Calculation and analytical methods for MEP/HVAC components

Deliverable report 1.6

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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.

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Colophon

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

Fulfilment of the Description of Action (DoA) in D1.6

Accessibility of this deliverable

This deliverable is presented in 1 part: Report / documentation (this document). For INSITER consortium and European Commission representatives, the deliverable is available both in the EC Participant Portal (INSITER project) as well as in the SharePoint project website.

After approval by the European Commission, the public version of this deliverable will be published on the INSITER public website, and disseminated through the common dissemination channels.

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: − Key Measurement aspects and parameters addressing quality and energy performance − Techniques for self-inspection and self-instruction in different types of projects (new construction, refurbishment, commissioning, and maintenance).	**Addressed:** − For each critical HVAC component, the relevant KPIs have been elaborated, based on the KPI table from D1.1 (See section 2.3). − Conceptual techniques to perform self-inspection in a building process are proposed (See chapter 4). − The most critical MEP/HVAC components are defined, including in depth analysis of tools and methods relevant for inspection of these components (See sections 3.x.2 and 3.x.4). − This deliverable serves as an input for creation of the guidelines for self-inspection and self-instruction in different type of projects (new construction and refurbishment) that will be developed in the follow-up deliverables within Task 1.1.

Summarised objectives as stated in DoA	Results presented in this deliverable
Task 1.3 scope and objectives: − Investigating MEP/HVAC critical components (e.g. valves, pumps), subsystems (e.g. heat pumps), and systems (e.g. heating/cooling systems), by reflecting on their specific properties and KPIs for energy-performance. − Identification of difficulties in assessment and analysis of MEP/HVAC systems during construction and refurbishment. − Adaptation and further development of existing inspection techniques and instruments (e.g. flow measuring), with their best practices and shortcomings, as input to develop self-inspection techniques. There is a need for methodologies for the non-invasive and cost-effective assessment to detect faults and measure/estimate the performance. − Integrating the calculation and simulation methods (such as TRNSYS) and monitoring techniques (such as SIMAXX) in BIM. − Embedding self-inspection in the quality assurance systems and standardisation.	**Addressed:** − Defining the MEP/HVAC critical components, subsystems, and systems. (See sections 3.1 and 3.x.2) − Identification of difficulties in assessment and analysis of MEP/HVAC systems during construction and refurbishment. (See sections 3.x.3) − Real measurement of the systems performance (See sections 3.x.4) − Methodologies for the non-invasive and cost-effective assessment to detect faults and calculate the performance. (See sections 3.x.5) − Further development of existing inspection techniques and instruments (See chapter 5) − This deliverable serves as input for further elaboration of process methods for self-inspection of MEP/HVAC components in new construction and refurbishment will be completed in the follow-up deliverable D1.7. − This deliverable serves as input for integration in BIM and qualification of the key performance parameters that will be implemented in the follow in D1.7 and D4.4. − This deliverable serves as input for embedding self-inspection methods in the quality assurance systems and standardisation in D1.7 and D6.2.
Deliverable D1.6 scope and objectives: − Calculation and analytical methods for MEP/HVAC components describing conceptual measurement protocols and quantitative method for self-inspection of MEP/HVAC components, with a focus on self-inspection of critical MEP/HVAC components that affect quality and energy performance in all phases of a building project.	**Achieved. Specific results fulfilling the deliverable objectives:** − Measurement protocols as described in the sections 3.x.4. − Quantitative methods as described in the sections 3.x.5. − Specific self-inspection of critical MEP/HVAC components as described in the sections 3.x.6. − General (conceptual) self-inspection techniques as described in chapter 4.
Project's progress relevant to the deliverable within the corresponding timeframe (Year 1-2): − Clear identification of existing bottlenecks, most frequent errors, and shortcomings in skills in the construction processes across the EU. Such identification is based on reliable and up-to-date investigations (e.g. Dutch "Bouw Transparant", UK "Constructing Excellence", and similar reports from Germany, Spain, and Italy). − Critical review of process, performance, and inspection norms (e.g. Dutch norm NEN 2767 on condition assessment, Energy Performance Coefficient norms)	**Achieved. Explanation:** The most frequent errors of prefab buildings and existing bottlenecks have been further elaborated and defined in this deliverable. **Achieved. Explanation:** The main EU inspection norms and performance standards have been collected and presented; calculation and analytical methods for building components, this is comprehensively addressed. For MEP/HVAC components condition assessment will be applied to lesser extent. EPC-norms (and software) are reviewed.

Summarised objectives as stated in DoA	Results presented in this deliverable
− Definition of plausible KPIs. KPIs are integrated in the self-inspection protocols/manuals.	**Achieved. Explanation:** The main KPIs for MEP/HVAC components have been defined (see section 2.3).
− Calculation methods for performance assessment as well as self-instruction.	**Achieved. Explanation:** The calculation methods and self-instruction on MEP/HVAC components are defined in this document (chapter 3 and 4). The parallel deliverable D1.4 describes the methods, tools and techniques for building components.
− Further developing self-inspection techniques coherent with an efficient construction process workflow. Stakeholder analysis becomes of a key importance to determine the most effective communication and coordination methods, and to clarify responsibilities and liabilities, Professional Indemnity Insurance, as well as organisational and legal constraints	**Achieved. Explanation:** The self-inspection techniques and efficient construction process workflow have been addressed. A first stakeholder analysis has been made, and will be further elaborated and evaluated later in the project.

Publishable executive summary

Research on calculation and analytical methods for MEP/HVAC components concentrates on developing a methodology to prevent common errors on MEP systems and improve the building's indoor environmental quality and energy performance. The methodology covers the full building process, from prefabrication and construction to the in-use phase and maintenance. The methods apply for new buildings, as well as for refurbishment and maintenance projects. The main objectives of this deliverable are:

1. To define quantitative analytical methods for performance assessment of building components
2. To determine the calculation of KPIs regarding the overall performance of MEP/HVAC systems;
3. To eliminate the difficulties in assessment and analysis by introducing conceptual self-inspection protocols for quality assessment and supporting instruments;
4. Recommendations for implementation of the inspection process.

This deliverable presents the research outcomes on performance assessment, frequent construction errors, key performance indicators and relevant standards specific for MEP/HVAC components affecting the quality and performance of energy-efficient buildings (EeB). The focus of this deliverable is on calculation and analytical methods for MEP/HVAC components.

The self-inspection process

The self-inspection process is integrated in INSITER's 8 step methodology. This methodology describes a detailed procedure where newly developed methods, tools and techniques (MTTs) contribute to INSITER's goal to close the gap between design and realization. Self-inspection on MEP/HVAC components takes place in different steps of the methodology and in different phases throughout the building process. Figure 1 depictures these inspections and the time-interval concerned.

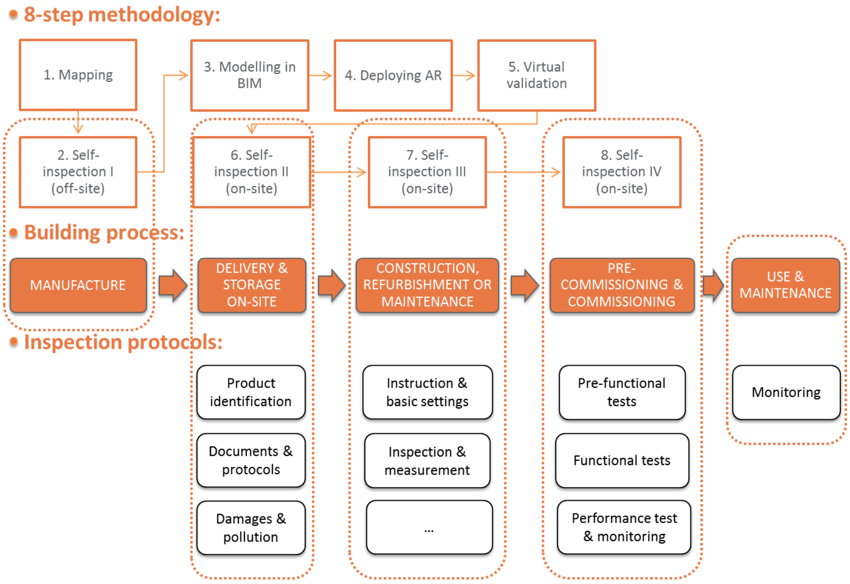

Figure 1: Inspections for MEP/HVAC components during the different building phases

All inspections revolve around the same concept: to eliminate errors that have a major influence on a definite list of KPIs. Because of the complex multitude of actions, INSITER's methodology will follow a structural approach. This method follows the concept of eliminating errors 'top down' and 'bottom up' concurrently, or so-called 'up-stream'. The levels of inspection are defined as 'components', 'subsystems', and 'systems' van bottom to top. The inspections are executed during the successive phases and system-specific proceedings of the realization phase.

Common errors are classified in one of the following categories (type of error):

01. The component is damaged or polluted
02. The wrong component is installed
03. The component is installed incorrectly
04. The component is provided with the wrong settings

Critical MEP/HVAC systems affecting EeB performance

Four leading MEP systems are elaborated for self-inspection, together covering for over 90% of all MEP systems with a relation to indoor environment and energy usage. These systems are:

- Heating & cooling (with heat pump);
- Mechanical ventilation (with heat recovery);
- Solar hot water;
- LED lighting.

The systems are described in detail, presenting their components and related common errors that we see in construction projects today. The mentioned errors lead to deviations on INSITER's KPIs, and obviously, need to be eradicated. Every component has standalone functionality and will eventually work like a cog in a machine. Errors or mismatches that won't get solved as soon as possible in the process have a good chance to get covered up, making it hard or almost impossible to discover. So INSITER's job is, to detect errors and solve them before it is too late. This is exactly how the inspections work; they will be executes at a certain level (component, subsystem or system), on a particular time in the process and with a technique that is associated to the type of error. These three elements play a crucial part in the inspections of MEP/HVAC components.

Furthermore, every MEP system has its own specific function and therefore all MEP systems are being provided with their own individual measurements and calculations. All the defined measurements and calculations have a clear relation with one or more KPIs. Where MEP systems interconnect, assessment is performed for all systems related. For example, the temperature in the occupied zone is being influenced by the heating system, but most of the time also by the ventilation system. In that case, measurement of this temperature is carried out with the aim to assess the heating system, as well as the ventilation system.

Conceptual self-inspection protocols for MEP/HVAC components

Basically, self-inspections for MEP components start at delivery on-site. MEP components are hardly prefabricated, and if they are, inspection can be executed as if it were a single component. In case a component or range of components (like piping) is prefabricated at the factory, inspection will start there. More often we see pipelines and duct systems integrated in prefab elements. They will be subject to inspections as part of the prefab element, before being transported to the building site. The first inspections on-site will be to make sure the right component is delivered and that it is flawless. These are visual inspections, making use of INSITER tools on a mobile device.

After delivery, the components will be transported to their location of mounting, in the building. More inspections will be executed to make sure the right component will be installed at the right place in the right manner. Again, the MEP worker is using the INSITER tool on his mobile device to perform the inspections.

When installation of a component or subsystem is completed, another visual check with a mobile device is executed, to make sure the component is installed the right way. INSITER provides information from BIM with guidelines and inspection protocols to help the MEP worker on-site. The next step is to make sure the control settings will be applied as intended, making this the final check on component level.

At this time the commissioning phase has started. Inspections are moved to subsystem and system level and measurements are being carried out to assess the performance of the (sub) system. Meanwhile, monitoring tools will be integrated in the control system, to start monitoring the performance. While measurements are carried out, results will be compared to the design model in BIM and deviations are being quantified. A feedback loop will make sure that corrections will be constantly checked and evaluated.

Total building quality and further research

The interaction of MEP components with building component takes place from day 1. Whether MEP components are integrated in building elements, or installed in the building as single components. Performance of the building will always depend on both. So during inspections, for example, checks will take place on the connections of MEP components with building elements. Sometimes intended, to seal off lead-throughs, or unintended, to prevent the transfer of vibrations.

As construction is forwarding, constant comparison and evaluation to the BIM model is making sure deviations to the design will stay within limits. This will be executed for the building elements, as well as the MEP systems. Then, when the building is coming close to completion, a simulation tool (like Vabi, see chapter 4) will take over and will be used to assess the overall performance of the building. The process is being visualized in

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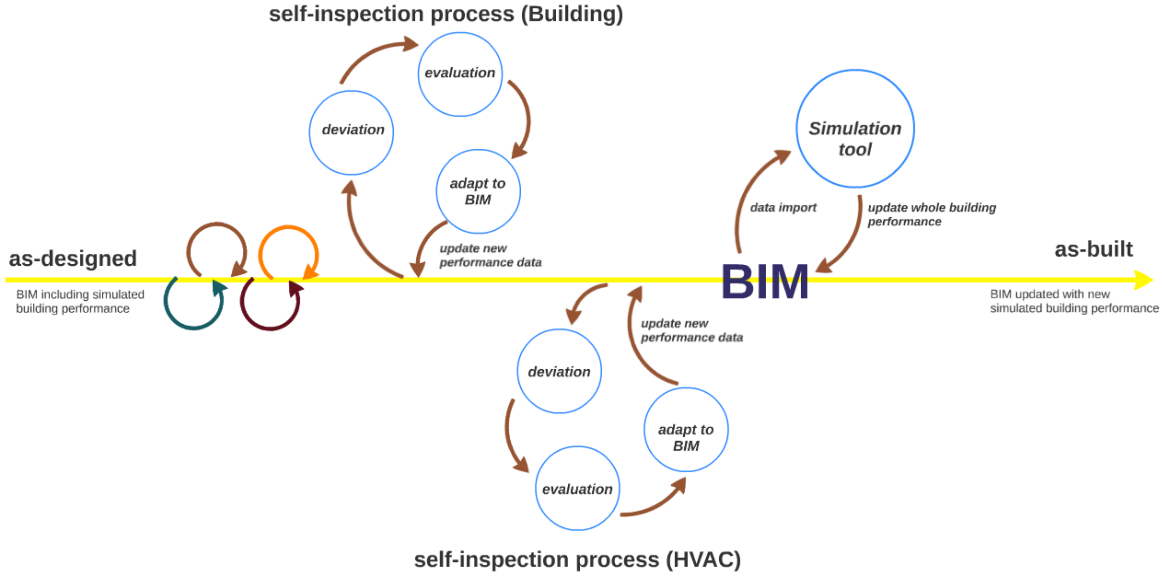

Figure 2: Illustration of the assessment of total building performance

During this process, continues quantification is being carried out by calculation and analysis of MEP/HVAC components and systems. The next step for INSITER is to qualify the results with the aim to decide whether a deviation should lead to corrections. This will be elaborated and defined in the follow-up deliverable within the INSITER project.

List of abbreviations and symbols

Abbreviation / acronym	Description
AEC	Architecture, Engineering, and Construction
AHU	Air Handling Unit
AR	Augmented Reality
ATES	Aquifer Thermal Energy Storage
BIM	Building Information Modelling
BVU	Bidirectional Ventilation Unit
CAV	Constant Air Volume (in contrast to VAV)
DCV	Demand-controlled ventilation
DHW	Domestic Hot Water
DoA	Description of the Action
DoW	Description of the Work
DX	Direct eXpansion
EE	Energy Efficiency
ERV	Energy Recovery Ventilator (or ventilation)
HRV	Heat Recovery Ventilator (or ventilation)
HVAC	Heating, Ventilation, Air Conditioning
IAQ	Indoor Air Quality
KPI	KPI
MEP	Mechanical, Electrical, Plumbing
MTT	Method, Tools, and Techniques
MVHR	Mechanical Ventilation Heat Recovery
NRVU	Non-Residential Ventilation Unit
PFT	Pre-Functional Testing
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RVU	Residential Ventilation Unit
TAB	Testing, Adjusting and Balancing
UVU	Unidirectional Ventilation Unit
VAV	Variable Air Volume (in contrast to CAV)
VU	Ventilation Unit

Symbols

Symbol	Quantity	Unit
A	Area	m²
C	Effective heat capacity of a conditioned space	J/K
c	Specific heat capacity	J/(kg·K)
E	Energy	MJ
H	Heat transfer coefficient	W/K
h	Surface coefficient of heat transfer	W/(m²·K)
Q	Quantity of heat	MJ
R	Thermal resistance	m²·K/W
T	Thermodynamic temperature	K
t	Time, period	Ms
V	Volume of air in a conditioned zone	m³
q	Airflow rate	m³/s
Φ	Heat flow rate, thermal power	W
Z	Heat transfer parameter for solar walls	W/(m²·K)
η	Efficiency, utilisation factor	-
θ	Celsius temperature	°C
ρ	Density	kg/m³
τ	Time constant	h

Definitions

Commissioning (Cx)

Commissioning MEP/HVAC systems is the process of verifying that these systems achieve the project requirements of new buildings as intended by the building owner and as designed by the building architects and engineers. Commissioning activities normally consist of operating the MEP systems and making adjustments necessary for satisfactory operation of the system or part thereof. Also included are functional checks of components and subsystems, to prove that the component or subsystem functions correctly. Commissioning can be applied throughout the lifetime of the building.

Conditioned space

A conditioned space is that part of a building that is heated or cooled, or both, for the comfort of occupants.

Construction worker

The term 'construction worker' is used generically for all workers on-site, regardless their trade. Amongst construction workers are carpenters and masons, but also electricians, plumbers, and HVAC mechanics.

Contaminant

A contaminant is an unwanted airborne constituent that may reduce acceptability of the air.

Exhaust air

Air flow discharged to the atmosphere.

Heat (energy) recovery ventilation system

A heat or energy recovery ventilation system is a device or combination of devices applied to provide the outdoor air for ventilation in which energy is transferred between the intakes and exhaust airstreams. There are different types of heat (energy) recovery systems with different specifications and different performances. Some heat recovery systems can also recover moisture.

- Air heat exchanger is the heat exchange element used in air handling units
- Heat recovery unit is a device with build in (air) heat exchanger.
- Heat recovery ventilation (HRV) or mechanical ventilation heat recovery (MVHR) is the ventilation system with heat recovery.

Infiltration and exfiltration

Infiltration and exfiltration are the unintentional or accidental airflow into or out from a building, typically through cracks in the building envelope. Infiltration is sometimes called air leakage. It is caused by wind, negative pressurization of the building, and by air buoyancy forces known commonly as the stack effect.

Mechanical ventilation

Mechanical ventilation means ventilation provided by mechanically powered equipment, such as motor-driven fans and blowers, but not by devices such as wind-driven turbine ventilators and mechanically operated windows.

MEP worker

The MEP worker is used as a collective name for the plumber, electrician, and HVAC mechanic. These are the people that do the specialized work concerning the MEP systems, e.g. installing or adjusting MEP/HVAC systems and commissioning. For some activities, it is also thinkable that non-specialists will fill in. For example, to mount MEP components or to assemble pipes and ducts when they are integrated in a prefab building element.

Natural ventilation

Natural ventilation means ventilation provided by thermal, wind, or diffusion effects through doors, windows, or other intentional openings in the building.

Outdoor air

Controlled air entering the system or opening from outdoors before any air treatment.

Pre-Commissioning

Preparing the components and systems for commissioning. Pre-Commissioning activities overlap mechanical completion activities and start from component level to subsystems to system level. Activities include: checking for design conformity, checking the status of electrical, mechanical and instrument installations, running-in of equipment, flushing and cleaning activities.

Return air

The return air is the air removed from a space to be then recirculated or exhausted.

Sound intensity

Sound intensity also known as acoustic intensity is defined as the sound power per unit area. The SI unit of sound intensity is the watt per square metre (W/m^2). The usual context is the noise measurement of sound intensity in the air at a listener's location as a sound energy quantity.

Sound pressure level (Lp)

Sound pressure level (Lp) or acoustic pressure level is a logarithmic measure of the effective pressure of a sound relative to a reference value. Sound pressure level is measured in dB. The commonly used reference sound pressure in air is: $p_0 = 20\ \mu Pa$. This is considered as the threshold of human hearing (roughly the sound of a mosquito flying 3 m away).

Supply air

Air flow entering the treated space, or air entering the system after any treatment. The supply air is made up of clean outdoor air and is sometimes mixed with or exists completely out of recirculated air.

Testing, Adjusting and Balancing (TAB)

A testing and adjustment of constructed and installed components and systems to ensure that the equipment and systems operate to meet the specifications written in the design documents. It includes adjusting water flow in pipes, air flow in ducts, and tuning control parameters.

INSITER INTUITIVE SELF-INSPECTION TECHNIQUES

Content

1. Introduction

1.1 Objectives and structure of this deliverable

The main objectives of this deliverable are:

- To define quantitative analytical methods for performance assessment of building components
- To determine the calculation of KPIs regarding the overall performance of MEP/HVAC systems;
- To eliminate the difficulties in assessment and analysis by introducing conceptual self-inspection protocols for quality assessment and supporting instruments;
- Recommendations for implementation of the inspection process.

The deliverable is organized in six main sections. Each section introduces different topics related to each other as it follows.

- **Section 1** introduces the deliverable's objectives; the structure of the main contents and relations; the methodology adopted to achieve the results presented and the research limits.
- **Section 2** focusses on the input from other work packages and KPIs, related to the self-inspection process for quality assessment
- **Section 3** introduces the MEP/HVAC systems, their relation to KPIs, building errors and the analytical methods for performance assessment and calculation of the individual systems
- **Section 4** describes INSITER's self-inspection process on MEP/HVAC systems and the different inspections and assessments to be taken during the realization phases.
- **Section 5** connects the building envelope, interior systems, load bearing systems and MEP-HVAC systems for overall building quality assessment and analysis and defines the link to process management and implementation of the inspection protocols
- **Section 6** describes the implementation of quantitative methods and calculations in the building process. When to take up the methods, what are the adaptations to existing tools and are the calculations and methods adequate for self-instruction and self-inspection?

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

This deliverable presents the main results of the research for calculations and analytical methods that are applicable in INSITER's methodology. Information is basis on experience by the Task 1.3 partners on MEP/HVAC system and on modern day methods that determine the current and near-future way of building. Also, considered are the regional standards, complemented by some national standards or guidelines that describe measurements and calculations in the building services field.

Elaboration of common errors and relevant standards derive from the previous deliverable D1.1, where preliminary information on these subjects is provided. In this document, unnecessary information has been left out and relevant parts have been deeply analysed and elaborated for use in INSITER. Also, the defined list of KPIs from D1.1 is adopted, though has been adapted to fit the assessment methodology.

The global planning and process that is followed, is shown in Figure 3.

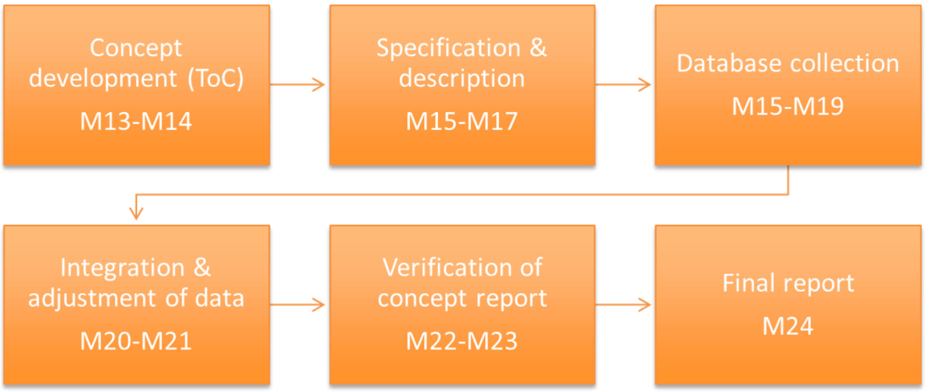

Figure 3: Project planning T1.3 / D1.6

1.3 Main achievements and limitations

The deliverable presents the results achieved by Task 1.3 during the second year of the INSITER project that can be summarized in:

- Definition of the **MEP/HVAC protocols in a standard building process** in order to improve the construction quality and energy performance of prefab buildings. Following the INSITER 8-step methodology, the integration of the different assessments concerning the MEP/HVAC systems, is being lined out, to make clear what inspections take place in what building phase.
  [See section 2.1]
- Identification of the **relevant regional (EU) and international standards** for assessment of the MEP/HVAC systems. The importance of this collection lies in the fact that a lot of test and measurement procedures and performance verification has already been captured in regional or international standards. Inspection procedures in INSITER's methodology are, to a great extent, based on these standards;
  [See section 2.2.1 and
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- Appendix 1]
- Determination of the definitive list of **KPIs and measurement aspects** regarding the building quality and energy performance as far as this is influenced by the MEP/HVAC systems [See section 0];
- Definition and reasoning for **INSITER's scope** regarding the MEP/HVAC systems. This is crucial because it underlines the choices being made to set the focus on a few systems that have the greatest influence on INSITER's KPIs. [See section 3.1]
- Introduction of a basic approach to categorize **construction errors** related to MAP/HVAC systems, subsystems, and components.[See section 3.1.2]
- Description of the **MEP/HVAC systems**, with identification of the **critical components** and related construction errors. [See sections 0, 0, 0 and 0]
- Elaboration of **conceptual self-inspection and self-instruction protocols** to prevent and to detect construction errors in MEP/HVAC systems. [See chapter 4].

The following table presents limits suggested by Task 1.3 to define the scope of the INSITER project:

TOPIC	LIMIT
1. Standards	Final collection of standards to determine the performance and quality requirements of HVAC components. This will be addressed in D1.7.
2. KPIs	Definition of tolerances for INSITER's KPIs and measurement aspects. This will be addressed in D1.7.
3. Common errors	INSITER's approach is to prevent common errors, which typically count for more than 50% of rework cost. This is a speculative definition, because the cost of an error cannot always be determined in advance. So D1.6 considers all common errors potential to be prevented. D1.7 will quantify the errors and from the new insight possibly adapt the current list of errors.
4. Assessment of MEP/HVAC components	Assessment of MEP/HVAC components is executed within the realization phase and maintenance. Many mistakes however, start during the design phase. Some of these faults will be identified by INSITER methodology, but are not part of the research. The BIM model can be updated, but it is not possible to prevent these errors with the use of INSITER.
5. Connection with building elements	MEP systems have a close relation with the building elements. At some points, it cannot even be made clear where MEP ends and the building element begins. For example, where hollow cores of floor elements are used as ducts for the ventilation system. D1.6's approach is that where systems are subject to performance tests, the component in that system needs assessment following the methodology in this document. Where it comes to connecting piping and duct systems being part of a (prefab) building element, the method of D1.4 applies.

Table 1: Limitations of this deliverable in T1.3

1.4 Positioning of this deliverable

This document, D1.6, is the first deliverable of task 1.3. For development, it relies on the input from some of the deliverables from other tasks, and consequently, its output will be used in, again, other tasks. This is shown in Figure 4. Generally, Task 1.3 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. De 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 Task 1.2 and Task 1.3.

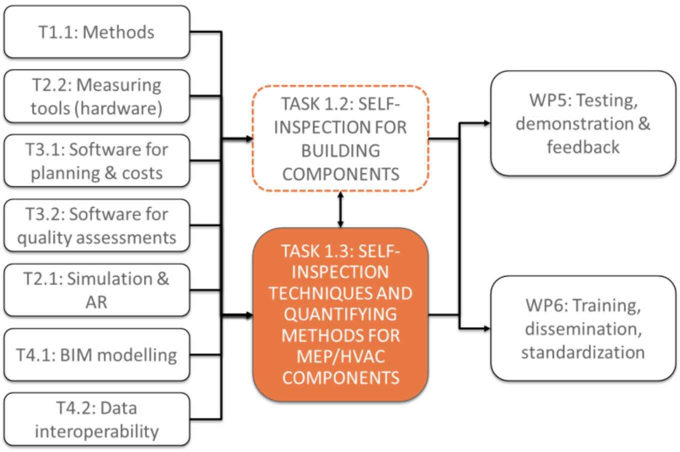

Figure 4: Input and output of task 1.3.

As D1.6 is developed in Task 1.3, D1.4 is synchronically developed in Task 1.2. Because of the similarities, the approach is equal. The content differs though, because of the differences between MEP/HVAC systems and building elements.

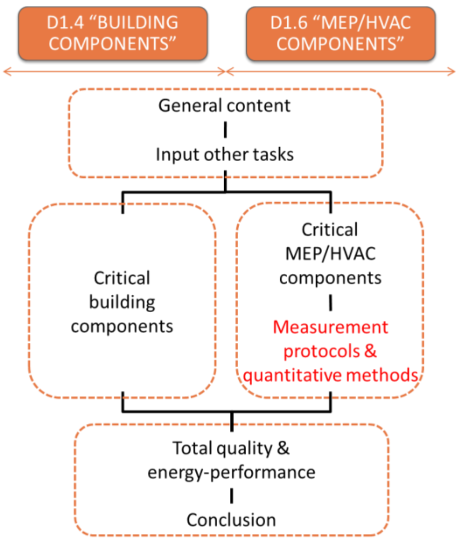

Figure 5: Development of and difference between D1.4 and D1.6

In Figure 5 the difference between D1.4 and D1.6 is shown, mainly concerning the 'Measurement protocols & quantitative methods'.

Finally, within Task 1.3 there are two deliverables to be developed: the present D1.6 and D1.7. D1.7 begins where D1.6 ends, focussing on evaluation and decision-making for the results from the analytical methods in D1.6. See 6 below for a visual explanation.

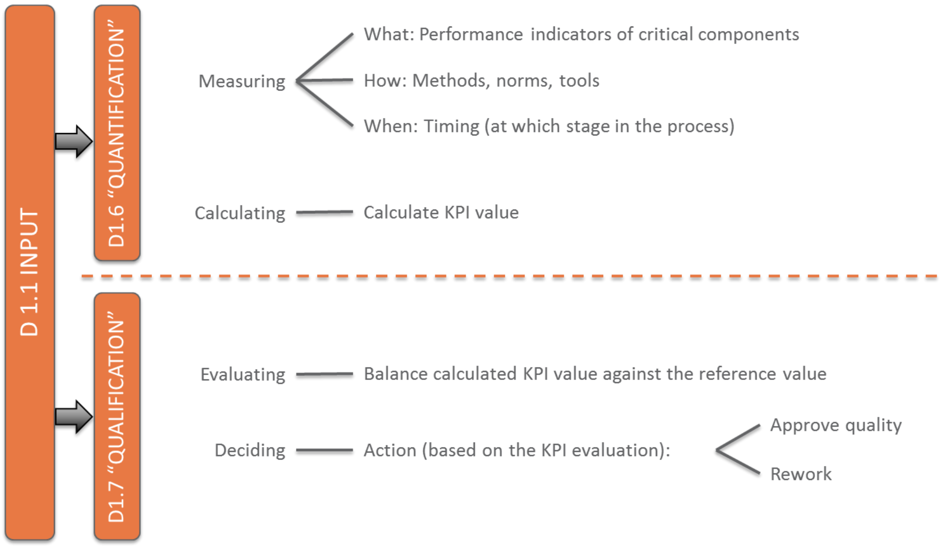

Figure 6: Successive development of D1.6 and D1.7 in task 1.3

2. Self-inspection process

2.1 Introduction

INSITER provides self-inspection protocols to assure building quality and energy performance during construction. These protocols differ from model checks and inspection for damages to full installation inspections, all to be carried out in different phases of the realization process.

Within the scope of INSITER, a faultless design is assumed, i.e. the realization phase starts with a perfect set of prefab components. And without any mistakes, the building will also be as faultless as the design is ('as build' is 'as designed'). Unfortunately, mistakes are being made throughout the process and therefore INSITER aims to minimize the errors by introducing smart self-inspection protocols.

INSITER approach will prioritise the prevention of common errors, which typically account for more than 50% of rework cost. By the model checking and self-inspection it is possible to minimize the errors or to fix the errors before the project delivery, but not all errors are relevant or sometime the effort to fix the errors is not justified with the error effect. The evaluation of the error effects will be possible with the support of BIM model and energy simulation software. However, within this task it is important to consider the expertise of the on-site workers and new developments.

