Grant Agreement No: 285540

Project acronym: EASEE

Project title: Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-storey multi-owner residential buildings

Funding scheme: Collaborative Project

Thematic Priority: EeB.NMP.2011-3 - Energy saving technologies for buildings envelope retrofitting

Starting date of project: 1st of March, 2012

Duration: 48 months

D5.4 – Final Release and Evaluation of the Retrofitting Planner

Due date of deliverable: 31st August 2014
Actual submission date: 16th September 2014

Organisation name of lead contractor for this deliverable: *IES*

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Table of Content

1 EXECUTIVE SUMMARY

This report Deliverable 5.4 constitutes the final deliverable of Work Package 5 “Retrofitting Planner and Design Tool” and reports the progress towards developing the final version of the Retrofitting Planner and Design Tool. The following tasks contributed to the development of the tools: T5.1, T5.2, T5.3 and T5.4; a description of these tasks are included within Section 3.1.

The consortium agreed for the EASEE Retrofitting Planner to be a consulting only service to ensure services performed are of a high standard, are accurate and consistent; there may be alternative options later for potential users of the tool to be formally trained in the use of the software. For the purpose of this report the user of the tool will be named **EASEE Agent** (approved and fully trained person able to offer consulting services in the use of the tool).

The Retrofitting Planner & Design Tool services specifically consist of:

- **Building envelope assessment** using 3D laser scanning techniques (Developed by POLIMI)
- The “computer based procedure” utilizing **IES’s Virtual Environment** software otherwise known as the VE. The VE software is an advanced simulation tool designed to analyze building performance and for the purpose of EASEE project to test and validate retrofitting solutions developed by the manufacturing partners within the EASEE project. (Developed by IES)
- The “Design Tool” module, sometimes referred to as **EASEE Editor**, providing the manufacturers of the prefabricated elements the technical specifications for the customized component fabrication (Developed by CIM-MES)

These tools working together, allows the EASEE Agent to take a 3D model of a building (built from scratch or alternatively from point cloud data (T5.1)), apply common data utilizing pre-built master templates (containing common thermal attributes), search for existing panels and replace with new retrofitting options; the parametric batch tool and sim schedular tool will then queue up simulation options and execute them in a formal order; the best optimized options will be displayed through a value choice tool called Deft which will be sent to the Design Tool to specify exact technical specifications for production. Note that the following sections will describe each of the tools developed in more detail.

User testing and feedback resulted in iterative changes being made to the Retrofitting Planner; these changes can be seen within Section 6 of this report. The tools have been fully developed and are being tested on the EASEE demonstration buildings, although the specific deliverable reporting on the performance of the demonstration buildings is not due until February 2016 (D8.2) – this in fact allows for additional user testing.

This report presents how the Retrofitting Planner and Design Tool came together, outlining the individual processes applied to develop each of the individual tools (services).

2 INTRODUCTION

The present document constitutes Deliverable 5.4 ‘Final release and evaluation of the retrofitting planner’. The main aim of the deliverable is to report about the progress on the development of the individual tools that constitutes the **EASEE Retrofitting Planner and Design Tool**, the software that has been created for it and how this was achieved including a worked example, showing how the tool works together as the Retrofitting Planner.

To this aim, the deliverable is structured in the following manner:

- **Section 3** describes the deliverable as per Annex I – Description of Work (DoW) including the work plan that was put in place as a result including the sub-tasks and Gantt Chart.
- **Section 4** then describes the overall workflow for WP5 and the importance the individual processes have on the Retrofitting Planner and Design Tool as a whole.
- **Section 5** describes the technical development and methodology behind Task 5.1(Deliverable 5.1 “Methodology for data acquisition and fusion for affordable envelope assessment”).
- **Section 6** describes the technical development and methodology behind Task 5.2 (Deliverable 5.2 “Computer based procedure for selection materials, components or systems for facades”). The typical workflow for software development is also illustrated via a simple diagram; each of EASEE’s outputs follow this prescribed workflow. Included also in this section is a worked example of the tool.
- **Section 7** describes the technical development and methodology behind Task 5.2 (Deliverable 5.3 “Tool Module providing specifications for design of prefabricated components”).
- **Section 8** introduces Lessons – A web based database for sharing and disseminating success stories / knowledge.

Finally **Section 9** summarizes the conclusions from the overall deliverable including a worked example using one of the EASEE demo buildings.

3 DELIVERABLE DESCRIPTION AND WORKPLAN

3.1 Deliverable description and relation to the report

This report constitutes Deliverable 5.4 "Final Release and Evaluation of the Retrofitting Planner". The deliverable directly relates to the following tasks, as described in the Annex I – Description of Work (DoW):

Task 5.1: Building envelope assessment and development of building model (POLIMI)

This task has the main goal to define a procedure for the assessment of the building envelope by collecting, integrating and elaborating all the structural and energetic data of the envelope as well as all other non-technical parameters and indicators that will be useful for the planning of the retrofitting intervention. The structural conditions will be evaluated through state of the art non-destructive technologies as Scanning Laser Vibrometry combined with sonic waves generators to obtain information on the stability of the envelope plaster, and to plan any local fixing action (plaster removal and integration) if necessary. A map of the envelope will be obtained by 3D laser scanning, providing digital points clouds for high detailed CAD plans allowing through pattern recognition techniques to provide specifications of the prefabricated components (shape, joints, composite layered structure). Finally, temperature maps will be acquired to evidence thermal bridges or heat losses and other building data as for example wall and plaster thickness and characteristics of the critical points as windows and balconies. IESVE already has a comprehensive suite of interoperability tools to import 2D/3D CAD,3D Models and BIM data into the VE and fully support products such as Google SketchUp, Revit, AutoCAD, ArchiCAD and Bentley. The software will have to be adapted to existing buildings where there are out of data or no drawings. Import of laser scanning will be provided as well as import of models from Google Earth and Google Warehouse in order to facilitate building good analysis models for façade assessment.

A methodology for the generation of the 3D model which takes into account geometrical aspects, structural aspects and thermal aspects has been developed both for the Retrofitting Planner and the Design Planner. The developed methodology used a 3D laser scanning survey of the building to derive accurate and precise geometrical information. Starting from the survey plants and cross sections are derived in a CAD environment. Once this data is derived a 3D digital model of the building is obtained either as a BIM model or STL model. The 3D accurate model derived is used to provide specifications of the prefabricated components (shape, joints)

In addition to the geometrical assessment, thermal mapping was carried out to assess the quality of the structure at this stage before any retrofitting has been applied to the façade. Two types of cameras were used to create the thermal image of the 3D envelope, these technologies are well described, the two types of camera are a traditional thermal camera and a UAV camera.

