. Since the velocity of the laser is known, the distance measurement can be inferred from the travelling time. TLS using the “phase-shift” technique emits an amplitude modulated continuous wave and measures the phase shift between the emitted and reflected signals. The distance measurement can be obtained based on the “phase-shift” and the wavelength of the modulated continuous wave. Between these two techniques, the “time-of-flight” technique has a longer measurement distance while the “phase-shift” technique has higher measurement speed and higher accuracy.

Laser scanning operation components include a “scanner”, which is connected to a “laptop computer” through a serial connector type RS-232 or RS-422 depending on the scanner type or through a TCP/IP network cable. The scanner cannot operate without scanning software installed on the laptop and that is the reason for the presence of the laptop. The scanning software can enhance the scanned image, such as removing destructing points caused by some obstacle from the point cloud image, before exporting it to the modelling software application, which is the last step in the 3D scanning operation.
Important 3d scanners capabilities are:

- “speed”, how many points per second can it reads (e.g. 1.000÷1.000.000 points/s);
- “range”, distance from the scanner to the object to be scanned (e.g. 0,08÷6.000 m);
- “accuracy” are important factors that are considered in new scanners (e.g. 0,05÷25 m).

The inspection quality depends largely on the specifications of the laser scanner such as laser source type, laser wavelength and operation principles. In addition, different inspection checklists may have different scanning requirements. For instance, checking the alignment of an anchor bolt attached to a precast concrete element may require higher scanning resolution than simply identifying the existence of an anchor bolt. Therefore, the selection of the most appropriate laser scanner for a given project is critical for successful inspection.

M.-K. Kim et al. (2015) proposed 5 criteria for the selection of a laser scanner:

1. Inspection tolerance: this refers to the limit of an acceptable discrepancy value (normally in mm) between the actual and the reference model for a specified inspection checklist. For example, the tolerance for length and width of a precast slab for bridge construction is ±6 mm according to the PCI. Note that the tolerance which is project-dependent is the criterion to be first considered for the selection of an optimal laser scanner.
2. Accuracy: This refers to how close a measured value is to the actual (true) value. In laser scanning, this is often referred to as the ‘error’ in the range measurement. The accuracy of a laser scanner depends on its working principle. Typically, phase-shift laser scanners offer a relatively higher accuracy (up to 2 mm at 20 m) than time-of-flight (TOF) laser scanners (up to 4 mm at 100 m). Note that there is a certain condition for the optimal scanner selection that the accuracy of a laser scanner should be below the tolerance of inspection checklists.
3. Measurement range: This refers to an allowable scanning distance for the laser scanner. The measurement range is mainly affected by the working principle and laser source of the laser scanner. In general, TOF laser scanners have a longer measurement range (up to 6000 m) compared to phase-shift laser scanners (up to 120 m).
4. Price: In this study, it is assumed that the quality inspection of precast concrete elements is conducted using a commercially available laser scanner.
5. Scanning time: This refers to the time required for scanning the desired inspection area. The scanning time depends mainly on the se- lection of a laser scanner's angular resolution, which dictates horizontal and vertical scanning rate

of the laser scanner. The scanning time is also influenced by the size of the target precast concrete element.
Depending on the goal of each checklist, different weighting on each aforementioned criterion can be assigned.
For instance, to check the dimensional QA which requires a tolerance of ±6 mm, accuracy is the most important criterion for the laser scanner selection and thus, a higher weighting can be given.

2.3 Applied KPIs

Using TLS is possible to assess the following aspects of the construction process:

- Progress monitoring on-site in comparison to the project plan (Gantt)
- Components dimension and geometry during the delivery stage (on-site)
- Components deformation measurement during the assembly stages (on-site)
- Components surface damages (e.g. scratches, cracks, corrosions, moisture).
- Building geometry (As-Built situation).

2.4 Procedure, methodology and techniques

Different studies proposed the use of TLS and BIM in order to compare the AB condition with the AD.
C. Suchocki, J. Katzer (2018) proposed a TLS technique for moisture detection in building materials. *Z. Pučko et al. (2018)* presents a novel approach to automated construction project progress monitoring, based on the comparison of the 4D AB BIM and the 4D AD BIM models (Scan-vs-BIM).
D. Rebolj et al. (2017) has developed a continuous Scan-vs-BIM method that will support automated construction progress monitoring.
T. Omar, M.L. Nehdi (2016) proposed a Categorization methodology for data acquisition technologies considering: (i) collecting as-built data; (ii) organizing as-built data: and (iii) analyzing as-built data.
M.-K. Kim et al. (2016) presents an automated dimensional quality assurance (DQA) technique and its data management system for full-scale precast concrete elements using 3D laser scanning and BIM technology.
Q. Wang et al. (2016) proposes an automated quality assessment technique for estimating the dimensions of precast concrete elements with geometry irregularities, particularly focusing on the transverse sides of precast concrete bridge deck panels.

The following paragraphs introduce two examples of potential use of 3D TLS with BIM in order to assess the progress monitoring of the construction work (4.1) and the geometric deformation measurement using exemplarily the prefab concrete panel (4.2). The last section (4.3) is dedicated to introduce the procedure applied on the INSITER Cologne demonstration case in order to check the geometrical quality.

2.4.1 Time (automated construction progress measurement)

The Scan-vs-BIM method proposed by *Z. Pučko et al. (2018)* for Automated Continuous Construction Progress Monitoring (ACCPM) requires the existence of 3D and 4D As-Designed (AD) BIM.
The automated construction progress monitoring method proposes the following steps:

- 3D scanning [a single scanner provides multiple frames during a specific time interval Δt]
- Registration of frames for each scanner [locally registered partial point clouds (pPC)]

- Registration of partial point clouds into the reference coordinate system [4D AB PC (i) for the ith time interval Δt Positioning and orientation information within the reference system is required for each pPC 4D AB PC(i) point cloud cleaning and cutting]
- identification of BIM elements contained in 4D AB PC(i), using the 3D AD BIM as the reference model [Δt AB BIM]
- Adding Δt AB BIM, which represents changes in Δt, to the complete 4D AB BIM
- Finding differences between 4D AD BIM and 4D AB BIM.

The 4D AD BIM is permanently compared to the on-site situation in form of a 4D AB BIM, which is generated through a series of partial point clouds generated by 3D laser scanners. The obvious way to capture every change is to mount a scanner to every actor on a building site. In case of workers, the protection helmet is the most practical place as it moves with the eyes and consequently with the hands and tools of a worker. In case of machines, a scanner shall be mounted on a location that will follow the view of the active parts of a machine. In this way, scanners capture all changes performed on the building, and partial point clouds ensure views on all emerging components, indoor and outdoor of the building. Partial point cloud data is enhanced with location and time information, which ensure its adequate registration, including merging into the 4D AB PC of a specific time interval i (e.g. an hour or a day). At the end of the time interval Δt, the 4D AB PC(i) is merged into the total 4D AB PC, which includes all changes from the beginning of construction, i.e. the complete as-built situation. In the next step, identification process with merging elements from the 3D AD BIM with the 4D AB PC is made and, resulting in a structured model of the on-site situation, the so-called 4D AB BIM. The 4D AB BIM is then compared to the 4D AD BIM and a list of differences is generated. Since the difference elements are linked to activities, the delayed activities or those ahead are recognized and listed.

Workers' protection helmets shall be equipped with scanning devices that are acceptable low in mass, volume and cost, ensure continuous point cloud acquisition in the vicinity of the worker's area (up to 3 m), enable indoor and outdoor operation, enable location and time detection, and are fully mobile with power autonomy for a working day. Positioning and wireless communication functionality shall be supported for easier processing.

The essential novelty of the ACCPM is in the way of point cloud acquisition, which (i) is continuous, (ii) does not require any additional monitoring or surveying activities, and (iii) data acquisition is taken automatically only where changes occur. In ACCPM each change is scanned and merged with other partial scans within a given time interval Δt, creating a Δt AB BIM. The 4D AB BIM is then an accumulation of a continuous sequence of all Δt AB BIM from the beginning of the project until the present moment. Hereby Δt is typically shorter than the scan intervals in other methods and can be set to any desired value, e.g. an hour or a day.

D. Rebolj et al. (2017) proposed a similar method. The method's inputs are the BIM model and a point cloud obtained by scanning the facility under construction. It is assumed that the point cloud is aligned with the model in such a way that the cumulative distance between the elements of the BIM model and the point cloud is minimal. Thus, the proposed method allows for automatic identification of existing elements by assessing the percentage of elements' surface being covered by the point cloud.

An approach to obtain the area covered by each point is required, as points are dimensionless. To this end, first an element is projected to three orthogonal planes. In the next step, projections are rasterized within a regular grid. This is followed by projecting the points in the element's proximity onto the same grids. The area of grid-cells containing projected points is considered as a covered area. The same resolution of the grid is not suitable for elements of all sizes. For example, an element can be smaller than a single cell, which could make the coverage estimation unreliable. Thus, smaller elements need to be assessed with a larger resolution, which is why the grid-cell size adapts dynamically to the size of the element's projection.

C. Kim et al. (2013) proposed an automated construction progress measurement using a 4D building information model and 3D data. The process is divided into 3 phases:

1. "Alignment of the as-built data with the as-planned model": To initiate the measurement of construction progress, the relevant as-planned data must be extracted from the BIM, and the relevant as-built data must be extracted from the 3D data acquired via remote-sensing technology. For this purpose, the as-planned data to be used in the construction progress measurement must be filtered and then mapped to the internal information structure of the data processing software. The 3D data obtained from a construction site with remote-sensing technology include not only the as-built data on the building project itself, but also data on various objects, such as heavy equipment and materials, that are present on the construction site. Because the as-built data that are used in the construction progress measurement characterize individual structural components of a building project, the structural components must first be detected from the overall set of 3D data acquired on the construction site. After generating the as-planned model and acquiring the as-built data, 3D registration is performed to align the coordinate system of the as-built data with that of the as planned model.
2. "Matching of the as-built data to the BIM": After alignment of the as-built 3D data with the as-planned model, matching of the aligned 3D data to the data in the 4D BIM is performed to determine the as-built status of each component. The pro- posed matching method, which is based on machine learning, consists of three steps: segmentation of the 3D data into data sets that correspond to structural components in the BIM, extraction of features from those data sets, and determination of the as-built status of each component by classifying the corresponding 3D data set as a column, a beam, a slab, or other.
3. "Updating of the as-built status": in order to measure construction progress accurately, a revision phase is needed in order to modify the in- accurate as-built status of a component if that inaccuracy is due to an incomplete data set. The revision phase consists of two stages: re- vision based on the sequence of activity execution and revision based on the connectivity between structural components. In the first stage, where the revision is based on the sequence of activity execution, the as-built statuses of structural components involved in prior activities are modified. However, revision based on the sequence of activity execution cannot be used to modify the as-built statuses of components involved in the same activity. Revision using the connectivity be- tween structural components is therefore needed for modification of the as-built statuses of such components. Through these two revision phases, it is possible to modify the inaccurate as-built status of any component if that inaccuracy is due to an incomplete data set.