2.1.1 Building process

INSITER's prefab building process from deliverable D1.1 is shown in Figure 7. With a red line is marked where the focus of the building elements methodology is set. The blue line marks the focus of T1.3 for MEP/HVAC components. Because the latter are hardly prefabricated, the components come straight from the factory or distribution centre and cannot be inspected or tested in the factory. After assembly on-site, the building elements are ready for final inspection. In case of MEP/HVAC components, the commissioning has still to take place and inspection/monitoring will be needed all through the final stages of construction and in-use (including maintenance).

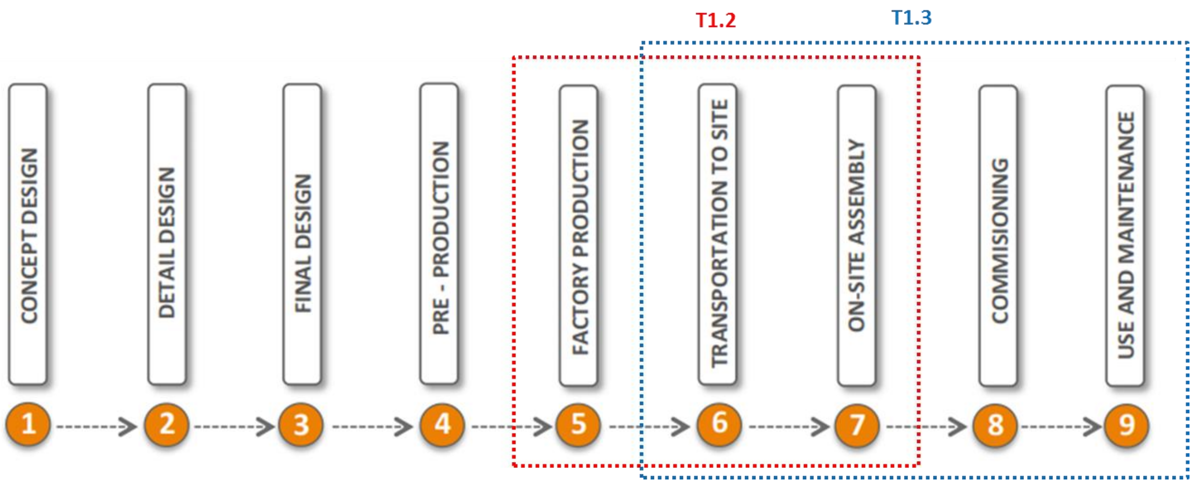

Figure 7: INSITER prefab building process and scope of T1.2 and T1.3

2.1.2 8-step methodology

According to the INSITER methodology, an 8-step process is defined, which is supported by the measurement and diagnostic instruments. These steps are also displayed in *Figure 8* and can be explained as follows:

1. Taking an accurate reference situation: Mapping the actual technical conditions of the site and building, and performing economic valuation of the property and land.
2. Selecting high-performance building components: Self-inspection at procurement, production, and delivery of prefab components.
3. Creating realistic models of buildings and sites and their performance target: Modelling of the building, site, and surroundings in Building Information Model (BIM).
4. Virtual validation of quality and performance in BIM: Model Checking and Clash Detection; as well as value and process optimisation by Virtual Reality simulations.
5. Intuitive use of Augmented Reality (AR) by workers on site: Generating and deploying BIM-based Augmented Reality (AR) for self-instruction and self-inspection.
6. Validating site conditions: Self-inspection during preparation of sites and logistics.
7. Validating preliminary results: Validating Self-inspection and self-instruction during construction / refurbishment / maintenance process.
8. Connecting performance target and user operation / behaviour: Self-inspection during pre-commissioning, commissioning, and project delivery; self-instruction for users.

In 8, a diagram is shown with INSITER's 8-step self-inspection methodology. Below the methodology, the 5 important phases of the realization process are shown in correlation with the 4 self-inspection steps. The fifth phase, use & maintenance are, in self-inspection terms, basically an extension to the commissioning. The diagram starts where the prefab building element is manufactured. Some inspections and tests will be done in the factory. On the contrary, inspections of MEP/HVAC components start on-site. The first checks will be done after transportation.

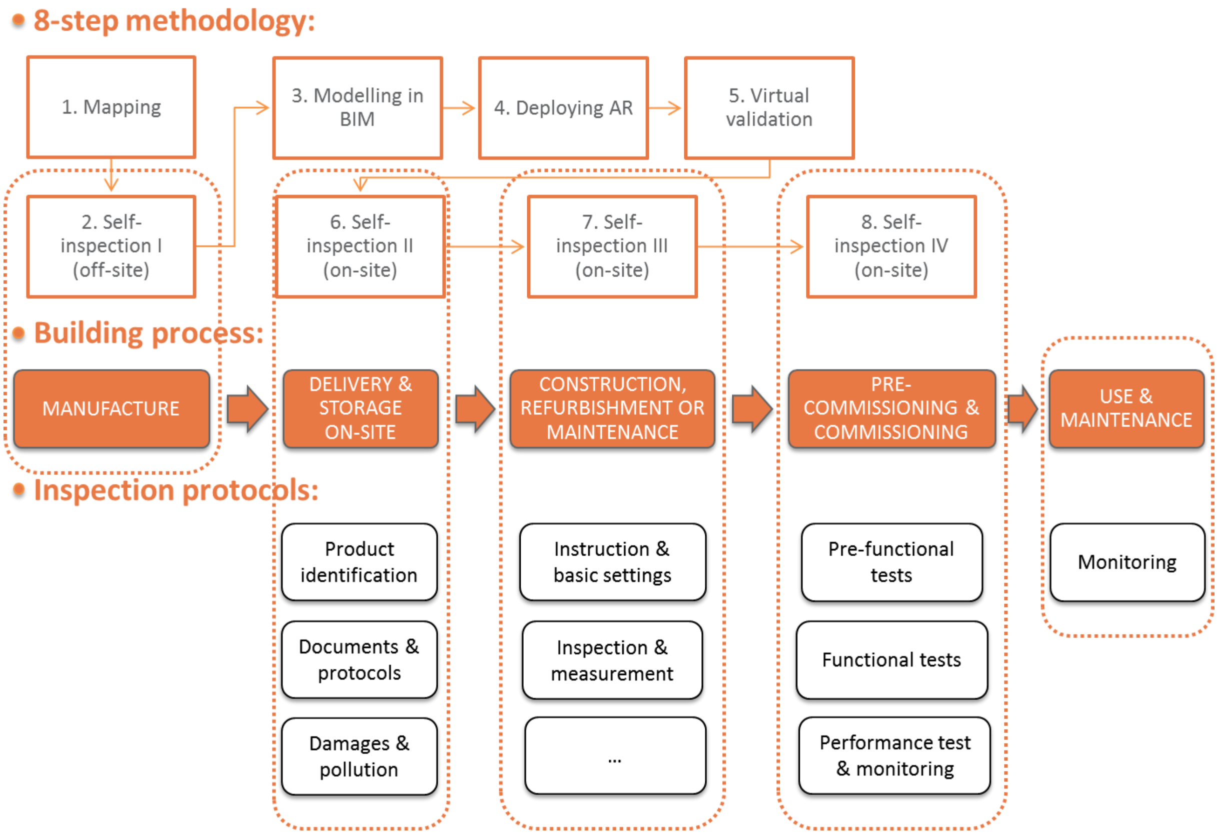

Figure 8: Inspections for MEP/HVAC components during the different building phases

Brief description of checks, to be further elaborated in chapter 4:

- Product identification: these checks cover all that is necessary to assure that the right element or component is delivered, including specifications, dimensions, quality certificates (if applicable), structural checks and performance checks.
- Documentation & protocols: Check that all elements and components are accompanied by the right documentation, including specific assembly instructions, manuals, and self-instruction protocols.
- Damages & pollution: Whenever the element or component is transported, damages can occur. So, it is appropriate to perform damage checks after every transit. Damage checks also cover checks for undesirable pollution (after storage).
- Instruction & basic settings: Preparing installation of HVAC components, collecting installation manuals & self-instruction guidelines. If applicable, predefined settings are applied for basic functionality.
- Inspection & measurement: Inspections and measurement verifications are performed to ensure that every component and every subsystem in a building is installed correctly and can start up and run properly. The inspection and measurement process aims at answering several questions, e.g.,
  - Is the right component installed?
  - Is the component properly installed? Also, the interaction and connection with building elements are considered.
  - Are the settings of the controller parameters correct?
- Pre-functional tests: Some (pre-) functional tests are committed to ensure correct installation and operation of

individual MEP components.

- Functional tests: Functions are tested by feeding them input and examining the output. Each individual test focuses on a slice of functionality of the whole system.
- Performance test & monitoring: This test focuses on the first performance of the whole system and building. If necessary, overall performance is recalculated and updated in the BIM model. Monitoring with appropriate monitoring software is started.

2.2 Input from other work packages

The building quality is a criterion that influences customer satisfaction with regard to the performance of construction projects.

Inspection is one of the most essential processes in quality control. It is the act of measuring or carefully examining a product's quality and preventing defects to assure that the final product meets specifications and fulfils the customer's requirements. This section focuses on the procedures for monitoring the conditions of the MEP/HVAC systems in buildings. Inspection of such systems is scheduled both during construction and during their life in order to guarantee that their quality meets the customer's requirements.

In the previous deliverable D1.1, a generic approach for MEP/HCVAC quality assessment (see Fig. 14 in D1.1) has been presented which can be applied at different stages of the life of the system (installation, use, maintenance). The approach establishes that the desired condition/project parameters must be verified, the discrepancies quantified, the maintenance plan and budget assigned (see Fig. 20 in D1.1). D1.1 identifies also the main MEP/HVAC components (section 3.1.2) that influence the building energy efficiency and the most common errors (section 3.2) faced by those components.

D1.6 focuses on a detailed analysis of the building systems to detect the most common errors when installed and induced during the in-use period and maintenance.

2.2.1 Relevant technical norms

We need some standards on which we can base:

- Inspection and test methods for components and (sub)systems,
- Measurement of KPIs and aspects, and
- Calculations needed for evaluation of the building quality and energy efficiency.

Ideally, some standards that apply in all European countries, e.g. European (CEN) and International (ISO) standards could be used as reference. All other standards can only be used to distract information for further elaboration in INSITER.

Main standards

In Figure 9 below, the main European standards for Energy Performance of Buildings and Indoor Environment are shown.

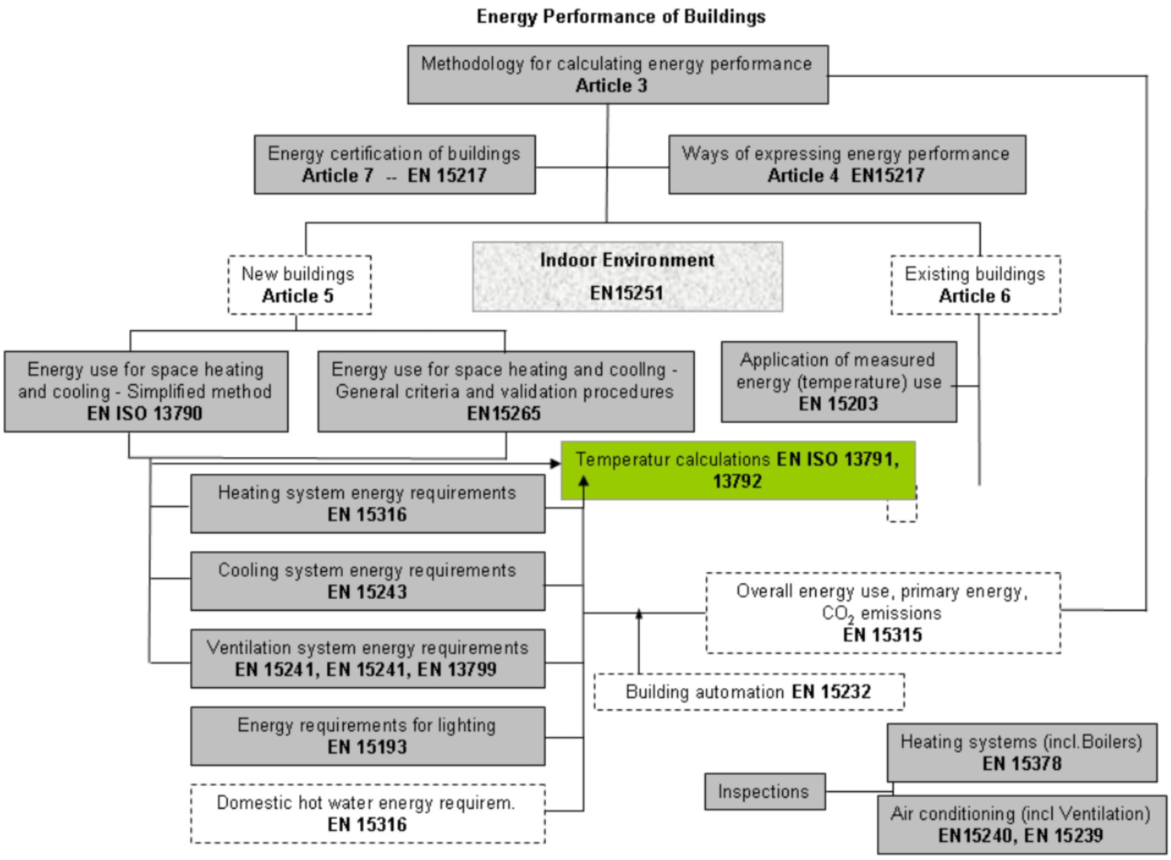

Figure 9: CEN Standards for Energy Performance of Buildings (CEN, 2007)

The Technical Committees of CEN for relevant standards are:

- CEN/TC 89 Thermal performance of buildings and building components;
- CEN/TC 156 Ventilation for buildings;
- CEN/TC 169 Light and lighting;
- CEN/TC 228 Heating systems in buildings;
- CEN/TC 247 Building automation, controls and building management.
- CEN/TC 264 Air quality

In

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Appendix 1 a list is given of all the technical standards that are used in this INSITER methodology.

2.3 Key Performance Indicators (KPIs)

In the previous deliverable D1.1, a preliminary list of KPIs is given. In this document the list will be further elaborated. At points where deemed necessary, the list is changed.

2.3.1 Energy Performance

The KPIs for the energy performance of the building and their relation to MEP/HVAC systems are listed in Table 2.

KPI	Measurement aspects	Measurement instrument
Heat transfer	Air leakage due to ventilation	Pitot tube flowmeter
	Heat recovery system efficiency	Resistance thermometer
Efficiency of heat/cold generation	Efficiency of a heat pump / chiller	Energy meter / monitoring
	Efficiency of an aquifer / ATES	Energy meter / monitoring
	Efficiency of the gas fired boiler	Energy & gas meter / monitoring
	Efficiency of hot water generation and storage	Energy meter / monitoring
Efficiency of heat/cold distribution	Efficiency of a heating/cooling distribution system	-
	Efficiency of a hot water distribution system	-
Energy use or production of electrical devices	Energy use of fans and drives	Energy meter / monitoring
	Energy use of pumps	Energy meter / monitoring
	Energy use of lighting	Energy meter / monitoring
	Energy production of photovoltaic panels	Energy meter / monitoring

Table 2: Energy Performance KPIs related to MEP/HVAC systems

Brief explanation of energy performance measurement aspects, related to MEP/HVAC systems:

- Heat transfer:
    - Air leakage due to ventilation: a measure of the air leakage caused by the ventilation, measured in lost volume per second [m^3/s].
    - Heat recovery system efficiency: the percentage of heat that is recovered by the HRE, in [%].
- Efficient heat/cold generation
    - Efficiency of a heat pump / chiller: the efficiency of a heat pump or chiller, displayed as COP or SPF
    - Efficiency of an aquifer / ATES: the efficiency of an aquifer (ATES), displayed as COP or SPF
    - Efficiency of the gas fired boiler: the efficiency measured in [%]
    - Efficiency of hot water generation and storage: the efficiency measured in [%]
- Efficient heat/cold distribution
    - Efficiency of system: the efficiency measured in [%]
    - Efficiency of hot water distribution: the efficiency measured in [%]
- Efficient energy use/production of appliances:
    - Energy use of fans and drives: the amount of energy that is used by the fan in [kWh] annually

- Energy use of pumps: the amount of energy that is used by the pumps in [kWh] annually
- Energy use of lighting: the amount of energy that is used by the lighting system in [kWh] annually
- Energy production of photovoltaic panels: the amount of energy that is produced by the photovoltaic panels in [kWh] annually

2.3.2 Indoor Environmental Quality

Indoor Environmental Quality can roughly be divided in four main aspects. Figure shows an overview of these aspect and the requirements from the 'building envelope' and the 'MEP/HVAC systems' point of view to manage their quality.

Measurement aspects	Draught rate Maximum and minimum air velocity Vertical air temperature Warm and cool floors Relative Humidity Radiant asymmetry	Luminance Color temperature UGR value Daylight factor LTA (Light Transmission Aggregometry)	Sound intensity field Sound pressure level distribution	CO_2 Emission from appliances and interior materials Air supply rates
Indoor environmental aspects	thermal comfort	visual comfort	acoustic comfort	air quality
Requirements for the building envelope	Thermal insulation Solar control Airtightness	Daylight Glare control	Acoustic insulation	Natural ventilation openings Airtightness
Requirements for the MEP/HVAC systems	Room temperature control Ventilation control	Sufficient lumination Correct lightsource Lighting control system	Silencers in ventilation system Low-noise components	Forced ventilation

Figure 10: Indoor environment measurement aspects and requirements for the building envelope and MEP/HVAC systems

For Indoor Environmental Quality, the following main KPIs are considered (Table 3).

KPI	Measurement aspects	Measurement instrument
Thermal comfort	Draught rate	-
	Air velocity	Air Velocity Meter
	Vertical air temperature	Thermometer
	Warm and cool floors	Thermometer
	Relative Humidity	RV meter
	Radiant asymmetry	Thermometer
Visual comfort	Illuminance	Lux meter
	Colour temperature	Colour temperature meter
	UGR value	Calculation based on illuminance
	Daylight factor	Calculation based on illuminance
Acoustics	Sound intensity	Sound level meter

KPI	Measurement aspects	Measurement instrument
	Sound pressure level	Sound level meter
Indoor air quality	CO_2 value	CO_2 meter
	Air supply rates	Air flow capture hood or Pitot tube flowmeter

Table 3: Indoor Environmental Quality KPIs related to MEP/HVAC systems

Brief explanation of indoor energy performance measurement aspects and their relation with MEP/HVAC systems:

- Thermal comfort:
  - Draught rate: the percentage of people predicted to be dissatisfied because of a draught [%]
  - Air velocity: the speed of air moving across a person, where the air is cooler than the environment [m/s]
  - Vertical air temperature: the temperature difference between head and ankles (1,1 and 0,1 m above floor), in degrees Celsius [°C]
  - Warm and cool floors: surface temperature of the floors, in degrees Celsius [°C]
  - Relative Humidity: is the ratio of moisture in the air, compared to the potential saturation level (100 %), in [%]
  - Radiant asymmetry: the asymmetric thermal radiation, calculated in percentage dissatisfied (PD), [%]
- Visual comfort:
  - Illuminance: the total luminous flux incident on a surface, per unit area [Lux]
  - Colour temperature: the colour temperature of a light source, in Kelvin [K]
  - UGR value (Unified Glare Rating): the level of direct glare from luminaires of a lighting system
- Acoustics:
  - Sound intensity field: is the sound power per unit area in a free field, in watt per square metre [W/m^2] and represented as a vector field in space.
  - Sound pressure level distribution: is a logarithmic measure of the effective pressure of a sound relative to a reference value, in weighted decibels [dB(A)], here represented as a function of space for sound source localisation purposes.
- Indoor air quality:
  - Carbon dioxide (CO_2): is a natural component of air, found in higher concentrations indoor than outdoor, because it is exhaled by people. It is used as an indicator for the pollution of indoor air. The unit of measurement is particle per million [ppm].
  - Air supply rates: is the amount of (fresh) air supply to a space, in volume per second [m^3/s].

Some European Standards to determine the performance and quality requirements are:

- CR 1752:1998 Ventilation for buildings - Design criteria for the indoor environment
- EN 12665:2011 Light and lighting - Basic terms and criteria for specifying lighting requirements
- EN 13142:2013 Ventilation for buildings - Components/products for residential ventilation - Required and optional performance characteristics

- EN 13779:2007 Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems
- EN 15193:2007 Energy performance of buildings - Energy requirements for lighting
- EN 15217:2007 Energy performance of buildings - Methods for expressing energy performance and for energy certification of buildings
- EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics
- EN 15665:2009 Ventilation for buildings - Determining performance criteria for residential ventilation systems
- EN ISO 11855-1:2015 Building environment design - Design, dimensioning, installation and control of embedded radiant heating and cooling systems - Part 1: Definition, symbols, and comfort criteria (ISO 11855-1:2012)
- ASTM Standard D-6245 – 12, "Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation," May 2012.

3. Critical MEP/HVAC systems affecting EeB performance

3.1 Introduction and scope

3.1.1 MEP/HVAC systems

HVAC stands for Heating, Ventilation, and Air Conditioning systems, while MEP (Mechanical, Electrical & Plumbing) covers the whole range of building services. Building services are the systems, installed in buildings that make them comfortable, functional, efficient, and safe. MEP systems are generally not part of the constructional elements of a building, but do interfere with the building envelope. Also, MEP components like piping and ducts can be integrated in (prefab) building elements. Within INSITER we focus on the installations that influence the indoor environmental quality and/or energy efficiency.

INSITER scope

Because not all building services have a large impact on the INSITER KPIs, or have any impact at all, we do not have to include all systems. Figure 10 shows the energy consumption in residential and commercial buildings. Both pie charts make clear that space heating is the largest energy consumer. In residential buildings water heating is also a major consumer, while lighting is of less importance. In commercial buildings, however, lighting is still of reasonable importance. The 'Other (16%)' part of commercial buildings is primarily made up by ICT appliances.

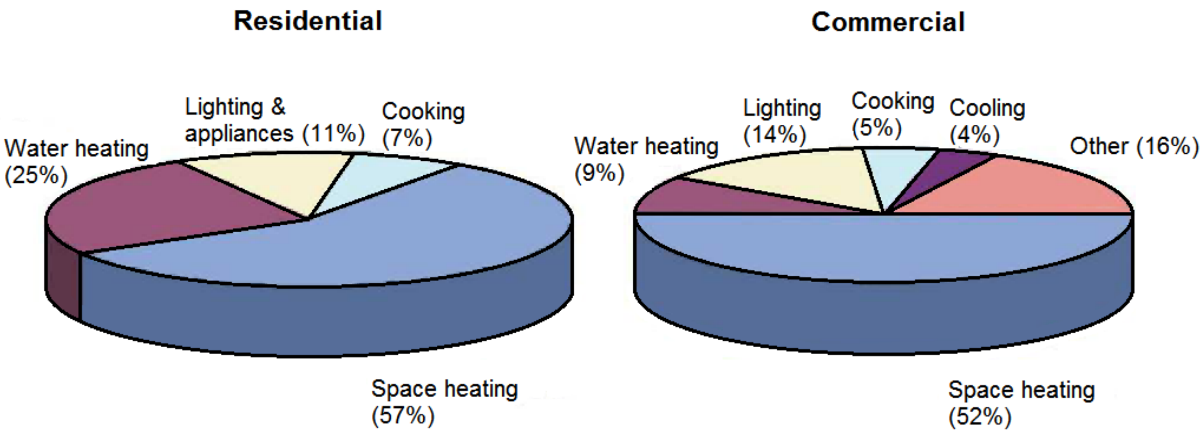

Figure 10: EU building energy consumption for residential and commercial buildings (National University of Ireland, 2014)

For indoor environmental quality, the comfort factors are influenced by multiple disciplines. For example, thermal comfort depends on the heating and cooling system of a building. But it is also influenced by the building envelope. If there is leakage of cold outside air through connections to building elements to each other or lead-through, discomfort can occur due to draught.

The INSITER KPIs are influenced by:

- Thermal comfort: Building envelope (thermal insulation, airtightness), heating, cooling, ventilation systems.
- Visual comfort: Building envelope (windows), lighting systems.
- Acoustics: Building envelope (acoustic insulation), large HVAC components, and appliances.
- Indoor air quality: Ventilation system, appliances (pollution).

Because appliances are not a part of the building design, the main influencers to INSITER's KPIs are

- Heating & cooling;
- Ventilation;
- Hot water;
- Lighting.

<u>System choices</u>

Following INSITER's Key Performance Indicators, the most important building services are heating & cooling, ventilation, hot water, and lighting systems. It is expected that 90% of the new buildings will be heated and cooled by heat pump systems and will be ventilated by a balances ventilation with heat recovery. For hot water systems, solar heating is widely spread and gaining more ground.

An estimation is made in Table 4 is made of the relevance of the most common MEP systems, based on its influence on the KPIs, the complexity of the system and the future proofing (probability of its appearance in the future). The three rates are multiplied and form an overall score. Of all systems, only one system concept is chosen. For example, for a heating system, heating with heat pumps is more relevant to INSITER than heating with a biomass boiler.

System	Influence	Complexity	Future proofing	Total
Heating w/ heat pump	80%	90%	90%	65%
Heating w/ biomass boiler	60%	70%	60%	25%
Heating w/ gas/oil boiler	60%	50%	10%	3%
Cooling w/ chiller	40%	50%	30%	6%
Mechanical ventilation	70%	70%	80%	39%
Natural ventilation	50%	20%	20%	2%
Electrical boilers	30%	10%	40%	1%
Solar hot water	50%	80%	60%	24%
LED lighting	50%	40%	90%	18%
Solar panels (photovoltaic)	50%	20%	80%	8%

Table 4: Relevance of MEP systems to INSITER

Based upon this diagram, research within INSITER is not limited to, but does have a focus on:

- Heating & cooling with heat pump systems;
- Balanced ventilation with heat recovery;
- Solar hot water systems;
- LED lighting systems.

Successive levels

To be able to perform correct analyses and inspections of MEP/HVAC systems, the system (heat pump system, ventilation system) needs to be divided into subsystems and components. In following order, from small to big, INSITER's methodology will perform inspections at the 3 successive levels:

1. Component level (inspection of critical components);
2. Subsystem level (verification of the performance of subsystems);
3. System level (measurement and calculation of the overall performance of the MEP/HVAC system).

Components and subsystems

An HVAC component is a device with a specific function within the HVAC system. Components are merely used for their function. They are fabricated in the factory and are generally delivered on site in one piece. Exceptions are large components like air handling units or cooling towers.

A subsystem is a set of interacting and interdependent components, forming a system itself, but also acting as a component of a larger system. E.g. heat generation, water distribution, air supply, heat recovery, water storage or heat delivery. Subsystems are traditionally installed on-site, but some parts like piping and duct systems can be (partly) prefabricated. The performance of a subsystem is influenced by every individual component.

3.1.2 Common errors in relation to inspections

Each component has a well-defined function inside the whole HVAC system. Any malfunction can compromise the correct behaviour of the whole system. The malfunction may be due to:

- Design faults
- Selection or sizing mistake
- Manufacturing fault or initial deterioration due to damages and pollution
- Installation fault
- Wrong tuning
- Control failure
- Abnormal conditions of use.

INSITER's focus is on common errors that occur during the realisation phase (so including work preparation by the construction company) can be bluntly categorized in four main categories:

05. The component is damaged or polluted
06. The wrong component is installed
07. The component is installed incorrectly
08. The component is provided with the wrong settings

The categories are encoded with a number. In combination with an abbreviation for the respective MEP/HVAC system, this will form a reference code to categorize construction errors. So, for example, H02 is the installation of a wrong component in a heating installation and L03 is the improper installation of a lighting component. For reference codes, see the list of subscripts in the pre-sections of this document.

01. The component is damaged or polluted

A component that is damaged or polluted can have a significant impact on the performance of the whole HVAC system. Furthermore, other problems with poor indoor environment or contamination can occur.

The inspection is purely visual. Though, it is important that the executor of the inspection is competent and knows where to put the focus.

- What: Visual inspection
- When: Before and after installation of a component, and another quick inspection before a component is sealed off, insulated, or covered by a construction element (for example a shaft or ceiling)
- Who: Construction worker

02. The wrong component is installed

If a wrong component is installed, the system may not perform the way it is supposed to do. Even minor differences can result in major deviations on performance aspects or building quality. For example, the performance of a heating system with heat pump depends on the consistency of the total system. If a slightly different model of heat pump is installed, this can cause major deflection on the performance of the whole heating system.

A wrong component can easily be detected by visual inspection. This needs to be done before installation, to prevent unnecessary costs. Time of inspection is right before the actual mounting of a component.

- What: Verification by making use of scanning device for QR codes
- When: Before installation of a component
- Who: MEP / construction worker

03. The component is installed incorrectly

Installing a component the wrong way can result in a major performance gap or a complete system stop. But it can also lead to minor deviations, hardly noticeable. For that reason, some components need inspections, others do not.

Because components need to be installed according to mounting instructions or manuals of the manufacturer, the inspection to follow is in line with the instruction. Check points can be the critical installation regulations. Time of inspection is right after a component is mounted.

- What: Visual inspection, making use of smart checklist
- When: After installation of a component
- Who: MEP / construction worker

04. The component is provided with the wrong settings

A component can be properly installed, but if the control settings are made wrongly, there’s a good chance the system will not perform like it should. For example, a distribution pump is correctly installed, but its parameter setting is wrongly executed or not executed at all, this can have major effect on the overall performance of the system.

Inspection means the verification of the parameter setting for the component

- What: Parameter setting verification
- When: After parameter adjustment
- Who: MEP worker or building control technician

Furthermore, there are problems that do not originate in the construction phase but earlier, for example during production of the components or during design.

05. Additional errors

Some errors occur because of design mistakes. The INSITER project does not aim to solve these issues, because an erroneous design cannot be corrected just by inspection protocols. But the proposed method can prevent some of the design issues. Namely when the component does not meet its specifications or the design is insufficiently detailed.

<u>The performance of a component is insufficient</u>

On regular occasions the components in practice do not meet the specifications of the manufacturer. This is often the case with heat exchangers and coils. Deviations can occur because the performance specifications are only specified for full load operations, while in practice, it is more common to operate in partial load. The component meets the requirements of the design, but it's performance does not. To avoid these issues, the purchaser can ask the supplier to provide proof that his product meets its specifications. If not, INSITER's protocols will expose the errors.

- What: Measurement of performance/capacity
- When: During commissioning
- Who: Commissioning engineer

<u>Unintentional mismatch of components</u>

If a design is insufficiently detailed, for example by selecting components using the rule of thumb, the result might not be the best. Performance gaps arise because of the unintentional mismatch of components. Sometimes this leads to minor deviations, but can also lead to major discrepancies. One way to avoid the problem is to check the design for the lack of details. Where this is not possible, or for any reason is not carried out, INSITER's protocols will expose the errors.

- What: Measurement of performance/capacity
- When: During commissioning
- Who: Commissioning engineer

3.1.3 How to deal with construction errors and component that are not yet defined in INSITER

Construction errors

INSITER's methodology describes common construction errors and how to deal with them. In basics, the list of construction errors is endless and INSITER's focus is on errors that have a significant impact on the building quality and energy performance.

All construction errors are categorized, see section 3.1.2. From these categories, all errors can be classified and used in INSITER's methodology. For well-known construction errors, this has already been done. But it is crucial that also newly identified construction errors can be implemented in INSITER. The procedure is standard:

1. Identify the construction error as a frequent error. Errors that occur rarely are inevitable and hard to prevent. To introduce more errors to the INSITER methodology means more work and can have a significant impact on the time and money management of a building process. Therefore, the focus should stay on frequent errors.
2. Identify the construction error as an error with significant impact on the building's energy performance and/or indoor environmental quality. For the same reason as number 1, it is undesirable to introduce all errors in INSITER.