Task 5.2: Holistic evaluation of a façade/building envelope option (IES)

The goal of this task is to define a virtual test environment where a manufacturer can test its component and/or façade solution. This would be a simpler yet more extensive method of testing new facades which would complement physical testing. Benchmarks for standard building types and climate regions would be established in order that the new option could be comprehensively tested to verify which building categories the façade option would be optimal. These would be a comprehensive analysis of façade options taking holistic account of energy and carbon emissions reduction, daylighting, capital and running cost savings, life *cycle performance, etc. A standard performance report would be generated that would be acceptable throughout Europe and beyond. A software checking system will be also developed, where the compliance of the façade complies with the national and regional building regulations codes. A standard methodology to test the potential benefits and savings of the new façade and to verify and quantify the façade performance post installation. The principal objective is to optimise the project ROI. This methodology could be used as part of any tax incentive scheme or performance contract. All of these capabilities currently exist but enhanced multivariate parametric assessments need to be developed in order that the 'best' façade option can be selected. Note that users of any skill levels (i.e. novice to expert) will be able to optimise their façade with the intended retrofitting planner.*

Section 6 outlines the work carried out for Task 5.2. This work includes the creation of a number of software tools that are required for the EASEE Retrofitting Planner. Section 6 describes in detail how these tools have been developed and overall how they will connect to the outputs from the other tasks from POLIMI (Point Cloud Data Model) and CIM-MES (Panel Specification Software).

Task 5.3 Component construction guidelines module (CIM-MES)

This task is dedicated to the development of the software module which provide the manufacturers of the pre-fabricated elements the technical specifications for the customized component fabrication. The specifications (size, geometries, joints, special elements) will be elaborated by the tool starting from the 3D CADs obtained during the building assessment. The tool will statistically analyse the CAD data of the building, identifying the minimum number of element geometries to allow the complete retrofitting of the façade, generating the 3D target surfaces that will serve as input for the flexible mould control kit, or for the realisation of fixed moulds. The software will also provide the position where panels have to be fixed on the façade. Strong interactions are foreseen with WP6 within this task.

Section 7 outlines the work carried out for Task 5.3 As determined in the Description Of Work (cited above), all activities were focused on creating a software tool designed for providing technical specification of insulating panels to be produced. Section 7 provides a brief description of the tool, including a general overview as well as end user identification.

Task 5.4 Retrofitting planner integration, testing and evaluation

This final task will be aimed at integrating and testing the retrofitting planner, that will finally support:

- *the owner and building manager in identifying the most suitable and affordable solution and compare performances/savings,*
- *the designer/architect to prepare a detailed design, commission the supply and supervise the overall implementation*
- *The component manufacturers in producing customized options for the specific building optimizing materials and workforce;*
- *the contractor to be fully involved in the decision making and facilitated in implementation through specific guidelines and work instructions originated by the tools.*

This will create a clear link and proactive engagement of all the stakeholders concerned, creating a link between design, commissioning and delivery (including off-site and on-site construction).

To accelerate the benefits that would accrue from this project the results of the assessments should be lodged in a web based database held by IES. As the number of projects increase this database would become a rich source of information for the European community not only for manufacturers and potential customers but also to master planners, local authorities, governments and so on. This information could be accessed via products such as Google Earth. This database would help societal acceptance and make wide-scale commercial application feasible. Finally, the developed retrofitting planner will be extensively tested and evaluated by end users of different levels (construction companies in the consortium through theirs architects and designers, component manufacturer as Magnetti, apartment owners recruited through the contacts of the partners, experts in energy efficiency as BPIE and designers from CIM-MES involved in the data acquisition from the Retrofitting Planner to the Design Tool), in order to assess the performances of the tool before applying it in the planning of retrofitting intervention for the demo sites.

This deliverable reports the completion of the Retrofitting Planner and Design Tool.

3.2 Work plan

The main goal of this deliverable was to deliver the final version of the Retrofitting Planner and Design Tool as well as testing and evaluating the tool using test case scenarios.
The Gantt chart below illustrates task dependency for WP5:

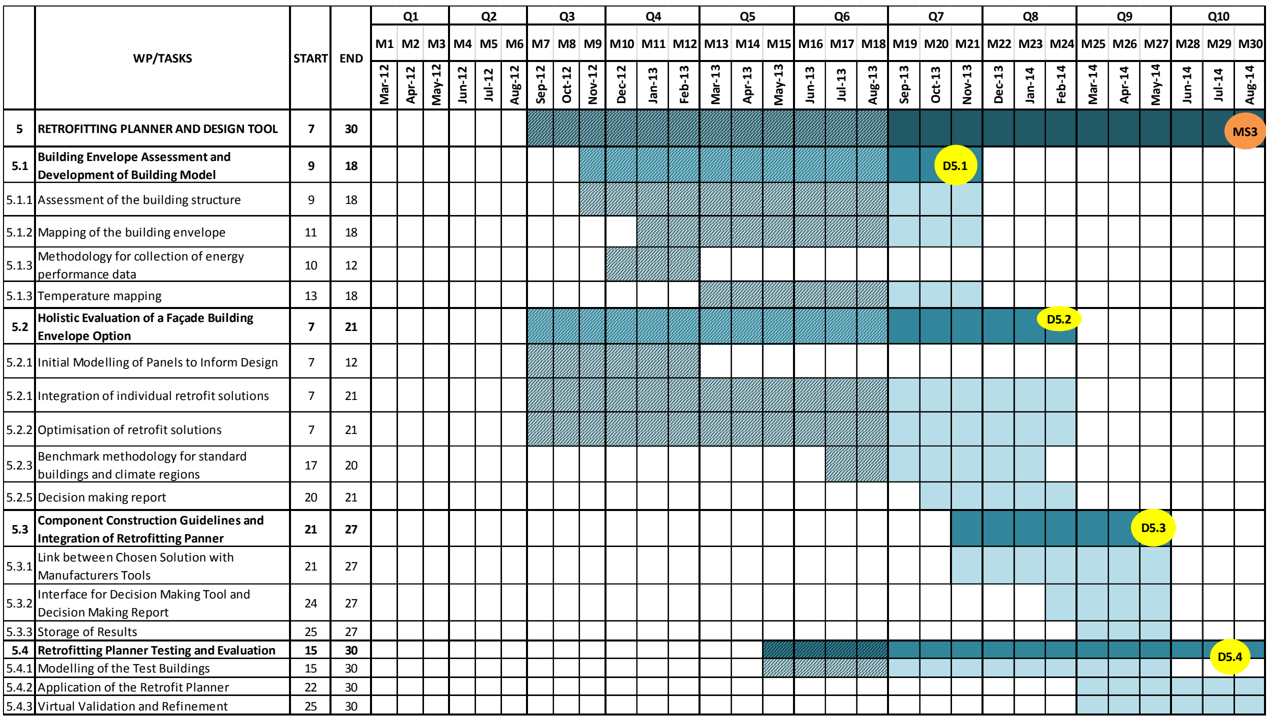


Figure 1: Gantt chart for WP5

3.3 Partner(s) involved and responsibilities

The effort involved to meet Deliverable 5.4 came from the thee key WP5 partners, they were: IES, POLIMI and CIM-MES

IES Responsibility: To develop a virtual test environment utilizing IES's Virtual Environment software to enable manufacturers (& other end users) to test, validate and evaluate retrofitting options (innovative panels designed specifically for EASEE).

This includes the development of core software tools such as Master Templates, Search and Replace, Parametric Batch and Deft, all of which are described in Section 6 of this report.

POLIMI Responsibility: Responsible for Task 5.1 (D5.1) and the creation of the 3D geometrical and envelope model.