Construction progress measurement is based on the use of as-planned data from the BIM and 3D as-built data obtained on the building site via remote-sensing technology. The BIM contains various types of information on the predefined or user-defined properties of the building's structural components. Geometric information from the BIM is used in concert with the as-planned schedule to generate the as-planned model.
To obtain the 3D data used in the progress measurement, as-built data on the structural components is identified and extracted from the 3D data obtained on the construction site. To align the as-built data with the as-planned model, 3D registration is performed. Once the as-planned model is aligned with the as-built data, the features of the as-built data that correspond to those in the 3D CAD model are extracted. Then a matching process uses the extracted features to

determine the as-built status of each structural component. However, if only the as-planned model and the as-built data are used to determine the as-built status of each component, an incomplete 3D data set may yield an inaccurate assessment. Therefore, the as-built status of each component is examined, validity checks are performed to determine whether the statuses of the structural components are mutually consistent, and inaccurate statuses that are due to incomplete 3D data sets are modified.

To help identify as-built statuses that are inaccurate, the construction sequence - defined by the sequence of activity execution which is recorded in the BIM—is first examined. If any inconsistencies between the construction sequence and the as-built statuses of structural components are detected, the pertinent as-built statuses are modified.

Then the topological relationships among the structural components - defined by the connectivity between components which is recorded in the BIM - are examined. If any logical inconsistencies in those topological relationships are detected, the pertinent as-built statuses are modified. The as-built status revision phase results in an accurate assessment of the as-built status of the structural components, demonstrating that this methodology can be used to correctly measure construction progress.

The approach presented *by Y. Turkan et al. (2012)* combines three dimensional (3D) point clouds with project 3D CAD model and schedule information to track construction progress. On one hand, 3D laser scan data provides current site conditions. On the other, the 3D CAD model combined with schedule information (the project 4D model), provides designed (as-planned) spatial characteristics of the facility under construction over time. Using such a 4D model, a time-stamped 3D CAD model can thus be formed automatically for a given date.

The proposed system for automated progress tracking and schedule updating requires the 3D point clouds and the 4D model to be registered in the same coordinate system to be able to extract useful data for progress tracking. Once registered, as-built objects can be recognized, progress estimated, and the schedule updated all automatically.

The approach proposed 3 main stages:

1. Three dimensional (3D) object recognition

   The recognition system is built upon the algorithm proposed by *Bosche et al. (2008)* to recognize designed 3D model objects in laser scanned point clouds. The approach is robust with respect to occlusions sourced from either 3D model objects or non 3D model objects (e.g. temporary structures, equipment, people). The approach requires converting the input 3D model into triangulated mesh for- mat (OBJ and STL are currently supported) as a pre-step, and follows a three-step process:

   - Manual coarse registration performed by manually matching n pairs of points selected in the 3D model and in the scan;
   - Model fine registration implementing a robust Iterative Closest Point (ICP) algorithm;
   - Object recognition using a robust surface-based recognition metric.

   The coarse registration step (step 1) is currently performed manually, while the model fine registration and object recognition steps (steps 2 and 3) require that the user define only a few input parameters (though default parameter values generally achieve satisfactory results).

2. Three dimensional progress calculation

   Construction progress at date ScanDate is calculated by the system based on the object recognition results from the analysis of scans acquired on that date. The system only estimates progress for the activities that are on-going, i.e. with scheduled start dates earlier than ScanDate and scheduled end dates later than ScanDate, as a first step. This means that all objects that are built during activities with end dates earlier than ScanDate are considered already built, and similarly the objects built during activities with start dates later than ScanDate are considered not built. This is done by the algorithm assigning 100% recognized progress to the activities with the end dates earlier than ScanDate, and 0% recognized progress to the activities with start dates later than ScanDate. This assumption is made under the premise that, if the system is used frequently enough, then only on-going activities need to be assessed.

For each on-going activity, the system compares the number of recognized objects with the number of expected objects, i.e. scheduled and visible from scanner's location(s). If the number of expected objects for the activity is equal to zero, then the recognized progress is assigned as 0%.

3. Three dimensional progress calculation

   The schedule is updated based on the estimated progress. The resulting updated schedule can then be used: (1) by management to identify deviations and then implement corrective actions, but also (2) for the analysis of scans acquired at future dates.

2.4.2 Geometry and deformation measurement

M.-K. Kim et al. (2016) proposed an automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM. The technique proposed is composed of six data processing steps:

1. It starts with “acquisition of the point cloud data” for a precast concrete element using the laser scanner. The laser scanner is assumed to be located right above the center of the pre-cast concrete element so that the entire surface of the precast concrete element can be scanned in a single scan.
2. Once a set of point cloud data is acquired, “coordinate transformation is undertaken”. The initial coordinate system with respect to the laser scanner is transformed into a new coordinate system with respect to the precast concrete element so that next data processing steps can be automated and easily implemented.
3. In the next step, the “extraction of key dimensional features”, i.e. edges and corners, is performed. An edge extraction algorithm, called the ‘vector-sum’ algorithm, is applied to the coordinate transformed point cloud data to extract only the edge points of a precast concrete element. The corners of the precast concrete element are then extracted by fitting the edge points to straight lines and finding the intersection points of these fitted lines.
4. “The dimensional properties of the precast concrete element are computed from the extracted corners”. However, the initial estimates of dimensions are always less than the true dimensional values due to a phenomenon called the mixed-pixel phenomenon. This phenomenon occurs when the laser beam is split into two and reaches two distinctive surfaces which have different distances from the laser scanner. To compensate for this dimension loss due to the mixed-pixel phenomenon, an edge loss model is employed and correction values are added to the initially computed dimensions.
5. “Dimensional error calculation” is followed by comparing the finally estimated dimensions of the precast element with the corresponding design dimensions.
6. Finally, a “decision” on the appropriateness of the tested precast concrete is made based on a comparison of the computed dimensional errors with the specified tolerance values.

Another automated quality assessment methodology of precast concrete elements using terrestrial laser scanning is proposed by *Q. Wang et al. (2016)*. Also in this case the BIM model is provided to represent the AD geometry of the panel. Taking the BIM model as a reference, the scan data are processed through 5 steps:

1. Data classification: once the scan data are acquired, data classification is performed to extract data points belonging to the intended target surface. Data classification aims to remove background points and mixed pixels while retain valid points.
2. Coordinate transformation: once the as-built object is extracted, coordinate transformation is conducted to ensure the as-built object best matches with the as- design object. To this end, a 3D transformation of the as-built object needs to be computed. However, since the target object is a quasi-2D object, the problem of finding a 3D transformation can be simplified to finding a 2D transformation as follows. (1) Find the fitted planes of the as-built and as-design objects. The fitted plane of the as-built object is obtained using all the scan data based on the least squares method. Since the as-design object is expressed by a BIM model, sampling points are generated on all the surfaces of the BIM model with identical sampling density, and the least squares fitted plane of sampling points is used instead. (2) Transform the as-built object so that its fitted plane overlaps that of the as-design object. This plane is then defined as the X–Y plane of a new Cartesian coordinate system. The origin of the coordinate system is positioned at one corner of the object, and the X and Y axes overlap with the two boundaries of the object, respectively.
3. extraction of inner corners
4. extraction of outer corners
5. dimensions estimation.

In consideration of the fact that current methods of dimensional and surface quality assessment (QA) for precast concrete elements are manually assessed by certified inspectors using contact type measurement devices such as measuring tapes, callipers and straightedges, *M.-K. Kim et al. (2015)* proposed a holistic framework for dimensional and surface QA of precast concrete elements based on BIM and 3D laser scanning technology.

The QA procedure proposed is composed of 4 phases:

1. “Supply”: Suppliers manufacture the precast elements ordered for a given project and deliver the elements to an inspection site. It is important to note that the inspection site can be at a predetermined location in the manufacturing factory or at a certain location in the construction site. The suppliers also store the reference CAD model of each precast concrete element and their material and geometry properties, such as the concrete strength and dimensional tolerances of the precast elements in a BIM library.
2. “Preparation”: Prior to the implementation of the QA, preliminary action on both the precast concrete element and the laser scanner is performed. This action includes the confirmation of the information of the precast element, inspection set-up, treatment for the precast elements and the selection of the optimal scan parameters of the laser scanner. Here, the confirmation of detail in- formation of the precast concrete elements, which is stored in the BIM library, is ideally carried out through portable electronic devices such as a smartphone or personal digital assistants (PDAs). Once the confirmation of the information of the precast element is completed, the precast element is sent to a designated location, and treatment processes such as the surface checking and cleansing of finished (hardened) precast concrete are under-taken before actual inspection. At the same time, the optimal scan parameters of the laser scanner are selected.

3. “Scan and inspection”: Once the preparation for scanning is completed, data acquisition using the laser scanner is undertaken. In this step, the selection of the region of interest (ROI) is con- ducted with a coarse scan, followed by a dense scan for effective and accurate inspection. Once the raw scan data is acquired, data processing, which includes data cleansing and feature extraction, is conducted to automatically measure the intended inspection goals. Since the raw scan data has a high data capacity, data cleansing and feature extraction algorithms are needed for reducing number of data and computation cost. Subsequently, comparisons between the measured inspection results and the reference CAD model exported from the BIM library are conduct- ed. In this phase, the inspection results are also delivered to and stored in the BIM library.
4. “Decision and delivery”: At this stage, the decision of whether the discrepancies between the actual element and the reference model are within the tolerances in the inspection checklists is made. If any specific discrepancy exceeds the corresponding tolerance, disposal or rework of the precast element follows. Other- wise, the precast element is approved for use and delivered to a construction site for assembly. Here, the classification and detail information of the accepted and rejected elements are also accessible through the BIM library so that field engineers in the construction site can access and check the condition of the delivered precast concrete element via portable electric devices.

2.4.3 Cologne demonstration case “geometrical checks” experience

As introduced, the point clouds provide a very useful base for validating existing 3D models against the real on-site situation. If a 3D model already exists, the deviation analysis of the existing 3D model to the new point cloud is very helpful to highlight changes between previous design and as built situation.

The laser scanner technologies have been applied on the Cologne demonstration case in order to check the geometric quality (deviation analysis) and to map the existing technical conditions of the site and building. The following 3D laser scanner has been used: Leica Scan Station P30 integrated with the following software: Leica Cyclone, Leica TruView, Hexagon 3DReshaper.