The focus is on errors with a significant impact.

3. Determine what MEP/HVAC component causes the error or is affected by it.
4. Perform all the INSITER inspections necessary to eliminate the error (see chapter 4). Inspections can be on component level, but also subsystem or system level, wherever the component is part of.

Components

The same approach applies if new components are used. In this document we have described the most common components in MEP/HVAC systems, but not all components that are used in building installations. This is for the same reason as mentioned above, to prevent INSITER's methodology to become excessively comprehensive. It is possible though, that developments with relatively new techniques will be increasingly applied. Also, national regulation in European countries or grants can contribute to an increased usage of a certain component. In that case, it can be desirable to have the component implemented in INSITER. The standard procedure is:

1. Identify the component as a critical component. Only critical components are worthwhile embedding in INSITER's methodology. It is undesirable to have all components, because the method would become too comprehensive. Critical components are those that have a substantial influence on the building's quality and energy performance.
2. Identify the weaknesses of the component and its sensitivity to errors. For components, though critical, that are usually installed flawlessly, there is no need for inspection.
3. Determine and sum up the construction errors with a consequential impact on the building quality.
4. Perform all the INSITER inspections necessary to eliminate the error (see chapter 4). Inspections can be on component level, but also subsystem or system level, wherever the component is part of.

3.2 Heat pump system

3.2.1 Introduction

Heat pumps are one of the most efficient heating and cooling systems on the market today and expected to be the number one heating system in the future. A high efficiency is reached through the principle that in a heat pump most of the heat or cold is moved rather than generated. Moving heat requires a source to move this heat from. Generally, the outside air or aquifer thermal energy storage (ATES) is used as a heat and/or cold source depending on the geographical region and climatological conditions and demand. The outside air varies with the seasons, with the disadvantage that when heating is required the source (outside air) is at a low temperature. An aquifer thermal energy storage (ATES) system stores cold during the winter period to be released for cooling during the summer period. The other way around heat is stored during the warm summer period and is used to heat the building during cold periods.

In winter, a heat pump is used to bring the low temperature from the source to a higher temperature for space heating. During the summer, if an ATES is used, the source is sufficiently cold to be used for space cooling directly, when the outside air can be used as a source the heat pump operates as a cooling machine. At periods of low demand a buffer tank is used to store the excess of heat or cold generated by the heat pump, this prevents short cycling of the heat pump while allowing for a continuous supply to the distribution circuit. For peak heating demands, often a gas-fired boiler is added, either to limit the size of the heat pump, or compensate for periods where the source (outside air) is unable to provide sufficient heat. In the near future, though, more gasless buildings will be constructed.

The heat or cold is transported to the terminal units throughout the building by the distribution system. A heat pump system is suitable for low temperature heating and high temperature cooling systems, meaning that terminals units should be designed in accordance. A typical supply temperature for low temperature heating is 30-35°C, for cooling this is 10-12°C.

3.2.2 Critical components

The critical components described are the main components of the heat pump system. For the heat pump itself, the components are discussed separately. To give a complete description of key components and their functionality independent of the manufacturer the critical components inside the sub systems are described separately. The main components are:

- Heat pump (Compressor, evaporator, expansion valve and Condenser)
- ATES (Well, source pump, heat exchanger)
- Gas-fired boiler
- Distribution circuit
- Buffer tank
- Control system

The distribution circuit and the control system are most sensitive to errors because they are custom systems, designed especially for one specific building. Components such as the gas-fired boiler and heat pump are mass produced components that only must be connected the system on-site (note that the design and sizing of the components is considered flawless in the design). Errors mainly occur during the administering of the correct setting of the components and cooperation of components through the control system.

Heat pump

A heat pump moves heat from the source to the distribution circuit and adds heat through compression. The working principle is based on the transfer of latent heat and the dependence of the boiler temperature on fluid pressure. A heat pump is composed of four main components (compressor, expansion valve, condenser, and evaporator) that are discussed separately below. Because most the heat is moved instead of generated, a heat pump has a high efficiency. To do so a heat or cold source is needed, generally, this is the outside air or an ATES system.

<u>Compressor (heat pump)</u>

The compressor is located inside the heat pump and pressurizes the refrigerant. As a result, the boiling point of the medium rises. The medium is compressed until it reaches a superheated state. To prevent damage to the compressor, it is important that the refrigerant is in a completely gaseous state before entering. To ensure life expectancy, the cycle time of the compressor should be kept sufficiently long. The compressor is the main energy-consuming component in the heat pump, efficiency of the compressor has a large effect on the efficiency of the total system. Usually compressors are only limitedly controllable.

Condenser (heat pump)

In the condenser and surrounding piping, the high-pressure superheated gas is cooled down to its boiling temperature. The phase transition to liquid transfers heat to the surrounding. When the transport medium is completely condensed, the liquid state refrigerant is subcooled to ensure that no gas arrives at the expansion valve. The condenser contains a heat exchanger that uses the transport medium of the building or the heat source for cooling the refrigerant depending whether the heat pump is used for heating or cooling. The heat released during the phase transition of the refrigerant is transferred to the transport medium.

Expansion valve (heat pump)

In the expansion valve, the pressure of the high-pressure subcooled refrigerant is reduced. This causes the boiling temperature of the refrigerant to drop.

Evaporator (heat pump)

In the evaporator, the subcooled, low-pressure refrigerant that is leaving the expansion valve is heated by the surrounding to its boiling point where its phase changes to gas. During this phase change, heat is absorbed from the surrounding. After the refrigerant is in a completely gaseous state, it is super-heated to prevent any liquid from entering and damaging the compressor.

The evaporator contains a heat exchanger that uses the transport medium of the building or the cold source for heating the refrigerant depending whether the heat pump is used for heating or cooling. The heat absorbed during the phase transition of the refrigerant is extracted from the transport medium.

Relevant technical standards:	– EN 15316-4-2, EN 13613, EN 15450, EN 378-2, ISSO 81, EN 14511,
Common errors:	– H03: The heat pump is installed incorrectly, supply and return flows are interchanged
	– H03: Construction errors in the distribution circuit
	– H04: Incorrect settings of the controller parameters
Affected KPIs:	– Efficiency of a heat pump / chiller
Measurement aspects:	– SPF
	– COP-heating of the heat pump
	– COP-cooling of the heat pump

Hot source & Cold source (ATES)

An aquifer is a permeable layer of sand containing water. The layer is vertically separated by impermeable layers that typically consist of clay. The hot and cold source can be located at different depth in different aquifers or in the same layer with a certain horizontal distance in order to prevent short-circuiting. A source consists of a well drilled into the ground, typically to a depth of 30 m to 150 m. Where a perforated tube injects or extracts the ground water from the aquifer making use of a pressure difference inside the well. For this purpose, the well is closed off at the top. In the summer period, cold ground water is extracted from the aquifer and used to cool the building. The heat that is extracted from the building it is transferred to the water and inserted in the hot source. During heating season, the hot ground water is extracted from the hot source, when the heat is transferred to the building the cooled water is in turn injected in the cold source.

Source pump (ATES)

Both sources contain a separate source pump. This pump creates a pressure difference inside the well to extract the water from the aquifer and pumps the water through the heat exchanger to the opposing source. The pump is located permanently under water. When water from the source is extracted, the low pressure inside the well results in a rise of the water level. When water is inserted in the source, the high pressure in the well will result in a fall of the water level.

Heat exchanger (ATES)

The water that is extracted from the source is not used in the building itself, instead the heat is transferred to the transport fluid of the distribution circuit with a heat exchanger. This has multiple reasons, the water from the well can be corrosive (salt, oxygen) or polluted and might form flakes or bubbles when under low pressure. Furthermore, the ATES is not a closed system, pumping the water to higher floors would require a substantial amount of energy. The heat exchanger is typically a counter flow heat exchanger for its high efficiency.

Relevant technical standards:	–	BRL 11000-11001, ISSO 39
Common errors:	–	H03: One of the supply and return pipes of a counter flow heat exchanger are interchanged. The heat exchanger still exchanges heat, however, since the flows are not in the opposite direction the efficiency is severely decreased.
Affected KPIs:	–	Efficiency of an aquifer / ATES
Measurement aspects:	–	SPF
	–	Aquifer flow rate
	–	Aquifer pressure
	–	Efficiency of the heat exchanger

Gas fired Boiler

A gas-fired boiler is often used to satisfy the peak heating demand. When the heat pump has to satisfy the peak demand, it will become very large. The result of a large heat pump is a decrease in efficiency at periods of low demand and a high initial investment. The gas-fired boiler only operates when the heat pump operates at full capacity. It is important that the return temperature to the gas-fired boiler is sufficiently low to allow condensation of the exhaust gasses. Without condensation, the efficiency of the boiler is strongly reduced. This applies to the distribution system but also to the temperature regulation system, mechanisms where heated water is mixed with the return water should be prevented.

Relevant technical standards	–	NEN-2767-2, EN15378, EN15316-4-4

Common errors:	–	H04: Incorrect settings of the controller parameters
	–	H03: The gas-fired boiler is installed incorrectly. For example, supply and return flow are interchanged, for either the fume exhaust or hydraulic circuit.
Affected KPIs:	–	Efficiency of the gas fired boiler
Measurement aspects:	–	Total gas consumption

Distribution circuit

The distribution circuit takes care of distributing heat or cold trough the building and between different components. The system exists, among others, of pipes, fittings, pumps, control valves, adjusting valves, buffers and pressure regulators and generally uses water as a transport medium.

Because of the different system characteristics, system layout and demands of each building the distribution circuit is designed especially for each building. This lack of standardisation in manufacturing and installation makes the distribution circuit prone to errors. Furthermore, the system is complex and settings of components vary depending on the operating mode and momentary demand.

For the terminal units to create a comfortable indoor climate it is important that the circuit is sufficiently balanced. This means that the water flow to each individual terminal unit is in accordance with the portion of the heating demand in which it has to fulfil. Furthermore, the selection of pumps and valve settings has a large influence of the energy used for heat distribution.

To achieve a high efficiency of the heat pump and boiler, and keep the flowrate (and therefore size) low, it is important that the temperature difference over the circuit is sufficiently high. Short circuit situations where heated or cooled water from the supply flow is transferred to the return flow without being used for heating or cooling should be avoided at all times.

Stratified buffer vessel

Essentially the buffer vessel is part of the distribution system. Because it is often regarded a separate key component it is discussed separately here. Performance is indicated within the working of the distribution circuit no additional KPI is specified. The buffer vessel is a short time energy storage system. The demand for short time heat storage exists because of the required cycle time of the compressor and limited controllability. During the operating time of the heat pump, the buffer tank is charged. When the tank is completely charged the heat pump stops operating and the buffer tank is discharges in order to provide heating or cooling for the building. It is important that the buffer is of sufficient size and is sufficiently stratified to supply heat or cold when the heat pump is terminated to allow a long cycle time for the heat pump. The water that is injected last should be extracted first; this is possible because of the stratification (hot at the top/ cold at the bottom.

Relevant technical standards:	–	NEN 1006

Common errors:	–	H02: The wrong component is installed
	–	H03: Pipes are not properly insulated or the insulation is damaged. This may result in condensation and corrosion.
	–	H04: Inaccurate balancing of the hydraulic circuit. For example, when a short circuit pipe is installed around a condensing gas fired boiler. When heated water is mixed with the return water, the temperature can rise to such levels that no condensation can occur.
	–	H01: Flow through a component in the circuit is obstructed.
	–	H04: Incorrect settings of the controller parameters
	–	H03: There is leakage in the distribution system
	–	H03: Pipes are connected in the wrong location causing clashes with other components
	–	H03: Valves are mounted or wired the wrong way around
	–	H01: Pipes are damaged “stepped on” during construction
	–	H03: Buffer tank is connected upside down, hot at the bottom and cold at the top
	–	H04: The buffer is overcharged or discharged to deep, shot-circuiting the supply and return flow.
Affected KPIs:	–	Efficiency of the distribution system
Measurement aspects:	–	N/A

Control system

The control system controls the components in the heating system. For example, valves, regulators, and pumps but also the boiler, heat pumps and ATES systems. The control system determines which way the water flows in the hydraulic circuit but is, among others, also responsible for charging the ATES, use of preferred heating devices, realising supply, and return temperatures. Because each heating installation has a different layout and different components, the controls are programmed specifically for each building. The controls system gets its information from a large number of sensors that are connected. The control system is generally incorporated in the building control system together with controls of among others, the ventilation system. The Control system controls the heating and cooling installation based on information from sensors throughout the installations. These sensors can be individual components placed in the distribution system or sensors embedded in for example the heat pump.

Part of the control system is outside of the scope of INSITER because it is programmed and built outside of the building process and can be considered a purchased component. However, during construction and commissioning a large number of parameters will be set in the control system, determining the correct operation of the MEP/HVAC systems.

Relevant technical standards:	–	N/A
Common errors:	–	H04: Settings are applied incorrectly, or sub-optimally.
	–	H03: Connections of different sensors are mixed up
	–	H02: Defaulted sensors
	–	H03: Sensors are installed in the wrong place for example: For example, a flow sensor that is installed right after a bend will not return the correct flowrate.
	–	H03: Sensors are installed the wrong way, for example there is no thermal paste applied around temperature sensors located in thermo-wells. As a result, the sensors response time will severely decrease.
	–	H04: The system is insufficiently controlled for return temperature
	–	H04: Buffer vessel is overcharged or over discharged causing short circuiting
	–	H04: The ATES is insufficiently charged
	–	H04: The preferred heating device is insufficiently used
Affected KPIs:	–	Vertical air temperature
	–	Warm and cool floors
	–	Radiant asymmetry
Measurement aspects:	–	Air temperature in the room
	–	Surface temperature of floors
	–	Radiant asymmetry

3.2.3 Difficulties in assessment and analysis

In many cases the functional test of components are dependent on the completion of the system. For example, the distribution system must be largely completed before being able to perform functional tests on the heat pump. As a result, a large part of the inspections moves towards the end of the construction process. This is in contrast with the desired self-inspection process where the construction worker immediately inspects his work upon completion.

Furthermore, the system is dynamic with respect to the seasons and dependent on environmental factors. In other words, the behaviour and response of the systems depends on the operating mode and temperature in the building. Efficiency of the heat generation is largely dependent on the temperature difference over the supply and return flows of the distribution system.

3.2.4 Measurement of performance

Evaluation of the performance of the heating and cooling system requires measurement data. Most of the measurement equipment necessary for gathering this data is already present in the various components of the distribution circuit. This is used for measurement and control of the system. Sensors are connected to the building control system and measurement results can be logged, viewed, and exported from the control system.

Some tests require additional testing equipment. Pressure leakage test on the distribution circuit requires a measurement system that pressurizes the system and measures the dissipation of pressure over time. Testing of the distribution circuit and control system requires additional, currently non-existing methods for testing the various operation modes and responses of the control system to internal and external influences.

Water tightness of the distribution system

When: During construction

Verification of: Pressure drop of the piping system (Δp in Pa)

Measurement tool(s): See relevant standard

Tolerance: To be determined in D1.7.

Description: The distribution system is pressurized to detect leakage in the distribution system. Pressure test is performed in accordance with NEN 1006 –(Wb 2.3) of UFGS 23 64 26. The tests are performed when the section of the distribution circuit is installed but still accessible to repair any leakages.

3.2.5 Calculation of KPIs

The performance of a heating and cooling installation is assessed based on both energy performance and realised comfort. Additional criteria such as conformity with permits and regulations are generally based on either of the two assessment criteria (For example, environmental performance is an additional assessment criterion but this falls outside of the scope).

The performance assessment is based on KPIs. The main indicators that express performance on system level are the used amount of energy per square meter and indoor temperature. The total amount of energy used for space heating and cooling per square meter is determined based on the design and weather conditions using simulations. The actual energy use is measured and logged in the building control system. For comfort, the KPI for the heating and cooling system is the indoor air temperature as opposed to the set point. Where the set point is used because it is the value the heating system tries to approach, the deviation from the set points indicates the system's ability to do so.

Level	KPI (Energy)	Description
System	Electricity consumption	Total electricity consumption of the heating and cooling system [kWh]
	Gas consumption	Total electricity consumption of the heating and cooling system [m³]
Subsystem	ATES	SPF (seasonal performance factor) [-]
		Aquifer flow rate [m³/h]
		Aquifer pressure [kPa]
	Heat exchanger	Efficiency of the heat exchanger [%]
	Boiler	Efficiency of the gas-fired boiler [%]
	Heat pump	COP-heating of the heat pump [-]
		COP-cooling of the heat pump [-]
	Distribution circuit	Water tightness of the distribution system

Level	KPI (Comfort)	Description
System	Comfort	Indoor air temperature [°C]

Table 5: KPIs for heating systems

The KPIs related to energy are specified on three cascading system levels. The top level is the total performance containing all subsystems and components. When the energy consumption of the total system is within the specifications from the simulations, the overall systems function as designed regarding energy efficiency. This does not necessarily mean that all subsystems and components function as specified. Energy performance of the subsystems can be assessed individually; similarly, components can be assessed individually. Each KPI is described where the time of evaluation, source for verification and maximum deviation are discussed. Different KPIs are assessed in different phases of construction. The total system indicators can only be assessed when the building is finished and use for a certain period. In an earlier stage, the performance of the subsystems and components can be assessed. The required measurement equipment is already built in the hydraulic system for monitoring and control purposes.

The performance of critical components is embedded in the KPIs on subsystem level. Although the Distribution circuit and Control system are critical components, their performance is only embedded in the system level KPIs and the quality of connections and seals is tested for water tightness. When the system level KPIs are up to their respective predicted levels, the control and distribution systems perform up to measure. The distribution circuit and the control system are heavily interdependent. The behaviour is complex and dependent on many external variables but also their own behaviour in the preceding period. This makes the systems unfit to be described by a simple KPI.

The expected behaviour changes with changing operating modes. A way of testing would be created if the control system would allow for test scenarios. In these scenarios, the control system overrules the sensor data with data compliant with the scenario. The response of the system can then be compared to the response anticipated in the design. However, such a system is currently not commercially available. This way not only the control system is checked but also the distribution circuit. For example, when a valve is opened further, the flowrate in the pipe should increase. If the flowrate is contra-proportional to the valve setting, the vale is closed instead of opened. This logical behaviour can be checked, and if it checks out this means both the distribution circuit and control system are built according to their design.

Total electricity consumption [kWh/m²]

When: After 1 year of operation

Verification: Expected electricity consumption from dynamic simulations using weather data from the same period

Measurement: Combined kWh meters for individual installations or grouped installations

Max deviation: 5%

Description: When the total electricity consumption of the heating and cooling system is compared to simulated electricity consumption, an overview is obtained of the performance of the total system. Normalisation based on the floor area of the buildings allows for better understanding and inter building comparison. The electricity consumption is measured according to directive 2014-32-eu (MID - measurement instrument directive). The indicator is very broad as it applies to the entire heating and cooling system. A value in accordance with the expectation indicates a good performance of the system. However, it does not necessarily mean that each individual component has a good performance. Note that the influence of user behaviour needs to be acknowledged.

Total gas consumption [m³/m²]

When:	After 1 year of operation
Verification:	Expected gas consumption from dynamic simulations using weather data from the same period.
Measurement:	Combined gas meters for individual installations or grouped installations
Max deviation:	5%
Description:	When the total gas consumption of the heating and cooling system is compared to simulated gas consumption, an overview is obtained of the performance of the total system. Normalisation based on the floor area of the buildings allows for better understanding and inter building comparison. The gas consumption is measured according to directive 2014-32-eu (MID - measurement instrument directive). The indicator is very broad as it applies to the entire heating and cooling system. A value in accordance with the expectation indicates a good performance of the system. However, it does not necessarily mean that each individual component has a good performance. Note that the influence of user behaviour needs to be acknowledged.

Air temperature in the room

When:	During commissioning / use
Verification:	Temperature set point
Max deviation:	0.5^0 C / 1^0 C (depending on the quality demand of the owner)
Description:	The air temperature in a room is measured and compared to the set point for indoor temperature that applies to that room. The heating and cooling system should be able to keep the room on the set point temperature during different weather conditions both at very high of very low outside temperatures. Temperature measurement can be performed with sensor present in that space when the control system is evaluated (i.e. to asses if the control functions this is the value it tries to approach). Additional measurements to ensure correct placement and functioning of the sensors can be conducted with additional measurement devices.

SPF-heating (seasonal performance factor) [-]

When: After 1 year of operation

Verification: design criteria / permit

Max deviation: Permitted SPF is minimum demand

Description: The seasonal performance factor is a measure that relates the supplied heating and cooling energy to the consumed electrical energy or equivalent gas energy, like the COP for a heat pump. The difference is that in the Seasonal performance factor all systems related to the Heat pump system and ATES are considered. For example, source pumps and dry coolers for regeneration of the cold source. Heat Generation of a gas-fired boiler is not taken into account because there is no direct relation to the ATES. The SPF is determined according to EN 15316-4-2.

$$SFP_{bes} = \frac{Qw_{bes} + Qk_{bes}}{E_{bes} + G_{bes}}$$

Where,

Qw_{bes} is the heat delivered to the building,

Qk_{bes} is the cold delivered to the building,

E_{bes} is the electricity used by the ATES (including all related systems), and

G_{bes} is the electrical equivalent of the gas used by the ATES (including all related systems).

Efficiency of the heat exchanger [%]

When: During commissioning

Verification: Specifications supplied by the manufacturer for the current operating conditions

Max deviation: 5%

Description: The efficiency of the heat exchanger is the amount of energy that is transferred from the primary to the secondary side as a percentage of the theoretical maximum where the secondary outlet flow equals the primary inlet flow. Determining the efficiency required measurement of the temperature difference over both the primary side and secondary side, together with the flowrate trough both the primary and secondary side.

Efficiency of the gas fired boiler [%]

When: During commissioning / operation

Verification: Simulation results

Max deviation: 5%

Description: When a gas-fired boiler operates at optimal conditions, the efficiency will be close to the predictions made during simulations. Efficiency is depending on the operation and therefore several factors among which are the load and load profile. Simulations should be performed using the weather data of the measurement period.

The efficiency of the gas-fired boiler can be determined using the used amount of gas measured on a flow meter in the gas pipes and a delivered power using temperature difference and flow over the boiler.

COP of the heat pump [-]

When: after one year of operation

Verification: according to specification of the manufacturer

Max deviation: 5%

Description: COP of the heat pump is a measure of efficiency. Dividing the provided heat power by the consumed electric power yields the efficiency in the form of a Coefficient of performance. The COP is dependent on the temperature difference between supply and return temperatures of the distribution network, and it changes depending weather the heat pump works at full or partial load. The COP should be specified by the manufacturer both in full load and at partial load. Determination of the COP takes place in accordance with EN 14511 or NEN-EN 14825.

Aquifer flow rate [m³/h]

When: realisation

Verification: Design criteria

Max deviation: Minimal value

Description: A sufficient amount of ground water should be extractable from the sources. To do so, the filters should be clean and the soil sufficiently permeable. Measurement is executed for both sources and is a flowrate measurement at the maximum operation condition of the source pump. The source should be able to meet the design flowrate while within the design limit for the water level in the well.

3.2.6 Self-inspection for heat pump systems

Self-inspection and self-instruction takes place on three successive levels, component level, system level and subsystem level. On component level answering the three aforementioned questions: Is the right component installed, is the component properly installed and are the settings of the controller parameters correct? This three-step methodology is explained in section 3.1.2 also the conceptual self-inspection protocols are given and explained. These processes for identification of products, verification of their location and retrieving of optimal settings are uniform for different installation types such as heating and cooling, ventilation, lighting, or solar hot water systems.

On subsystem and system level, installation specific self-inspection is done using the aforementioned KPIs specific to the installation type. For KPIs to have meaning, they should be compared to reference values or demands that are either obtained from legal requirements, minimum demand or from building performance simulations.

Reference values

Calculation and simulation tools support the INSITER method for self-inspection. The tools provide settings for self-instruction, reference values for self-inspection and decision support when issues arise. The main reason for simulating is to obtain insight in the building's performance in the design phase. In turn, this insight can be used to optimize the design. The performance of different design variations can be compared to arrive at an optimum, depending on the wishes or demands. The INSITER method focusses on the construction process; here simulation can be of additional value in assessing the effect of deviations from the design that arise during construction. The effect on the energy efficiency and comfort related KPIs returned by the simulations, supports the decision-making process. The main application of calculation tools for hydraulic systems is to calculate the size of components. For INSITER to provide reference values for correct commissioning of systems, calculations must go a step further and calculate the optimal settings as well as simulate the effect of deviations.

Ideally, the simulation and calculation tools are implemented in BIM to prevent repeating the same input in different models. The other way around the simulation tools should be able to store information in and alter the BIM. Currently the state of the art in simulation and BIM has not arrived at this point jet. The following subsections, give an overview of what is required from the BIM and the simulations tools for the INSITER self-instruction and self-inspection processes. Furthermore, the capabilities and limitations of current widely used calculation/simulations software is described.

Simulation software should return:

- Reference values for performance indicators. (building performance)
- Impact of deviations on the performance (decision support system)

Calculation software should return:

• Component sizes:	pipes, pumps, valves, pipe connections	Hydronic system optimisation
• Component settings:	pumps, valves, subsystems	Hydronic system optimisation

To support the heating and cooling installation different simulation/calculation tools can be used. Both simulation and calculation software packages are described with different functionality, level of detail and integration options. Connecting to BIM remains an issue for building performance or installations calculation or simulation software. The main reason is the different approach to installations. In BIM, the installation consists of objects and relations between these objects, in most calculation or simulation software installations are represented by their concept or working principle.

Hydraulic system optimisation

Self-instruction and Self-inspection in commissioning the building requires reference values. This reference is supplied by virtually testing, optimizing, and commissioning the building. This hydronic system optimisation tool returns the optimal sizes and settings of the hydronic system, such as pipes, pumps and valves but also test the control strategies of the installation. These settings are to be stored in the BIM and serve as self-instruction and reference for self-inspection for the on-site worker who administers the settings to the component. The hydronic installation is modelled during de design phase. This phase falls outside of the scope of INSITER. However, modelling is a precondition to be able to execute the self-instruction and self-inspection processes defined in the INSITER method. The simulation of hydronic systems using hydronic system optimisation software is not yet common practice. Software to this extent has currently a limited commercial availability. Hydronic system optimisation is currently not standard practice.

<u>HYSOPT</u>

HYSOPT is a hydronic system optimisation tool used to optimize, balance and virtually test the hydraulic system and calculate the optimal sizes and settings of components during the design phase. The software is web/cloud based and developed by HYSOPT N.V. a spin-off from the University of Antwerp. The software is currently unable to connect to a

BIM or read files in *.IFC format. The model must be made, run, and maintained separate from the BIM. The optimisation results and optimal settings can be exported in *.XLSX format but not coupled to the BIM directly. HYSOPT is not interoperable with other software packages. However, the approach to installations is similar to the approach in BIM where the installation consists of components and relations between the components. The similar approach is promising for future developments in BIM integration. Calculations and simulations can be made/done during the design phase. Before making the model, the system concept should be known as well as the building layout and shell. The model is made schematically although pipe lengths are necessary input for the calculations. Control strategy as input is necessary only when the tool is used for simulations.

3.3 Ventilation system

3.3.1 Introduction

Ventilation is the intentional introduction of outside air into a space or room. Ventilation is mainly used to control indoor air quality by diluting and displacing indoor pollutants, such as CO_2. Ventilation can be categorized as either mechanical ventilation, or natural ventilation. Mechanical ventilation uses fans to drive the flow of outside air into a building and natural ventilation is the intentional passive flow of outside air into a building through planned openings (such as louvers, doors, and windows). Natural ventilation does not require mechanical systems to move outside air, it relies entirely on passive physical phenomena, such as wind pressure, or the stack effect. There are four recognised ventilation systems that vary from completely natural ventilation to mixed ventilation and mechanical ventilation. These systems are often indicated with the letters A to D (ISSO, 2010).

- System A: natural air exhaust and air supply;
- System B: natural air exhaust and mechanical air supply (rare);
- System C: natural air supply and mechanical air exhaust;
- System D: mechanical air exhaust and mechanical air supply (balanced ventilation).

<u>System A: natural air exhaust and air supply</u>

System A is an installation that does not contain any electrical driven components. Fresh air is supplied naturally through vents built in the windows. The air intake of these vents can be adjusted manually. Polluted air is expelled via vertical ducts in toilets, bathroom and/or kitchen or also through the vents in the windows. Air flow is caused by pressure differences between the building and its surrounding.

<u>System B: natural air exhaust and mechanical air supply (rare);</u>

A controlled supply of fresh outside air is forced through the building using a fan and the outdoor air is transported into the building by ducts. The air exhaust takes place on a natural way by ventilation openings, windows, or shafts because of the forced overpressure in the building. To prevent draught, the air supply in the room must be placed as high as possible or the incoming air should be preheated. An air filter can be used to clean the incoming air.
Because of the mechanically produced over pressure in the building, the system is less dependent on the weather conditions than a completely natural ventilation system.

System C: natural air supply and mechanical air exhaust;

The mechanical air exhaust system creates an under-pressure in the building, through which this system is also, like system B, less dependent to weather conditions than completely natural ventilation. The mechanical air exhaust creates a pressure difference over the ventilation openings, so air is suck in. But because of the natural air-inlet, a high wind pressure or temperature difference can result in draught problems. To prevent draught the air supply openings have to be placed as high as possible.

A controllable exhaust fan controls the ventilation capacity. In residential buildings exhaust takes place from at least the kitchen, the bathroom, and the toilet. In non-residential buildings suction mostly takes place from the corridor. Exhaust air ducts are needed.

System D: mechanical air exhaust and mechanical air supply (balanced ventilation).

In this system, the supply air and the exhaust air are transported mechanically. In comparison with the other three systems the advantages of balanced ventilation is the possibility of extracting heat from the exhaust air and use it to preheat the fresh air supply (heat recovery). Like system B it is possible to use preheating, pre-cooling, humidifying and/or an air filter. By controlling the ventilators, it is possible to control the ventilation capacity of the system.

For proper functioning of the system the building must be sufficiently airtight.

3.3.2 Critical components

Critical components are those whose influence on the energy efficiency or indoor environment of the building is significant and the possibility of errors leading to unwanted deviations is substantial. All components described are part of the ventilation system. The components description is independent from manufacturer differences.

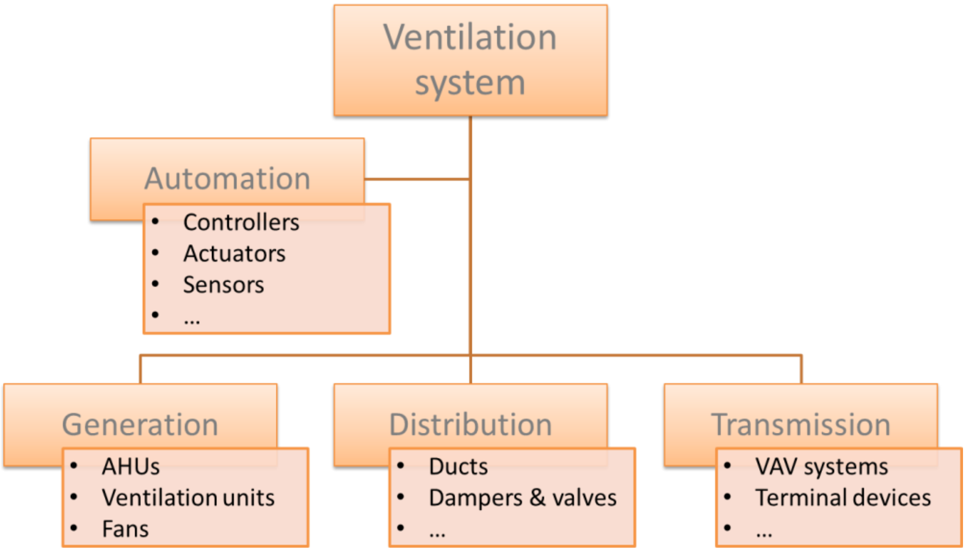

Figure 11: Ventilation system structure diagram

Air Handling Units (AHU)

Factory made encased assembly consisting of sections containing a fan or fans and other necessary equipment to perform one or more of the following functions: circulation, filtration, heating, cooling, heat recovery, humidifying, dehumidifying and mixing of air. (CEN, 2003). The more functions an air handling unit has, the greater its influence is on the energy performance and indoor environmental quality of a building.