CIM-MES Responsibility: Responsible for Task 5.3 (D5.3) and the creation of the Design Tool otherwise known as the EASEE Editor.

4 WORKFLOW OF EASEE RETROFITTING PLANNER

4.1 Workflow, description and integration with other tasks in wp5

The main aim of WP5 was to create a Retrofitting Planner and design tool to allow the building owners (& manufacturers) to assess their options with respect to the various insulation solutions that are being developed in WP2, WP3 and WP4.

Figure 2 describes the overall work flow of WP5 and the relationship between each of the Work Package tasks.

Task 5.1 is the backbone of all tasks in WP5. In order for the Retrofitting Planner to provide accurate results, a geometry and thermal model of the building is required. In order for the panel's to be dimensioned accurately and passed to the manufacturers for production, a geometry model is required.

Task 5.2 provides the functionality to virtually test building performance with the retrofitting solutions applied (the baseline model will also be available for a performance comparison to take place)

Task 5.3 is dedicated to the development of the software module which provides the manufacturers of the retrofitting panels the ability to specify exact technical measurements for production e.g. size, geometries etc.

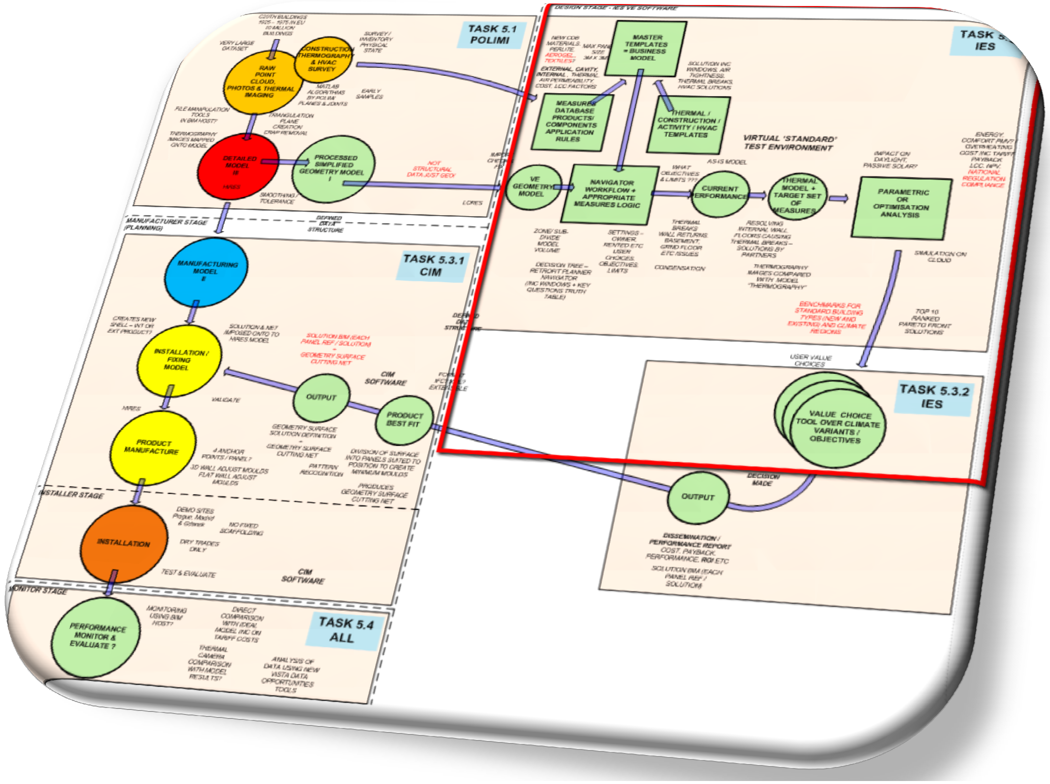


Figure 2: EASEE WP brainstorm map

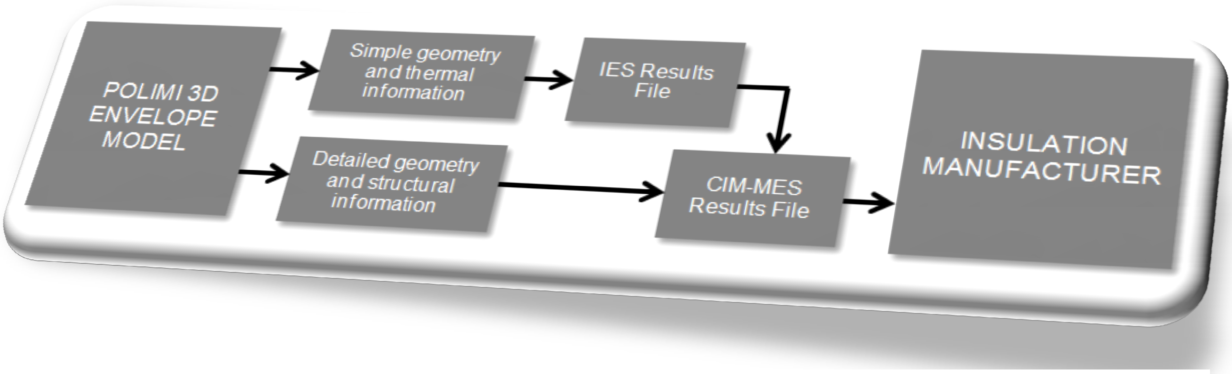


Figure 3 WP5 Workflow Diagram

T5.1 involves the creation of the 3D building envelope geometry and thermal file. This is passed to IES as simple geometry and to CIM-MES as detailed geometry. IES use the data to create an operational model of the building, apply the retrofit planner tools (described in Section 6) and use these to allow the building owner to make an informed decision with respect to the insulation option he would like to implement. These results are then sent to CIM-MES who have also received the detailed geometry file from the POLIMI 3D geometry file. CIM-MES use both of this data to dimension the various panel choices onto the various facades and then send this information to the manufacturer of the panel, ready to go to production.

The IES results file is created in T5.2 – "Holistic evaluation of a façade/building envelope option". This includes the generation of a suite of tools including a navigator to guide the EASEE Agent through the use of the tool; a method to Search for facades with values above or below x (from a wide list of parameters) and replace these facades with the new options; an optimise tool that allows multiple façade options to be applied to the building and the corresponding results generated into a single file; and a user value choice tool which allows the user to choose the option that best suits their needs. The final result chosen by the user is then delivered in a report to the client and also to CIM-MES for the dimensioning of the panels.

The CIM-MES software is created in T5.3 – "Component construction guidelines module" takes in the IES results file and the POLIMI geometry and the software developed will dimension the panels according to the façade and the chosen insulation option. This is then sent as a results file to the manufacturers of the panel for the production of the options for retrofit.

Finally T5.4 (reported in this deliverable) brings all of these elements together into a final evaluation tool (service) called the EASEE Retrofitting Planner and tests the solutions on the demonstration buildings.

The following sections now describe in detail the development that went into the Retrofitting Planner and Design Tool.