This section describes the methodology applied; some more information are also included in the following report: D2.3, D4.2, D5.3 and D5.4.

The scope of the analysis proposed in the Cologne demonstration case uses the existing 3D model that was compared to new the point cloud in order to highlight changes between previous design and as built situation. The methodology applied has been elaborated in synergies between WP2 and WP4.

The deviation analysis has been performed using the 3D Reshaper software. The procedure has followed these steps:

- acquisition of the point cloud data with 3D laser scanner Leica Scan Station P30 (performing laser scans on site). During this step, several point clouds were stored on the laser scanner memory.
- import the Point Clouds stored on the laser scanner into Leica Cyclone software in order to post process the data as follow:
  - Purge Point Clouds
  - Align Point Clouds (registration) accordingly x, y and z orientation
  - Optimization results (post computing) to match the best possible results.
- Result: aligned point clouds in Leica Cyclone

- Merge point clouds (to merge all point clouds in one big single point cloud) & export to e57-format (it is not recommended to include all points from all point clouds, because the data volume would become too big and cannot be processed reasonably)
- Create a 3D-Mesh from As-Built BIM model (Hexagon 3D Reshaper)
- Loading the Point cloud and 3D-Mesh on 3D Reshaper
- Create overlay of e57 and 3D-Mesh (alignment step)
- Perform deviation analysis: compare point clouds with current as-built model. Before to start this step is possible to set-up the estimated thresholds represented by different colors
- Evaluate results of deviation analysis and identify issues
- Adjust range and re-do deviation analysis
- Retrieve details from deviation analysis
- Reporting of deviation analysis (Print the generated report as pdf-file or export the generated report as html-file or export the generated report as csv-file).

2.5 Thresholds and tolerance

All on-site manufacturing, tracing and assembly processes of prefab building components are characterized by geometric-dimensional variability. Tolerances define the limits of variability with respect to the nominal design values.

In order do not compromise the safety of the structure during the construction life and achieve the expected energy performance, the components and buildings tolerance value is defined by the project (by the designer and/or components manufacturer).

In agreement to the INSITER project aims, it is possible to define three main different measurable dimension tolerances through 3D laser scanner:

1. the "manufacturing tolerance" of the building components related to the geometric deviation during the factory production of prefab components and delivered on-site.
2. the "assembly tolerance" of the components related to the geometric deviation measurable during the on-site assembly phase of the prefabricated components;
3. the "architectonic tolerance" related to the geometric dimensional deviation (linear, surface and volume dimension) of the building. It is applicable in order to detect the site conditions before the refurbishment interventions or to inspect the post-intervention.

Please note that the expected dimension tolerance must be defined by the project in relation to the building typologies and function; building components analyzed; expected energy performance and structural condition.

Considering the technical point of view, if the dimension tolerances (defined also as thresholds) are not respected also the expected energetic and environmental performance will be alternated (in negative). For instance, an inadequate air and water sealing would compromise the thermal and acoustic insulation of the building envelope and the relative energy balance of the entire building.

Therefore, tolerance values (thresholds) must be taken into account during the construction phase in order to accept or not accept dimensional variations of the delivered component components on-site or for the possible following construction assembly errors.

In consideration that is not possible to directly measure the impact of dimensional construction errors in terms of energy-environmental performance, INSITER considers that arbitrarily no constructive error beyond the tolerance imposed in the design phase can be accepted.

This choice is motivated by the fact that even a not relevant change with respect to the dimensional deviation imposed by the tolerance limit can compromise the building energy performance.

An example is represented by the assembly of prefab panels to realize the external building walls. In that case the construction errors to measure using the methodologies described in the previous paragraphs are:

- acceptable geometric dimension of the prefab panels delivered on construction site
- acceptable dimension panel assembly (linear and flatness conditions)
- correct positioning and / or assembly of several panels between them.

If, for example, the technical design documentation specifies a maximum tolerable assembly distance between one panel and the other of ± 3 mm, a superior distance is not acceptable because it could imply a possible passage of air which would compromise the thermal transmittance values.

2 different European norms analyze the building dimension tolerance.

In Italy the UNI10462:1995 norm define the "Tolerance and accuracy for building".

Considering the INSITER project the main tolerances to mention are:

- <u>Natural manufacturing tolerance:</u>
  - Limits declared to linear deviation, i.e. the difference between an actual dimension in a given direction of a building element and the corresponding nominal size.
  - Decrease in angular deviation, i.e. the difference between the actual angle and the corresponding nominal angle.
  - Decreased limit of shape that can be defined with two different deviations:
    - *Of a specific line, that is the maximum distance between a line actually materialized and the corresponding nominal one.*
    - *Of a surface, that is the distance between an effective surface and the corresponding nominal surface*.
- <u>Natural assemblage tolerance:</u>
  - Declared limit to position deviation after assembly, i.e. the difference between the actual position of a point or materialized line or a surface of an element after assembly and the corresponding nominal position.
  - Declared limit to orientation offset, i.e. the difference between the actual orientation of a line or a surface of an element after assembly and the corresponding nominal orientation.

The UNI10462:1995 does not present admissible tolerance values; these acceptable thresholds must be defined in the technical project documentation and defined before the start of the construction site (delivery and assembly stages).

In Germany the DIN18202 norm defines the "Building Tolerance". DIN 18202 applies to structures and their parts.

The scope of the standard is limited to buildings of general construction as a rule of application. Structures that are not attributable to general building construction because they differ significantly from a regular building construction in terms of their nature, their function, their dimensions, the used building materials or construction methods, are no longer within the scope of DIN 18202. The tolerances according to DIN 18202 apply independent of construction material and therefore equally for components or structures made of masonry, concrete, reinforced concrete, pre-stressed concrete, steel, wood, etc. Constructions made of a combination of different materials are therefore subject to uniform dimensional stability requirements. The purpose of DIN 18202 is to define the basics for tolerances and their testing. In comparison to the Italian norm UNI10462:1995 this norm proposes some example of limit values for dimensional and angle deviations.

Despite this the German norm does not provide a conclusive regulation for the individual case (in accordance with the variety of different construction tasks).

Considering the introduced norms, the state of the art and the INSITER purpose (to reduce construction errors in order to achieve the expected energy performance), this section proposes tolerance value applicable only for building components or building parts that, independently or joint with other components, influence the building energy calculation.

In this case, the dimensional tolerance thresholds considered are:

- "Production dimension tolerance" acceptable value is ± 6 mm considering that within this value it is possible to carry out not relevant interventions on-site to avoid altering the expected work;
- "Dimensional tolerance of positioning and assembly" acceptable value is ± 3 mm, assuming that within this value it is possible to carry out interventions on-site that do not alter the intended work;
- "Architectural dimensional tolerance" (shape, volume or height of the building) not exceeding 2% of the pre-intervention status (As-Built) in case of recovery projects or compared to the concession project in case of new buildings.

These values serve as an example and may vary depending on the specific technical design specifications. Therefore, as also expressed by the UNI10462: 1995 and DIN 18202 standard, each tolerance value must be clearly explained in the project documentation.

Please note that the building components or parts of the building that are not relevant for the energy balance of the building are not taken into consideration.

2.6 Conclusion

In conclusion the scientific analysis proposed confirm that the application of prefab components to realize energy efficient building (new and refurbishment) can suffer of possible system failures regarding dimensional-geometric discrepancies of prefab products.

Early assessment of the dimensional and geometric quality on-site is crucial to propose corrective action planning to achieve the expected energy efficiency performance.

2.7 References

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3. Thermal measurement - Thermal bridges localization

3.1 Practical techniques and physical context (factory/site)

Inspection on new and existing buildings has the objective to check if the building envelope presents any irregularities that can influence the building thermal performance and therefore its energy efficiency, like areas of leakage, thermal bridging or less than adequate insulation. Those irregularities can be identified by measuring the temperature distribution over the whole building envelope surface which is commonly performed by Infrared thermography, a camera sensitive to the infrared emission of the observed surface (ISO 6781, Thermal Insulation — Qualitative detection of thermal irregularities in building envelopes — Infrared Method). The surface temperature distribution measured by an InfraRed (IR) camera is called thermograms, or thermal images. Each thermogram is characterized by a colour scale that shows the relative temperature indicated by the colour in the image. The lowermost value on the scale indicates the minimum temperature converted to a colour in the image. Anything that is black in the image is colder than this value. The uppermost value on the scale indicates the maximum temperature converted to a colour in the image. Anything that is white in the image is warmer than this value. The temperature range may be adjusted to accentuate anomalies that the thermographer wishes to highlight and may be different for each image.

Thermal bridges are localised as weaknesses or discontinuities in the thermal envelope of a building. They generally occur when the insulation layer is interrupted by a more conductive material. Thermal bridges can account for 20-30% of the heat loss in a typical new building. Sometimes they are easily localised since they are visible (e.g. condensation or mould). A quantitative way to identify thermal bridges/anomalies on the envelope is represented by the Thermal Index (TI) (see equation *(1)*), also known as Surface Temperature Factor. It is a ratio of temperature differences and it can be calculated for each thermal image. TI is defined as:

$$TI = \frac{(T_{SI} - T_O)}{(T_{AI} - T_O)} \quad (1)$$

Where:

T_{SI} = Temperature of the anomaly (°C) measured by the infrared camera on the area interested by the thermal bridge;

T_O = External temperature (°C);

T_{AI} = Internal "ambient temperature" (°C).

BRE Information Paper IP 1/06, "Assessing the effects of thermal bridging at junctions and around openings", makes recommendations for limits to thermal bridging. In particular, the threshold fixed for dwellings is 0.75, in office or shops 0.5. Using the developed threshold-based approach (see Section 3.2), according to the set limit values, it is possible to identify the position and the extension of the areas of anomalous surface temperature patterns. In the following paragraph, the complete procedure for thermal bridges identification and localization is detailed.

3.2 Diagnosis/analysis

Thermal bridges identification and localization can be performed according to the developed procedure, described in the following steps. The main required devices are a thermal camera, able to measure envelope emissivity distribution, for the thermograms acquisitions, and a smartphone or a digital camera, for capturing the visible images framed by the IR camera. After the acquisitions phase, the post-processing occurs through dedicated scripts implemented in MATLAB environment.

Step by step procedure:

1) **Preliminary check:** Thermal bridges in building envelopes can be accurately localised if a sufficient indoor-outdoor thermal gradient is present, which is fixed to at least 10°C. If the room under test in not conditioned and the gradient is less than 10°C a portable heater/cooler should be applied in order to realise this condition.