Air handlers usually connect to a ductwork ventilation system that distributes the conditioned air through the building and returns it to the air handling unit. Sometimes air handling units supply and return air directly to and from the space served without ductwork, like for example in a packaged rooftop unit.

Relevant standards:	− EN 13053:2006+A1:2011
	− EN 13141-8:2014
	− EN 1886:2007
Common errors:	− V03: Wrong assembly causing leakage of the unit casing
	− V03: Wrong placing of the air handling unit causing vibration and noise
Affected KPIs:	− None (see KPIs for air handling unit components)
Measurement aspects:	− None (see aspects for air handling unit components)

In addition to the unit casing, one or more components will be part of the air handling unit. Some are necessary for operation of the unit, like the fan, drive, and a heat exchanger. Others are optional, like cooling units or humidifiers. In the section below, the components are being explained.

Fans

A fan is a rotary bladed machine, used to maintain a continuous flow of air. The fan is the heart of the air handling unit and a significant energy user in a building. Commissioning and re-commissioning fans and drives is a key factor for ensuring that a building's efficiency goals are met over the life of the building. There are both indirect and direct components to a fan's energy consumption. The indirect component relates to the system the fan serves. The fan must transmit enough energy to the air stream to overcome the system's resistance to flow.

In addition to the air handling unit, the following procedures apply.

Relevant standards:	− EN ISO 12759:2015
Common errors:	− V02: Wrong type of fan or motor.
	− V04: Fans and drives are installed with the wrong settings.
Affected KPIs:	− Energy use of fans and drives.
	− Air supply rates
Measurement aspects:	− Electricity use of fans and drives
	− Air flow rate of the ventilation system

Filters

All ventilation systems employ a filtration system. The level of filtration can vary widely, from a bird screen preventing the entry of animals and small objects, to Ultra Low Penetration Air filters (ULPA) with efficiencies of 99.999% on 0,3 micron test particles. Most ventilation unit or air handling units have low efficiency roughing filters to protect the heat transfer elements and maintain a basic level of cleanliness in the system. The level of filtration selected by the designer is related to the requirements of the process. These requirements are driven by the need to maintain indoor air quality (IAQ), protect the occupants from airborne hazards and contaminants, or maintain cleanliness in an occupied zone or production area.

In addition to having a major impact on IAQ, filters can have a significant impact on energy consumption in the system due to the pressure drops associated with them. Both factors make commissioning the filters and their related framing and monitoring systems critical for ensuring a systems IAQ performance and energy efficiency. Proper monitoring and change out procedures combined with creative approaches to achieving the desired filtration efficiency at low pressure drop can significantly reduce the operating cost and waste streams associated with the HVAC equipment.

In addition to the air handling unit, the following procedures apply.

Relevant technical standards:	–	EN 779:2012
	–	EN ISO 29462:2013
Common errors:	–	V02: Wrong type of filter causing a higher pressure drop
	–	V03: Incorrect placement of the filter section, or parts of the filter section
Affected KPIs:	–	Energy use of fans and drives
Measurement aspects:	–	Pressure drop of a filter section

Heat Recovery Element (HRE)

A heat recovery device of many types is used in an air handling system between supply and return airstreams for energy savings. The amount of energy that is transferred by the heat exchanger is known as its ‘effectiveness’ or ‘efficiency’. If a heat exchanger were to be able to transfer the entire energy from one medium to another, it would be rated at 100% efficiency. There are various types of heat exchangers:

- Fixed Plate: A plate type heat exchanger where air guiding passages are separated by a ‘transfer media’ such as aluminium or plastic. The orientation and direction of the flow of adjacent air passages is be used to describe the type of plate heat exchanger.
  - Cross flow heat exchangers have their primary and secondary streams operating in a perpendicular orientation to each other.
  - A counter flow heat exchanger has the primary and secondary air streams directly opposing each other. This leads to a higher efficiency as primary air progressively transfers with ‘stronger’ secondary air that holds more of the energy of its initial state.

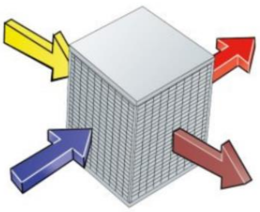

Figure 12: Cross flow HRE

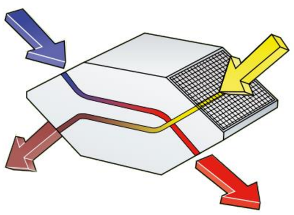

Figure 13: Counter flow HRE

- Thermal Wheel: Primary air is directed into one section of the wheel through a solid 'heat storage matrix' which absorbs some of the energy. The wheel is continuously rotating and as the heat storage matrix travels to the opposing side, a secondary air stream passes through it and the energy in the storage matrix is then transferred into the secondary air stream. The thermal wheel can have high efficiencies comparable to a counter flow plate heat exchanger; however, some of this is lost in the power input required to rotate the wheel.

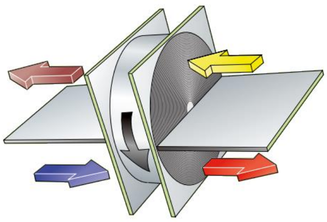

Figure 14: Thermal wheel HRE

- Heat Pipe: In a typical heat pipe application exhaust air and fresh air are flowing in opposite directions. Heat transferred from the warm air being exhausted provides the energy to evaporate the working fluid in the sealed heat pipe. That vapour flows to the other end, where it condenses, giving up the heat to the incoming fresh air. The condensed liquid flows back to the warm end to complete the cycle.
- Run-around coil: A typical run-around coil system exists of two or more coils connected to each other by a pumped pipework circuit. The pipework is charged with a heat exchange fluid, normally water, which picks up heat from the exhaust air coil and gives up heat to the supply air coil before returning again.

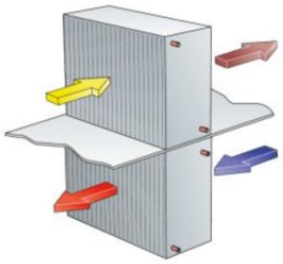

Figure 15: Run-around coil HRE

Air to air heat exchangers can also be divided into 'sensible only' or 'enthalpy' types. Sensible systems transfer temperature only. In an enthalpy system, the heat exchanger is able to transfer moisture in addition to temperature. Most thermal wheels and some fixed plate heat exchangers can recover moisture. (Ciraldo, 2014)

In addition to the air handling unit, the following procedures apply.

Relevant standards:	– N/A (In the Netherlands: NEN 5138)
Common errors:	– V01: The heat recovery element is damaged
	– V04: Incorrect settings for the heating, for example wrong sequencing of heating and cooling elements
	– V05: Insufficient performance of the heat recovery element
Affected KPIs:	– Heat recovery system efficiency in %
Measurement aspects:	– Temperature of primary air before and after the heat exchanger in °C
	– Temperature of secondary air before the heat exchanger in °C
	– Moisture content of primary air before and after the heat exchanger in kg/kg
	– Moisture content of secondary air before the heat exchanger in kg/kg

Heating element:

The heating element or coil is used to heat up air to a desired temperature level. This can be outside air to room temperature, but also for warming up a space or room. From a psychrometric and HVAC process standpoint, not all heating elements are the same. The specific function they provide depends on:

- The location of the coil in the system relative to other components.
- The manner in which the coil is connected to its supply of heating energy (to prevent freezing).
- The manner in which the coil is controlled.

If the heating element is used for preheating (as in an air handling unit), it is critical that possible issues be taken into consideration when the system is configured and the heating element is connected. Failure to do so can result in, at a minimum, the inability to provide the required level of performance and, in the worst case, can damage coils and building elements due to freezing.

If a heating element is part of the air handling unit, the following procedures apply.

Relevant technical standards:	– EN 1216:1998, EN 305:1997, EN 306:1997, EN 307:1998 and EN 308:1997
Common errors:	– V01: The heating element is damaged
	– V03: Incorrect installation of the heating element
	– V04: Incorrect settings for heating, for example wrong sequencing of heating and cooling elements
	– V05: Insufficient performance of the heating element
Affected KPIs:	– Draught rate
	– Vertical air temperature
Measurement aspects:	– Air temperature in the occupied zone
	– Air velocity in occupied zone

Cooling element / dehumidifier

A cooling element or coil is used to cool the air to the required temperature or to remove moisture (dehumidify) from the air. Cooling is one of the primary functions provided by air-handling systems. Common approaches to mechanical cooling include:

- Chilled water or glycol: Refrigeration equipment generates cold water or glycol, which is then pumped to coils located in the air handling units to cool and dehumidify the air stream. Capacity control is typically achieved by modulating the flow of water through the coil or by bypassing air around the coil.
- Direct expansion refrigeration: Refrigerant flows through the evaporator coil in the air handling system, often referred to as the DX coil (short for Direct eXpansion), to cool the air. Capacity control is achieved on the refrigeration side by an expansion device at the coil coupled with compressor unloading and hot gas bypass. Compressor unloading systems are generally step devices, which limit capacity modulation.
- Heat pumps: Heat pumps are a variation on the direct expansion refrigeration approach typically found in package and unitary equipment. When the air handling system requires cooling, the system works like a traditional direct expansion system. But, if the air handling unit requires heat, the system reverses and uses the coil in the air handling unit as a condenser and the coil used to reject heat to the atmosphere as the evaporator. The system cools the

outdoors to heat the air stream in the air handling unit.

- Direct and indirect evaporative cooling: This system cools the air by spraying water onto a media and allowing it to evaporate into the air stream. The air leaves the process cooler and with a higher specific moisture content. Indirect evaporative cooling uses a direct evaporative process to cool a secondary air stream, usually the exhaust stream from the area served or an outdoor air stream. This secondary air stream is then used to cool the primary air stream serving the space using a heat exchanger.

If a cooling element is part of the air handling unit, the following procedures apply.

Relevant technical standards:	–	EN 1216:1998, EN 305:1997, EN 306:1997, EN 307:1998 and EN 308:1997
Common errors:	–	V01: The cooling element is damaged
	–	V03: Incorrect installation of the cooling element
	–	V04: Incorrect settings for cooling, for example wrong sequencing of heating and cooling elements
	–	V05: Insufficient performance of the cooling element
Affected KPIs:	–	Draught rate
	–	Vertical air temperature
Measurement aspects:	–	Air temperature in the occupied zone
	–	Air velocity in occupied zone

Humidifiers

Active humidification systems are complex, expensive to operate, and maintenance intensive, so these systems are seldom employed unless they are essential. Eliminating unnecessary humidification systems can yield substantial benefits. Active humidification is an energy intensive process that can also create moisture problems if not properly designed, installed, and implemented. Thus, the commissioning of these systems can be critical to their success.

Methods for humidification include:

- Direct or indirect steam injection
- Evaporative approaches
- Compressed air driven
- Ultrasonic
- Air washers
- Sprayed coils

Humidification processes tend to be energy intensive. The obvious costs are in the direct energy and water consumed to vaporize liquid water into the air stream. Thorough commissioning of the humidification system is needed to help ensure that humidification is only being provided to the extent necessary and that the loads are minimized when humidification is not required.

For humidifiers as part of the air handling unit or humidifiers in ducts close to the air handling unit, the following procedures apply.

Relevant technical standards:	–	N/A
Common errors:	–	V03: Incorrect installation of the humidifiers, not enough distance downstream of the humidifier causing inadequate absorption
	–	V04: Incorrect settings for the humidifier
Affected KPIs:	–	Relative Humidity
Measurement aspects:	–	Relative humidity in the room

Ventilation Units

A 'ventilation unit' (VU) is an electricity driven appliance equipped with at least one impeller, one motor and a casing and intended to replace utilised air by outdoor air in a building or a part of a building (European Commission, 2014).
The same Regulation ('Energy labelling of residential ventilation units') makes a difference between residential ventilation units (RVUs) and non-residential ventilation units (NRVUs), where, clearly, the Regulation only applies to RVUs. Also, small ventilation units with an electric power input of less than 30 W per air stream are exempted from the scope of the Regulation.

There are two different types of VUs:

- Unidirectional ventilation units (UVUs): ventilation units producing an air flow in one direction only, either from indoors to outdoors (exhaust) or from outdoors to indoors (supply), where the mechanically produced air flow is balanced by natural air supply or exhaust;
- Bidirectional ventilation units (BVU): ventilation units producing an air flow between indoors and outdoors and are equipped with both exhaust and supply fans;

Bidirectional ventilation units equipped with a heat exchanger are commonly known as 'Energy Recovery Ventilators' (ERVs) or 'Heat Recovery Ventilators (HRVs). An ERV is a type of air-to-air heat exchanger that not only transfers sensible heat but also latent heat, whereas an HRV can only transfer sensible heat.

Relevant standards:	–	EN 13141-4:2011, EN 13141-6:2014, EN 13141-7:2010, EN 13141-8:2014, EN 13141-11:2015 and ISO 16494:2014
Common errors:	–	V02: The wrong type of ventilation unit is installed
	–	V03: Wrong installation of the ventilation unit, the unit is not properly mounted or mounted to the right construction element causing noise and vibration
	–	V03: Wrong connection of ducts to the unit
	–	V04: The ventilation unit is installed with the wrong settings
	–	V05: Insufficient performance of the heat recovery element

Affected KPIs:	–	Energy use of fans and drives.
	–	Air supply rates
	–	Heat recovery system efficiency, if applies
	–	Sound intensity
Measurement aspects:	–	Electricity use of fans and drives
	–	Air flow rate of the ventilation system
	–	Temperature of primary air before and after the heat exchanger in °C
	–	Temperature of secondary air before the heat exchanger in °C
	–	Sound intensity of a noise source

Duct systems

The distribution system (ducts) provides the path between the outer air, the air handling system and the terminal equipment that distributes the conditioned air. While relatively passive, it can often account for a significant portion of the system's energy consumption due to the static pressure requirement it imposes on the fan. Ducts can be constructed from plate material or plastic on-site, but can also be integrated in (prefab) construction elements.

The fabrication of the duct fittings in an air handling system can have a significant impact on the static pressure requirements for a system and, therefore, a significant impact on energy consumption and its ability to meet the design intent. Air that leaks from the distribution duct system often represents wasted energy both in terms of the fan energy used to covey the air, and the HVAC process energy used to heat, cool, humidify, dehumidify, filter and otherwise condition the air. Therefore, controlling duct system leakage is an important step in controlling the overall energy consumption rate and efficiency of a system.

Relevant technical standards:	–	EN 1507:2006, EN 12237:2003, EN 15727:2010, EN 15780:2011
Common errors:	–	V01: Ducts are damaged or polluted
	–	V02: Application of incorrect flow dividing fittings (tees), turns (elbows) and reducers
	–	V02: The wrong ducts are used, flexible ducts where rigid ducts were prescribed
	–	V02: Incorrect duct geometry (e.g. because of unforeseen obstructions)
	–	V03: Wrong installation of ducts, duct turns too close to the fan's discharge
	–	V03: Improper fabrication and bracketing, causing leakage
	–	V03: Wrong application of insulation on ducts, causing condensation and/or heat loss
	–	V03: Leakages or thermal bridges at duct lead-throughs through building elements
	–	V04: Inaccurate balancing of the duct system
Affected KPIs:	–	Air leakage due to ventilation
	–	Air supply rates

Measurement aspects:	–	Air tightness of the duct system
	–	Pressure drop of the duct system

Silencers

A silencer is used for the noise absorption generated by the ventilation units and spreading via the air ducts of the ventilation system. In order to select the right silencer, the design of the ventilation system and its components must be known. Because the design changes and no adaptions are made to the selection, often the wrong silencers are applied. Also, the 'rule of thumb' is used too often, causing noise problems in the building.

Relevant technical standards:	–	EN ISO 11820
Common errors:	–	V05: Wrong silencers, or no silencers at all, is causing noise in the room of destination
	–	V05: Silencers causing a high pressure drop
Affected KPIs:	–	Sound pressure level
	–	Air supply rates
Measurement aspects:	–	Sound pressure level in the room
	–	Air flow rate in the room

Dampers and valves

A damper is a valve or plate that stops or regulates the flow of air inside a duct, air handling unit or other air handling equipment. A damper can be used to regulate air flow rate for room-by-room temperature and climate control. Its operation can be manual or automatic. Manual dampers are turned by a handle on the outside of a duct. Automatic dampers are used to regulate airflow constantly and are operated by electric or pneumatic motors, in turn controlled by a thermostat or building automation system.

Relevant technical standards:	–	EN 1751:2014
Common errors:	–	V01: The damper or valve is damaged, causing air leakage or malfunction
	–	V01: A breached cable is causing malfunction
	–	V05: The damper or valve is not able to regulate the airflow well
Affected KPIs:	–	Air supply rates
Measurement aspects:	–	Air flow rate in the room

Air Terminal Devices (ATDs)

Components of the installation which are designed for the purpose of achieving the predetermined movement of air into or from the treated space [(e.g. grilles, diffusers) (CEN, 2003)].

The terminal equipment associated with an HVAC system provides the interface between the HVAC process that conditions the air and the occupants and processes occurring in the space. For the HVAC system to be perceived as successful by the end users the terminal equipment must reliably perform its intended function, otherwise the system will not effectuate its design intent, regardless of the level of performance at the central system.

Examples of terminal equipment are VAV & CAV systems, fan coil units, induction units and diffusers/grills.

Relevant technical standards:	– EN 13030:2001, EN 13141-10:2008, EN 13141-2:2010, EN 13141-1:2004, EN 13264:2001, EN 1397:2015
Common errors:	– V02: Wrong type of components / mismatches.
	– V01: Pollution and damaging of equipment, causing malfunction.
	– V03: Malfunction of equipment because of improper installation. This also includes incorrect wiring of electrical components.
	– V03: Wrong placement of air diffusers. Along with the next bullet this can cause major comfort problems due to high air velocities and draught.
	– V03: Inaccurate balancing of the terminal equipment in relation to the duct system. Along with the prior bullet, this can cause major comfort problems due to high air velocities and draught.
	– V04: False programming / parameter setting.
Affected KPIs:	– Air velocity
	– Sound pressure level
	– Air supply rates
Measurement aspects:	– Air velocity in occupied zone
	– Sound pressure level in the room
	– Air flow rate in the room

Control system

The control system or building automation system is the operator of the ventilation system. It operates the fan, heating/cooling elements, humidifiers, dampers, valves, and terminal equipment. The most common functions are the control of space temperature and indoor air quality and thus cannot be seen completely separate from the heating/cooling system. In addition to these functions, ventilation specific function like humidity control and filtration systems can be employed.

The controls system gets its information from a large number of sensors that are connected. Consequently, it depends on the accuracy of these sensors. The sensors can be individual components placed in the duct system or rooms, but can also be embedded in components like VAV-systems and ventilation units.

The control system is generally incorporated in the building control system together with the control of among others, the heating system. Part of the control system is outside of the scope of INSITER because it is programmed and built outside of the building process and can be considered a purchased component. However, during construction and commissioning a large number of parameters will be set in the control system, determining the correct operation of the MEP/HVAC systems.

Relevant technical standards:	–	CEN/TR 15500-2:2016, EN 15232:2012, EN ISO 16484-1:2010, EN 15500:2008
Common errors:	–	V05: Sensors are not correctly sized (especially flow sensors) or specification do not meet the requirements.
	–	V05: Sensors are not correctly calibrated.
	–	V03: Sensors are located or fitted incorrectly.
	–	V04: False programming / parameter setting.
	–	V04: The control, protection and monitoring strategy is incorrectly specified and/or implemented
Affected KPIs:	–	Thermal comfort (all aspects)
	–	Indoor Air Quality (all aspects)
Measurement aspects:	–	Air flow rate in the room
	–	Air temperature in the occupied zone
	–	Relative humidity in the room
	–	Air velocity in the occupied zone
	–	CO_2 value in the room

3.3.3 Difficulties in assessment and analysis

There is a fairly specific order of testing associated with the functional testing process. Generally, testing should proceed from the support system level, to the component level, to the subsystem level, to the system level. In most cases, tests at the support system level and component level can occur concurrently. For example, the electrical contractor can verify the power distribution equipment associated with an air handling unit while the mechanical contractor is testing the coils and terminal equipment, and the control contractor is verifying sensor wiring and calibration. Simultaneous testing is also possible at the subsystem level as long as the various subsystems are not interdependent for the process under test.

3.3.4 Measurement of performance

Evaluation of the performance of the ventilation system requires measurement data. Most of the measurement equipment necessary for gathering this data is already present in the various components of the distribution circuit. This is used for controlling, regulating and monitoring of the system. Sensors are connected to the building control system and measurement results can be logged, viewed, and exported from the control system.
Some tests require additional testing equipment. Pressure leakage test on the distribution circuit requires a measurement system that pressurizes the system and measures the dissipation of pressure over time. Testing of the distribution circuit and control system requires additional, currently non-existing methods for testing the various operation modes and responses of the control system to internal and external influences.

Some performance aspects require additional checks, test methods or measurements to verify the fitness for purpose of the installed systems. This includes:

- Air flow rate in individual rooms
- Air flow rate of the ventilation system

- Pressure drop of a filter section
- Pressure drop of a silencer
- Relative humidity [RH]
- Air velocity in occupied zone
- Air temperature in occupied zone
- Sound pressure level in the room
- Sound intensity of a noise source
- CO_2 value in the room

Air flow rate in the room

When:	After completing the air flow adjustments
Verification of:	Air flow rates at the air terminal devices (q_v in m^3/s or m^3/h)
Measurement tool(s):	Air flow capture hood.
Tolerance:	To be determined in D1.7.
Description:	Measurement is done at the exhaust or intake of the air terminal device and for minimum and maximum control setting of the fan. Measurement should be carried out according to EN 12599 or national standards and directives.

Air flow rate of the ventilation system

When:	After completing the air flow adjustments (commissioning phase)
Verification of:	Air flow rates of each ventilation system, as designed (q_{vt} in m^3/s or m^3/h)
Measurement tool(s):	Pitot tube flow meter.
Tolerance:	To be determined in D1.7.
Description:	Measurement is done downstream of the fan or ventilation unit and for minimum and maximum control setting of the fan. Measurement should be carried out according to EN 12599 or local standards and directives.

Pressure drop of a filter section

When:	After first operation of the air handling system (AHU or subsystem)
Verification of:	Filter pressure drop (Δp in Pa)
Measurement tool(s):	Differential manometer.
Tolerance:	To be determined in D1.7.
Description:	Measurements of pressure drop is being taken between measuring points located in the duct wall before and after the filter section. The filter must be clean and pressure tested at multiple air flow rates. Measurement should be carried out according to EN 779 or successive standards.

Pressure drop of a silencer

When:	After first operation of the air handling system (AHU or subsystem)
Verification of:	Silencer pressure drop (Δp in Pa)
Measurement tool(s):	Differential manometer.
Tolerance:	To be determined in D1.7.
Description:	Measurements of pressure drop is being taken between measuring points located in the duct wall before and after the silencer. Measurement should be carried out according to EN ISO 11820.

Air temperature in occupied zone

When:	After completing the air flow adjustments
Verification of:	Indoor air temperature in the occupied zone (θ_o in °Celsius)
Measurement tool(s):	Temperature meter
Tolerance:	To be determined in D1.7.
Description:	Measurement is done in the occupied zone of a room, as agreed between the parties concerned. When measuring the air temperature precautions shall be taken in order to reduce the effect of thermal radiation and inertia of the probe. Measurement should be carried out according to ISO 7726, EN 12599 or national standards and directives.

Relative humidity in the room

When:	After completing the air flow adjustments
Verification of:	Relative humidity of air in the room (RH in %)
Measurement tool(s):	RH meter
Tolerance:	To be determined in D1.7.
Description:	Measurement is done in the occupies zone of a room, as agreed between the parties concerned. In connection with the measurement of the air humidity, the air temperature shall also be measured at the same location. The use of recording instruments is necessary. The recording period shall last for 24 h at least. Measurement should be carried out according to ISO 7726 or national standards and directives.

Air velocity in occupied zone

When:	After completing the air flow adjustments
Verification of:	Indoor air velocity for different measurement times, e.g. at periods of 100 s (v_a in m/s)
Measurement tool(s):	Air velocity meter with omnidirectional probe
Tolerance:	To be determined in D1.7.
Description:	Measurement is done in the occupied zone of a room, as agreed between the parties concerned. Measurement should be carried out according to ISO 7726, EN 12599 or national standards and directives.

Sound pressure level in the room

When:	After completing the air flow adjustments
Verification of:	A-weighted sound pressure level in the room (L_p in dB(A))
Measurement tool(s):	Sound level meter with microphone
Tolerance:	To be determined in D1.7.
Description:	The A-weighted sound pressure level shall be determined at places of work. Corresponding conditions within the room are given in CR 1752. The measurement, as well as determination of number and positions of measurements, according to EN ISO 16032. Also, some national standards and directives may apply.

Sound intensity of a noise source

When:	After completing the installation of a ventilation system
Verification of:	Sound power level of a noise source like an air handling unit, ventilation unit or fan (L_W in dB)
Measurement tool(s):	Sound level meter
Tolerance:	To be determined in D1.7.
Description:	The measurement and equipment in accordance with EN ISO 3741. Measurement to be made for minimum and maximum flow rates of the fan. The background noise will be measured to correct the measured sound pressure level in compliance with EN ISO 3741.

CO_2 value in the room

When:	After completing the air flow adjustments
Verification of:	Level of carbon dioxide in the room in parts per million (CO_2 in ppm)
Measurement tool(s):	CO_2 meter
Tolerance:	To be determined in D1.7.
Description:	Measurement is done in the room. The use of recording instruments is necessary. The recording period shall last for 24 h at least. Measurement should be carried out according to ISO 16000-26 or national standards and directives (e.g. VDI 4300-9).

3.3.5 Calculation of KPIs

The performance of a ventilation system is based on both energy performance and indoor environmental quality. The assessments are done in accordance with the set of KPIs from section 0. Since ventilation has only part in the performance of the total building, this section is only related to the influence of the ventilation system on the KPIs. Analysis of total building quality is described in chapter 5.

In the subsections below, the desired calculations are explained.

Heat recovery system efficiency

When:	After pre-commissioning the ventilation system
Verification of:	The temperature ratio value of the heat exchanger (the difference between the temperature of the heated air stream before and after the heat exchanger divided by the maximum temperature difference over the heat exchanger) and the temperature of supply air
Measurement tool(s):	Resistance thermometer
Tolerance:	To be determined in D1.7.
Description:	Measurement is done at the exhaust or intake of the air terminal device and for minimum and maximum control setting of the fan. Measurement should be carried out according to EN 12599 or local standards and directives. Calculation of the actual efficiency by using the equation:

$$\eta_t = \frac{(\theta_{p,out} - \theta_{p,in})}{(\theta_{s,in} - \theta_{p,in})}$$

Where,

- η_t is the temperature transfer efficiency of the heat exchanger;
- $\theta_{p,in}$ is the temperature of primary air before the heat exchanger in °C;
- $\theta_{p,out}$ is the temperature of primary air after the heat exchanger in °C;
- $\theta_{s,in}$ is the temperature of secondary air before the heat exchanger in °C.

The latent transfer efficiency of a heat recovery unit can be expressed as:

$$\eta_x = \frac{(x_{p,out} - x_{p,in})}{(x_{s,in} - x_{p,in})}$$

Where,

- η_x is the latent transfer efficiency of the heat exchanger;
- $x_{p,in}$ is the moisture content of primary air before the heat exchanger in kg/kg;
- $x_{p,out}$ is the moisture content of primary air after the heat exchanger in kg/kg;
- $x_{s,in}$ is the moisture content of secondary air before the heat exchanger in kg/kg.

Table 3: provides the typical efficiency of different heat exchangers.

Heat Exchanger Type	Type of Transfer	Typical Efficiency
Thermal Wheel	Latent** & Sensible	0.7-0.8
Fixed Plate (cross-flow)	Latent** & Sensible	0.55-0.65
Fixed Plate (counter-flow)	Latent** & Sensible	0.7-0.8
Heat Pipe	Sensible	± 0.6
Run around (twin) coil	Sensible	0.4-0.6

Table 6: Heat exchanger type, transfer, and efficiency

**Total Energy Exchange only available on Hygroscopic units and Condensate Return units

In order to avoid frost growth on the heat exchanger at low outdoor temperatures, the minimum temperature of exhaust air (the air leaving the ventilation unit) is usually controlled by reducing the efficiency of the ventilation unit. Where more precise data are unavailable, the minimum temperature of exhaust air is controlled as follows:

1) in residential buildings, to +5 °C in the case of a plate heat exchanger and to 0 °C in the case of a rotary heat exchanger or a plate heat exchanger with humidity recovery;
2) in other non-residential buildings without humidification and significant humidity production, to 0 °C in the case of a plate heat exchanger and to –5 °C in the case of a rotary heat exchanger.

Electricity use of fans and drives

When: During functional checks of the fan

Verification of: The current drawn by the motors of the air handling units (I_m in Ampere) and the total electricity use in kWh per year.

Measurement tool(s): Ampere and power meter

Tolerance: To be determined in D1.7.

Description: The current shall be measured after the last fuse for each phase.
The efficiency of electricity use is assessed based on specific fan power of the ventilation system at a calculated air flow rate and shall be determined according to ISO 5801. Specific fan power is the ratio of the total power of the system to the air flow rate (either supply or exhaust air flow rate, the higher to be selected) in kW/m3/s.

$$E_V = P_V \cdot \frac{\tau_d}{24} \cdot \frac{\tau_w}{7} \cdot t$$

Where,

E_V is the electricity use of a fan in kWh annually;

P_V is the electrical power of the fan in kW;

τ_d is the number of the operating hours of the fan at a calculated air flow rate per 24-hour period;

τ_w is the number of the fan operating days per week at a calculated air flow rate d;

t is the period of 8760 hours in respect of which the calculation is performed.

The electrical power input shall be used to calculate the energy consumption per unit of total air flow rate.

Electrical energy use of (small) ventilation units

When:	During functional checks of the ventilation unit
Verification of:	The electrical energy use Ev (kWh/y) of small ventilation units whose air flow rate is lower than 0,25 m3/s (suitable for small residential buildings and apartments).
Measurement tool(s):	Power meter
Tolerance:	To be determined in D1.7.
Description:	The electrical power of the ventilation unit is considered to equal the value which is provided by the manufacturer of the ventilation unit for the design air flow rate. The standard EN 13141-7 applies. Calculation is by means of the following equation:

$$E_V = P_{V,s} \cdot t_{V,sn}$$

Where,

E_V is the annual electrical energy use of small ventilation units in kWh;

$P_{V,s}$ is the electrical power of the ventilation unit in kW at design air flow rate;

$t_{V,sn}$ is the annual number of operating hours of the ventilation unit at design air flow rate (in general, the value of $t_{V,sn}$ is 8760 h, except in the case of systems controlled on a demand basis);

Draught rate

The Draught Rate (DR) is the percentage of people predicted to be dissatisfied because of a draught. may be calculated by using the following equation:

$$DR = (34 - t_{a,l}) \cdot (\bar{v}_{a,l} - 0{,}05)^{0{,}62} \cdot (0{,}37 \cdot \bar{v}_{a,l} \cdot T_u + 3{,}14)$$

For $\bar{v}_{a,l} < 0{,}05$ m/s: use $\bar{v}_{a,l} = 0{,}05$ m/s

For $DR > 100$ %: use $DR = 100$ %

Where,

$t_{a,l}$ is the local air temperature, in °C (20 °C to 26 °C) (for measurement of air temperature, see section 3.3.4);

$\bar{v}_{a,l}$ is the local mean air velocity, in m/s (< 0,5 m/s) (for measurement of air velocity, see section 3.3.4);

T_u is the local turbulence intensity, in percent (10% to 60%) (if unknown 40% may be used).