5 METHODOLOGY FOR THE GEOMETRIC, THEMATIC SURVEYING AND STRUCTURAL ASSESSMENT (T5.1/D5.1)

5.1 Introduction

This section presents the results of activities aimed at the definition of the geometric, thematic and structural analysis of the façade to support the building envelope assessment and development of Building Model. The activities had two primary aims:

A. The definition of a reference methodology to obtain (beginning from the surveying) a geometrically simplified building model to support the thermal assessment and <VE> tool.

B. The definition of a reference methodology to obtain (beginning from the surveying) a geometrically accurate building model to support the insulating evaluation for the Retrofitting Planner, the design development and the refurbishment of the façade including the experimentation of the potentials in the use of thermal maps, to derive temperature maps of building façade to evidence thermal bridges and heat losses, in order to better support the evaluation of insulating options.

5.2 The geometric and thematic assessment to support the insulating evaluation for the Retrofitting Planner

In this section, the methodologies used to derive the geometric model of the building are discussed both for the insulating evaluation, the design development and the refurbishment of the façade. Following this, the methodologies used to derive a global model of the building for thermal analysis are discussed.

5.2.1 Survey of the building geometry

To guarantee a correct geometrical description of the building both for the thermal analysis and design of the panels, a detailed survey of the façade shape has to be carried out. In particular, elements that mainly affect design of panels are windows, doors, balconies, etc, that act like a constraint for the panel sizing, and façade irregularities, for example, out of plumbs that affect the positioning and the size of anchors, needs to be investigated.
In order to generate a 3D model of the building a surveying methodology combining two surveying techniques, 3D Terrestrial Laser Scanning and Photogrammetry, was used. Terrestrial Laser Scanning (TLS) allows for rapid surveying of the geometry of object in the field of view of the instrument, by providing the 3D coordinates of millions of points. In this way digital point clouds can be generated. A robust geo-referencing of the multiple point clouds is guaranteed both by the laser scanning spheres and targets and by the geodetic topographic network in order to ensure a unique reference system.

Figure 4: 3D TLS (Terrestrial Laser Scanning) for rapid detailed model acquisition of dense cloud points to be processed for both the simplified model and the detailed model

This kind of survey allows reducing in a significant way the time needed for the survey and allows also the survey of complex geometries. Even if the scan acquisition phase is quite simple due to the automation reached by nowadays technology, some aspects of the surveys need a special care:

- **Self-occlusions**: The scanner can survey only points that are in the field of view of the instrument. To avoid self-occlusions and shadow areas due to external object the scanner positioning needs careful planning. However, in some cases, like building survey, the object itself produces some shadow areas (e.g. due to undercuts) and more scans are needed to survey the entire objects and reduce empty areas.
- **Acquisition angle**: The accuracy of the acquired 3D points is a function of the angle formed by the laser beam and the surface to be surveyed. In particular, the more the laser beam is tangent to the surface, the lower the accuracy of the signal reflected back to the instrument. To reduce this problem positioning the scanner in a frontal way with respect to the surface to be surveyed enhances not only the quality of the final model but also the mapping of images over the model. This also means that in the case of high rise buildings, the scanner need to be positioned to an adequate distance to the building itself to enhance the surveying of the top floors.
- **Good overlap among scans:** This requirement is mainly aimed at guaranteeing the completeness of the survey reducing problems connected to self-occlusion and overlapping areas.
- **Scan resolution**: The resolution of the scans has to be sufficient to describe in a non-ambiguous way lower detail required for the survey. This is important when scanning objects at a significant distance to the instrument. Indeed, having fixed the angular step of the scan, the farther the object is, the lower the number of points describing it. In addition increasing the distance from the object, the measurement accuracy worsens determining a higher ambiguity in the definition of the break-lines and discontinuities.
- **Target position:** An important aspect when performing a laser scanner survey is the proper positioning of the targets. The scanner performs all the measurements in an instrumental reference system. For this reason, more scans are performed and a proper number of targets have to be positioned in order to reference all the scans in the same reference system. In particular, to register two scans in the same reference system at least three targets surveyed in both scans are needed. However, to have a better control on the solution, a redundant scheme is preferable by using several targets to be viewed by several scans. In this case, the registration is performed by using a least square adjustment solution. A further important aspect is associated with the distribution of targets. To have fully controllable solution, targets need to be distributed in a homogeneous way all around the scanning point. In particular, targets have to be positioned both on the object to be surveyed and around it. This distribution of targets gives a higher controllability of the least squares solution both in terms of internal and external reliability.

- **Topographic support:** In the case of complex architectures, buildings are surveyed by means of laser scanning technology and the scan registration needs a topographic support. In the case of registering several tenths of scans, the resulting registration can undergo significant deformations of the network, resulting in unrealistic estimations of the building dimensions and shapes. To avoid this effect, a topographic support is requested to the support the laser scanning survey. Topographic measurements (e.g by using a total station) of the targets can be included in the least square adjusting systems as pseudo-observations. Those additional measurements included in the solving system with an adequate weight, established in accordance to their accuracy, help in controlling the solution and prevent deformations in the laser scanner registration.

A principal limitation of laser scanning techniques is that the object boundaries cannot be directly detected by the laser beam. In correspondence of edges, corners and other features, the spatial resolution of the point cloud could not be enough to describe these features. On the other hand, those elements can be individuated in a simpler way by using photos and integrating this information with point cloud the quality of a 3D building model can significantly increase. Break-lines are of primary importance because they act like a constraint in the panel design phase. Also to perform a Photogrammetric survey some basic requirements should be taken into consideration to extract break-lines with an adequate accuracy as follows:

- **Camera calibration:** In order to use a camera for photogrammetric purposes, its calibration should be carried out to determine the interior orientation parameters and to compensate for the effects of lens geometric distortion. In particular for central perspective cameras the Brown's model which is based on 8 parameters (principal distance, principal point coordinates, 3 coefficients for radial distortion compensation, and two parameters for decentering distortion) can be effectively used. These parameters can be estimated by using a proper calibration polygon which must be imaged from different positions and running a proper calibration project where calibration parameters are estimated.
- **Acquisition scheme:** In order to orient image by means of bundle adjustment, images need an overlap and an acquisition scheme. To orient a block of images, the same object point should be individuated in at least two images. These image points called homologous points can act either as Tie Points (in the case their coordinates are unknown) or as Ground Control Points (GCP) (in the case their position is known in a defined reference system). In particular, an overlap of about 80% between images can be a good choice which allows one to find Tie Points (TPs) on 3-4 images. To have a reliable image, the orientation of a sufficient baseline between consecutive images should be guaranteed. Due to all these considerations, in the case of a façade survey, a robust configuration can consist in a strip of images with an overlap of 80% enriched with of some convergent images enclosing all the façade and a second strip at a higher distance to stabilize the image block.
- **Image resolution:** Ground resolution of an image, measured in terms of Ground Sampling Distance (GSD) (area of a pixel projected to the ground) is of primary importance to guarantee the accuracy of extracted break-line. The accuracy of extracted break-lines can be evaluated in a first rough way comparable to the GSD. Given the accuracy in the break-line definition the GSD should be chosen as a consequence. Two factors mainly influence the GSD: the camera object distance and the lens system. In particular, reducing the camera-object distance the GSD reduces, but the number of images to be processed increases, because the image footprint reduces. On the other hand, considering the same camera and the same camera-object distance, GSD of wide-lens systems is far larger than the one obtainable with telephoto lens. However, the

limited field of view of telephoto lens generally doesn't allow having proper image geometry for a stable bundle block adjustment.