2) **Device positioning:** The IR camera and the smartphone/digital camera are placed in a dedicated support such as to capture the same scene in the same time. They have to be positioned in front of the analyzed façade/room wall surface, or part of that, at such distances as will catch the required building envelope portion. In order to highlight the "cold" points of the façade, which represent the thermal bridges, the correct temperature scale has to be set in the thermal camera acquisition software. The maximum and minimum values on the temperature scale must to be set in function of the indoor and outdoor temperature.

3) **IR and visible images capturing:** Two pictures are taken for each field of view, one IR image and one visible picture. The acquired images have to be exported in a standard image file formats (".png", ".jpeg", ".tiff", ".bmp", etc.). In addition, the IR thermal map (temperatures spatial matrix) has to be exported as text file (".txt") in order to be used for the post-processing.

Thermogram pre-processing: this series of steps allows the overlaying of the thermogram images into the visible image in order to visualise thermal discontinuities and localise them into the captured picture of the framed surface

4) **Undistortion pre-processing:** The IR image results distorted because the thermal camera has a wide-angle lens, required for framing large areas. The distortion must be corrected by applying a straightening processing to the IR image. In particular, the "undistortImage" function corrects the image for lens distortion and optical anomaly, finding a correlation between reference points in both pictures: thermal and visible (image file formats). A Matlab script has been created for this post-processing phase. This step allows to set the required distortion parameter of the thermogram with respect to the visible image and to save this parameter to be used in step 9 for applying the undistortion processing to the thresholded thermal index.

5) **Overlapping pre-processing:** At this point the IR and visible images are ready for the superimposition phase. A MATLAB script has been implemented using the "fitgeotrans" function. The function fits geometric transformation to control point pairs. In particular, it overlaps the two images through a correlation between reference points identified in both pictures. The purpose of this processing is to recognize in the visible image if the elements with different emissivity value from the average (which appear as "cold" in the IR image) are possible thermal bridges or insignificant anomalies (e.g. glazing reflection). This step allows also to calculate

the geometric transformation (roto-translation matrix) that can be used to align the two images, the visible one to the thermal one. The transformation matrix will be applied to the visible image to align it to the thermal one. The transformed visible image will be then used also for the overlapping with the thresolded thermal index applied in step 9.

6) **Insignificant anomalies correction pre-processing:** Once recognized insignificant elements from a thermal point of view, a dedicated post-processing procedure has been developed for correcting thermal images from fake. A dedicated Matlab script has been implemented where the operator can select regions in the image where objects, decorations, materials with different emissivity with respect to wall under test are located. The difference in emissivity will create a discontinuity in the thermal map, which is not related to an thermal bridge thus producing into the thermal map a false positive. The Matlab script uses the "roipoly" function, which allows specifying polygonal region of interest; then, the adjacent temperature values detected in the IR file (.txt) is assigned to the polygonal regions to override the fakes.

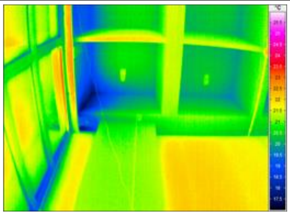
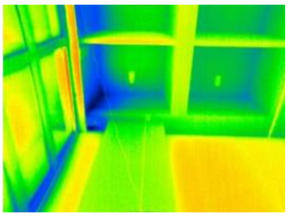
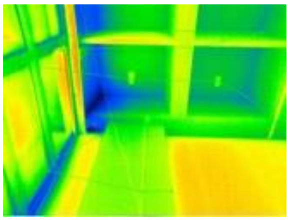
Thermogram post-processing: this series of steps allows calculating the thermal index from the thermogram representing the surface temperature of the framed wall and localize thermal anomalies by applying the threshold-based approach.

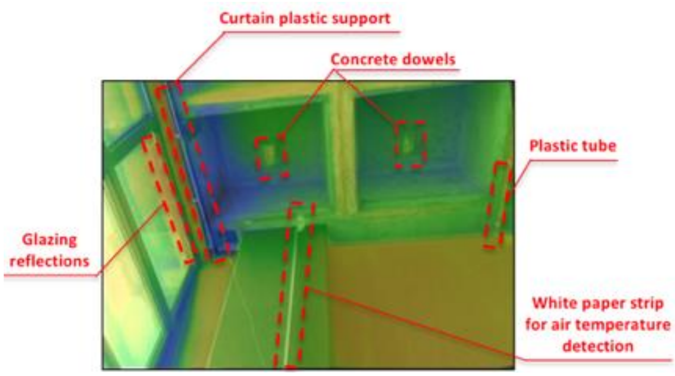
7) **Thermal Index calculation**: Hence, for any acquired IR matrix (.txt file), the Thermal Index (TI) can be calculated *(1)*. According to BRE Information Paper IP 1/06 , if TI is less than 0.75 (threshold fixed in dwellings), it is likely that condensation will form on the surface at some time in a typical year.

8) **Binarization post-processing:** The TI is therefore transformed in black and white image using the aforementioned threshold. The resulting map is a matrix of 0 and 1 value, where 0 is the value assigned to each pixel where TI is less than 0.75 and 1 is the value assigned to each pixel where TI is higher than 0.75. For the sake of evidence, the areas where the Thermal Index is lower than the threshold (0.75) are represented in red color, instead than black, highlighting the thermal anomalies. Finally, the binary matrix is transformed in a RGB image suitable for the superimposition to the transformed visible image in the next step.

9) **Visible image-Thresholded TI index overlapping post-processing and thermal anomalies localization:** The transformed visible image generated in step 3 is overlapped to the binarized TI image, to visualize the thermal anomalies position and estimate their extension.

To better clarify the complete procedure and the steps partial outputs, the case study of an internal portion of the envelope is shown in Table 2:

<table>
<tr><th>STEP 1: Preliminary check</th><th>STEP 2: Device positioning</th></tr>
<tr><td>
room conditioning</td><td></td></tr>
<tr><th>STEP 3: IR and visible images capturing</th><th>STEP 4: Undistortion pre-processing</th></tr>
<tr><td>
</td><td></td></tr>
<tr><th colspan="2">STEP 5: Overlapping pre-processing</th></tr>
<tr><td colspan="2">


</td></tr>
</table>

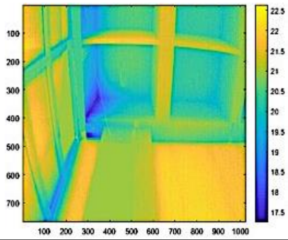
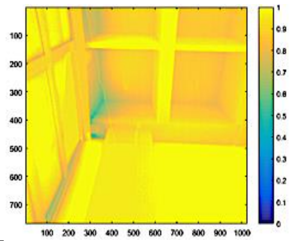
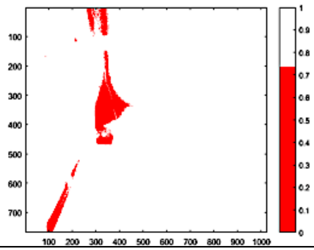
STEP 6: Insignificant anomalies correction pre-processing	STEP 7: Thermal Index calculation
	
STEP 8: Binarization post-processing	**STEP 9: Visible image-Thresholded TI index overlapping post-processing and thermal anomalies localization:**
	

Table 2: Step by step procedure example

3.3 Applied KPIs

KPI level: energy efficiency, KPI: Heat transfer, Measurement aspect: Thermal Bridge, Parameter: envelope internal surface temperature.

3.4 Threshold/tolerances

The threshold value of 0.75 is considered appropriate to demonstrate good practice in all buildings whether they are dwellings, offices, learning facilities on any other type of buildings. The value can be applied to areas of air leakage and air movement as well as thermal bridging and missing insulation because all of these result in reduced surface temperature. If TI is less than the fixed threshold, it is condensation could appear on the surface at some time in a typical year. Anyway, a small percentage of the structure having a lower TI at locations known as thermal bridges is allowed from the building regulations, in particular where the construction requires that a part of the building structure to be less well insulated than the bulk of the structure.

3.5 Reference

- Information Paper IP 1/06, BRE, 2006

4. Thermal measurement – Calculation of energy use in relation to estimated thermal bridges

4.1 Practical techniques and physical context (factory/site)

Problems during the construction phase like insulation loss or damages of the building elements could cause thermal transmittance and consequent energy-saving loss. It is crucial to identify the thermal bridge and to evaluate its effect on the building energy efficiency.

The envelope thermal transmittance can be assessed by means of heat flux meters in agreement with the standard ISO 9869-1 or IR thermal camera whose thermal data can be processed in conjunction with a thermal numerical model data in order to improve results as described in deliverables D2.3 and D5.2. The latter procedure has been developed in INSITER and called the Soft-Sensing methodology.

A building element thermal bridge affects the thermal transmittance of the element itself. A thermal camera allows measuring a thermogram representing the temperature distribution of the building element on which it is possible to identify distinctly the thermal bridge and the sound area. In order to estimate the influence of the thermal bridge on the initial transmittance of the element, that thermal transmittance (U_{1D}) must be known. If it is not known from the design, it can be measured by a heat flux meter positioned on the sound area of the element or by the IR camera used for investigating on the thermal bridges. The thermal bridge will increase the initial thermal transmittance by a factor called the Incidence Factor of the Thermal Bridge (I_{tb}).

$$U_{tb} = U_{1D} * I_{tb} \tag{2}$$

This index expresses the effect of the thermal bridge on the thermal transmittance and estimates the real thermal transmittance of a building element in presence of that thermal bridge (U_{tb}) as deviation from the ideal thermal transmittance (U_{1D}) that is known from the design or measured from a portion of the thermogram located in a sound area.

The Incidence Factor of the Thermal Bridge is defined as the ratio between the heat flowing in real conditions (Q_{tb} *[w]*) and the heat flowing in absence of the thermal bridge (Q_{1D} *[w]*):

$$I_{tb} = \frac{Q_{tb}}{Q_{1D}} \tag{3}$$

As demonstrated in D2.3 section 2.2, the thermal bridge incidence factor can be estimated not only from the measured flow through the building element but also from the temperature distribution registered over the entire element surface (measured by the IR camera) as following:

$$I_{tb} = \frac{\sum_{p=1}^{N}\left(T_i - T_{pixel\_is}\right)}{N * \left(T_i - T_{1D\_is}\right)} \tag{4}$$

- T_{pixel_is}: *Inner surface temperature for each pixel of IR Camera*
- T_i: *Inner air temperature;*
- T_{1D_is}: *Inner surface temperature (avarage temperature in the sound area (A_{1D}))*

Since commercial instrument devices commonly use proprietary software, the acquired thermogram must be exported in a text standard format (.txt files) and processed according to the formulas described in the paragraph 4.1. Matlab scripts have been developed within the INSITER project to perform the post-processing.

Once the thermal transmittance of the different building envelope components is known, it is possible to calculate the Envelope Thermal Transfer Value (ETTV). The ETTV takes into consideration the three basic components of heat gain through the external walls and windows of a building.