Air tightness of the duct system

The air leakage factor of a duct section is the leakage flow rate per unit surface area of the ductwork of the tested section. It is calculated by using the following equation (EN 12237):

$$f = {}^{q_{vl}}/_{A_j}$$

Where,

f	is the air leakage factor, in m^3/s per m^2;
q_{vl}	is the air leakage flow rate of the ductwork under test, in m^3/s;
A_j	is the duct surface area, in m^2 (see EN 14239).

Vertical air temperature:

The vertical air temperature is measured (see section 3.3.4). The following equation is derived from EN ISO 7730 and shows the percentage dissatisfied (PD) as a function of the vertical air temperature difference between head and ankles. The discomfort only applies when the temperature increases upwards. People are less sensitive under decreasing temperatures (and warmer air tends to rise).

$$PD = \frac{100}{1 + exp(5{,}76 - 0{,}856 \cdot \Delta t_{a,v})}$$

Where,

$\Delta t_{a,v}$	is the vertical air temperature difference between head and feet, in °C (max 8 °C) (for measurement of air temperature, see section 3.3.4).

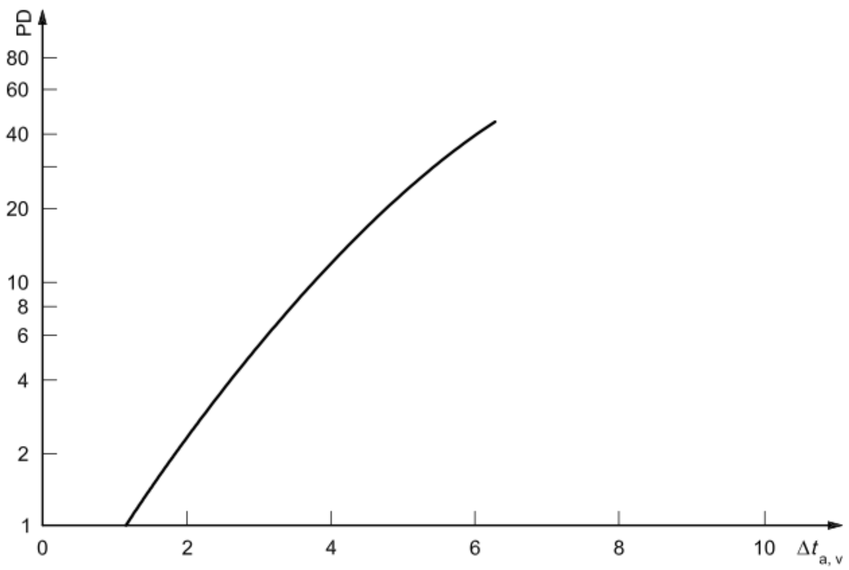

Figure 16: Local discomfort caused by vertical air temperature difference (ISO, 2005)

3.3.6 Self-inspection for ventilation systems

Self-inspection on different levels

Self-inspection and self-instruction takes place on three successive levels, component level, subsystem level and system level. On component level answering the four aforementioned questions:

1. Is the component polluted or damaged?
2. Is the right component installed?
3. Is the component installed correctly?
4. Are the correct parameters set?

The inspections succeeding these critical questions are further explained in chapter 4: *Analytical self-inspection protocols*. For ventilation systems, all these questions apply.

On subsystem and system level, installation specific self-inspection is done by measurements and calculation of the KPIs related to the ventilation system. For KPIs to have meaning, they must be compared to reference values or demands that are either obtained from legal requirements, minimum demand or from building performance simulations. More information is given in section 3.2.6; Self-inspection for heat pump systems. In-depth research will be taken place in D1.7.

<u>Building performance simulation</u>

Overall building performance can be simulated with software that is used to model the interaction between the building, the MEP/HVAC systems, and external factors. The installation is regarded a black box and is modelled on system level. Examples of suchlike building performance software are VABI-elements of TRNSYS. The performance of the ventilation system can be simulated as a part of interacting building elements and installations. More about VABI and TRNSYS in section 3.2.6.

Self-inspection in different phases

For visual explanation of the inspections and phases, see Figure 8 on page 23 and Figure 17 below.

Figure 17: The five building phases, relevant for assessment of the ventilation system

In the first relevant building phase, manufacture of the components, the components will be checked and verified in the factory according to prevailing rules and regulations and the specifications demanded by the design model.

During the second relevant building phase, transportation to the site, the critical components of the ventilation system must be checked for:

- Comparison of the delivered system with the design specification in the BIM model

- Cleanliness or damages
- Whether all documents necessary for installation (instruction) and inspection are available

This includes the first question of the component-inspection methodology (check for cleanliness). The second and third questions are being dealt with in the third relevant building phase, on-side assembly phase. In this step, self-instruction is introduced by smart protocols, based on manufacturers' information, and supported by the QR scan and augmented reality (AR).

The last question, whether the parameters are set correctly, will be assessed in the pre-commissioning phase. The ventilation system, by then, is completely assembled and the building automation system (control system) is completely operational. Verification will include all the checks necessary to make sure the ventilation system will operate as intended during design. This will be monitored by the updated BIM model with the feedback included from all previous inspections.

Monitoring starts in the commissioning phase and will continue throughout the in use and maintenance phases. For monitoring, a software tool like Simaxx can be used. Aspects that are to be included will be determined by the building partners

Relevant standards

For installation checks, tests and inspections of ventilation systems, the following standards apply:

- EN 15239:2007 Ventilation for buildings - Energy performance of buildings - Guidelines for inspection of ventilation systems
- EN 14134:2004 Ventilation for buildings - Performance testing and installation checks of residential ventilation systems
- EN 12599:2012 Ventilation for buildings - Test procedures and measurement methods to hand over air conditioning and ventilation systems
- EN 16573:2016 Ventilation for Buildings - Performance testing of components for residential buildings - Multifunctional balanced ventilation units for single family dwellings, including heat pumps

3.4 Solar hot water system

3.4.1 Introduction

Solar thermal systems are one of the main current installed HVAC/MEP systems in building with the aim of generation Domestic Hot Water (DHW). It is the main renewable sources for generation of this energy. Solar thermal systems use free energy from the sun (solar radiation) to produce useful heat in a first instance. The solar radiation, which is received on the earth plane, is called "global radiation", which is made up of direct and diffuse radiation. Depending on the type of collector, in addition to the direct radiation it is also possible to use the diffuse radiation.

The generated heat can be used for different applications and combinations of applications: Heating, cooling, domestic hot water, swimming pool, although the main use is still DHW. The standard schema of these systems is depicted in Figure 18 where how the multiple elements and components are basically joint with the aim of providing thermal energy.

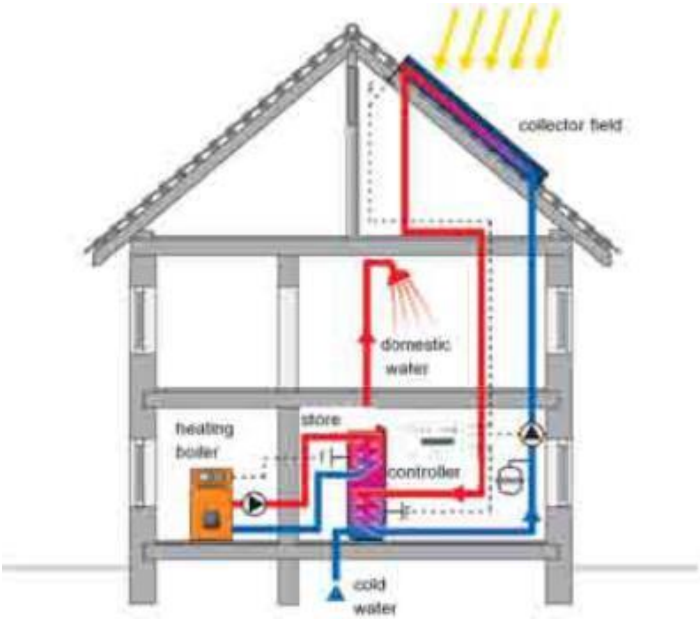

Figure 18: Standard solar water heating system

Construction errors

The amount of solar thermal system installations has grown in the last years. As well, the number of installation technicians has been increased, while the expertise has decreased. In this sense, the mistakes at time of installing and commissioning these systems have been exponentially incremented and a very diverse number of errors are made. Commonly, the faults are grouped by components because these mistakes are various and, thus, Figure 19 represents the main ones per component of the system. It is remarkable how some of the faults are repetitive in different components, such as:

- Damages or defects that contribute to the errors as they do not comply with the design features. That is why it is crucial to render initial checks before going ahead with the installation.
- Wrong dimensioning and leakages, which reduce the performance of the component taking into account that they do not comply with the specification and, probably, the final installation with these mistakes could not cover the energy demand. Some of these faults are made during the installation of the components because of geometrical divergences, therefore, guidelines are very helpful while installing.
- Under-performance that is diverse depending on the component. For example, in a pump, the rotation speed could be problematic, whereas, in a pipe, low flow could provoke less delivered energy than designed. At commissioning stage, the performance parameters must be ensured. Obviously, with the pass of time, these values are decreased and, thus, during maintenance, this evaluation of the performance is pivotal.

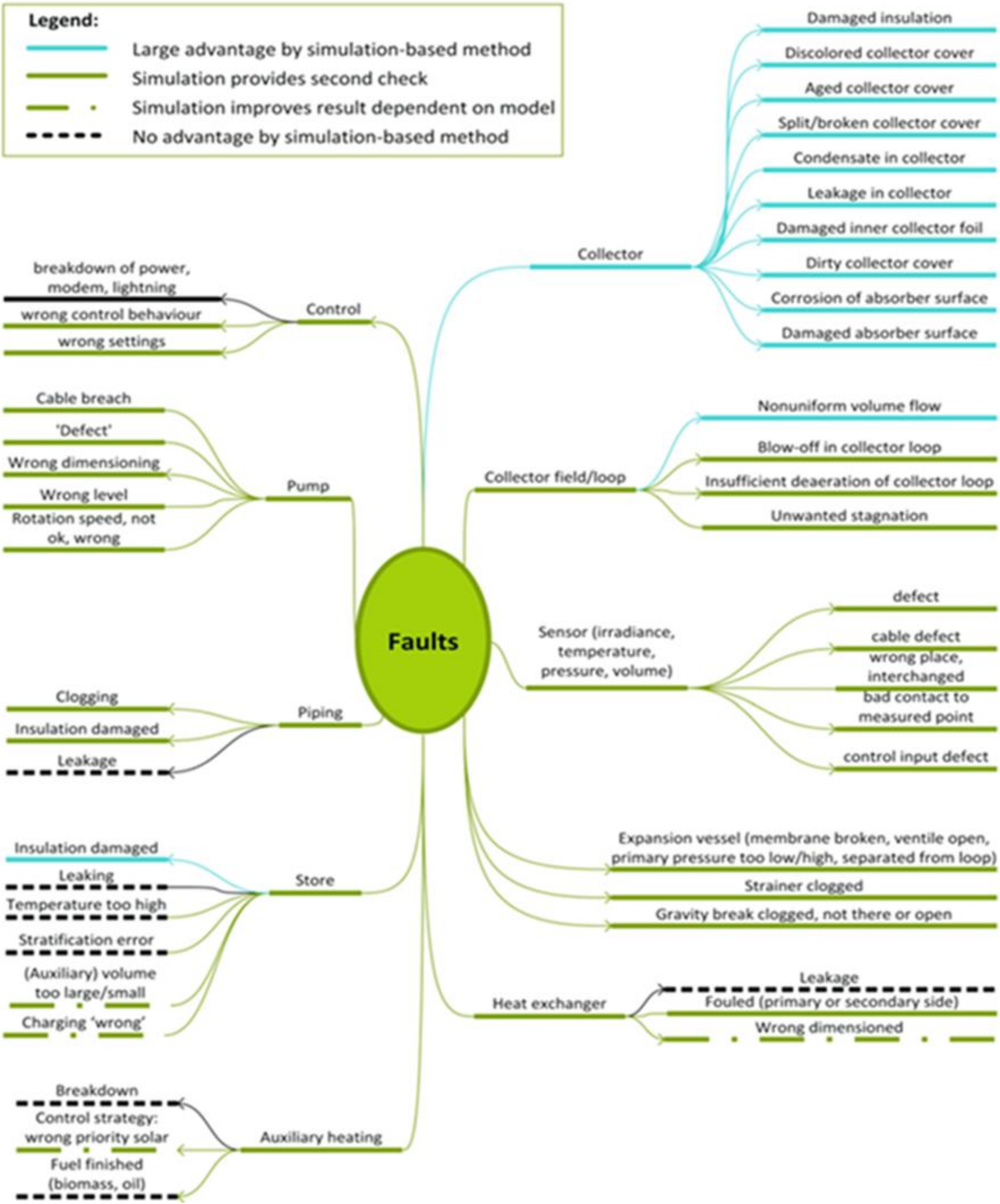

Figure 19: Common errors in solar thermal systems

Related norms and protocols

Historically, a US ASHRAE standard (93-77) was the first to be widely used. Then, the ISO 9806 series of standards were developed and afterwards the European standards series EN 12975 was created. Recently, the International Standards Organisation (ISO) and the European Committee for Standardization (CEN) have developed together a new standard based on ISO 9806 and EN 12975. This new international standard, the EN ISO 9806:2013 replaced the EN 12975-2 in the CEN countries and is likely to be widespread in other regions. Several national standards are also available, most often based on the EN ISO 9806. In summary, the standards related to solar thermal collectors applicable within the scope of INSITER are illustrated in

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Appendix 1.

Systems and system components, other than collectors, are at very different stages in the standardization process. There is progress for systems in Europe, with European standards series covering Factory-Built Systems (EN12976) and Custom-Built Systems (EN 12977), where the latest standards (e.g.: 12977-3/4/5) also include components, such as stores and controllers.

The European standards are well established not only inside Europe but also in some countries beyond (e.g. Tunisia) but it is still unclear how the international harmonization of standards applicable to systems will evolve. Latest ISO developments show that there is a common will to increase efforts towards enhanced international cooperation. This is reflected in the latest revision of ISO 9459-4:2013 8 aiming at some harmonization on the EN 12977 series.

3.4.2 Critical components

Solar collectors

By nature, the collectors are the most visible of all solar thermal components – they are typically mounted on the roof of a building, but can also be placed on the façade, on balconies or mounted on ground structures. All collector types have in common that solar irradiation is absorbed by a dark – often black or dark-blue – surface, which heats up and from which the heat is transferred directly or indirectly to water. For lower temperatures (ca. up to 100°C) three different collector types are most common: Evacuated tube collectors, flat plate collectors and unglazed absorbers. Due to the temperature levels they can usually provide, the latter are used almost exclusively used for swimming pool heating, while the former are used for a wide variety of applications. Typical evacuated tube or flat plate collectors are rectangular, covering an area of 1.5-2.5m2 but much larger sizes are available (12-15 m²), sometimes even custom built for individual projects. Their height is usually between 80-120mm for flat plate collectors and 120-200mm for vacuum tubes, depending on the manufacturer and model. Multiple collectors can be combined to form a collector array. (Trenkner & Dias, 2014)

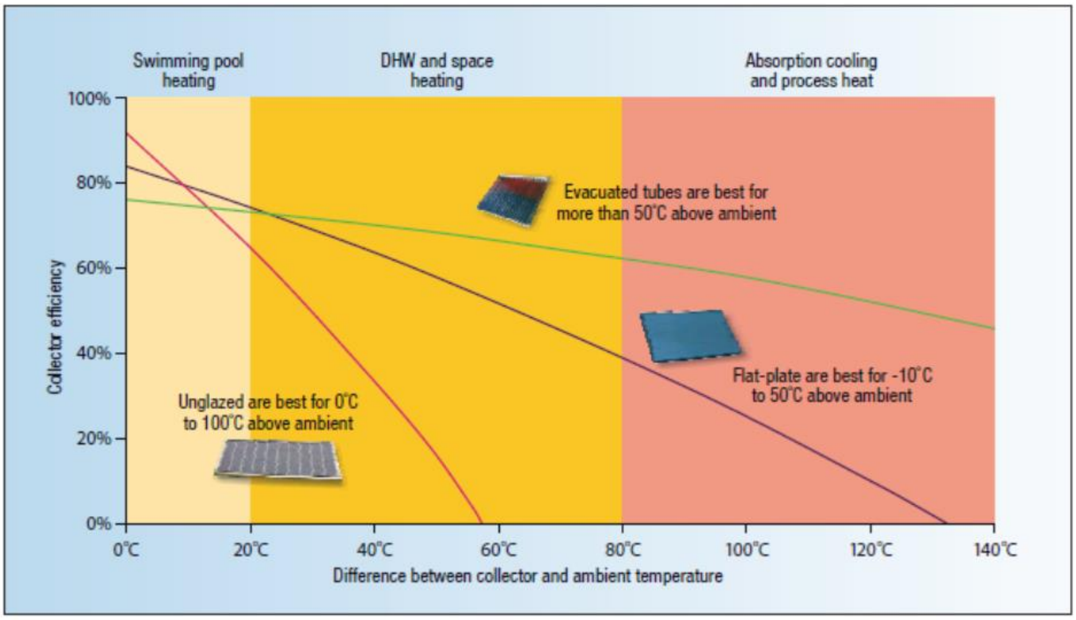

Figure 20: Collector efficiencies at different temperature levels (IEA, 2012)

Relevant technical standards:	–	EN12975-1:2006+A1:2010, EN12977-2:2011
Common errors:	–	W02: Damaged insulation
	–	W02: Discoloured collector cover
	–	W02: Split/broken collector cover
	–	W02: Leakage in collector
	–	W02: Condensate in collector
	–	W02: Corrosion in absorber surface
	–	W03: Air in circuits
Affected KPIs:	–	Efficiency of hot water generation and storage
	–	Efficiency of hot water distribution
Measurement aspects:	–	Radiation
	–	Temperature of the water in the solar collectors

Pump

For pumped systems, the use of electricity for pumps should be kept as low as possible, and therefore over dimensioning of the power of the pump should be avoided. The pump should be chosen in a manner that a difference of between 8°C and 12°C is produced between the feed and return lines.

Relevant technical standards:	–	EN ISO 22975-3:2014
Common errors:	–	W02: Cable breach
	–	W04: Wrong parameter setting, for example water flow
	–	W04: Incorrect control of the pump
	–	W05: Wrong dimensioning or using the 'rule of thumb'

Affected KPIs:	–	Energy use of pumps
Measurement aspects:	–	Energy use of pumps

Heat exchanger

For the transfer of the heat gained from the sun to the domestic hot water, a heat exchanger is required in twin circuit systems. We can differentiate between internal and external heat exchangers.

Relevant technical standards:	–	ISO 9806:2013, EN12977-2:2011
Common errors:	–	W02: Leakage
	–	W02: Dirty
	–	W04: Wrong flow (primary and secondary circuit)
	–	W05: Wrong dimensioned
Affected KPIs:	–	Efficiency of hot water distribution
Measurement aspects:	–	Primary and secondary circuits generation flows

Thermal storage

The heated water is typically stored in an insulated cylinder. The water in the tank can be separated from either the water in the collector and/or the actual drinking water through heat exchangers, but very simple thermosiphon systems are of the open-loop type in which sanitary water from the mains flows through the collector and tank.

Tank size and collector area should match: Having one of them too small or too big reduces usable heat output and/or creates problems with overheating. Under the heading "sizing" you will find simple calculations to assess the required tank volumes and collector areas. This will help you assess whether the site is suitable for solar thermal and e.g. the roof area which should be covered by solar collectors. Solar water heaters for swimming pools do not use a storage tank: The pool itself is "the tank".

Relevant technical standards:	–	N/A
Common errors:	–	W02: Insulation damaged
	–	W02: Leaking
	–	W04: Temperature too high
	–	W05: Wrong dimensioned
Affected KPIs:	–	Efficiency of hot water generation and storage
Measurement aspects:	–	Inlet flow in the storage tanks
	–	Outlet flow from the storage tanks
	–	Temperatures in the bottom and upper parts of the storage tanks
	–	Insulation level of the tanks

Controller

The controller of a solar thermal system has the task of controlling the circulating pump to harvest the sun's energy in the optimum way. In most cases this entails simple electronic temperature difference regulation. Thermosiphon does not have controller.

Two temperature sensors are required for standard temperature difference control. One measures the temperature at the hottest part of the solar circuit before the collector output (flow); the other measures the temperature in the store at the height of the solar circuit heat exchanger. The temperature signals from the sensors are compared in a control unit. The pump is switched on via a relay when the switch-on temperature is reached.

The switch-on temperature difference depends on various factors. Standard settings are from 5°C to 8°C. In principle, the longer the pipeline from the collector to the store, the greater the temperature difference should be set. The switch-off temperature difference is normally around 3°C. A third sensor can be connected for temperature measurement in the upper area of the store, which permits the draw-off temperature to be read. An additional function is switching off the system when the maximum store temperature has been reached, as a means of overheating protection.

Frost protection is effected by adding antifreeze to the collector fluid, or by using the drain back system. In the latter system, the collector circuit is only partly filled with water, and when the pump is off the collector is completely dry. This obviously places special requirements on the design of the collector and the piping. Drain back systems, when well designed so that no water is left in the collector or any piping that could freeze when the pump is switched off, automatically work together correctly with a temperature differential controller. When the danger of freezing occurs, the pump will be switched off because the store will then be always warmer than the collector. (Earthscan, 2010) ad

Relevant technical standards:	–	N/A
Common errors:	–	W04: Wrong control behaviour
	–	W04: Wrong settings
	–	W04: Breakdown of power
	–	W04: Lost communication
Affected KPIs:	–	Efficiency of hot water generation and storage
	–	Efficiency of hot water distribution
Measurement aspects:	–	Primary and secondary circuits generation flows
	–	Temperatures in the bottom and upper parts of the storage tanks

3.4.3 Difficulties in assessment and analysis

The list of faults and common errors is very large and more errors appear, although these are exception, but affecting the performance of the whole system. Nevertheless, if the performance must be assured, then, the checks are required, which is not always an easy task. In this sense, some standard procedures are followed for each country with its own regulations. The challenge lies in the time when the process is rendered because it is done at commissioning step. For instance, in Spain, a checklist is completed before the start-up. However, intermediate checks are not realised, which entails additional mistakes. While, checking intermediate stages of the installation and commissioning would reduce the costs and improve the schedule, the need of solving these mistakes after the installation produces additional costs and delays that are not taken into account at the planning stage.

Similar to before, the design process infringes mistakes because it is not usual to come with simulated designs, but theoretical calculations. In this way, simulation tools like TRNSYS are very useful to simulate not only the specific HVAC system, but the integration with the remaining systems and building components. Nevertheless, that is a very time-consuming task. Firstly, it needs the intervention of a specialist to create the model and, secondly, it requires a lot of time to model all the facilities of the building. Then, it is never tested the operation of these systems together the building facilities, which do not provide the estimated "real" performance of the system. Simple questions like whether the solar thermal would cover the DHW demand are not always answered in prior phases.

Having this in mind, it needs to be added that expert workers in solar thermal systems do not usually carry out the installation process. Then, they follow the guidance of data sheets and technician guides. However, no BIM methodologies are still implemented and integrated in this process which would help to improve the installation process because they would guide step-by-step the technicians.

All of these topics are challenges and difficulties in the quality assurance of the installation of solar thermal systems. Nevertheless, from INSITER perspective, thanks to the integration of self-inspection and self-instruction tools to be developed under the project, these challenges would be removed or, at least, decreased. Firstly, the self-inspection techniques would allow checking intermediate steps of the installation in order to solve any issue in advance. Secondly, the current methods for commissioning would be improved according to the use of new technologies that help the technician. Finally, self-instruction tools would guide the workers to reduce the number of mistakes, as well as the impact of them.

Additionally, to the aforementioned challenges or difficulties, the final analysis of the performance is not always an easy task where the lack of tools is one of the problems. Moreover, these installations are not sufficiently monitored to extract useful data to assess the performance. Finally, it has been observed that the KPIs are sometimes badly defined and its importance is vital for the proper evaluation of the final performance. Although the definition of these sensor networks is out the scope of the INSITER project, the capability of integrating tools for monitoring and visualization, as well as calculation of KPIs according to the well-established ones in this document, relieves the mistakes produced at this stage.

3.4.4 Measurement of performance

INSITER is developing several tools in order to measure the performance of the systems or, at least, to support the gathering of information that provides the capability of analysing the performance of the components, as well as the whole system. In this way, several measurements are required in order to comply with the requirements:

- Primary and secondary circuits generation flows
- Inlet flow in the storage tanks
- Outlet flow from the storage tanks
- Radiation
- Temperature of the water in the solar collectors
- Temperatures in the bottom and upper parts of the storage tanks
- Insulation level of the pipes and tanks

These measurements provide certain values and input for the KPI calculation that gives an idea about the total performance of the system. Nevertheless, there is required the installation of a set of measurement devices in order to collect the aforementioned data-points. A list of this equipment is established below:

- Temperature probes
- Flow meters (either ultrasonic or “intrusive”)
- Radiation sensor
- Data loggers
- Thermography camera

3.4.5 Calculation of KPIs

Solar fraction

Represents the measure of how efficiently solar thermal production is used respect to the final energy demand for thermal. It is evaluated as the ratio between heat produced by solar thermal (E) and the final energy consumption thermal (Ed):

$$\eta_{ST} = \frac{E}{Ed}$$

Where.

$$E = m * C_p * (Ti - To)$$

Ed: The final energy consumption of a building corresponds to the energy entering the building needed to cover the Domestic hot water demand.

System efficiency

The system efficiency gives the ratio of solar heat yield to the global solar irradiance on the absorber surface with respect to a given period of time. The system efficiency is strongly dependent on the solar fraction. It is higher at lower solar fractions (when the solar water heater size is small compared with the hot water demand). If the solar fraction is increased by increasing the collector area, the system efficiency is reduced, and every further kilowatt-hour that is gained becomes more expensive. (Earthscan, 2010)

Solar Thermal System				
Indicator	**Equation**	**Rule**	**Fault aim**	**Fault**
Primary Flow	$\frac{\dot{m}_{mesured}}{\dot{m}_{set}} = \dot{m}_{prim}$	$0{,}95 < \dot{m}_{prim} < 1{,}05$	Detect normal operation of pump	Primary pump out of nominal conditions
Secondary Flow	$\frac{\dot{m}_{measured}}{\dot{m}_{set}} = \dot{m}_{sec}$	$0{,}95 < \dot{m}_{sec} < 1{,}05$	Detect normal operation of pump	Second pump out of nominal conditions
Heat Exchanger	$\frac{\eta_{measured}}{\eta_{nominal}} = \eta$	$0{,}85 < \eta < 1$	Detect abnormal operation of solar system	Outperformance of solar system
Temperature of the collector fields		$T_{coll} < T_{coll,h}$	Protection of solar system	Stagnation risk

Table 7: Solar thermal system KPIs

Pumping modules				
Indicator	**Equation**	**Rule**	**Fault aim**	**Fault**
Flow	$\frac{\dot{m}_{measured}}{\dot{m}_{set}} = \dot{m}$	$0{,}7 < \dot{m} < 1{,}3$	Detect pump operation outside nominal regime	Pump error
Electric Power	$\frac{\dot{W}_{measured}}{\dot{W}_{foreseen}} = W$	$W > 1{,}25$	Fault in facilities after 30 sec. from start	Extra energy consumption
Temperature, Temp. ref.		$\lvert T_x - T_{x,ref} \rvert < \varepsilon_x, persistent$	Detect possible problem with valve. Detect possible problem with PID parameters, or with IO&C board	Wrong supply temperature

Table 8: Solar thermal pumping system KPIs

Storage system			
Indicator	**Rule**	**Fault aim**	**Fault**
Temperature	$T_{storage} < 50ºC$	Detect abnormal operation	Storage temperature too low

Temperature	$T_{storage} > 90ºC$	Detect storage overheating	Storage temperature too high
Temperature, Temp. ref.	$\|T_x - T_{x,ref}\| < \varepsilon_x$, *persistent*	Wrong supply temperature	Possible problem with valve. Possible problem with feedback PID parameters, possible problem with IO&C board

Table 9: Solar thermal storage system KPIs

3.4.6 Self-inspection for solar hot water systems

Currently, there is no protocol about the evaluation of solar thermal systems apart from visual inspection when the installation is running and checklists that corroborate the proper behaviour of the installation. Nevertheless, these are not standard across Europe, but each country follows its own recommendations. For instance, in Spain the RITE (Reglamento de instalaciones térmicas en los edificios – Regulation of thermal installation in buildings) recommendations are set. In this way, there is not applicable the usage of diagnostic tools as INSITER looks for. In this case, a technician must visually check the installation according to the initial design. Some of the characteristics, among others, are:

- Safety and health
- Capacity and size depending on the number of occupants
- Compatibility
- Freeze protection
- Operation limits
- Insulation

However, these checklists compile the information about the commissioning of the installation. It is important to highlight that INSITER treats the development of tools for self-inspection and self-instruction along the whole process. As the entire process is very difficult to cover, within the D1.6 some limits are necessary. Then, this document assumes that the design and factory production are well-established procedures with quality methodologies, which ensure the proper implementation of the solar systems. In Figure 7, the project phases and scope of T1.3 is displayed. For solar hot water systems (as for all MEP/HVAC systems) the process starts delivery and transportation on site, all the way through to the in-use phase and maintenance of the installation. According to it, the four phases are used to implement the self-inspection/instruction mechanisms, as explained below.

Transportation to site

First, the transportation to site is the initial stage where the self-inspection mechanism takes place. As mentioned before, the scope of INSITER is on-site. Then, the self-inspection methods are still mainly visual in order to detect damages, hits, cracks in the components. Although, it is visual inspection, additionally BIM-based tools are helpful. In this way, through these BIM-based tools are possible to check that the components are the expected ones. For example, the diameter from design of one pipe could be 1", but thinking in confusion with the pipe on-site is 0.8", the mistake could not be detected in this early stage. Comparing the real element on-site with the BIM modelled one, this geometry errors are easily detected. In summary, two procedures are complementary defined in this step:

1. Visual inspection for cracks, hits and/or damages

2. BIM-based tools for comparison of the real component with the BIM modelled one in order to detect inconsistencies before the installation.

On-site assembly

The second stage is the on-site assembly. In this step of the building life cycle, self-instruction tools are more important that self-inspection ones. The guidance to the technician at time of installing will reduce the number of mistakes when commissioning. In this way, from WP2, simulation process tools based on augmented reality (AR) are very useful to step-by-step determine the installation procedure and the final checks that the technician would require. In fact, sometimes the installation technicians are not experts in the systems and errors like the direction of the flow are wrongly identified. On the other hand, the self-inspection procedures are related to the final check of the installation, which is also included in the AR tools within the simulation assembly process.

On-site assembly

Third step is commissioning, which verifies the start-up of the installation and that is the most complicated process. This step should not only check the behaviour of the system as-a-whole, but also the correct installation of the components. Therefore, two mechanisms are related, firstly, make use of the WP2 tools in order to detect inconsistencies in the physical installation and, secondly, make use of monitoring equipment to calculate KPIs. Regarding the physical installation, 3D laser scanner methods are useful when detecting inconsistencies in terms of geometrical deviation (e.g. joint between a pipe and a pump) and humidity (e.g. stagnant water in any duct). Moreover, thermal parameters are easily measured by thermography. Although D2.3 and D5.2 are more related to building envelope, thermography is also applicable under these systems. The objective is the detection of temperatures of ducts, insulation of the pipes, operational temperature of valves and pumps. With respect to monitoring, also from WP2 ultrasonic measures are helpful at commissioning stage because they allow the determination of operation values without the need of “intrusive” heat-meters, such as flows in different pipes that provide values to ensure the designed flow is going on. Besides, the monitoring systems, connected to software like Simaxx, provide information and KPIs (calculated as before) with the aim at determining the performance of the solar thermal components.