- **Topographic support:** Also in the case of image orientation, block deformations can occur. To prevent this, a series of GCPs, whose coordinates are determined with topographic techniques, can be added to the solving system to control the solution. Furthermore, to integrate laser scanning and photogrammetric surveys topographic measurements have to be carried out in the same reference system.
- **Low cost and time reducing acquisition procedures and processing reducing test in the case of multiple image acquisition to guarantee High Resolutio:** To guarantee a quick extraction of break-lines and orthophoto production of the façade, a panoramic head was used to generate an image obtained via stitching and gnomonic projection of the acquired images (Figure 5). The main advantage of this system is the possibility to increase the field of view of a camera equipped with use a telephoto lens. The obtained gnomonic image has a better ground resolution than a photo acquired with a standard wide-angle lens and a similar field of view. A set of images taken with a rotating camera (same perspective centre but different attitude) can be registered and stitched through homographic transformation equations. To obtain a rotating camera we used a mechanical head consisting of a cardanic joint that allowed the camera to turn around it. To guarantee the rotation around the perspective centre on the camera a fast and simple calibration is needed. This calibration can be easily carried out using two vertical wires and adjusting the main ruler of the head to find a good alignment between the camera-wire systems when the sensor is rotated. The camera can be correctly aligned by using a theodolite, which is then removed to mount the head on the base. In addition, on the top of rotating head, there is a joint for the installation of a GNSS antenna or a prism for theodolite measurements. The acquired photos are than stitched together by using either scientific or commercial packages (e.g. PTGui, Hugin, Panoweaver, etc.) and then re-projected by using a gnomonic projection. The obtained gnomonic image is a new central perspective image and can be processed like standard images to obtain rectified images and orthophotos.

Figure 5:The panoramic head used to generate gnomonic images

5.2.2 Building geometry representation

In order to show the process from the laser scanning data input to the simplified model, a workflow for generating a simplified building model for the Retrofitting Planner is summarized in Figure 6. Once the point clouds are registered together and break-lines are extracted from the photogrammetric project, the modelling of the building is performed by using standard practice modelling software (Rhino, AutoCAD, or other software).

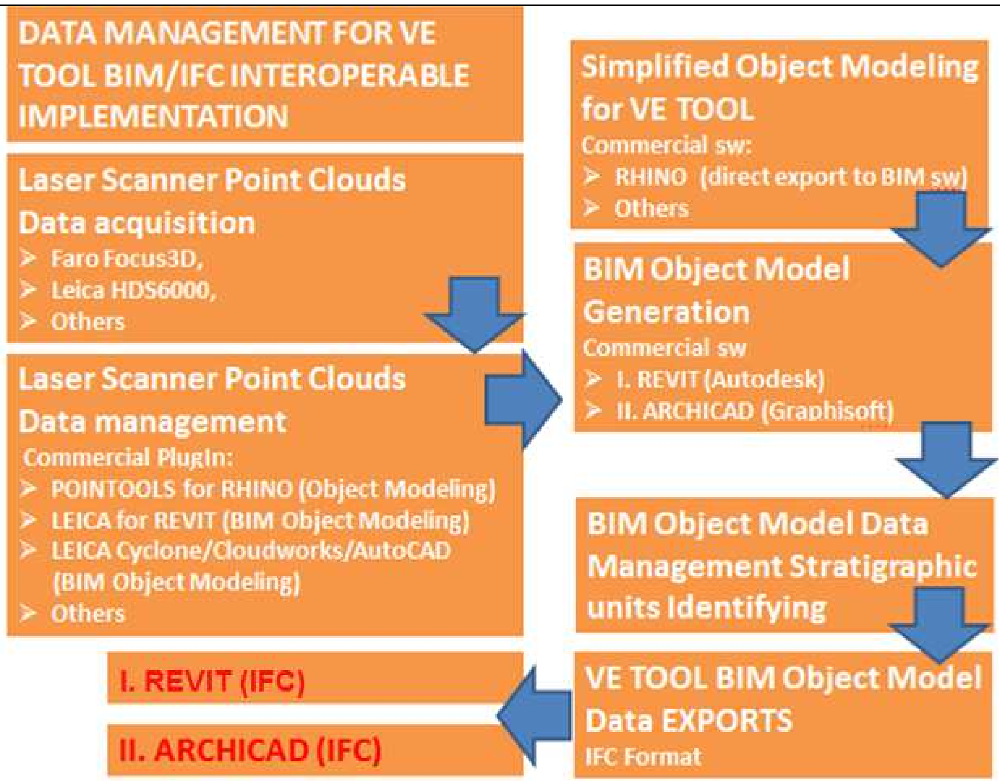


Figure 6:Workflow for the production of a simplified building model for the Retrofitting Planner

The handling of those data into modelling software is performed by using some commercial plug-ins available on the market for point cloud handling in modelling environment. There are very few plug-ins able to manage point clouds, and to manage the memory capacity of such mass data inputs (millions of points) in a spatial 3D environment. Among them, the most common are the plug-ins developed for Rhino modeller (PointTools Bentley, now on development due to the market diffusion of laser scanning data; perhaps as an internal functionality fully available within Rhino software), or Cloudwork for Autodesk developed by to manage the Leica Cyclone software clouds data management. A few Open source plug-ins are available too, but limited at the actual state of the art to the managing of few clouds and limited functionalities.

For these reasons a new plug-in to be developed within <VE> tool hasn't been considered, to ensure a unique modelling environment for the different phases, i.e. the simplified model requested by <VE> tool requirements and the detailed model requested for the final Retrofitting Planner development. Also, it has been taken into account that the common skill in modelling are friendly with commercial software (such as Rhino) that allows at the same time both simplified and complex modelling.

Because the <VE> tool requires a global building model, the required geometrical accuracy is, in fact, lower compared to the one needed by CIM-MES for detailed dimensioning of the panels. For this reason construction drawings can be integrated with laser scanning surveying and other direct surveying. The building modelling for the Retrofitting Planner should be focused on identifying and defining the main thermal zones of the building. For this reason the requested geometric resolution of the model, in terms of building and façade irregularities (like out of plumbs) can be skipped while more significance is given to the modelling of interior rooms and their connection. Once having performed the modelling of the building definition of building characteristics (wall stratigraphy, windows and doors typologies, etc.) and thermal zones are defined into software allowing for BIM generation (e.g. REVIT, ARCHICAD), directly able to inherit by Rhino modellers, or Cad modellers, or other (i.e. Rapidform, Geomagic, etc.) the Object Model generated for the different purposes inside such modellers.

Because the model needed for thermal analysis requires a lower geometrical accuracy than the one needed for the design planner an additional simplified methodology was developed (Figure 7). In this second methodology the generation of simplified plans, elevations and cross sections staring from the original point cloud is performed by using commercial CAD software allowing for point cloud management. Once the geometrical information are derived the generation of a simplified building model is performed inside the VE environment. The transfer of data between these two different environments is performed by means of DXF file format.