These are:

- Heat conduction through opaque walls
- Heat conduction through glass windows,
- Solar radiation through glass windows

These three components of heat input are averaged over the whole envelope area of the building and introduced in the overall ETTV equation (5):

$$ETTV = 12 * (1 - WWR) * U_{1D} + 3.4 * (WWR) * U_f + 211 * (WWR * CF * SC) \quad (5)$$

where:

- ETTV: overall ETTV [W m^{-2} K^{-1}]:
- U_{1D}: Thermal transmittance of opaque wall [W m^{-2} K^{-1}];
- U_f: Thermal transmittance of fenestration [W m^{-2} K^{-1}];
- CF: correction factor for solar heat gain through fenestration;
- SC: shading coefficients of fenestration;
- WWR: window-to-wall ratio (fenestration area / gross area of exterior wall).

The Solar Correction Factor (CF) for the wall is reported in the standard SBCA, 2004, see Table 2.

Pitch Angle	Orientation							
	N	NE	E	SE	S	SW	W	NW
70°	1.17	1.33	1.47	1.35	1.21	1.41	1.56	1.38
75°	1.07	1.23	1.37	1.25	1.11	1.32	1.47	1.28
80°	0.98	1.14	1.30	1.16	1.01	1.23	1.39	1.20
85°	0.89	1.05	1.21	1.07	0.92	1.14	1.31	1.11
90°	0.80	0.97	1.13	0.98	0.83	1.06	1.23	1.03
95°	0.73	0.90	1.05	0.91	0.76	0.99	1.15	0.96
100°	0.67	0.83	0.97	0.84	0.70	0.92	1.08	0.89
105°	0.62	0.77	0.90	0.78	0.65	0.86	1.01	0.83
110°	0.59	0.72	0.83	0.72	0.61	0.80	0.94	0.78
115°	0.57	0.67	0.77	0.67	0.58	0.75	0.87	0.73
120°	0.55	0.63	0.72	0.63	0.56	0.71	0.81	0.69

Table 3: Shading Correction Factor (CF)

The shading coefficient (SC) is a means of assessing the total amount of solar radiation passing through a glazing system (not including the frame). It is derived by comparing the solar radiant heat transmission properties of any glazing system against the solar radiant heat transmission properties of 3 mm clear glass, which has a solar heat gain coefficient (SHGC) of 0.87 (87%) and is given a shading coefficient of 1.0.

The shading coefficient is calculated by equation (6):

$$SC = SHGC / 0.87 \tag{6}$$

If more than one type of opaque material and/or fenestration is used, the related terms should be expanded in sub-elements, as follows:

$$ETTV = \frac{12 * (A_{w1} * U_{1D1} + A_{w2} * U_{1D2} + \cdots + A_{wn} * U_{1Dn})}{A_0} + \frac{3.4 * (A_{f1} * U_{f1} + A_{f2} * U_{f2} + \cdots + A_{fn} * U_{fn})}{A_0} + \frac{211 * (A_{f1} * SC_{f1} + A_{f2} * SC_{f2} + \cdots + A_{fn} * SC_{fn}) * (CF)}{A_0} \tag{7}$$

where:

- A_{w1}, A_{w2}, A_{wn}: Areas of different opaque wall [m^2];
- A_{f1}, A_{f2}, A_{fn}: Areas of different fenestration [m^2];
- A_0: Gross area of the exterior wall [m^2];
- $U_{1D1}, U_{1D2}, U_{1Dn}$: Thermal transmittance of opaque wall areas [W m^{-2} K^{-1}];
- U_{f1}, U_{f2}, U_{fn}: Thermal transmittance of different fenestration types [W m^{-2} K^{-1}];
- $SC_{f1}, SC_{f2}, SC_{fn}$: shading coefficients of different fenestration types.

Considering the thermal transmittance of walls affect by thermal bridge it is possible to calculate the ETTV(tb).

$$ETTV(tb) = \frac{12 * (A_{w1} * U_{tb1} + A_{w2} * U_{tb2} + \cdots + A_{wn} * U_{tbn})}{A_0} + \frac{3.4 * (A_{f1} * U_{f1} + A_{f2} * U_{f2} + \cdots + A_{fn} * U_{fn})}{A_0} + \frac{211 * (A_{f1} * SC_{f1} + A_{f2} * SC_{f2} + \cdots + A_{fn} * SC_{fn}) * (CF)}{A_0} \tag{8}$$

From the ETTV and ETTV(tb) it is possible to calculate the % of thermal performance loss of the envelope, moreover from equation (9) the energy loss due to the thermal bridges can be estimated.

$$\Delta E = HDH * \Delta ETTV * 1/\eta \tag{9}$$

ΔE: Energy savings [kWh/m^2] (per m^2 area of construction elements) [kWh/m2a;

HDH: Heating degree hours (per year) [kKh/y];

$\Delta ETTV$: ETTV(tb) – ETTV [W/m^{2}K];

η: Efficiency of heat generation and distribution;

$$HDH = HDD * 24/1000 \tag{10}$$

A ‘Heating Degree Day’ (HDD) is a proxy for the energy demand needed to heat a home or a business building; it depends on the outdoor temperature and consequently on the climate conditions.

Table 4 highlights the value of HDD in different European countries in 2012.

City	HDD	City	HDD
Aberdeen	3503	Madrid	1965
Athens	1112	Malaga	796
Belgrade	2798	Milan	2639
Berlin	3155	Rome	1443
Bilbao	1612	Stockholm	4239
Brussels	2911	Tambere	5020
Larnaca	759	Warsaw	3614

Table 4: HDD in different European countries [1])

4.2 Required devices

Table 5 lists the instrumentation requested for the thermal measurement.

Instrumentation	***Measurement range***	***Uncertainty***
Thermocouples Type T	-185 – 400 °C	± 0.5°C
Thermal Camera spectral		± 1.5°C
range	7-14 µm	
spatial resolution	> 640x480	
Heat Flux Transducer	-2000 to 2000 W/m^2	± 3%
Hygrometer	10% - 99%	± 0.1%

Table 5: List of instrumentation requested for the thermal tests

A thermal gradient of 10 °C must exist between indoor-outdoor temperature otherwise the room must be conditioned.

4.3 Applied KPIs

KPI level: energy efficiency, KPI: Heat transfer, Measurement aspect: Thermal transmittance, Parameter: U value.

KPI level: energy efficiency, KPI: Heat transfer, Measurement aspect: Thermal bridge, Parameter: % of ETTV loss

4.4 Threshold/tolerances

The EU periodically issues directives to promoting the improvement of the energy performance of buildings within the EU and providing a stable environment for investment decisions to be taken. The standard UNI EN ISO 52003-1:2018 [2] suggests to use seven classes (A-G) distributed in such a way that the boundary between Class B and Class C corresponds to the Energy Performance Regulation reference (i.e. the minimum performance requirement for new buildings) and the boundary between Class D and Class E corresponds to the Building Stock reference (i.e. the energy performance reached by about 50% of the existing buildings). Thresholds and reference building characteristics are defined by the national regulation following the target on the energy efficiency indicate by EU [3]. The thermal transmittance value measured with the INSITER procedure must be related to the value of the reference building reported in the standards in order to establish the energy class of the building under test. Furthermore, the ETTV level allows estimating the thermal energy saving related to the envelope transmittance. This level must be considered in agreement with the EU prescription in terms of building energy efficiency.

4.5 Reference

[1] K.Tsikaloudaki, K.Laskos and D.Bikas, On the Establishment of Climatic Zones in Europe with Regard to the Energy Performance of Buildings, Energies 2012, 5, 32-44; doi:10.3390/en5010032 [1] Energy Performance of Buildings Directive, https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings, 2010

[2] UNI EN ISO 52003-1:2018, Energy performance of buildings - Indicators, requirements, ratings and certificates - Part 1: General aspects and application to the overall energy performance

[3] https://ec.europa.eu/energy/sites/ener/files/documents/article_3_eed_indicative_national_energy_efficiency_targets_2020_january_2017.pdf

[4] Energy Efficiency Directive, https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings, 2012

4.6 Conclusion

Thermography in construction is a diagnostic technique that can provide important indications for the identification of problems during the pre-construction and construction phases.

The most recent applicable standards on energy efficiency have certainly pushed the possibility of thermographic investigation to play a crucial role in the construction process.

5. Air tightness - Leak localization and extension

5.1 Practical techniques and physical context (factory/site)

Air-leakage generates energy loss which is correlated to the most common infiltration indicator, the air change rate, that can be measured by a conventional blower door test as described in the standard ISO 9972 *“Thermal performance of buildings — Determination of air permeability of buildings — Fan pressurization method”.*

The air change rate, n_{pr}, has to be measured at an indoor/outdoor pressure difference (*pr*) that has to be realised by the pressurization fan. The pressure difference is defined by the national regulation. In many European countries it is fixed at 50 Pa as prescribed by the ISO 9972. The air change rate at 50 Pa, n50, is the ratio between the air flow rate (q50 in [m3/h]) and the room volume (V in [m3]):

$$n_{50} = \frac{q_{50}}{V} \qquad (11)$$

The air flow rate (q50) depends on the indoor/outdoor pressure gradient (50 Pa) through the volumetric air leakage coefficient (*CL*):

$$q_{50} = C_L(\Delta \mathrm{P})^n \qquad (12)$$

*C*L =air leakage coefficient (the procedure for the calculation is described in the standard ISO 9972)
*Δ*P=50 Pa

According to national regulation, the value assumed by n50 establishes which the house energy class is. In many European countries for a house to be in the class A it is required that n50 is less than 0,6 [1/h].

When the value is over the limit, it is necessary to locate the leakage by considering different measurement aspects:
- building envelope surface temperature (by means of IR camera)
- air flow speed (by means of scanning anemometer).
- motion of chemical or theatrical smoke, emitted by special generators.

Those methods are suggested by the Operation Manual - Retrotec, Residential Pressure and Air Leakage, rev-2014-02-15.

INSITER proposed to use an UltraSonic (US) system to localise the leak.

5.2 Diagnosis/analysis

The main required devices for US air leakage localisation are an ultrasound generator and an ultrasound detector as reported in D5.2 where a lab application has been described. A smartphone or a digital camera is also necessary for capturing the visible image framing the same area scanned by US detector.