Use and maintenance

Finally, use and maintenance are really similar to the commissioning procedure in terms of monitoring because the continuous monitoring and calculation of KPIs through visualization tools like Simaxx provide continuous assessment of the performance. According to the aforementioned thresholds, wrong operation is easily identified and maintenance costs are reduced.

In short, the process is drawn in Figure 21 where the steps and methodologies are identified.

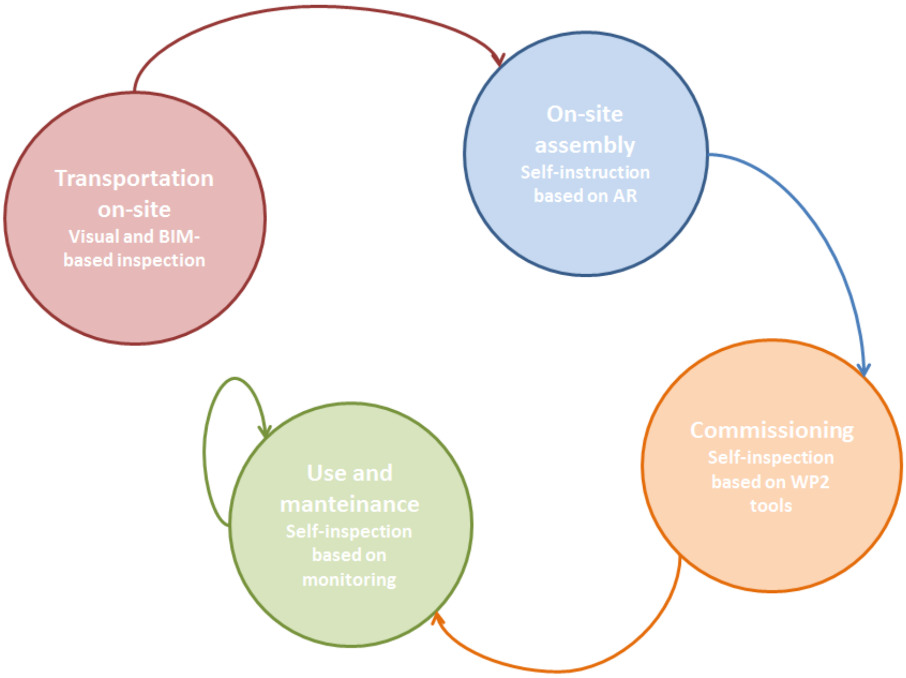

Figure 21: Process for solar thermal systems

3.5 LED Lighting Systems

3.5.1 Introduction

Lighting systems are installed to provide a building with artificial lighting when natural lighting is insufficient or unavailable. This can be because a space has no windows, insufficient windows, or when the space is to be used at times when there is insufficient daylight. Lighting can be provided by different types of systems, currently most office buildings are lit using fluorescent lighting. There is a transition going where fluorescent lighting in existing buildings is increasingly replaced by LED lighting, and in new buildings, LED lighting being applied initially. LED lighting systems can consist of LED's only or be hybrid systems where LED lighting is combined with more traditional light sources such as fluorescent lighting. In hybrid system, generally the task surface is lit using traditional lighting while the surroundings, hallways, meeting rooms, and other areas not containing task surfaces are lit using LED lighting. The main advantage of LED lighting is the low power consumption. LED's convert energy into light much more efficiently than traditional systems. The power consumption is usually expressed in Lumen/Watt, this normalised quantity can compare luminaries of different size and strength (Note that often the pure consumption of the LED is mentioned as opposed the power consumption per lumen of the luminary including the driver, lenses, and fluorescent layer).

LED is an abbreviation of Light Emitting Diode, referring to the diode that emits light and is the heart of the lighting system. Luminaries often consist of an array of multiple LED's. The configuration of the array depends on the application of the luminary. An LED requires direct current at low voltage, and is generally dimmed by modulating the input signal, to do so a driver is required. Contrary to traditional light sources LED's are sensitive to the surrounding temperature that greatly influences the life expectancy. Light emitted from the diodes is polarized, directional and has a very thin spectral bandwidth. To overcome this limitation, a system of lenses/diffusors is used together with a fluorescent layer. The different components are supplied together in a luminary by the supplier, and are installed on site.

The lighting of a task surface is only partly dependent on the lighting system. It is a summation of the natural daylight entering through the windows, the lighting system, and the properties of the room's boundary surfaces. Changing the location/size of the windows, shading, wall colour or texture influences the lighting design.

3.5.2 Critical components

Control system

Lighting systems are often centrally controlled per room or part of the building. Either way multiple luminaires are connected to one control system. In its simplest form this is an on/off switch near the entry of a room, more advanced systems use schedules, occupancy detection and/or daylight detection.

Because the intensity of the light (dimming) and de duration over which the lights are switched on are greatly influencing the total energy consumption the lighting system. The electricity consumption can be reduced by only using artificial lighting when it's needed and only as much as is needed. Different control strategies all have their pros and cons. For example, a light switch per room is in theory only switched on when light is needed. However, it's largely dependent on user behaviour and is often left on unnecessary. The most energy efficient way of control is the use of a combination of both daylight- and occupancy detection. The use of daylight detection is not limited to the room a whole but can also be applied on zones, for example there is lower demand for artificial lighting near the windows than deeper into the building.

Relevant standards:	- EN 12464-1
Common errors:	- L03: The luminary is not correctly connected to the control system.
	- L03: Occupancy sensors are installed with a wrong orientation, occupancy is therefore not properly detected
	- L04: Schedules are not set, set incorrectly or inefficiently
	- L04: Sensitivity or timing of occupancy is set incorrectly; as a result, lights are switched of when the occupants are not extensively moving.
	- L04: Software is programmed incorrectly, and switches the wrong luminaries, or switched the luminaries incorrectly.
Affected KPI's:	- Illuminance
	- Energy use of lighting
Measurement aspects:	- Measurement of the illuminance on a task surface
	- Measurement of luminance of boundary surfaces
	- Electricity consumption of the lighting system
	- Uniformity

Luminary

The luminary is the composition of the LED's and supporting components. The luminary is selected and purchased as one piece. The manufacturer of the luminary composes the combination of components. The different components are described separately. A luminary is generally composed of the following components.

- Driver
- Array of LED's
- Heat sink
- Lenses / diffusor
- Fluorescent layer

Driver

The driver transfers the Alternating Current (AC) of the internal electrical grid to Direct Current (DC) as required by the LED's and reduces the voltage. The desired voltage is dependent on the array in which the LED's are arranged and whether they are connected in series, parallel or a combination.

Dimming is also done by the driver; this can be controlled by reducing the voltage. A more elegant way is by using Pulse Width Modulation (PWM) where the light is rapidly switched on and off. The switching occurs at a frequency that is undetectable by humans and the LED's appears to have a constant brightness (for humans, frequencies from around 100 Hz and up are undetectable, note that different animals, for example dogs, can detect higher frequencies).

A good driver does not cause harmonic distortion in the electrical grid of the building, have a sufficiently high frequency and when a PWM signal us used the 'angle of power increase' is sufficiently shallow to limit the fluctuations in the electromagnetic field. For cheap, improperly designed drivers this is often not the case.

LED

An LED is an electrical semiconductor, more specifically a diode that emits light when a current is applied in the forward direction. The colour of the light that is emitted is dependent on the material used in the semiconductor. One LED only emits one colour of light with a very narrow bandwidth. Colours in the visible spectrum that can be produced are: red, green, blue, yellow and orange. Other colours can be created by combining LED's of different colour. For example, white light can be created by combining a red, green, and blue LED. This however creates a direct light that appears white, but has a very poor colour rendering index. This happens because spectrally the light is concentrated in three small parts of the spectrum (red, green, and blue) but not the colours in between. To create white light a blue LED is used in combination with a fluorescent layer.

Heat sink

The temperature at which the LED operates has a large effect of the life expectancy. For example, a LED that operates at a surrounding temperature of +-20ºC can have life expectancy above 50.000 hours. Under high operating temperatures the life expectancy can easily drop to 10 000 hours and far below, depending on the surrounding temperature.

Although the conversion of electricity into light has a much higher efficiency than traditional lighting systems, not all electricity is converted to light; part of the energy is converted into heat. This heat causes a temperature rise in the LED and therefore a decrease in life expectancy. To avoid this decrease, the LED should be sufficiently cooled. LED's are generally cooled with air, the air flows along a heat sink that is connected to the LED. It is important that there can be sufficient airflow around the heat sink.

Lenses/diffusor

LEDs emit light focussed in a certain direction while often a more diffuse emission of light is desired. Furthermore, a luminary usually consists of an array of LEDs; each LED has a very high brightness caused by the relatively small surface where light is emitted. To achieve a diffuse and uniform distribution of light emittance over luminary surface a system of lenses/diffusors is used. The composition of the system is dependent on the user requirements. The system of lenses/diffusor is additionally used to counter the polarised light that an LED emits.

Fluorescent layer

LEDs are capable of producing light with a small spectrum. The corresponding colours to these parts of the spectrum are blue, red, and green. To achieve a comfortable colour rendition, the spectrum of the light should be as complete (wide) as possible. The photons emitted by the LED collide with the fluorescent layer which in turn emits light in large range of the spectrum. The fluorescent layer is designed in such a way that the emitted light has a spectrum that approaches that of the visible range. Light emitted outside of the visible range is not seen by humans and therefore regarded as waist.

Relevant standards:	− EN 12464-1; EN 13032
Common errors:	− L02: A luminary with a substandard quality is selected for budgetary reasons; − L03: The luminary is installed incorrectly, for example with an increment form the ceiling or close to a beam; − L03: The luminary is installed on the wrong location; − L03: The driver is not connected to the electricity grid or connected incorrectly; − L03: Incorrect placement, like a LED placed in an enclosure, preventing a sufficient airflow around the heat sink for good cooling.
Affected KPI's:	− Energy use of lighting; − Illuminance; − UGR; − Colour temperature;
Measurement aspects:	− Measurement of the illuminance on a task surface − Electricity consumption of the lighting system − Measurement of luminance of boundary surfaces and luminaries − Measurement of colour temperature in the room − Measurement of the Colour rendering index in the room − Uniformity;

Reflecting surfaces in the room

Only a small part of the perceived light is directly coming from the luminary, most of the light is reflected by one or more of the surfaces in the room before reaching the eye. In each reflection part of the light is transferred into heat. Witch part of the spectrum is absorbed is depending on the colour or the surface. The amount of light that is absorbed in that part of the spectrum is depending on the structure (finish) of the surface. When for example, a room has a red ceiling and an indirect lighting system where the luminaries light the ceiling, only the red part of the light will be reflected and the light incident on the desk will be red.

Relevant standards:	– EN 12464-1
Common errors:	– L02: The surface finish is changed during construction or not determined before the building is delivered. Changing the colours and textures may result in improper lighting.
	– L03: Luminaries are mounted and set with incorrect orientation
Affected KPI's:	– Energy use of lighting;
	– Illuminance
	– UGR
Measurement aspects:	– Measurement of the illuminance on a task surface
	– Electricity consumption of the lighting system
	– Measurement of luminance of boundary surfaces
	– Uniformity

Furniture placement

The lighting demands are not uniform throughout a room, for example extra “luminance” is required on the desk. This means that the lighting design is dependent on the layout of the room, especially the location of for example desks. Furthermore, the surface of the desk is important and is often unknown during the lighting design. The illuminance on the desk can be calculated; however, the luminance is dependent on the colour, material, and texture of the surface.

Common errors:	– The interior of the room does not match the design, for example desks locations or screens.
	– The properties of the placed desks do not match the design specifications.
Affected KPI's	– Illuminance
	– UGR
measurement aspects:	– Measurement of the illuminance on a task surface
	– Measurement of luminance of boundary surfaces and luminaries
	– Uniformity

3.5.3 Difficulties in assessment and analysis

The desired lighting differs throughout the room mainly based on whether there are workplaces, or not. Therefore, it is often not possible to determine the quality of a certain lighting aspect for the room as a whole. This means that measurements must be conducted repeatedly to capture the lighting quality on each task surface or on each workplace.

Furthermore, the perceived lighting differs from the emitted lighting. Most of the light that reaches the eyes of the occupants of the room is not directly coming from the light source bur is reflected by one or multiple surfaces. These surfaces are selective of the part of the light that they reflect; this applies both the wavelength (colour) and intensity and is dependent on the surface colour, material, and texture. This means that before measurements can begin, the room must be fully painted. Preferable the room is also furnished because furniture covers part of the reflecting surfaces and therefore influences the reflections.

The measured values are related to the perception of light by the occupants. This light however, is not only coming from the artificial lighting system but is a summation of artificial light and natural light. This means that the light and therefore the measured quantities are weather dependent.

3.5.4 Measurement of performance

Assessing the “as-built” situation and comparing to the design requires capturing of the performance. Measurement devices are generally not sufficiently included in the lighting system to do so. Measurements are therefore conducted with external measurement devices.

For assessing the performance of the lighting system several quantities must be measured, most measurements take place in the room on the task surface of a workplace or location of the heat of the occupants. Measurement of energy consumption takes place in the electrical system. The measured values include

- Illuminance on the task surface; the illuminance is the amount of light that falls on the task surface and is therefore a measure if the lighting system can provide the task with enough light.
- Luminance of boundary surfaces and luminaries; the luminance is the amount of light that is emitted by a certain surface; this can be used to evaluate glare or uniformity form different angles.
- Electricity use of lighting; provides a measure of efficiency, when the desired quality is achieved, how energy efficient is this quality is achieved.
- Colour temperature in the room; is a measure of the “warmth” of the light.
- Colour rendering index in the room; provides a measure of how well different colours are rendered inside the room. With led lighting this can be problematic because of the small bandwidth in which an LED emit light.

The measurements and transfer to performance indicators is further described in section 0.

3.5.5 Calculation of KPIs

Multiple KPI’s are established to assess the quality of the lighting system. The KPI’s are directed either at the energy performance of the lighting system, or to lighting comfort and preventing disturbance by nuisance. The comfort indicators indicate whether and to what extent the lighting system performs its main task. The energy indicator is a measure of how efficiently this task is performed.

In the table below, an overview is given of the ventilation-related KPIs and to what level they contribute to the overall building quality performance.

Level	KPI	Description
System	Energy use of lighting	Electricity consumption of the lighting system
Subsystem	Illuminance	The amount of light incident on the workplace surface
	UGR	Glare on a workplace, expressed in the UGR value
	Uniformity	Uniformity of the luminance of different surfaces as seen from the workplace.
	Colour temperature	“Warmth” of the light on a workspace
	Colour rendering index	Spectral quality of the light on the workplace expressed as the colour rendering index (CRI)

Total electricity consumption [kWh]

When: After 1 year of operation

Verification: Simulations results with occupancy prediction.

Measurement: kWh meter, on separate electrical group containing only lighting.

Max deviation: 20%

Description: When the total electricity use of the lighting system is compared to simulation results, an indicator of the total performance is obtained. For example, when the occupancy detection or daylight detection is not properly functioning this will result an increase of the amount of lighting and corresponding electricity use.

Electricity consumption in kWh is measured according to directive 2014-32-eu (MID - measurement instrument directive). The indicator is very broad as it applies to the entire lighting system. A value in accordance with the expectation indicates a good energy performance of the system. However, it does not necessarily mean that each individual component has a good performance.

The threshold value for electricity consumption is quite lenient, when the control system is provided with occupancy detection the user behaviour (actual occupancy) is of large influence on the resulting electricity consumption.

Illuminance [Lux]

When: During construction when interior is finished

Verification: Design criteria

Max deviation: minimum value

Description: Illuminance is a measure for the amount of light incident on a surface. Each task requires a certain amount of light on the task surface. The illuminance on the workplace task surface is measured using an illuminance meter. Assessment of the illuminance is performed according to EN 12464-1. It is important that measurements take place a room that is fully finished (painted, decorated, and finished) because of the large influence of the surroundings to the illuminance on the task surface.

UGR [-]

When: During construction when the interior is finished

Verification: Design criteria

Max deviation: minimum value

Description: Glare is a measure of how much a user is blinded by certain surfaces. This can be, for example, a window, strongly lit wall, or a luminary. For visual comfort, glare should be limited to a certain amount. The amount of glare caused by the artificial lighting system can be quantified by the Unified Glare Rating (UGR) which is based on luminance. Assessment of glare is conducted according to EN 12464-1.

Uniformity [-]

When: During construction when the interior is finished

Verification: Design criteria

Max deviation: minimum value

Description: Uniformity is a measure that indicates the difference in luminance from different surfaces around the room such as the walls and ceiling. Uniformity is a measure that differs from workplace to workplace so it is nog constant throughout the room. The uniformity for a specific workplace is determined in accordance with EN 12464-1.

Colour temperature [k]

When: During construction when the interior is finished.

Verification: Design criteria

Max deviation: 10%

Description: Colour temperature is a measure of the “warmth “of the light and originates from the temperature of the filament in an incandescence lamp and corresponding colour. This means that a high colour temperature indicates a very white “clinical” light, while a low colour temperature indicates a warm yellowish light. Colour temperature is assessed according to EN 12464-1.

Colour rendering index (CRI) [-]

When: During construction when the building is decorated.

Verification: Design criteria

Max deviation: 10%

Description: Colour rendering Index is a measure that expresses the fidelity of the perceived colour. For example, a white surface appears red under red light. Because of the absence of blue and green light, this light cannot be reflected. The CRI is assessed according to EN 12464-1.

3.5.6 Self-inspection for LED lighting systems

To assess the result of a certain lighting configuration, simulations are performed. In Europe, the current industry standard for lighting simulations is DIALUX. These simulations are used during the design phase. However, the assessment of the lighting system will preferably be performed, based on the requirements of the system, rather than on the simulation results. The reason is, that with simulations assumptions have been made regarding the final furnishing of the rooms. Deviations from the design are often not in the lighting system itself but in the reflective surfaces in the room such as walls and ceiling finish and colour. During the design phase, standard values are assumed for reflections, however when the final paint colour of a wall changes this can have a significant impact on the total lighting quality, or illuminance.

During the lighting design, simulations are made using the design to determine the lighting quality on the specified task surfaces. Preferably, these simulations are conducted using a BIM based simulation method, so data can be exported to INSITER's BIM model, with all the properties and locations of the luminaries. Then, during the realization phase, assessment of the lighting system is conducted to the performance of the model in BIM. That way, deviations caused by furnishing of the room, is excluded. Measurements and calculations during realization will be used, but don't necessarily mean that deviations will be classified as an error to be resolved.

For the electricity consumption of the lighting system however, the normal procedure can be followed. So, deviations in energy use caused by lighting will be quantified to support the decision-making process. One thing to keep in mind though, is the effect of adaptions made to recover insufficient lighting when it appears that the 'as designed' situation doesn't correspondent to the 'as-built' situation. For example, when calculations are based on white surface of the walls and ceiling, and the colour is changes to dark grey or even black, this means that additional lighting is needed in the room. This in turn results in additional power consumption by the lighting system.

4. Analytical self-inspection protocols for MEP/HVAC systems

The INSITER processes focus on the construction phase including the work preparation. To enable a clean start, certain preconditions must be met during the design phase. In this section both the preconditions and accompanying processes and the self-inspection processes are described. The processes focus on self-inspection rather than inspection from an external auditor. A worker is supplied with methods to inspect the work they just performed and subsequently documents the inspection. When an inspection is performed by an external auditor before handover of the building, this inspection can consist of checking the documented self-inspection and sampling the correctness. The information stored in the BIM is the starting point. Self-inspection comes together with self-instruction. On a mobile device, the worker can access the BIM together with manuals and instructions corresponding to the component that must be installed.

Inspection is performed on different successive levels; component level, subsystem level and system level and during different project phases. The successive levels have been defined in section 3.1.1, the project phases are explained in section 2.1.1.

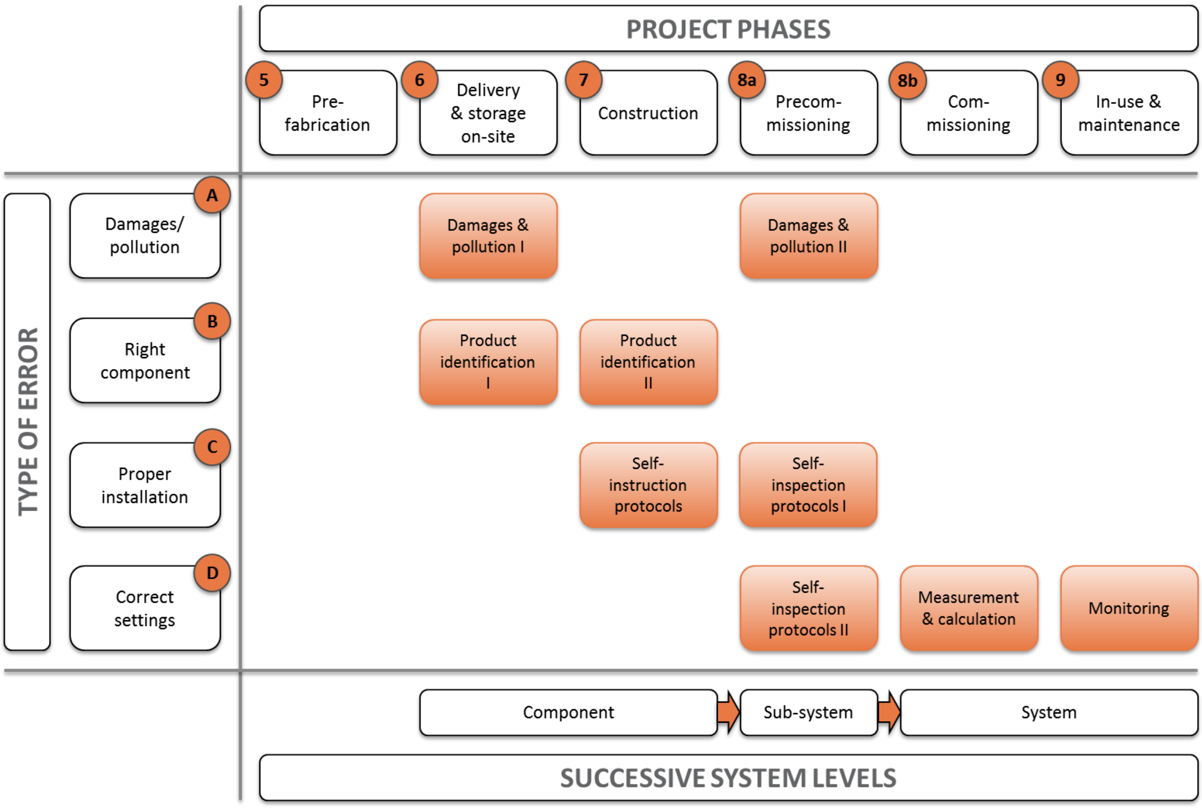

Figure 21: INSITER's MEP/HVAC methodology

In Figure a full overview is shown of the inspection protocols and their relation to the project phases, type of errors and system level. Below, the inspection protocols are explained. For better recognisability, the inspection protocols are coded with a number and a letter, corresponding the building phase and type of error. For example, 7-B for an inspection or check during the construction phase, detecting errors to prevent installing the wrong component (see Figure 21).

4.1 Inspection on different levels

Performance testing procedures are viewed from a system perspective, rather than a component perspective. This is especially critical for the overall success of the system. The performance of the system is dependent on four areas of interaction:

- The individual components in the system
- The components with each other as a subsystem
- The subsystem with other subsystems in a system
- The systems in a building with its environment.

From the building occupants' perspective, a comfortable, controlled environment will only be ensured if all of these components, subsystems, and systems can work together in harmony with other systems including the environment and the building functions and envelope.

To detect errors, one can either work 'top-down' or 'bottom-up. In a top-down approach the whole system functional performances are first verified, moving on to subsystems and then onto specific components as malfunctions are found and require investigation. The goal is not to verify if a component is 'good' or 'bad' itself, but to check if it's correctly integrated in the system considered. The bottom-up approach starts by confirming the performance of an elementary component and progressively working up to the whole system. This allows safer identification of local defaults, but it may require excessive effort.
INSITER is using the best of both worlds. This involves detecting the errors on component level and analyse them back through the hierarchy of systems. In the meanwhile, the system as a whole is monitored and verified to the design model of the building in BIM. By eliminating the errors on component level during construction phase, it gets easier and less demanding to detect system errors in a later phase. In Figure 22, a diagram is shown, clarifying the bottom-up approach during construction phase and top-down during commissioning and in use (on-going commissioning).

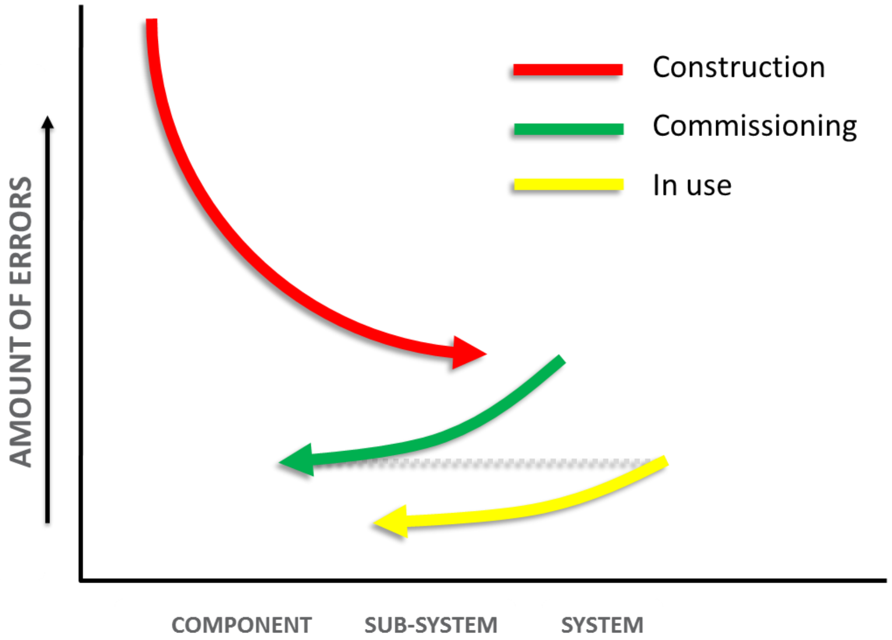

Figure 22: INSITER's Bottom-up and top-down analyses

4.1.1 Component level

In complex systems, such as MEP/HVAC, it is necessary to improve the performance and to minimalize errors, by a structured approach. This is done by sub optimization and optimization; that is, by first optimizing components, then subsystems and finally the complete HVAC system. When components influence each other in series it is possible to optimize the subsystem by sub optimization of the component. For example, consider a subsystem with 3 components. The output of component A equals the input to component B and the output of component B equals the input to component C. Component C does not affect any other component. Hence, the components are considered to be in series. Sub optimization may be started with the first component, component A, because at this stage it is the only component of which the input is known. Subsequently optimization of component B has no effect on component A, but it does have effect on the input of component C. And thus, component C will be last to optimize, because it doesn't influence any other component. The process is shown in Figure 23.

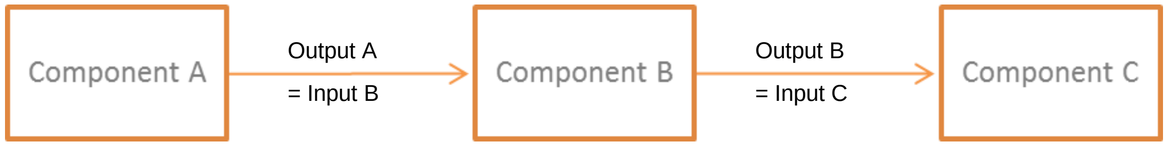

Figure 23: Optimizing a subsystem consisting of multiple components

4.1.2 Subsystem level

When the worker is confident that the correct components and prefabricated sections are installed the right way on the right location with the right settings, inspection moves to the subsystem level.

A subsystem is acquired from an external supplier and subject to the supplier's quality control system. Inspections whether the correct subsystem is supplied, the subsystem is installed on the right location and installed the correct way, follow the inspection process of the component level. Here the subsystem is regarded to be a component. The distribution net is regarded being a subsystem, inspection of the performance can be done on the subsystem as a whole or separately for different sections. Assembly is done either by the on-site worker or as prefabrication in a factory.

The inspection of the subsystems is performed subsequent to testing on component level. It mainly consists of functionality test that can be executed during the construction phase when a subsystem is complete or near completion. The tests that are performed are dependent on the specific subsystem. For example, when part of the distribution net is completed the worker pressurizes the system to detect any leaks. Test can be conducted using external measurement devices of measurement devices that are present in the subsystem for monitoring or control purposes.

The test that must be conducted on each subsystem are specified in the INSITER tool, together with the accompanying KPI or reference value that is obtained from the simulations on the most recent BIM of using this BIM as input. When a test is concluded, the results are transferred to the BIM. When the KPIs do not meet the design value that is predicted by the calculations or according to the specifications of the supplier, sub indicators can be used to find the cause of the problem. For example, if the supply temperature of an air handling system doesn't meet design specifications, a partial system test can be executed to detect the cause of the error. In Figure 24 this example is shown. The outgoing air temperature is measured and compared to the predictions from the BIM model. The BIM model uses simulation software to calculate the prediction.

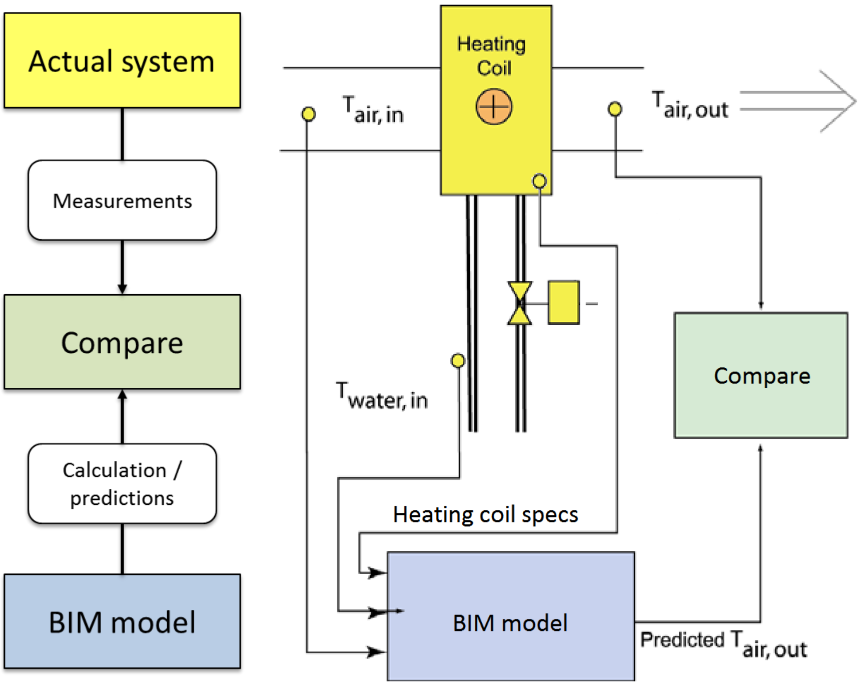

Figure 24: Model-based fault detection (left: conceptual; right: its application to a heating coil)

In many cases, the performance of subsystem cannot be assessed individually, for example to test a gas fired boiler and determine its efficiency a distribution system should be connected so the boiler can lose the produced heat. The efficiency can only be determined after a certain period with different weather types. The same holds for the heat pump. To assess the related KPIs, the building and the installation are monitored using monitoring software such as SIMAXX.