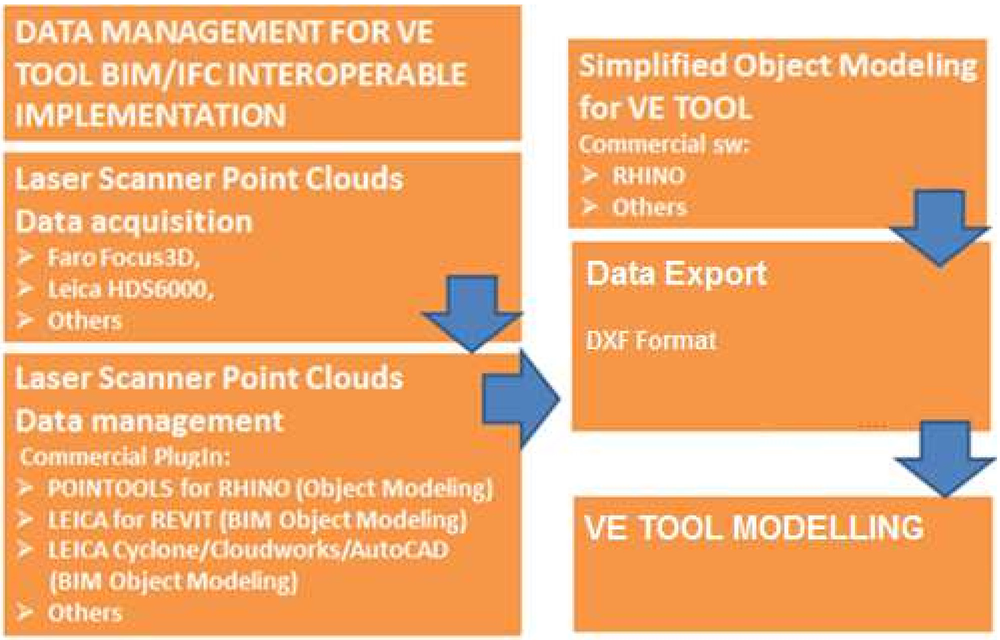


Figure 7: Simplified workflow for the production of a simplified building model for the Retrofitting Planner

5.3 The geometric assessment to support the design development and the refurbishment of the façade

Methodologies used to survey the building to derive the geometric model design development and the refurbishment of the façade are the same (Laser scanning and Photogrammetric survey) used also for the Retrofitting Planner.

In this section, methodologies used to derive a detailed model of the building for the Retrofitting Planner are discussed. The integration of this detailed building model and the façade thermal mapping that may give important information both in terms of thermal defects and anomalies (like thermal bridges) and for structural assessment (like the localization of different materials in the façade, localization of beams and columns positions, etc.) is described. This information influences the panel design in terms of size of the panels and positioning of the anchor system.

5.3.1 Building geometry representation

The workflow for generating a detailed building model for the design planner is summarized in Figure 8. Also in this case the modelling of the building is performed into the same commercial software (Rhino, AutoCAD, or other software) by handling point clouds by using the same proper plug-in previously mentioned. Unlike the previous case, lower significance is given to the building interiors (even if an accurate interior modelling is possible) with the main aim of modelling the façade. In particular, break-lines and façade irregularities play an important role. For this reason, the building modelling break-lines extracted from the photogrammetric survey need to be integrated with point clouds. In the case, the façade presents a significant statistic deviation from the verticality and out of plumbs; a refined modelling of the façade can be performed by meshing the portion of point cloud representing high irregular zone and integrating it in the global façade model. Once the modelling of the façade is carried out, interoperability with the design planner is performed by means of file data exchange via STL format. In the future also interoperability with BIM model and data exchange could be reached, as already explained.

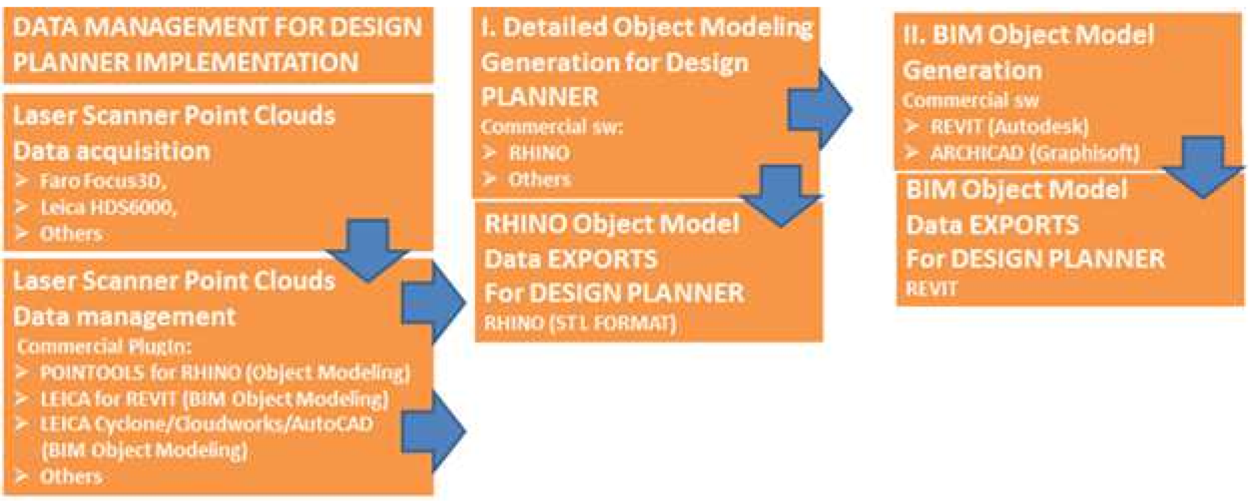


Figure 8: Workflow for the production of a simplified building model for the Design Planner

5.3.2 Façade thermal mapping

In order to obtain a thermal map of the building, highlighting the different construction typologies (brick block masonry, concrete elements, beams, pillars, chimneys and ducts), and at the same time thermal bridges, heat losses and possibly deriving on-site thermal materials properties, a procedure of integration between InfraRed Thermography (IRT), Red Green Blue (RGB) images, and Laser Scanning data was developed.

Even if IRT is a valuable diagnostic tool for predictive maintenance, a well-known major limitation in IRT surveys is connected to the narrow Field-of-View (FoV) of InfraRed (IR) cameras adopted for close-range applications. The analysis of a single thermographic image can be sufficient for identification of localized phenomena. However, in the case of large constructions or when thermal anomalies are evident only at a larger scale, the analysis of a single image may not be enough. In fact the higher resolution available on market is a 640x512 pixel matrix. That means that it is required to cover the façade with as many little images as possible to get a satisfying level of detail to be used for the decoding of the needed information.