<u>Step by step procedure:</u>

1) **<u>Device positioning:</u>**

The ultrasonic generator (emitting ultrasonic waves) is placed inside or outside the envelope to inspect. The ultrasonic receiver is placed outside or inside the envelope in the opposite ambient than ultrasonic generator. The environmental noise, i.e. background noise, affects the measurement by decreasing the Signal to Noise Ratio (SNR) of the ultrasound signal measured by the receiver probe. Consequently, the receiver must be positioned in the ambient (indoor or outdoor) where the background noise is lower. A preliminary test to ascertain the background noise is therefore requested. The US receiver must be connected to a digital acquisition board or datalogger to acquire the US signal and to send it to a PC to which is connected via LAN or Wi-Fi. In the PC, thorough a NI LabView code the signal is processed, i.e. its RMS is calculated and stored. The US receiver can be hold by the operator but, since it has to scan the complete surface of the envelope under test, it should be equipped with a mechanical spacer able to keep a fixed distance between probe and measured surface (few centimetres are suggested). For improving the positioning accuracy, the US receiver must be hold by an automatic positioning system allowing registering the sensor position during the scan. The scan can be performed continuously or at fixed positions with a spatial resolution of at least 1/5 of the minimum dimension of expected leak. The smartphone or photo camera has to be positioned in front of the envelope at a suitable distance to frame the entire surface under test.

2) **Ultrasonic scan calibration and US signal normalization**: to optimise the system sensitivity to the US signal passing through the leak the amplification level of the US receiver must be set for the SNR to be maximum. The following procedure can be applied:

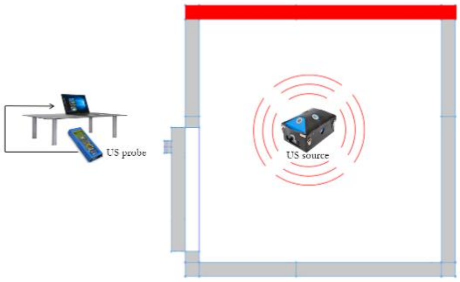
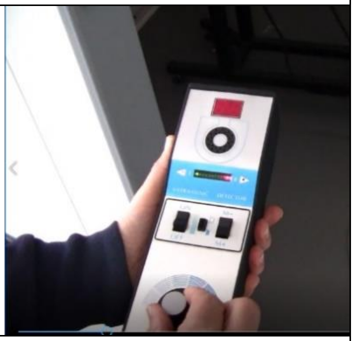
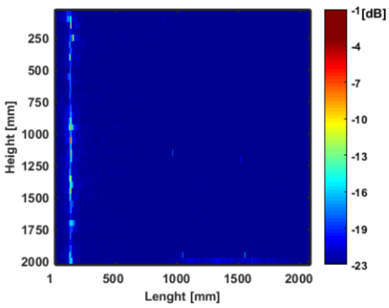
   - Installation of the US generator inside (or outside) the envelope and switching on at a medium level of emission.
   - Activation of the US receiver at the lowest level of amplification.
   - Positioning of the US receiver outside (or inside) the envelope.
   - Moving the US receiver over the whole area of the surface under inspection to verify that the SNR is always above 20 dB.
   - If the SNR is lower than 20 dB even with windows and door opened increase the US generator emission level or increase the US receiver amplification.

3) **Ultrasonics scan and visible images capturing:** At this point, the US receiver can move all over the tested surface for the scanning performance. When the scan is completed, the US signal RMS calculated at each position of the US receiver must be exported as text file (".txt"). The visible image must be exported in a standard image file formats (".png", ".jpeg", ".tiff", ".bmp", etc.). Those data will be processed with a dedicated algorithm developed in Matlab. The US signal RMS is plotted in a 2D map by setting a dynamic range of 20 dB in order to exclude the background noise.

4) **Binarization post-processing:** The RMS 2D map is converted into an image format and binarized with the threshold of 20dB. Hence, a binary image (.bmp) is generated, in which the pixels where the ultrasonic level is lower than the threshold (-20dB) are represented in red colour, highlighting the air-leakage.

5) **Air-leakage anomalies and visible images overlapping post-processing:** The image generated in the step 4, is overlapped to the visible picture, to better localize the air leak anomalies and their extensions.

To better clarify the complete procedure, the case study on a simplified mock-up is shown in Table 6:

<table>
<tr><td>STEP 1: Device positioning</td><td>STEP 2: Ultrasonic scan calibration and normalization</td></tr>
<tr><td>
</td><td></td></tr>
<tr><td>STEP 3: Ultrasonics scan and visible images capturing</td><td>STEP 4: Binarization post-processing</td></tr>
<tr><td>

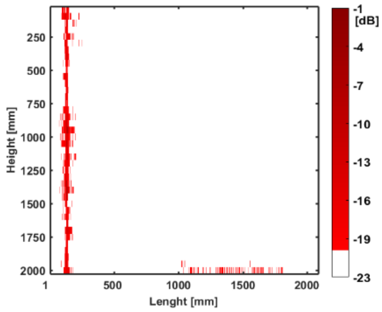
</td><td>
</td></tr>
<tr><td colspan="2">Step 5: Air-leakage anomalies and visible images overlapping</td></tr>
<tr><td colspan="2"></td></tr>
</table>

Table 6: Step by step procedure example

5.3 Applied KPIs

KPI level: energy efficiency, KPI: Heat transfer, Measurement aspect: Air tightness/leak localization, parameters: n_{50}-value [1/h], Air flow rate q_{50} [m^3/s].

5.4 Threshold/tolerance

In many European countries for a house to be in the class A it is required that n50 is less than 0,6 [1/h], this can be change with national regulation.

Ultrasound attenuation through a component (wall) can be exploited for leak localization. In acoustics typical threshold to establish SNR (signal to noise ratio) of an acoustic waveform is 20 dB. This threshold can be extended to acoustic attenuation. If the attenuation is higher than 20 dB a leak can be assessed and localized in to the map. Whether you have to fix the leak or not, depends on the decision of the project manager.

6. Acoustic measurements – Localisation of acoustic leakages

6.1 Practical techniques and physical context (factory/site)

The purpose of this section is to provide a review of the procedure for diagnosis and decision making regarding the acoustic performance of sound-insulating building components and junctions between one or more of them. The methodology used here is a result of developments throughout the INSITER project, part of which are published in previous deliverables. The content of the present section is aimed at being self-contained. Nevertheless, for complementary discussions and definitions regarding acoustic indicators in the context of INSITER, the reader is referred to deliverables D2.3, D5.1, D5.2 and D5.5.

Within the INSITER project and for the sake of simplicity and uniformity of building performance indicators, the term “acoustic leakage” has been used as a descriptor of the quality of a junction between building elements, such as panels, partitions, walls, windows and the like.

The diagnosis of acoustic leakages is tied to the experimental characterisation of these building components and their junctions in terms of indicators such as the sound prominence ratio (SPR), and optionally their sound transmission loss (STL).

Acoustic leakages are characterised as component or junction zones considered as outliers, as observed from the standpoint of their sound prominence ratio. Thus, components exceeding a predetermined threshold value for the sound prominence ratio will be flagged as anomalies requiring action.

The sound prominence ratio is defined as

$$\mathrm{SPR}(f) = 10\log_{10}\left(\frac{|I_{\max}(f)|}{|I_{\min}(f)|}\right)$$

where $I(f)$ denotes the sound intensity as a function of frequency. The sound prominence ratio can be interpreted as the difference, in decibels, between the maximum and minimum sound intensity level values within a spatial region of interest. The proposed indicator is a relative quantity and as such it is subjected to the assumption that the sound intensity level measured in the entire region of interest arises from a common source of noise. Therefore, as detailed in D5.5, the measurement is performed using a sound intensity probe on one side of the examined component, under excitation by a broadband noise source placed at the opposite side.

Alternatively, the measurement may be performed by means of a microphone array using a back-propagation algorithm such as beamforming or acoustic holography. In this case, the measured quantity is typically expressed as a sound pressure, leading to the sound prominence ratio in the form

$$\mathrm{SPR}(f) = 20\log_{10}\left(\frac{|p_{\max}(f)|}{|p_{\min}(f)|}\right)$$

Where $p(f)$ denotes the sound pressure.

The following paragraph details the diagnosis procedure for the identification of acoustic leakages in building component junctions based on the sound prominence ratio as the metric of choice.

6.2 Diagnosis and analysis – step-by-step procedure

The identification of acoustic leakages is described hereafter, following a series of steps.

The procedure utilises a sound intensity probe, ideally with the ability to automatically measure a three-dimensional sound intensity field without the requirement of manual indexing. For this purposes, the existing LMS SoundBrush probe is proposed. As detailed earlier-on in deliverable D5.1, this device is equipped with positioning measurement capabilities by means of optical and gyroscopic tracking.

The output of the acquisition consists of a large table of values of the measured sound intensity at the scanned points in space. This output is post-processed by means of a data parsing script written in the BASH and AWK programming languages. The output is a JSCAD program, which in turn is interpreted by OpenJscad to generate a STL or X3D model containing a representation of the measured sound intensity vectors as arrows whose size is proportional to their amplitude. The X3D format has the advantage of supporting colours, which carry the information of sound intensity amplitude in an additional format.

Step by step procedure:

0) **Preliminary check:** The use of the SoundBrush probe is currently limited to low light conditions in order for its optical tracking system to provide accurate positioning results. Therefore preliminary tests are performed and the light adjusted if necessary. If the tests are performed in the presence of natural light, it is recommended to cast shade on the measurement region. This limitation is not present on classical sound intensity probes (i.e. not having a 3D positioning system).
1) **Position calibration:** The SoundBrush probe and its dedicated camera are placed according to instructions provided within the software itself. The camera is placed such that the entire measurement area is visible from it. The setup also includes a calibration plate defining the centre of the coordinate system for the measurement. The coordinate system is local to the measurement. Thus an additional translation is needed in order to position the measurement data onto the global coordinate system, in particular used by the BIM software containing the building model.
2) **Sound source:** A broadband and omnidirectional noise source is placed behind the partition or junction to be tested. Sources that proved successful in INSITER measurement campaigns are dodecahedron loudspeakers and piston-driven tubular sources. The excitation signal must be stationary in space and time due to the fact that the probe is being moved to scan the area. Typical excitation signals include white or pink noise, ensuring that the frequency range in which the sound intensity probe is sensitive is covered.
3) **Scan:** The probe is dragged across the measurement area or volume. In the case of SoundBrush software, visual feedback is provided in real time such that the user knows whether they have covered the desired region with sufficient point density.
4) **Export:** The measured sound intensity values are exported as a table, either automatically (e.g. SoundBrush) or manually (e.g. classical sound intensity probe).
5) **Conversion:** The table is parsed by the BASH routine, providing the results as a standard 3D solid model. The results are ready to be incorporated in self-inspection tools.
6) **Visualisation:** The 3D model of the measured results can be superimposed onto the 3D model of the building component of interest. The colour scale must be provided with the model. Alternatively, a threshold may be applied in order to highlight the measured values that fail the acceptance test.