4.1.3 System level

Inspection on system level takes place on different moments in the construction process. Ideally, most of the inspections are completed before handover of the building. However, to get a complete overview of the building performance the building must be in use for a certain period with different weather types. It is debatable if the inspections that take place after handover can be categorized as self-inspection. However, it is an important part of the inspections since here the real performance can be assessed related to the expected performance.

The most important part of eliminating errors on system level is the commissioning phase. During commissioning, the start-up of the installation is verified, which is the most complicated process. This step should not only check the behaviour of the system as-a-whole, but also the correct installation of the components (top-down approach). Therefore, two mechanisms are related, firstly, make use of the WP2 tools and measurement instruments in order to detect inconsistencies in the physical installation and, secondly, make use of monitoring equipment to calculate KPIs. The monitoring system, connected to software like Simaxx, provides information and KPIs (calculated as before) with the aim at determining the performance of the components.

4.2 Inspection during the building phases

4.2.1 Delivery and storage on-site

First, the transportation to site (identified with number 6 in the diagram) is the initial stage where the self-inspection mechanism for MEP/HVAC takes place. As mentioned before, the scope of MEP/HVAC components is on-site. The first checks are intended to assure that the right components will be installed, that they are undamaged and clean and that they are in compliance with the building design and relevant technical rules. For example, the wrong ventilation unit is delivered. Its dimensions are the same and specs are similar, but it appears to be the wrong model. Mistakes like this are detected, if detected at all, when the construction worker is mounting the unit, or when the ventilation system is tested for operation. Comparing the real element on-site with the BIM modelled once, these types of errors are easily detected. In summary, two procedures are defined in this step:

1. Visual inspection for cracks, hits, and damages;
2. BIM-based tools for identification of the component in order to detect inconsistencies before installation.

(6-A) Damages and pollution I

What:	– Inspection for damages like dents, cracks, hits, scratches and broken or missing parts; – Checks on broken or missing sealing and pollution of the component.
When:	At or right after delivery on-site
How:	Visual inspection
Tolerance:	To be determined in D1.7.

Description:

During transport, components can get damaged. Therefore, it is important to check the state of the component after transportation. This will be done when the component is delivered on site. The on-site worker will check the components for visual damages. Broken sealing is an indication that the component might be damaged or scratched. The check is done upon arrival on-site. After that, components will be stored in containers, stored in open air, or brought to the final location, where it will be mounted.

(6-B) Product identification I

What:	– Comparison of the delivered component with the BIM specification; – Check of the component's compliance with technical and legal rules; – Check whether all documents necessary for operation (e.g. INSITER's self-instruction and self-inspection protocols) are available.
When:	At or right after delivery on-site
How:	By scanning or entering the QR code using the mobile device and matching to BIM
Tolerance:	To be determined in D1.7.

Description:
From the component list, the on-site worker can collect the necessary components and prefabricated components. Each component in the BIM is fitted with a QR code to identify the product. Prefabricated subsections contain a similar code. When real life components are installed, the QR code is scanned or entered using the mobile device and matched to the BIM. This way the worker checks if the component is the exact component described in the BIM.

The supplier is required to check his own work and provide proof that his product meets the specifications. This can be done using independent certification such as EUROVENT or ARI-norm, but also by using a database of independent quality certificates like in the Netherlands (Bureau CRG: www.bcrg.nl). The method of inspection is documented in different directives, dependent on the type of component. Preferably, the supplier has an internal quality system through which he keeps errors in the produced components at a minimum.

If the component does not match the prescribed component, the new component must be entered in the hydronic system optimisation tool. Simulation will return the impact of the deviation from the design. If the impact is unacceptable, the correct component must be order and installed. If the impact is positive or acceptable, the wrong component can maintain its position, the BIM and HYSOPT model are adapted to stay updated for future use. Note that impact relates not only to performance but also to costs and planning. This will be further elaborated in D1.7.

4.2.2 Construction

The second stage is the on-site assembly or construction phase. During this phase, components will be transported to the place of installation in the building. This can be right after delivery on-site, for example when using on-time delivery (OTD). But this can also be after a period of storage in containers or on-site. Transportation to the installation spot in the building might be done by other labourers than the actual MEP workers. When the component is in place and the MEP worker is ready for installation, a few checks will be performed:

1. Identification of the right component and extracting the available documents from the INSITER software tool.
2. Protocols for self-instruction, in order to install a component 'the right way'

(7-B) Product identification II

What:	- Comparison of the delivered component with the BIM specification; - Location check to make sure the component is installed in the right place; - Fetching all the documents necessary for installation (e.g. INSITER's self-instruction and self-inspection protocols).
When:	Before installing the component
How:	By scanning or entering the QR code using the mobile device and matching to BIM and indoor positioning system in the device.
Tolerance:	To be determined in D1.7.

Description:

A MEP or construction worker will mount the component, but will perform another last check on the component to make sure it is the right component and the right location where is has to be mounted. The location check is supported by the GPS module in the INSITER software tool. The component is coupled to the component in BIM where further information of the component can be retrieved from an external component database such as 2BA database.

The QR code is scanned or entered once more, using the mobile device, and matched to the BIM. This way the worker checks if the component he is about to install is the exact component from the BIM model. While doing so, he can download the product documentation, specification, and installation manual and, if available, instruction and inspection protocols from INSITER. Scanning the QR code gives direct access to all information that will help the worker in correctly installing the component.

(7-C) Self-instruction protocols

What:	Self-instruction for installation of the elementary components.
When:	Before installing the component
How:	By using up-to-date self-instruction protocols
Tolerance:	To be determined in D1.7.

Description:

The on-site worker has a mobile device that gives access to the BIM. Self-instruction starts with a work planning for the particular worker with tasks to perform that day. The planning is extracted from planning software that is used in combination with the BIM. Each task is connected to the corresponding section in the BIM that provides schemes of the installation, 2d and 3d images and dimensions, a list of components. For each component, documentation and installation manuals are available for instruction purposes.

The self-instruction protocols are digital guidelines for mounting, installing and operating the MEP/HVAC components. The protocols can be based on the guidelines from the manufacturer, for specific devices. But it can also be a database of general guidelines like ISSO's knowledge maps ("ISSO kenniskaarten") and digitally connected to INSITER's training material. ISSO's knowledge maps contain generic information about the installation and operation of HVAC components and are based on present-day knowledge about the subject. A knowledge database can be used and enlarged in INSITER as more experience is build up. The relation with a program like 'Build-up Skills' is an ever-evolving collaboration. The combination of evolving knowledge maps with continues input from INSITER, from manufacturers and from training programs like Build-up Skills will be very beneficial.

4.2.3 Pre-commissioning and commissioning

Commissioning is the phase between mechanical completion and start-up of the MEP/HVAC system. It is the most difficult and crucial phase in a good working MEP system, especially for HVAC systems.

Pre-commissioning is not an actual phase, but indicates the period where commissioning is prepared. It starts after mechanical completion and means checking and testing of equipment and construction to confirm that the installation is in accordance with the design specifications and in compliance with project requirements. During pre-commissioning, activities such as cleaning and pre-functional checks of components are being carried oud in order to prepare these components for commissioning. The important checks are:

1. Checking if installed components and subsystems are clean and unscathed.
2. Verifications and tests to ensure that every piece of equipment and every (sub) system in a building is installed correctly and can start up and run properly.
3. Air tightness testing of duct systems and leak testing of pipes and distribution systems.

(8-A) Damages and pollution II

What:	– Checks for damages like dents, cracks, hits, and scratches; – Checks for pollution of the component or subsystem.
When:	After mechanical completion of the MEP/HVAC system and before construction walls, ceilings or shafts are closed.
How:	Visual inspection
Tolerance:	To be determined in D1.7.

Description:

During the construction process, a lot of workers will be in the building doing their job. While doing so, they might step upon an installation part or accidently hit a pipe or duct. Because no one feels responsible for someone else's work, a lot of these damages will be covered up. If walls, floors, ceilings, and shafts are closed, the damages will never be detected. Therefore, it is important to check the state of the components and subsystems after completion. This will be done just before a construction element will cover the MEP component up. So, for example, checking the pipework and ducts before the final floor layer is poured. The MEP worker will perform a final check on the components and subsystems for visual damages or pollution.

(8-C) Self-inspection protocols I

What:
- Last verification that the component actually installed is the component from the BIM model;
- Verifying mechanical adjustments (e.g. belt tension of a fan and motor) and connections to other components;
- Checking piping and wiring connections, including air tightness and leak testing of duct and pipe systems.

When: After mechanical completion

How: By using up-to-date self-inspection protocols

Tolerance: To be determined in D1.7.

Description:

Using augmented reality, the worker can check if the components are installed correctly. On the mobile device, the virtual building is projected over the physical building. Making use of the positioning system in de building and the inclinometers in the device, the INSITER tool knows which part of the BIM must be projected on the image of the camera inside the mobile device. The worker than checks if the components he installed are on the right place and if he installed it the same way as in the instructions.

If the worker detects a deviation in the location where he installed for example a pump or pipe, the deviation is entered in the BIM to perform clash detection. From this detection, he concludes if the deviation will result in an issue when for example the ventilation ducts are installed. If there is a clash with the ventilation ducts, the worker should restore the deviating pipe. If the clash detection returns no issues with the new location, the pipe of pump can maintain it location. However, the route of the piping is changed in the BIM. This way the 'as-built' model remains updated for future use.

For air tightness and leak testing, see the sections 3.2.4, 3.3.4 and 0.

(8a-D) Self-inspection protocols II

What:
- Verifying calibration and sensor locations;
- Verifying control set points and safety settings;
- Testing electrical parameters like voltage and amperage.

When: After mechanical completion

How: By using up-to-date self-inspection protocols

Tolerance: To be determined in D1.7.

Description:

These self-inspection protocols are needed to verify that each independently commissioned component also functions as intended when interacting with the rest of the system. It is important to verify that all safeties, interlocks, and alarms are programmed (or hard-wired, if applicable) and functioning correctly.

Again, the MEP worker uses his mobile device to scan a component and gets access to the information from the BIM model. The information shows the sensor locations, control and safety settings and other parameters related to the component. The optimal settings that are previously calculated using HYSOPT and stored in the BIM are supplied along with the instructions. The settings of the controller can be applied right away.

After pre-commissioning tests and verifications have been performed, commissioning will start. During commissioning, it is necessary to verify and document proper operation which includes the start-up, shut down, and sequence of operation. After the equipment has been verified to operate properly, the HVAC equipment will be tested, adjusted, and balanced (TAB). This is the phase in a project after the start-up of the complete system in order to adjust, tweak, optimize and prepare the system for the performance testing phase which is the next step.

To ensure that the MEP/HVAC system will perform as desired, measurements will be taken and calculations will be carried out.

(8b-D) Measurement and calculation

What:
- Measurement of aspects
- Calculation of KPIs

When: During commissioning

How: Measurements and calculation according to INSITER's principles.

Tolerance: To be determined in D1.7.

Description:

During commissioning, the building's MEP/HVAC systems will be tested, adjusted and balanced. During this phase, measurements will be taken for an optimal performance of the systems. INSITERs methodology will follow a procedure of measurements and calculations to secure the building's performance from design phase and BIM model. The measurements and calculations will be carried out according to the sections 3.x.4 and 3.x.5 of this document.

4.2.4 Use and maintenance

When commissioning is done, the building is ready to be completed. But as soon as a building is operational, systems already begin to wear. Even the most energy efficient, “green” building systems will start to go “grey” right away. To prevent this, building need to be continually commissioned (on-going commissioning), even after realization. The activities during the use and maintenance phase are really similar to the commissioning procedure in terms of monitoring because the continuous monitoring and calculation of KPIs through visualization tools like Simaxx provide continuous assessment of the performance. Wrong operation is easily identified and corrected and maintenance costs are reduced.

(9-D) Monitoring

What:	– Integrated monitoring of the MEP/HVAC systems; – Continuous assessment of the building’s performance.
When:	Monitoring starts during the commissioning phase, when the monitoring system is operational. It’s already helpful during commissioning and will be even more during the on-going commissioning in the maintenance phase.
How:	Using monitoring tools like Simaxx.
Tolerance:	To be determined in D1.7.

Description:

The real performance is determined through monitoring. An external company or maintenance division within the construction company performs monitoring for which the sensors of the control system are used, together with additional sensors dedicated to monitoring purposes. The sensor data is transferred to KPIs representing performance using monitoring software such as SIMAXX. The KPIs can be calculated after the building endured periods with different weather types, preferably at least one full year. The simulations using building performance software such as VABI-elements or TRNSYS is repeated using climate data of the same year and location as the monitoring data and building. If the system does not perform as predicted, the subsystem level KPIs can be used to zoom localize the reason of the underperformance. The main purpose of inspection on system level is detecting issues with the control strategy and interaction between different subsystems. Issues with individual components are expected to be found during the previous inspection levels.

4.3 Inspection techniques further explained

IN the previous sections, the inspection protocols are lined out. In this section the methods will be further explained.

The INSITER project applies to the realisation phase and assumes the design is flawless. However, to ensure that delivered components meet the design specification a few inspections are needed:

- Product specification
- Product identification
- BIM model comparison

4.3.1 Product specification

During the calculations and simulations that predict the buildings performance the specifications of components and subsystems are used. The manufacturer of the component often supplies these specifications. To make sure the predicted performance approaches the measured performance, it is important that the specifications are accurate. Generally, the specifications are either given unsubstantiated, supported by internal measurement reports, or supported by an external measurement report. Manufacturers can be tempted to supply overly positive performance specification for marketing purposes, and sometimes feel pressured to do so when their competition does so as well.

It is clear that the performance specifications that come unsubstantiated or with an internal measurement report is often unreliable because of the direct advantage the manufacturer has from positive results. Note however that test reports from seemingly independent test institutes are often coloured. The manufacturer supplies the particular component that is tested, giving him the opportunity to optimize the component for the test. Products are often tested before the development is complete and are adapted for production of cost reduction purposes. Only the most positive from multiple measurements is reported.

Reliable specifications can be obtained using an independent certification such as EUROVENT or ARI-norm. Where tested products are completely developed and acquired through common commercial channels. The tests are performed by a test institute that is not selected by the manufacturer, removing commercial interest of the test institute to satisfy the manufacturer's interest.

To ensure the quality of each product leaving the factory, manufacturers can make use of a quality control system. An example is an ISO-9001 Certificate. The certificate can be obtained when, among others, sufficient processed for quality control are in place.

4.3.2 Product identification

Currently most commercial trade products (components) are identifiable using a QR code (Barr-code) that is supplied by GS1, a non-profit organisation for product classification. This is the same product identification system used in for example supermarkets. A QR code can be scanned by a specially designed infrared scanner but also using the camera that is available on most mobile devices.

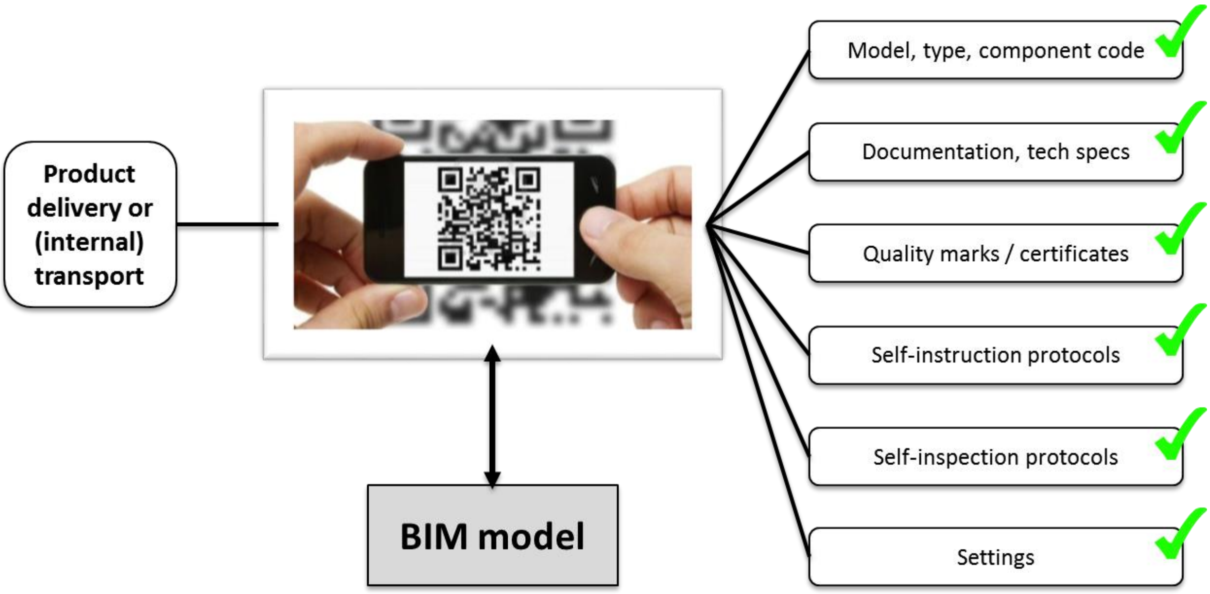

Figure 25: Product identification principles, using QR code

When a component is imported in the BIM the QR is already included in the BIM component most of the time, together with documentation and installation instructions. Otherwise, the purchaser assigns the QR code of the product he selected, to the component in the building information model. The documentation and installation instructions can be obtained from an QR based product database such as 2BA. On site, the worker scans or enters the code on the product or its package. When the code is not printed on the product or a label on the product or its package the product type can be entered that will be recognized and is coupled to the QR code.

Within the building, each component that requires maintenance, inspection of contains settings is already catalogued and given an identification number. This number is different from the QR/GTIN because within the same building multiple components of the same type are installed. Most of the time a tag containing this number is applied to the component or in the vicinity of the component for maintenance purposes.

QR code is used because most products already have this code and use the barcode to identify a product. There is already movement towards the used of near field communication techniques such as RFID to replace barcodes. When the installations sector moves towards such techniques the INSTITER method should follow.

4.3.3 BIM

The INSITER tool revolves around BIM. Although this design method and tools are widely available for some time now, BIM is used only in a small number of projects. The building, both architectural and installations are modelled three dimensionally in the same file, additionally this file contains a lot of background information. This building information model is a virtual version of the future physical building.

The INSITER method and accompanying processes for self-instruction and self-inspection rely on the model. Because the model supplies the drawings (2d or 3d) this will function as instruction but also documentation of the components. Furthermore, the virtual building is the reference to check if the building is built as designed. Functionality such as clash detection during the design phase prevents the on-site workers from improvising when the designed situation cannot be build. This improvisation is the root of many errors and reduced performance.

The BIM provides the simulation and optimization tools with input for the building and installation and is used to store the output of these simulations or is adapted by the result of the optimization. In an ideal case, the building is not only virtually built but also virtually tested. The integration of many different simulation methods and BIM is still in an early stage or completely absent. Ideally future BIM components do not only contain the geometry but also a model of the behaviour of the component that allows for calculation and simulation to be executed based on the BIM.

Related to self-instruction and self-inspection, Components in BIM should contain or be able to contain:

- Geometry (To create an AR overlay of the system design)
- QR code (For product type identification)
- Component code (For component location within the building)
- Certificates (proof that the component complies with the required specifications)
- Self-instruction protocol (Manual for installing/maintaining the component)
- Optimal Settings (Optimal settings for the component determined using the simulation tools)
- Self-inspection protocol (Protocol specific to the component type containing the self-inspection process)
- Inspection result (among others this can be a check box, measurement value or image or a combination)
- Reference values (To compare the test results to and indicate the “as-designed” performance)

4.3.4 Building performance simulation

Building performance simulation software is used to model the interaction between the building, the installation, and external factors. The installation is regarded a black box and is not modelled on component level.

A reference for the energy use of the building is obtained by modelling the building and its installations. Ideally, the performance simulations are done directly from the BIM. Because this is not (yet) sufficiently possible in the BIM, an external model is used that used the BIM as input. The model is used to quantify system level and sub system level KPIs regarding comfort and energy use. Additionally, the model is used for design purposes. However, this falls outside of the scope of INSITER. Simulations with building performance software such as VABI-elements of TRNSYS are currently common practice in designing installations. And the main goal while simulating is optimizing the installation and predict whether the building performs as demanded. The energy use is heavily dependent on the weather conditions. For example, in a year with a very soft winter the consumed energy for heating is much lower than in a year with a very cold winter. This is the reason that for the provision of reference values the weather conditions of the measurement period should be used for the simulations. This means repeating the simulation when the measurement period has ended.

VABI-elements

VABI-elements is a dynamic building performance simulation tool to simulate the buildings performance in which the installations are coupled to the building. Besides hydraulic systems, VABI-elements contains modules for ventilation, cost, and planning. The software is developed by VABI Software B.V. and runs from the user's computer. A one directionally connection to BIM is available where the building geometry is imported using the IFC (industry foundation classes) format. Installations are not imported, for the reason that VABI-elements works with systems or subsystems instead of components. Simulations have a low level of detail and can be performed in an early design stage, for example, when the installation concept is known or developed. The building is represented by a three-dimensional model of the building geometry including materials and their properties. Installation concepts are selected and control strategy must be entered.

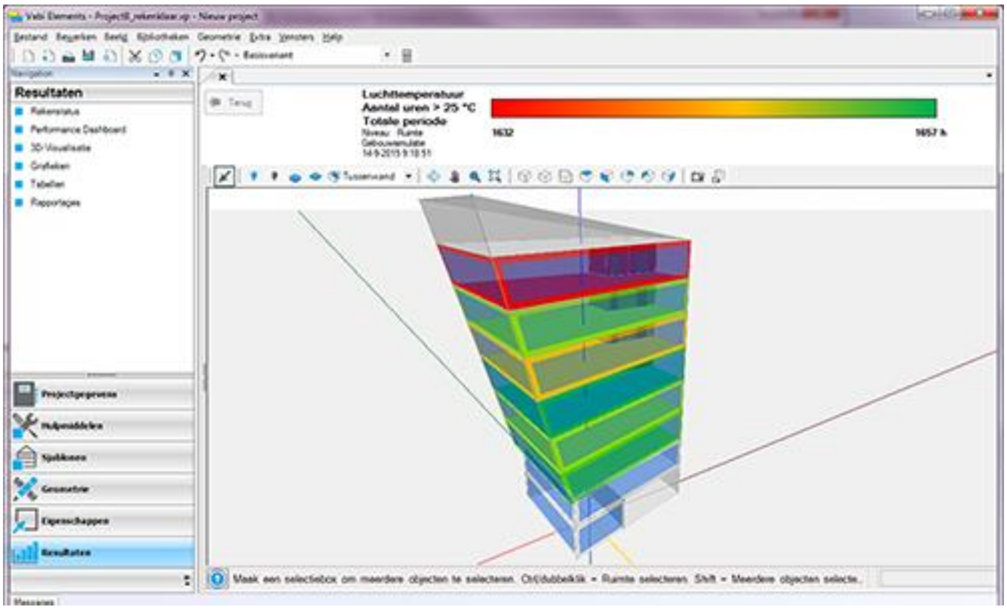

Figure 26: Vabi Elements screenshot (Vabi Software, sd)

TRNSYS

TRNSYS is a systems simulation program used to simulate the behaviour and energy consumption of transient systems, including installation concepts. The software is developed by the University of Wisconsin, has an open source code, and is run from the user's computer. A connection to the BIM is currently not available. The model should be made, run, and maintained separate from the BIM. The simulations results can be exported to several formats, but not coupled to BIM directly. TRNSYS is however interoperable with Excel and Matlab where TRNSYS sends input to the other software and receives output after the external processing. Simulations are done with a low level of detail where components are represented by black box models. The models describing components can be downloaded from a database or made manually. The simulations can be done in an early design stage where a concept is chosen and performance is simulated. The model is made schematically; there is no need for location and details of components.

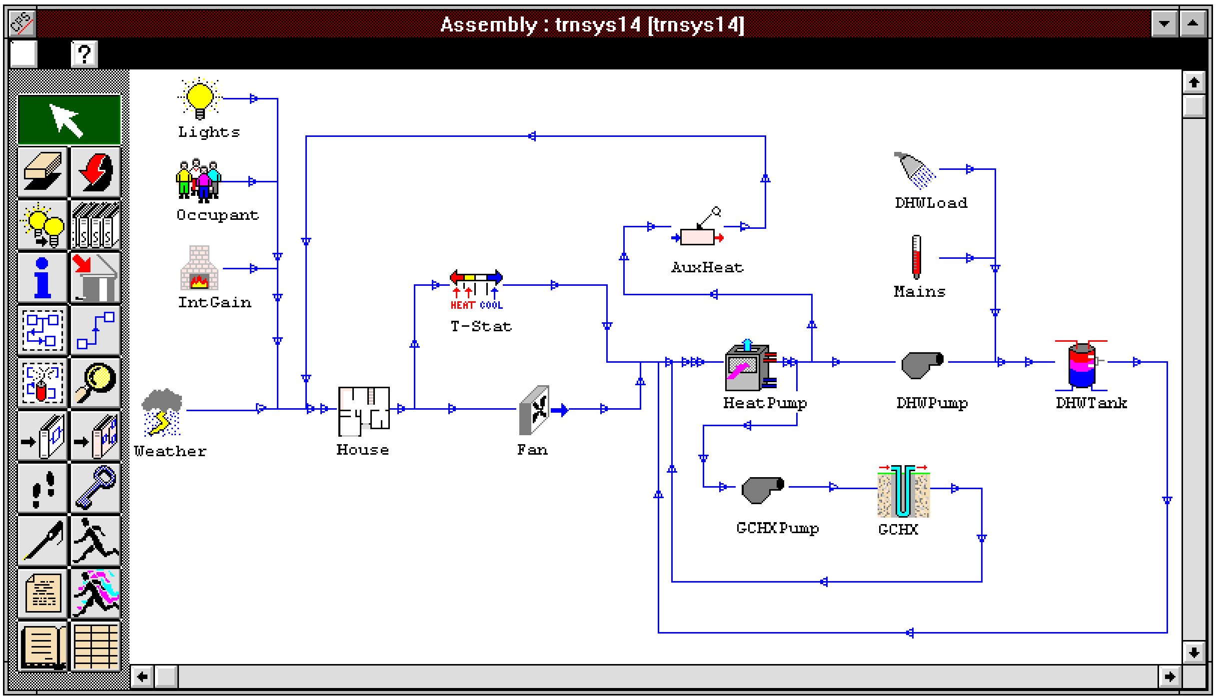

Figure 27: TRNSYS Ground Source Heat Pump simulation (University of Wisconsin Madison, sd)

4.4 Error handling

As mentioned in the process description of self-instruction and self-inspection on component level each deviation from the design must be processed in the building information model to assess the impact of the deviation on the building's performance. When the result is that the deviation does not result in future issues and does not unacceptably affect the building's performance, the BIM must be adapted to allow the assessment of future deviations and end up with an "as-built" BIM that can be used for, among others, maintenance. This is visualized in Figure 28. Using the "as-built" BIM the performance of the physical building can be predicted and reference values to assess KPIs can be set.

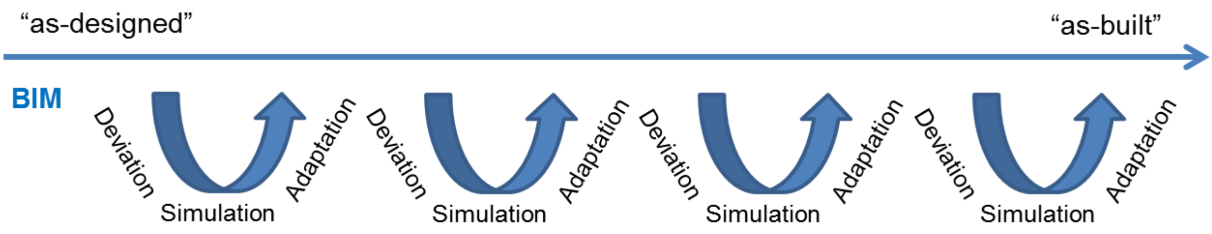

Figure 28: Error handling during the building process

5. Analysis of total quality of MEP/HVAC system

Success in construction projects is a function of the project management criteria including schedule, budget, and functional quality; the so-called golden triangle. Generally speaking, construction projects are therefore only successful if buildings have been realized in time, in budget and do meet beforehand agreed functional quality goals such as comfort, thermal, acoustic and energy performance across its lifecycle. The INSITER methodology supports successful realisation of construction projects through properly carrying out assembly/building activities in time, within budget and according to agreed quality levels.

Functional quality and related performance criteria (also called KPIs) will be discussed in the following sections.

5.1 Assessing building quality

KPIs, discussed in Section 0, are the base for assessing functional quality in buildings. Two groups of KPIs have been discussed: energy performance indicators and indoor environmental quality indicator. In the context of INSITER, two kinds of components can be distinguished: structural elements (such as facades and window's) and HVAC/MEP components (such as heat pumps and ventilation systems). Although each of these components could be assessed individually, building performance is a combined result of the performance of all building components as well as HVAC/MEP components. For this reason and to ensure building quality, it is very essential to (self-) inspect components individually as well as a whole building. For example, to ensure thermal comfort in a specific room it is very essential to ensure both thermal quality of the building façade and the thermal power delivered by the heating system. If any of these components fails to provide the expected performance, issues related to thermal discomfort and high energy consumption may be experienced.

In relation to the INSITER project, self-inspection processes consider component performance individually as well as a whole building.

<u>The INSITER approach</u>

Traditionally, most (self-) inspection processes are carried out separately by MEP workers. These separated processes result in good overview of individual performances of individual components but less in the whole building performance. Deviations in individual components result in lower building performance which is only to be evaluated if the building is properly monitored in the use stage.

Following the BIM process provides great possibilities to optimize the evaluation of the whole building during the realization phase. At the beginning of the realization phase, BIM includes design information, product data and simulated performance outcomes. BIM based self-inspection processes make use of the most recent building/component data and adapt new data to BIM including deviations and individual performance evaluations. BIM is in this approach a growing data bank (see Figure 29). In each sub-phase of the realization phase, it is possible to evaluate the whole building performance. This can be done by using data from BIM (data import by means of an IFC file) to perform a simulation analysis. Deviations in the building's performance can be detected and evaluated by comparing the outcomes of this simulation process with the outcomes of the design phase (simulation outcomes).This approach is based on the INSITER methodology, as introduced in the DoA. Step 7 is related to individual performance inspections, step 8 is related to the whole building performance.

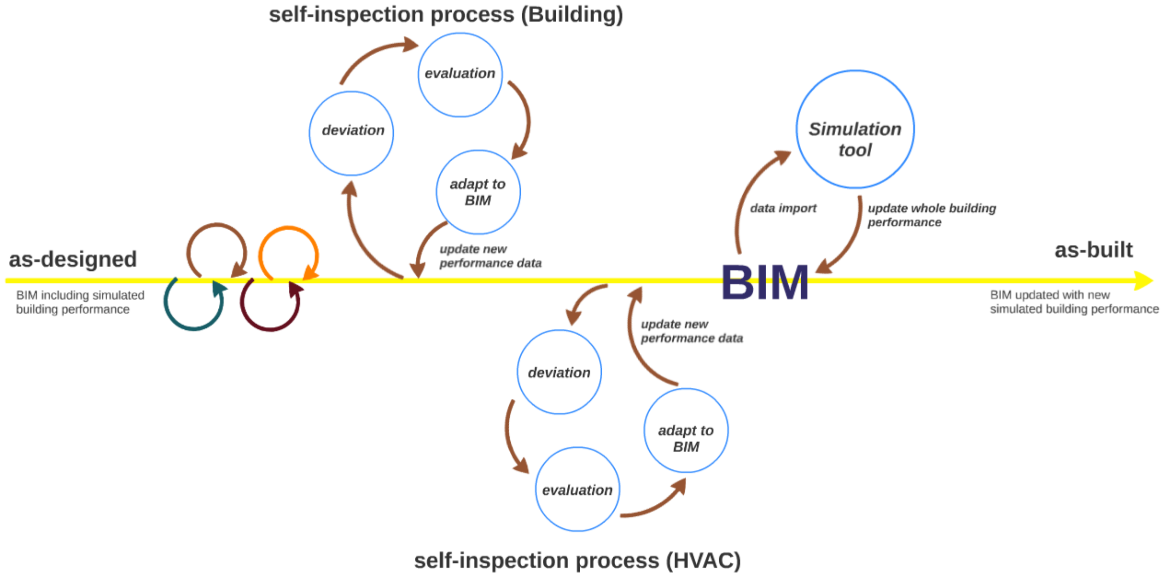

Figure 29: Illustration of the assessment of whole building performance

5.2 Link to project management

As discussed in the introduction of chapter 4, schedule and budget are important criteria for assessing the success of a construction project. Schedule and budget criteria will be first used for optimizing project planning and risk. This issue is described in the sixth step of the INSITER methodology (see below).