To partially overcome this problem a solution combining the geometric content of laser scanning data has been developed taking into account the RGB images and the temperature information derived from IRT into a single framework. This integration can be obtained by mapping thermal images on the 3D building model created with Terrestrial Laser Scanning. The final product consists of a thermography-textured 3D digital model of a building. This model can be interactively browsed and as a result, opening in this way, creates new possibilities for thermal investigators. Furthermore, starting from the textured model, raster products can be obtained such as thermo-graphic-mosaics and thermal othophotos geometrically related to the orthophoto obtained by the RGB HR images acquired in the visible range.

In order to have a rigorous mapping of detailed 3D models, the intrinsic calibration of the IR camera and the co-registration of both the thermal images and the scans are needed. In particular, the co-registration of the thermal images and the geometric 3D model of the building are crucial tasks. According to the structure of the surface and to the image acquisition procedure, the problem can be afforded by using different techniques such as:

- homographic transformation based,
- single image resection,
- bundle adjustment of a set of images .

The former technique is rigorous only when the 3D model of the building façade is flat. Single image resection techniques are the most popular in the case of thermal images, but unfortunately each image is processed individually, which results in overlapping areas. Furthermore, the achievable accuracy of orientation with texture-less images can be questionable. The latter has the advantage of exploiting common points between images, which results in the reduction of the total number of points to be measured. However, the resolution and the limited angle of view of IR sensor may determine an acquisition scheme of thermal images not adequate for a stable orientation of images with a bundle adjustment. In order to overcome these limitations the developed methodology makes use of both thermal and RGB images together. The combined orientation of both sets of data has several advantages:

- global redundancies allow an estimation of external orientation parameters better than those estimable with standard space resection techniques;
- RGB and IR image acquisition may be carried out independently, even in different days;
- this method allows the user to include new data taken at different epochs in order to monitor the thermal behaviour of the building before and after the retrofitting intervention.

Different thermal camera typologies testing

The developed monitoring strategy can be applied with different thermal cameras. In particular three camera typologies of thermal cameras have been investigated:

- low cost high resolution camera (640 x 512 pixels),
- low cost low resolution camera (160 x 120 pixels),
- high cost high resolution camera (640 x 512 pixels).

The most common high resolution Thermal cameras (i.e. FlirT400, T600) used for terrestrial purposes has a high range cost (20-35 kEuro). It has been tested also with high resolution thermal cameras generally used on board ultralight UAVs that due to the reduced weight UAV can carry reduced functionalities both in data acquisition and data output, but having a considerable reduced cost range (8-12 kEuro).

For example, the low cost high resolution FLIR Tau 1 camera (640 x 512 pixels) can be integrated with a micro Drone UAV platform, that can be used at the same time also for terrestrial ground measurements.
A UAV platform for thermal images acquisition presents several advantages:

- possibility to explore areas inaccessible from the ground like higher floors of buildings,
- possibility to have coarse camera orientation parameters from GPS and IMU data ,
- reduce the camera-object distance increasing the geometric detail of images,
- integration with data acquired from the ground.

For this aim an UAV platform has been tested to acquire the RGB and IRT analysis of the façade to be retrofitted and analysed as explained in the following paragraph.

An important aspect concerning the IRT analysis is given by the fact that IRT analyses are strongly influenced by the environmental conditions. For this reason some general aspect should be taken into account to perform an adequate IRT survey:

- operate in absence of solar radiation, preferably after sunset when the structure to be analysed is in the cooling phase, but it has been heated by the sun,
- operate in absence of rain and wind,
- thermal difference between the interior and the exterior of the structure to identify thermal anomalies that may be present.

For the geometrical aspects of thermal image acquisition the same considerations made in Paragraph 4.2.1 about photogrammetric survey still hold.

Once the image blocks have been acquired by ground and/or by UAV platform, the photogrammetric processing can be used by using also the RGB image block, in order to generate an IRT orthoimage geometrically correlated and referred to the RGB orthoimage. All the non-visible elements can be geo-referenced by the aim of Cad and GIS system in order to map all the materials, the constructive elements, whole, pipes and duct works, in order to give to the modeller all the needed information for the Object Model reconstruction useful for the Retrofitting Planner and for the assessment, together with the available drawing and the punctual inspections.

5.4 Worked example: Test façade POLIMI building 21

The experimental test was carried out on the façade chosen as the EASEE Test façade, which is part of the seven storey building named “Edificio 21” located at the POLIMI Campus in Via Golgi 39, Milano. The chosen test façade (Figure 9) presents existing precast panels at the two top floors, while the remaining part has a mortar finishing. An important issue related to the survey is the presence of a large tree just in front the façade, determining in this way a large occlusion cone to the laser beam in the left part of the façade itself. As such, this building is a good example of potential problems that may occur for many buildings in a city.

The different steps of the data implementation from CAD data to BIM model data management, including the Laser Scanning data management, are outlined as follows, to simplify the chain to the future users:

- **Step 1**: geometric survey;
- **Step 2**: plan and section of the building (CAD Format);
- **Step 3:** stratigraphic analysis and identification of the different stratigraphic units on the building drawings;
- **Step 4:** from Point Clouds and CAD drawing to the 3D Model Object Modelling (RHINO);
- **Step 5:** Simplified BIM Data management of the 3D Object Model and its component (REVIT, ARCHICAD, RHINO TO REVIT, RHINO TO ARCHICAD);
- **Step 6:** BIM export for the Design Planner;
- **Step 7:** Façade map temperature generation.

Figure 9: The POLIMI test Facade

5.4.1 Step 1: Geometric survey

The local datum was materialized by using 7 retro-reflective target in the nearby of the building while the ground control points used for referencing the scans were 8 checkerboard targets. Measurements for local datum and ground control point definition were performed by means of a first order theodolite Leica TS30. The network schema is presented in the figure below.

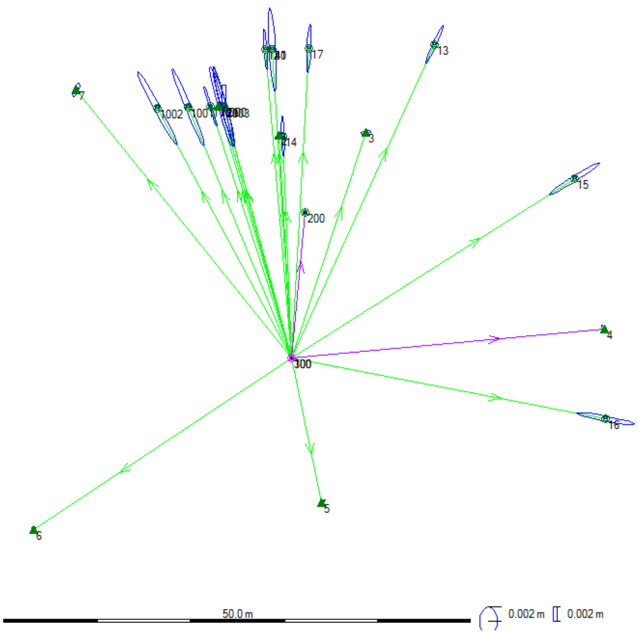


Figure 10: Geodetic network and error ellipses

After network adjustment the estimated accuracy in retro reflective target measurements is 0.5 mm while checkerboard accuracy is about 3.0 mm (Figure 11).