Alternative procedure using a microphone array:

0) **Preliminary check:** The microphone array is installed and its proper functioning is verified by scanning the sound source directly.
1) **Position calibration:** The microphone array is placed such that the entire measurement area is visible from it and if possible with the microphone plane parallel to the measured component. The coordinates of the measurement area are manually stored. A further translation is needed in order to position the measurement data onto the global coordinate system, in particular used by the BIM software containing the building model.
2) **Sound source:** see above.
3) **Scan:** A recording is made in stationary conditions.
4) **Export:** The measured sound pressure values are exported as a table, either automatically or manually, or as an image.
5) **Conversion:** The table is parsed by the BASH routine, providing the results as a standard 3D solid model. The results are ready to be incorporated in self-inspection tools.
6) **Visualisation:** The 3D model of the measured results can be superimposed onto the 3D model of the building component of interest. The colour scale must be provided with the model. Alternatively, a threshold may be applied in order to highlight the measured values that fail the acceptance test.

3D model arrows – intensity - 3D model balls – pressure - Same applies with thresholds.

6.3 Applied KPIs

Sound prominence ratio (SPR).

6.4 Thresholds

The sound prominence ratio is representative of the heterogeneity of the sound intensity field in the vicinity of the building component or junction of interest. Accordingly, the acceptance of the component is subjected to the corresponding value of its sound prominence ratio being lower than a threshold, predefined value. The acceptance of the component can be expressed as

$$\mathrm{SPR}(f) \leq \mathrm{SPR}_{\max}(f)$$

Where $SPR_{max}(f)$ denotes the maximum allowable value. This threshold may be defined as a constant or as a function of frequency. Indeed, it is worth noting that the sound prominence ratio is an application-dependent criterion, where its threshold value is decided by the manufacturer. Values of more than 6dB can be considered as representative of significant inhomogeneity. However, the maximum allowable sound prominence ratio may be set to a higher value depending on the type of building or partition, e.g. inner/outer partitions.

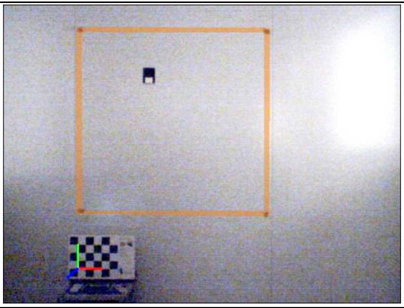
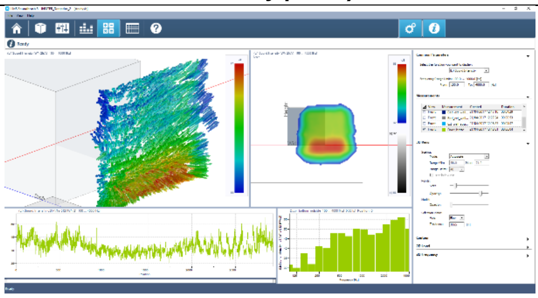
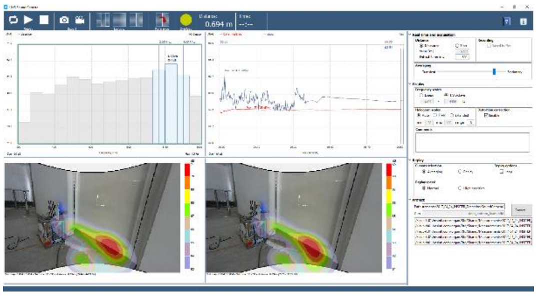
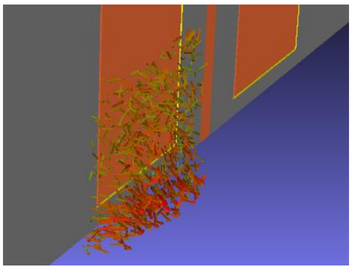
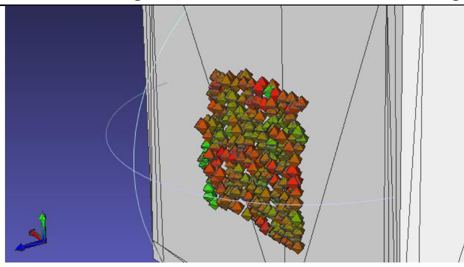
STEP 1: Coordinate calibration	**STEP 2: Omnidirectional sound source**
	
STEP 3: scan (sound intensity probe)	**STEP 3: scan (microphone array)**
	
STEP 4: data acquisition and exporting (SoundBrush intensity probe)	**STEP 4: data acquisition and exporting (Sound Camera microphone array)**
	
STEP 6: Visualisation (Sound intensity) Points exceeding the maximum SPR are red-flagged	**STEP 6: Visualisation (Sound pressure)** Points exceeding the maximum SPR are red-flagged
	

Table 7: Step by step procedure example

7. Acoustic measurements – In-situ evaluation of sound insulation

7.1 Practical techniques and physical context (factory/site)

The purpose of this section is to summarise the procedure for diagnosis and decision making regarding the acoustic performance of sound-insulating building components such as partitions, windows, walls, insulating panels, etc. The methodology used here is a result of developments throughout the INSITER project, published in previous deliverables. The content of the present section is aimed at being self-contained. Nevertheless, for complementary discussions and definitions regarding acoustic indicators in the context of INSITER, the reader is referred to deliverables D2.3, D5.1, D5.2 and D5.5.

The measurement of sound transmission loss for certification purposes is subjected to international standards [ASTM-E90-02-2002, ASTM-E2249-02-2008]. The methodology proposed in INSITER, in particular in work package 5, consists of guidelines for performing an equivalent test on site, using a compact toolset and designed for rapid execution and diagnosis.

Although many acoustic indicators exist, in the context of INSITER the sound insulation performance of a partition, wall or window is characterised by its sound transmission loss (STL). The latter provides a metric for the acoustical energy lost in the process of sound waves being transmitted from one side to the other of the component.

It is thus considered as a measure of performance or quality. Therefore, a component presenting a sound transmission loss lower than a pre-established threshold will be flagged as an anomaly requiring action.

The sound transmission loss is defined as

$$\mathrm{STL}(f) = 10\log_{10}\left(\frac{\langle |I_{\mathrm{in}}(f)| \rangle}{\langle |I_{\mathrm{out}}(f)| \rangle}\right)$$

where $|I(f)|$ denotes the magnitude of sound intensity as a function of frequency. Sound intensity is a vector quantity and therefore it is projected onto the normal to the component surface in order to extract the component directly related to sound transmission. Furthermore, an average over a 1-square-meter surface is used, as detailed further below in the step-by-step procedure.

The sound transmission loss can be interpreted as the difference, in decibels, between the input and output average sound intensity level values within a spatial region of interest on both sides of a partition. The proposed indicator is a relative quantity and as such it is subjected to the use of a stationary source of noise. Therefore, as detailed in D5.5, the measurement is performed using a sound intensity probe on both sides of the examined component, under excitation by a broadband noise source placed at one side, here referred to as the inlet face.

Alternatively, the measurement may be performed by means of a microphone array, provided that the microphones are within one wavelength of the surface. In this case, the measured quantity is typically expressed as a sound pressure, leading to the sound transmission loss in the form

$$\mathrm{STL}(f) = 20\log_{10}\left(\frac{\langle |p_{\mathrm{in}}(f)| \rangle}{\langle |p_{\mathrm{out}}(f)| \rangle}\right)$$

Where $<|p(f)|>$ denotes the average sound pressure on the inlet or outlet face of the panel or partition.

The following paragraph details the diagnosis procedure for the estimation of the insulation performance of building partitions based on the sound transmission loss as the metric of choice.

7.2 Diagnosis and analysis – step-by-step procedure

The estimation of the sound transmission loss is described hereafter, following a series of steps. The procedure utilises a standard sound intensity probe, or a microphone array. For these purposes, the existing LMS SoundBrush probe and the newly developed LMS Sound Camera microphone array are proposed. Both are now commercial products of Siemens Industry Software, Belgium.

In the case of 3D sound intensity measurements, the output of the acquisition consists of a large table of values of the measured sound intensity at the scanned points in space. This output is post-processed by means of a data parsing script written in GNU Octave, BASH and AWK programming languages. The output is a curve of the average magnitude of the normal sound intensity level, both for the inlet and outlet faces of the panel.

In the case of 1D (classical) sound intensity measurements, the output is directly a curve of the average magnitude of the normal sound intensity level, both for the inlet and outlet faces of the panel.

In the case of a microphone array measurement, the output is a curve of the average magnitude of the sound pressure level, both for the inlet and outlet faces of the panel.

The outlet curve is subtracted from the inlet curve, resulting in the sound transmission loss of the component as a function of frequency.

Step by step procedure:

0) **Preliminary check:** the evaluation of the sound insulation properties of a partition is subjected to the assumption that no other transmission paths are present in the measurement. It is thus recommended to perform a test of sound prominence ratio on the junctions of the component of interest for full confidence.
1) **Position calibration:** The sound transmission loss is an average measure for a full component and thus a QR code reference to the component is preferred and sufficient.
2) **Sound source:** A broadband and omnidirectional noise source is placed in the inlet room, at a distance larger than one meter away from the partition to be tested. The excitation signal must be stationary in space and time due to the fact that the measurement system is sequentially placed at the inlet and then outlet faces. Typical excitation signals include white or pink noise, ensuring that the frequency range in which the sound intensity probe (or microphone array) is sensitive is covered.
3) **Scan:** The probe is dragged across a surface of one square meter within 5cm of the panel face. In the case of SoundBrush software, visual feedback is provided in real time such that the user knows whether they have covered the desired region with sufficient point density. If using a microphone array, it is recommended to position the latter at several locations in the vicinity of the partition, covering a surface of one square meter.

The scanned surfaces must be coincident on both sides of the partition.

4) **Export:** The measured sound intensity values are exported as a table, either automatically (e.g. SoundBrush) or manually (e.g. classical sound intensity probe).
5) **Conversion:** The table is parsed by the BASH + GNU Octave routine, providing the results as a sound transmission loss curve. The value threshold may be included in order to highlight the frequencies where the component fails the acceptance test.
6) **Visualisation:** The results can be retrieved from within self-inspection tools by using QR code referencing.

7.3 Applied KPIs

Sound transmission loss (STL).

7.4 Thresholds

The sound transmission loss is representative of the insulation capabilities of the building component of interest. Accordingly, the acceptance of the component is subjected to the corresponding value of its sound transmission loss being higher than a predefined threshold value. The acceptance of the component can be expressed as

$$\mathrm{STL}(f) \geq \mathrm{STL}_{\mathrm{min}}(f)$$

where $SPL_{min}(f)$ denotes the minimum allowable sound transmission value. This threshold may be defined as a constant or as a function of frequency. Indeed, it is worth noting that this is an application-dependent criterion, where its threshold value is decided by the manufacturer.