Self-inspection and self-instruction during preparation of construction site and logistics:

- Checking the construction site and updating BIM site modelling based on actual conditions (e.g. weather, accessibility, construction equipment, transport, and logistic processes on-site)
- Optimising time and cost schedules (also linked to production planning); analysing risks of delay and budget-overrun; and updating the self-instruction guidelines for MEP workers.

Schedule and Budget will be also used for evaluating how to deal with errors and deviations. In some case, deviations could be accepted due to their negative impact on Schedule (project delay) or Budget (overrun).

5.3 Measurement and calculation

The measurement and calculation of the performance of the MEP/HVAC components is a pivotal process, which allows any user to determine the behaviour of the system. In this way, the definition of KPIs is one of the main issues, taking into consideration that these are critical from the assessment point of view.

5.3.1 Assessment of total quality

In order to measure and calculate energy consumption of the building the EU standard EN 15603 (2008) can be followed. This standard states that the assessment of the annual energy used by a building shall comprise the following services (CEN, 2008):

- heating;
- cooling and dehumidification;
- ventilation and humidification;
- hot water;
- lighting (optional for residential buildings);
- other services (optional).

This includes auxiliary energy and losses of all systems. It is important to underline that this standard gives input on how to measure and how to calculate energy rating. The actual method of monitoring (measurement) and simulation (calculation) can vary, depending on national or local requirements or the used tools. So in other words, the process of calculation is described, not the actual method. For this, INSITER's methodology exists, complemented by national regulation. Intermediate performance measurement and calculation would be feasible within the process where the MEP/HVAC system would be merged together the building static features (e.g. envelope) with the aim of obtaining a full view of the performance.

5.3.2 Instruments and software

Another matter within measurement and calculation is the capability of instruments. In this case, some of the existing hardware is not efficient for self-inspection procedures. Moreover, monitoring devices are not always well determined and the data-points to be collected are miss-estimated, being difficult to obtain real validation measurements. Thus, one lesson learnt from the existing inspection methods is the crucial aspect of defining a full set of measurement devices that will be applied and is useful for the performance assessment. In this way, INSITER improves the current stock of hardware equipment, as well as with the methodologies applicable for performance evaluation.

On the other hand, there is a fairly specific order of testing associated with the functional testing process. Generally, testing should proceed from the support system level, to the component level, to the subsystem level, to the system level. In most cases, tests at the support system level and component level can occur concurrently. Simultaneous testing is also possible at the subsystem level as long as the various subsystems are not interdependent for the process under test.

Both previous challenges agree with the well-known existing inspection methods. The objective is the improvement of the methods that are used today with the goal of determining the shortcomings and bridge the gap with new methods, such as the integration of KPIs and new instruments. Adaption of instruments and software to be used in INSITER is being described in task 2.2 and 3.2.

5.4 Implementation of inspection processes

INSITER's self-inspection and self-instruction are integral part of the building process. The methodology will be implemented by following INSITER's procedures and training of key persons involved. In this section, essential issues concerning the implementation are being addressed.

On certain areas INSITER'S KPIs may look the same but they are on another level and having done the analysis of different KPIs it became clear that the KPIs that are measured once a building is finalized cannot be also measured during the construction process. The KPIs are defined as: 'a set of quantifiable indicators used to measure building performance over time'. In order to precisely calculate these KPIs a closed structure is required. Whether this is possible, depends greatly on the complexity of the building and the construction process. In order to minimize the potential errors during the construction process, the INSITER methodology can be used, with the main focus on:

1. Testing en performance verification by the manufacturer
2. Visual inspection during preparation and during construction of the MEP/HVAC systems, using extended software and augmented reality applications (apps) on smartphones/tablets.
3. Measuring of performance indicators during pre-commissioning.
4. Measuring and monitoring of dynamic performance indicators during commissioning and in-use phase of the building.
5. Continues feedback by calculation and recalculation of building performance, throughout the entire construction phase.

Integrated in INSITER's 8-step methodology (see also *Figure 8* in the beginning of this document) that involves the following procedure.

- Step 2: The inspection is visual as far as damages and pollution should be checked. In this case, it is true that measurements and values could be taken, although this is not an automatic process, but manually the MEP worker must validate that the prefab components do not present any crack, hit and/or damage. As well, the documentation and data-sheets of the elements are a key factor to be considered because this information is the one against the performance, once installed, by which test the deployment. Besides, the connection with the 3D BIM database of the component should be noticed in order to be integrated during the step 3.
- Step 6: The most impact is related to the self-instruction in order to carry out the works in the proper way. It is crucial this step in the costs savings because, although obvious, less mistakes mean less time to correct them. Self-instruction processes are helpful at time of optimising time and cost schedules. Additionally, as mentioned before, the construction works should be also checked, where the same tools are usable. In this sense, updates under the BIM model could be required.
- Step 7: This covers validation of the correctness through instruments and measurement equipment that come from the WP2 in addition to common sensors or monitoring system already installed on the system. Then, pre-functional tests are covered to obtain quantitative measurements which could be compared with the data sheets values, as well as a set of thresholds. The major advantages are mainly focused on the early detection of mistakes or malfunctioning with the aim of correcting them in advance, which saves costs and time.
- Step 8: Self-inspection processes are carried out again with the measurement equipment previously mentioned, but also WP3 in terms of monitoring and visualization tools. Although the foreseen hardware from WP2 is very useful within this stage, the most relevant tools are related to the WP3 – monitoring and visualization tools, including simulation tools like TRNSYS, which allow the adjustment of the parameters of the HVAC systems to ensure their performance. Anyway, having in mind the usability of the tools from WP2 and WP3, the checks are determined according the KPIs that have been defined in the document. These KPIs are contrasted against the thresholds and specifications from the data sheets (collected from step 2).

6. Conclusion and further research

INSITER proposes a new methodology and tools which go beyond current practice with a focus on:

1. Intervening on time by:
   a) improving communication and reporting of observed error on site,
   b) accelerating decision making process,
   c) introducing a protocol feedback loop to provide continuous evaluation, and so to prevent errors before they occur.
   d) providing tools for efficient and quantitative evaluation thus facilitating a substantiated judgement on the actions to take
2. Reducing construction costs by standardization of the methodology and using advanced technologies.

6.1 Overall conclusion

6.1.1 Applicability

The question is not if INSITER's methodology is applicable for new construction, renovation/refurbishment, and maintenance, but rather how. Every building is different, as is the building process. Because INSITER methodology focusses on the proceedings of construction and does not depend on the used techniques, it will be quite feasible to integrate the methodology in new construction as well as refurbishment. So basically, new construction and refurbishment cover the phases transportation on-site, on-site assembly, commissioning, and use/maintenance (see Figure 7, p.21). While maintenance only covers the last phase (use/maintenance). For maintenance project, INSITER will only be able to perform on certain parts. Maintenance is comparable with the commissioning phase of the realization phase. All shafts and ceilings are closed, the components are already installed and functional tests have been executed. Therefore, the focus is on monitoring of the KPIs with special attention to the continued feedback loop and integration in BIM.

By correlating both the 8-step protocol with the building construction lifecycle it is possible to state that the analytical methods presented in this deliverable are applicable within the steps 2, 6, 7 and 8 of the process. It is important to mention that, although other steps also take into account the MEP/HVAC systems, such as steps 3 or 4. In this way, the evaluation of the HVAC quality assumes the existence of the BIM model, as well as the necessary tools (e.g. AR, Demo Re-Suite and Simaxx). Obviously, the validation and model check are also assumed under this task.

6.1.2 Effectiveness

In the previous deliverable D1.1, Figure 25 (p.99) a protocol feedback loop is introduced. This, in order to make sure that project knowledge evolves continuously by providing direct feedback to the design phase in order to adjust the design. This is communicated to the production phase in order to adjust the production line. This figure is actually a quality assurance during the construction process and enabling at the same time evolving of the project knowledge by signalling and communicating potential errors which may have significant impact on a whole construction project and total building quality. This is furtherly explained in section 5.1.

As far as this document goes, it is an innovative achievement which makes the 'old-school' analogue protocols redundant.

6.1.3 Benefit

INSITER's methodology will help to:

- Reduce the amount of errors during construction phase;
- Provide a logical feedback to other phases and also collect information from later stages of design (the loop) so that there is a natural evolution of knowledge within different layers and actors in the project;
- Enables producers to anticipate in early stages of development and signal possible challenges;
- Enables faster communication between the partners and the recording of on-site deficiencies so that they can be solved on time;
- Those who are end-responsible for a particular KPI can be empowered with the technology that will support them in conducting their work as good as possible and at the same time being able to correct their work early in the construction process. The INSITER methodology enables the construction worker to take the ownership of the work that they are conducting.

6.2 Further research: qualification, evaluation and decision-making methods

The following this deliverable, which focused on analytical and quantitative self-inspection methods, the follow-up deliverable D1.7 will deal with 'qualification'. The main objective D1.7 is to:

- Develop quality assurance methods based on primary information on the subject in D1.1 and the analytical methods as described in this document.
- Evaluate the KPI values and balance KPI values against the reference value
- Decide on action based on KPI evaluation (approve quality or rework)
- Integration of the qualifying process in the BIM model (continues data interaction)

6.3 Further interaction with other Work Packages within the INSITER project

6.3.1 Instrumentation for analytical methods

From WP2, in particular D2.3, but also complemented with D5.2, the existing tools and enhanced building diagnostic instruments developed within INSITER are very useful in the aforementioned process. In this way, this equipment provides values in order to calculate the KPIs both at building quality level and energy performance.

First of all, the positioning/sensing integration of acoustic/thermal imaging is described in detail in the section 4 of the deliverable D2.3. A specific computer application is being developed (INSITER-DLL) to allow the superposition of high quality digital pictures onto the polygonal model of a building made of prefab components, based on an image (2D) to mesh (3D) calibration procedure (upon a series of control points manually indicated on the 3D model and their corresponding on 2D graphics). Therefore, the superposition will be independent from the acquisition viewpoint and the type of device, since the graphical data frequently comes from different vendors and in different times. The result of the process is an accurate 3D multi-info digital model that is able to capture not only the building envelope components but also the MEP/HVAC systems. Additionally, geolocation is also considered to be included for the location of the equipment into the building.

Within this superposition of information, 3D laser scanning information is usable for the demonstration of its feasibility to detect humidity, as stated in D5.1. In this sense, the reflectance data are specifically manipulated for the detection of moisture, which is particularly important when talking about any system that makes use of water (e.g. solar thermal or water source heat pumps). One example is already illustrated in section 5 of D2.3, where the distinction of a small water leak on an elbow of HVAC at CARTIF-3 demo building is detected by means of the corrected reflectivity index.

On the other hand, as described in section 6 of D2.3, 3D laser scanner also provides usability in terms of geometry discrepancies or deviations. Therefore, thanks to this technology, the assessment of the installation of the prefab elements related to MEP/HVAC systems is feasible to determine any geometrical deviation with respect to the original design, which is supposed to be documented via BIM.

Moreover, thermal cameras are very helpful at time of self-inspection. The reasoning is the capability of detecting the temperatures in ducts and HVAC components. In D2.3, the procedure for thermal bridges and thermal transmittance is the focus and no specific methods for MEP/HVAC systems are described. Nevertheless, the capability of measuring the thermal transmittance is also applicable within the scope of this deliverable in order to determine the level of insulation of the ducts, generation systems, storage tanks or whatever component.

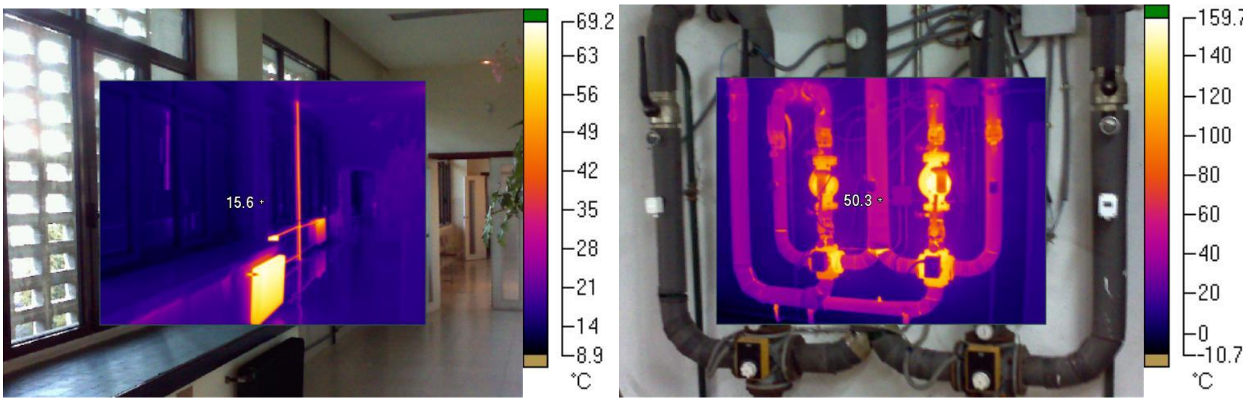

Figure 30: Thermography tests example

The SoundBrush or MEMS microphone array described in the D5.1 can be used for mapping of the acoustic pressure in the vicinity of an active component such as MEP/HVAC systems or ventilation apertures. SoundBrush requires that scanning area must exceed the dimensions of the object, such that the specific sources of noise are identified, could be apply for example to test noise on compressors and vacuum pumps. MEMS microphone array allows having directly a map of sound pressure of the field in front of the array to localize the noise source.

Besides, ultrasound devices are also usable in this field. From the WP2 perspective, air leakages are the goal, which are also crucial in HVAC. For instance, if any duct contains leakages, water could be lost, provoking condensation, moisture, and other problems. That is why similar techniques are applicable on these components. On the other hand, additional ultrasonic devices are in the market with well-established procedures for measurements. That is the case of ultrasonic flowmeters that allow any user to measure the flow in any duct without the need of intrusive equipment like probes. This instrument permits the detection of low or high flow in the distributions systems that do not comply with the expected operation of the component.

Finally, Augmented Reality tools, as explained in D2.1, are instruments whose focus is the self-instruction. Then, this tool supported by the BIM model is able to illustrate the construction process through simulation in order to provide step-by-step instructions to the MEP workers, as well as the end-user in terms about how to maintain or use the facilities from an efficient point of view with the aim of increasing the energy efficiency and life cycle.

6.3.2 Simulation and monitoring tools for analytical methods

From WP3, monitoring and visualization tools, where it can be included the simulation tools like TRNSYS, provide values associated to the operational stage of the elements. Starting with the monitoring tools, several applications like Simaxx are an important input for self-inspection methodologies. Here, it is remarkable that these tools are usable when the installation are operational during the commissioning or maintenance because they require a sensor network that gathers information from the status of the equipment, such as temperatures, flows or energy consumption, among others. Then, they can show this information together the calculation of the aforementioned KPIs, which evaluate the performance of the system. Then, through smart visualization of data, detection of malfunctioning is rendered in advance without the visual intervention of technicians, being the time to solve the problem reduced, as well as the associated costs. Figure 31 illustrates an example about a dashboard where the monitoring data would be available, as well as the KPIs. These tools are helpful from the point of view of the technician to solve malfunctioning in advance, but also from end-user perspective because they allow the detection of the performance with the objective of providing awareness too.

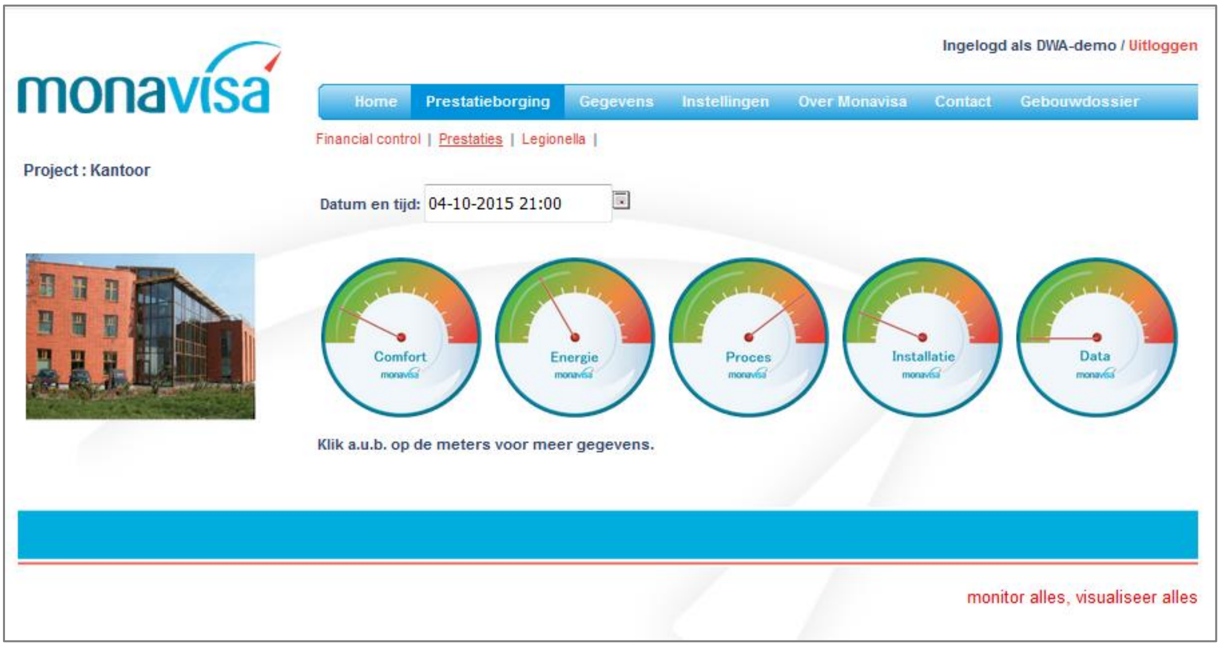

Figure 31: Visualization tools example (Simaxx, formerly known as 'Monavisa')

Secondly, simulation tools, as explained before, complement the monitoring equipment when this does not exist. For example, during design process, simulation tools calculate the performance of the facilities under certain conditions. In this way, prior detection of low performance is possible. The great advantage is the opportunity to modify the original design before being installed with the aim of avoiding repairs when the installation is functional. In this case, TRNSYS is one of the most used tools and it is able to simulation single HVAC systems, but also the combination of several systems, including the passive ones, i.e. building envelope. One example is illustrated in Figure 32 where heating/cooling heat pumps and inertia tanks are modelled, as well as the calculation of power.

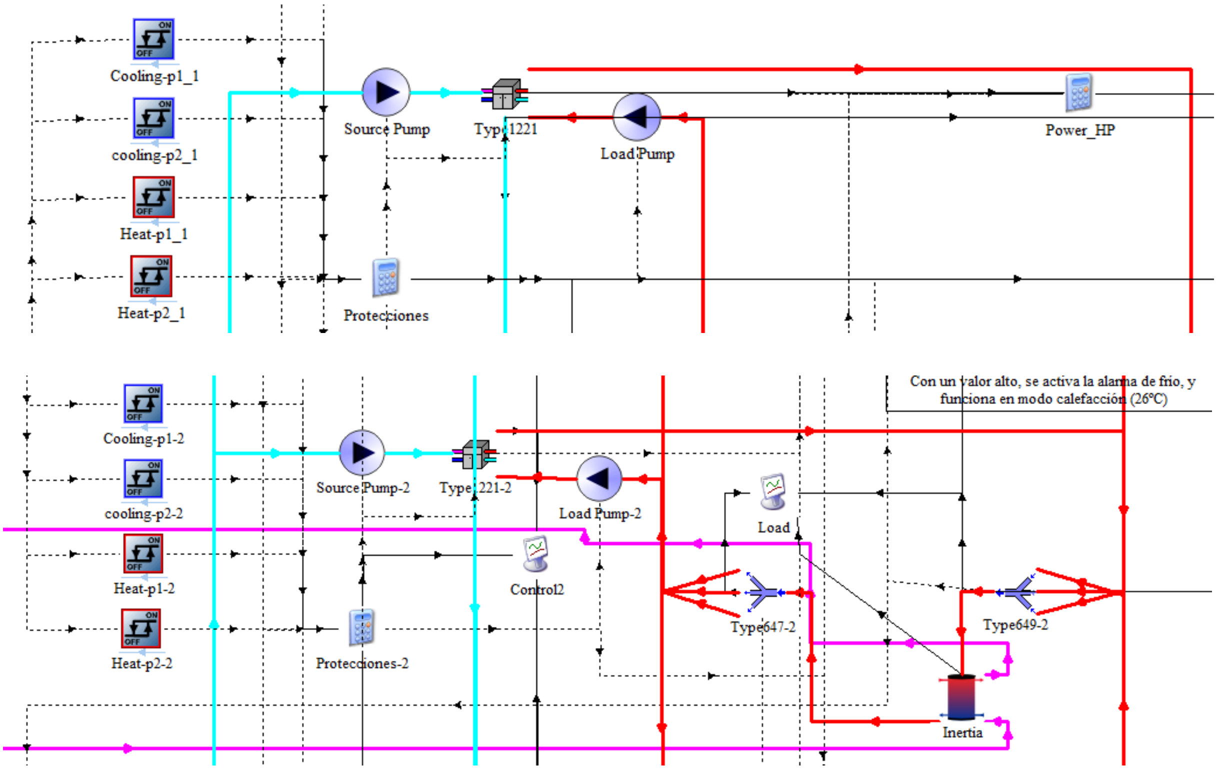

Figure 32: Example of TRNSYS HVAC systems modelling

Finally, the DEMO RE Suite software provides the capability of carrying out self-inspection and self-instruction procedures on-site in order to detect mistakes on-site. Based on pictures and supported by BIM, the usability of the tool is referred to the detection of mistakes when the installation is being made to detect them in advance, before having finished.

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Appendix 1 - Technical standards relevant for MEP/HVAC system

Overview of MEP/HVAC relevant technical standards

Reference	Title	Geographic level
Heat pump systems		
BRL 60021	Design, realisation, control, and maintenance of thermal energy storage systems	National (NL)
BRL SIKB 11000-11001	Design, realisation, control, and maintenance of the underground part of thermal energy storage systems	National (NL)
EMCS 3.0	European MEPcontent Standard, version 3.0	Regional (EU)
EN 12309	Gas-fired sorption appliances for heating and/or cooling with a net heat input not exceeding 70 kW	Regional (EU)
EN 13613	Heating and cooling systems in buildings — Method for calculation of the system performance and system design for heat pump systems	Regional (EU)
EN 14511	Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling	Regional (EU)
EN 14825	Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance	Regional (EU)
EN 15316 (all parts)	Heating systems in buildings - Method for calculation of system energy requirements and system efficiencies	Regional (EU)
EN 15378	Heating systems and water based cooling systems in buildings - Heating systems and DHW in buildings - Part 1: Inspection of boilers, heating systems and DHW	Regional (EU)
EN 15450:2007	Heating systems in buildings - Design of heat pump heating systems	Regional (EU)
EN 305:1997	Heat exchangers - Definitions of performance of heat exchangers and the general test procedure for establishing performance of all heat exchangers	Regional (EU)
EN 306:1997	Heat exchangers - Methods of measuring the parameters necessary for establishing the performance	Regional (EU)
EN 307:1998	Heat exchangers - Guidelines to prepare installation, operating and maintenance instructions required to maintain the performance of each type of heat exchangers	Regional (EU)
EN 378-2	Refrigerating systems and heat pumps – Safety and environmental requirements - Part 2: Design, construction, testing, marking and documentation	Regional (EU)
EN 50470	Electricity metering equipment (a.c.)	Regional (EU)
ETIM	European Technical Information Model	Regional (EU)
ISSO 39	Energy plant with aquifer thermal energy storages (ATES)	National (NL)
ISSO 81	Manual for integral design of heat pump installations for office buildings	National (NL)
NEN 2767-1	Condition assessment – Part 1: Methodology	National (NL)
NEN 2767-2	Condition assessment of building and installation components - Part 2: Lists of faults	National (NL)

Ventilation systems		
CEN/TR 15500-2:2016	Energy Performance of Buildings - Control for heating, ventilating and air-conditioning applications — Part 2: Accompanying TR prEN 15500-1:2015 - Modules M3-5,M4-5,M5-5	Regional (EU)
EN 1216:1998	Heat exchangers - Forced circulation air-cooling and air-heating coils - Test procedures for establishing the performance	Regional (EU)
EN 12237:2003	Ventilation for buildings — Ductwork — Strength and leakage of circular sheet metal ducts	
EN 12599:2012	Ventilation for buildings - Test procedures and measurement methods to hand over air conditioning and ventilation systems	Regional (EU)
EN 13030:2001	Ventilation for buildings - Terminals - Performance testing of louvres subjected to simulated rain	Regional (EU)
EN 13053:2006 +A1:2011	Ventilation for buildings - Air handling units - Rating and performance for units, components, and sections	Regional (EU)
EN 13141-1:2004	Ventilation for buildings - Performance testing of components/products for residential ventilation - Part 1: Externally and internally mounted air transfer devices	Regional (EU)
EN 13141-10:2008	Ventilation for buildings - Performance testing of components/products for residential ventilation - Part 10: Humidity controlled extract air terminal device	Regional (EU)
EN 13141-11:2015	Ventilation for buildings - Performance testing of components/products for residential ventilation - Part 11: Supply ventilation units	Regional (EU)
EN 13141-2:2010	Ventilation for buildings - Performance testing of components/products for residential ventilation - Part 2: Exhaust and supply air terminal devices	Regional (EU)
EN 13141-4:2011	Ventilation for buildings - Performance testing of components/products for residential ventilation - Part 4: Fans used in residential ventilation systems	Regional (EU)
EN 13141-6:2014	Ventilation for buildings - Performance testing of components/products for residential ventilation - Part 6: Exhaust ventilation system packages used in a single dwelling	Regional (EU)
EN 13141-7:2010	Ventilation for buildings - Performance testing of components/products for residential ventilation - Part 7: Performance testing of a mechanical supply and exhaust ventilation units (including heat recovery) for mechanical ventilation systems intended for single family dwellings	Regional (EU)
EN 13141-8:2014	Ventilation for buildings - Performance testing of components/products for residential ventilation - Part 8: Performance testing of un-ducted mechanical supply and exhaust ventilation units (including heat recovery) for mechanical ventilation systems intended for a single room	Regional (EU)
EN 13264:2001	Ventilation for buildings - Floor mounted air terminal devices - Tests for structural classification	Regional (EU)
EN 1397:2015	Heat exchangers - Hydronic room fan coil units - Test procedures for establishing the performance	Regional (EU)
EN 1507:2006	Ventilation for buildings - Sheet metal air ducts with rectangular section - Requirements for strength and leakage	Regional (EU)
EN 15232:2012	Energy performance of buildings - Impact of Building Automation, Controls, and Building Management	Regional (EU)
EN 15241:2007	Ventilation for buildings - Calculation methods for energy losses due to ventilation and infiltration in commercial buildings	Regional (EU)
EN 15243:2007	Ventilation for buildings - Calculation of room temperatures and of load and energy for buildings with room conditioning systems	Regional (EU)
EN 15500:2008	Control for heating, ventilating and air-conditioning applications - Electronic individual zone control equipment	Regional (EU)

EN 15727:2010	Ventilation for buildings - Ducts and ductwork components, leakage classification and testing	Regional (EU)
EN 15727:2010	Ventilation for buildings - Ducts and ductwork components, leakage classification and testing	Regional (EU)
EN 15780:2011	Ventilation for buildings - Ductwork - Cleanliness of ventilation systems	Regional (EU)
EN 15780:2011	Ventilation for buildings - Ductwork - Cleanliness of ventilation systems	Regional (EU)
EN 15805:2009	Particulate air filters for general ventilation - Standardised dimensions	Regional (EU)
EN 1751:2014	Ventilation for buildings - Air terminal devices - Aerodynamic testing of damper and valves	Regional (EU)
EN 1886:2007	Ventilation for buildings - Air handling units - Mechanical performance	Regional (EU)
EN 308:1997	Heat exchangers - Test procedures for establishing performance of air to air and flue gases heat recovery devices	Regional (EU)
EN 779:2012	Particulate air filters for general ventilation - Determination of the filtration performance	Regional (EU)
EN ISO 11820:1996	Acoustics - Measurements on silencers in situ (ISO 11820:1996)	International
EN ISO 12759:2015	Fans - Efficiency classification for fans (ISO 12759:2010, including Amd 1:2013)	International
EN ISO 16032:2004	Acoustics - Measurement of sound pressure level from service equipment in buildings - Engineering method (ISO 16032:2004)	International
EN ISO 16484-1:2010	Building automation and control systems (BACS) - Part 1: Project specification and implementation (ISO 16484-1:2010)	International
EN ISO 29462:2013	Field testing of general ventilation filtration devices and systems for in situ removal efficiency by particle size and resistance to airflow (ISO 29462:2013)	International
EN ISO 3741:2010	Acoustics - Determination of sound power levels and sound energy levels of noise sources using sound pressure - Precision methods for reverberation test rooms (ISO 3741:2010)	International
ISO 16494:2014	Heat recovery ventilators and energy recovery ventilators — Method of test for performance	International
Solar hot water systems		
EN 12975-1:2006+A1:2010	Thermal solar systems and components - Solar collectors - Part 1: General Requirements	Regional (EU)
EN 12976-1:2006	Thermal solar systems and components - Factory made systems - Part 1: General Requirements	Regional (EU)
EN 12976-2:2006	Thermal solar systems and components - Factory made systems - Part 2: Test methods	Regional (EU)
EN 12977-1:2012	Thermal solar systems and components. Custom built systems. General requirements for solar water heaters and combi-systems;	Regional (EU)
EN 12977-2:2011	Thermal solar systems and components - Custom built systems - Part 2: Test methods for solar water heaters and combi-systems	Regional (EU)
EN 12977-3:2008	Thermal solar systems and components - Custom built systems - Part 3: Performance test methods for solar water heater stores	Regional (EU)
EN ISO 22975-3:2014	Solar energy-Collector components and materials-Part 3: Absorber surface durability	International
EN ISO 9806:2013	Solar energy-Solar thermal collectors-Test methods,2013	International
EN12977-4:2012	Thermal solar systems and components - Custom built systems - Part 4: Performance test methods for solar combi-stores	Regional (EU)
EN12977-5:2012	Thermal solar systems and components - Custom built systems - Part 5: Performance test methods for control equipment	Regional (EU)

ISO 9459-2:1995	Solar Heating – Domestic water heating systems – Part 2: Outdoor test methods for system performance characterization and yearly performance prediction of solar-only systems	International
ISO 9459-4:2013	Solar heating -- Domestic water heating systems -- Part 4: System performance characterization by means of component tests and computer simulation	International
ISO 9459-5:2007	Solar heating -- Domestic water heating systems -- Part 5: System performance characterization by means of whole system tests and computer simulation	International
ISO 9806-2:2013	Test methods for solar collectors-Part 2: Qualification test procedures	International
Lighting systems		
EN 15193:2007	Energy performance of buildings - Energy requirements for lighting	Regional (EU)