7.5 Guidelines for the definition of a minimum threshold for the sound transmission loss

It is important to consider rudimentary aspects of the dynamic behaviour of panels under an acoustic excitation. For a homogeneous panel, its sound transmission loss is an increasing function of frequency. This is due to its mass per unit area in relation to the wavelength. Indeed, as waves with smaller wavelengths are more efficiently obstructed, the amount of transmitted energy through the panel decreases with frequency and thus the sound transmission loss increases. Therefore, the sound transmission loss of a panel tends to 0dB at the zero-frequency limit.

Furthermore, the so-called mass law for a homogeneous panel is a phenomenon whereby the sound transmission loss increases by 6 dB by doubling the frequency of observation. This is valid for sufficiently high frequencies, and in particular above coincidence frequencies such as the bending resonance of the panel or resonances within its thickness.

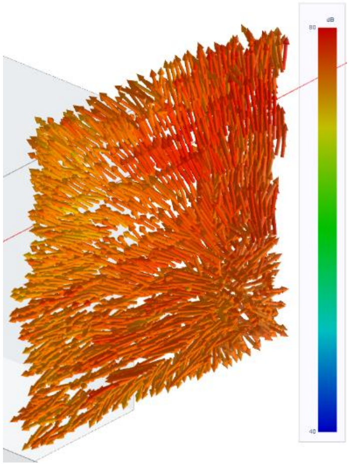
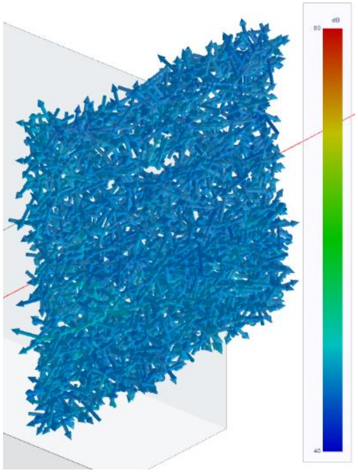
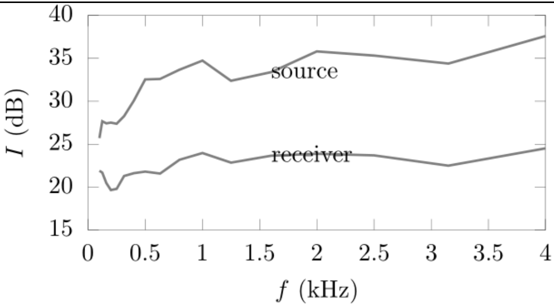
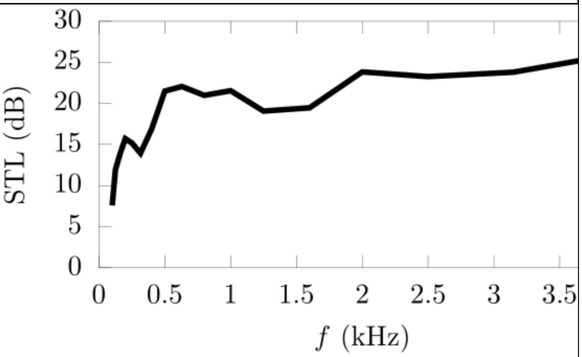
Scan at the inlet (source side)	Scan at the outlet (receiver) side
	
Sound intensity (source side)	**Sound intensity (receiver) side**
	
Sound intensity curves for inlet (source) and outlet (receiver) faces	**Sound transmission loss**
	

Table 8: Step by step procedure example

7.6 References

[1] ISO 16032:2004. Acoustics -- Measurement of sound pressure level from service equipment in buildings -- Engineering method

[2] ISO 9614-1:1993. Acoustics -- Determination of sound power levels of noise sources using sound intensity -- Part 1: Measurement at discrete points

[3] ISO 9614-2:1996. Acoustics -- Determination of sound power levels of noise sources using sound intensity -- Part 2: Measurement by scanning

[4] ISO 9614-3:2002. Acoustics -- Determination of sound power levels of noise sources using sound intensity -- Part 3: Precision method for measurement by scanning

[5] ASTM E90 – 09(2009). Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements

[6] ASTM E2249 - 02(2016). Standard Test Method for Laboratory Measurement of Airborne Transmission Loss of Building Partitions and Elements Using Sound Intensity

[7] ISO 15186-1:2000. Acoustics -- Measurement of sound insulation in buildings and of building elements using sound intensity -- Part 1: Laboratory measurements

8. Conclusions

In conclusion, the measuring and diagnosis solutions for inspecting building components described are applied to avoid quality and energy performance errors related to prefab components. One aspect of the described practical techniques using the INSITER solutions is to avoid possible failures regarding dimensional-geometric discrepancies of prefab products.

Early assessment of the dimensional and geometric quality on-site is crucial to propose corrective action planning to achieve the expected energy efficiency performance and to realize energy efficient buildings.

Several advanced automated dimensional quality assurance techniques are used today on construction site. In comparison to traditional methods, the 3D laser scanner is the main data acquisition method in consideration of the following advantages: good accuracy, high speed and range. Numerous laser scanners are available on the market; in order to select the most appropriate it is possible to analyse five main criteria: 1) tolerance; 2) accuracy; 3) measurement range; 4) price; 5) scanning time (see also activity proposed on WP4 and WP5).

The use of 3D laser scanners makes it possible to assess the following main aspects of the construction process:

- progress monitoring on-site in comparison to the project plan;
- components dimension and geometry during the delivery stage;
- components deformation measurement during the assembly stages;
- components surface; building geometry.

In consideration of the INSITER scope, "geometry and deformation measurement" it is crucial to maintain the expected energy building performance reducing the construction errors on-site (see also D1.1).

To assess the geometric-dimensional quality it is important to define the "assembly tolerance". Tolerance values (thresholds) must be taken into account during the construction phase in order to accept or not accept dimensional variations of the delivered component components on-site or for the possible following construction assembly errors. The expected dimension tolerance must be defined by the project before the start of the construction site.

To quantity the impact of geometric-dimensional construction errors in terms of energy-environmental performance is difficult during the building construction process. For this reason it is possible to consider that no constructive error beyond the tolerance imposed in the design phase can be accepted.

Another advantage to use the 3D laser scanner is related to obtain a point cloud of the building that will be compared with the existing 3D model in order to highlight changes between previous design and as built situation applied on the Cologne demonstration case and described in the section 2.4.3.

Thermography in construction is a diagnostic technique that can provide important indications for the identification of problems during the pre-construction and construction phases.

The most recent applicable standards on energy efficiency have certainly pushed the possibility of thermographic investigation to play a crucial role in the construction process for the following purposes:

- Identification of thermal bridges
- Analysis of thermal dispersions
- Identification of structural defects
- Identification of condensation / mould areas

- Identification of infiltration of air (air-tightness)
- Identification of infiltration of water
- Identification of ascent humidity
- Identification of plaster and coating detachments
- Support for energy certification
- Mapping of HVAC systems.

As explained, the INSITER project has developed guidelines and protocols to help contractors and building inspectors to use thermal measurements as follows:

- To estimate the area of thermal bridges
- To identify and localize thermal bridges, with a proposed method to assess the energy losses and the impact on the thermal performance of the envelope
- To identify and localize air leakages.

All such information can be integrated within the BIM model. The application is demonstrated in WP5 and documented in its deliverables D5.5, D5.4, D5.5 and D5.7. Furthermore, the BIM integration has been analysed and further developed in WP2, WP3 and WP4 based on the application of guidelines developed in WP1 D1.2 and D1.3.

The use of thermography is important in the field of energy efficiency of buildings, usually combined with other devices and measurement techniques such as heat flow meter, verification of air permeability, blower door test, verification of the presence of moisture, as well as all the parameters related to internal comfort. The complementary use of these diagnostic techniques allows a better definition of the problems related to the formation of condensate and mould and also of thermal bridges, which represent one of the most recurrent sources of problems in the construction sector. For this reason, thermal measurements can help in two different steps of the construction process: (a) it can be used by experts/technicians/building owners during the investigation and the mapping phases, to identify the existing problems in buildings and better understand the necessary interventions, and (b) it can be used by contractors/sub-contractors on construction site, during the installation of building components, to assess the position of thermal irregularities and air infiltrations through the building envelope before the envelope is sealed, in order to intervene as soon as possible and avoid in advance possible damage that would be visible only at the end of the works.

It is possible to detect the presence of humidity in the walls, either condensation, meteoric or rising. Also in this case the thermography should be added to other surveys, such as thermogravimetric analysis for the expression of a precise quantitative value. The thermography, in conjunction with instruments such as geophone, video inspection, etc., provides information in the field of leak detection and infiltration.

Together with the associated instrumental diagnostic investigations, thermal measurements represent the possibility of obtaining a real control of the construction process and of the quality of the execution in the building, both in new buildings and in interventions concerning the existing heritage.

Like all survey techniques, thermography also has its limits of action on the construction site. In particular, the following issues can be highlighted:

- seasonality, linked to weather-climatic conditions, which means not being able to carry out a certain type of thermal measurement in every season and with any weather condition.
- geometric and structural limits, that is to say that we are faced with situations that prevent the phenomenon to be investigated from being revealed on the surface, due to interposed structures that prevent heat flow

- thermography is a predominantly qualitative and non-quantitative survey. For this reason, it can be used in combination with other devices. In this context, the INSITER project has developed and proposed some calculation protocols for the preliminary estimation of energy efficiency, as more fully explained in the previous paragraphs.

Acoustic measurements and data analysis as described in chapter 6 and 7 is providing non-destructive testing methodology enabling the detection of e.g. air leakages at the same time. The coordinated action of 3D laser scan, thermal measurement and acoustic measurement is representing the expert devoted testing field of the INSITER toolset. Considering that tests as described demand special equipment and expertise the practical use of the data created is important to assure the INSITER quality level and offer the creation of dashboards for efficient and effective decision making processes at building sites.

In the INSITER project, experiments were carried out with various testing technologies and equipment -laser scanner, thermal scanner, air tightness, acoustic measurement- at building sites in Cologne, in Pisa, Italy and Valladolid, Spain. These experiments gave the following results:

- The crucial deviations being responsible for gaps and leakages at points of junction at building component level can be avoided by using enhanced measuring tools for dimensions and building physic performance;
- The scan time can be shortened;
- By using a linked tablet during the scanning, the results determine directly which parts should be scanned better;
- In terms of 3D laser scanning different pointclouds from the same equipment indicate that some pointclouds can be more easily translated to BIM than others;
- By using smaller parts, such as walls only, deviations between the BIM model and the pointclouds can be better mapped.
- Air leakages can be detected before closing the building envelope by enhanced acoustic measurement.