Point Id	Easting	Northing	Ortho. Hgt.	Sd. Easting	Sd. Northing	Sd. Height
1	232.1018	91.3157	302.0312	0.0005	0.0005	0.0001
2	238.5553	88.1892	300.2688	0.0005	0.0003	0.0001
3	247.9211	88.5006	301.5984	0.0007	0.0002	0.0001
4	273.3263	67.5079	301.9408	0.0004	0.0006	0.0002
5	243.1530	48.9364	302.2585	0.0005	0.0004	0.0001
6	212.3342	46.0090	301.6633	0.0003	0.0004	0.0003
7	216.9056	93.0269	301.5991	0.0005	0.0009	0.0003
Point Id	Easting	Northing	Ortho. Hgt.	Sd. Easting	Sd. Northing	Sd. Height
11	231.2501	91.2789	301.7112	0.0009	0.0027	0.0002
12	237.1892	97.3806	301.6696	0.0003	0.0029	0.0002
13	255.1567	97.9068	301.3787	0.0012	0.0026	0.0002
14	239.0031	88.1216	299.9913	0.0002	0.0028	0.0003
15	270.1778	83.5492	301.7950	0.0034	0.0022	0.0003
16	273.5103	57.8580	302.7983	0.0040	0.0009	0.0004
17	241.7492	97.5078	301.7410	0.0003	0.0033	0.0003
200	241.4028	79.9376	301.3572	0.0002	0.0002	0.0001

Figure 11: Geodetic network accuracy for retro reflective (top) and checkerboard targets (bottom)

The geodetic network was set up to include in future a differential GPS campaign. Aim of this campaign is to insert the survey in the cartographic UTM projected coordinate system to determine the exposition of the building façade.

The laser scanning survey consists of 3 scan acquisitions in order to survey the entire western facade of the building (Figure 12).

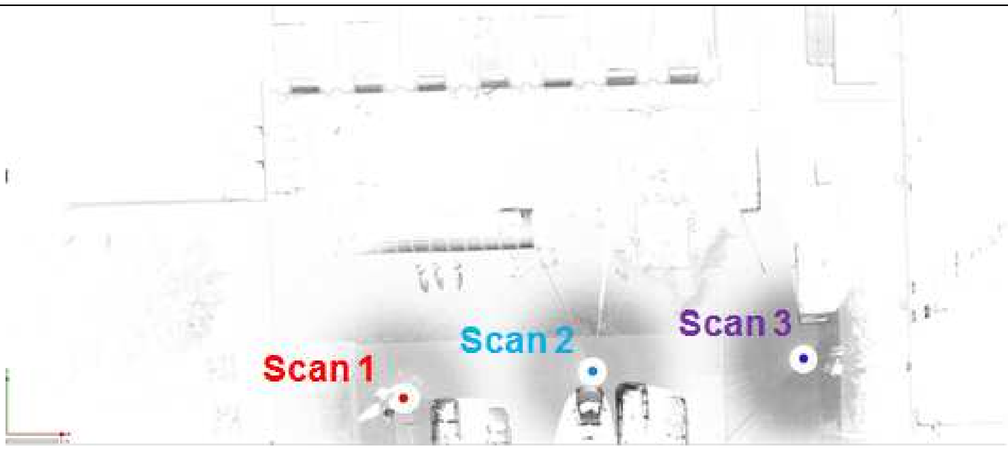


Figure 12: Laser scan stations

The survey was performed by using FARO – CAM2 FOCUS 3D laser scanner. Accuracies for the laser scanner used and given by the constructor are presented in Table 1.

Table 1: ***Accuracies for the laser scanner used***

	Precision at 10 m	**Precision at 25 m**
Surface with 90% reflectivity	0.6 mm	0.95 mm
Surface with 10% reflectivity	1.2 mm	2.2 mm

Each scan consists of 44 million points determining a mean Ground Sampling Distance (GSD) of about 2 mm. The GSD ranges from 1.5 mm in the lower part of the façade up to 3.5 – 4 mm in the upper part. Referencing of scans was performed by using as ground control points the checkerboard targets surveyed by theodolite and by means of 5 sphere targets used to strengthen the relative referencing of the scans. The mean referencing precision, evaluated observing residuals on the target measurements, is about 3 mm (Table 2). This is in a good agreement with the accuracy of measured checkerboard targets.

Table 2: Residuals on target measurements for each scan

Scan 1		**Scan 2**		**Scan 3**	
Target 11	2.9804	Target 11	1.3675	Target 11	2.635
Target 12	3.479	Target 12	4.7885	Target 12	3.297
Target 14	2.5897	Target 14	1.737	Target 14	1.615
Target 15	6.7061	Mean	2.6310	Target 17	2.267
Target 17	3.3537			Mean	2.4535
Mean	3.82178				

These accuracies and the GSD are comparable with the ones traditionally used for standard practice architectural drawings. However, final definition of the accuracy needed by the surveying would be given when the first test façade panel will be produced and accuracy in anchoring positioning will be defined.

5.4.2 Step 2: Plan and Section of the Building (CAD Drawing Format)

Once the geometric survey is performed plans and cross sections are derived from the point cloud. This is generally performed by using standard CASD software. To derive a plan or a cross section the point cloud is cut to keep only a slice of points. Starting from this the different elements (e.g. walls, stairs, etc) are manually vectorized.
In Figure 13 the available drawings of the Polimi test façade are illustrated.

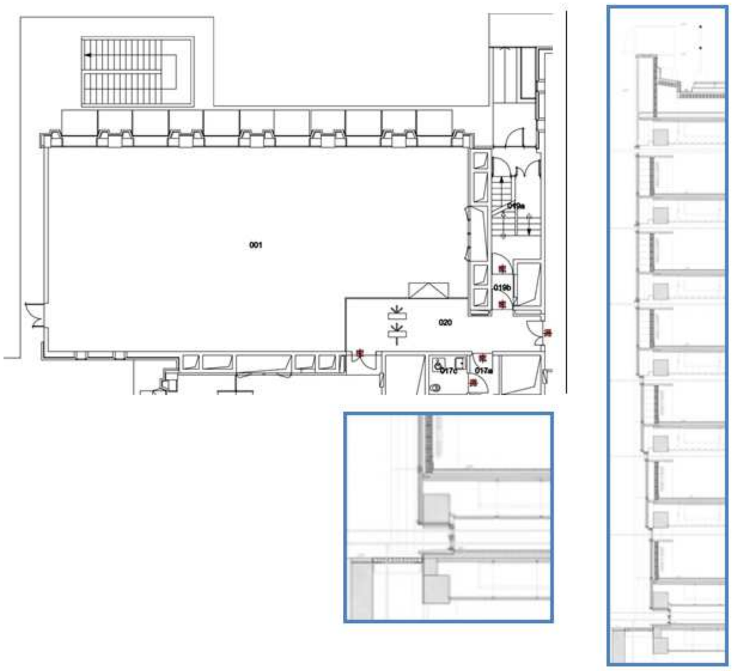


Figure 13: A Plan and a Vertical Section of the Polimi Test Façade Building (Cad Drawing) used or the thematic assessment to support the insulating evaluation of the Building

5.4.3 Step 3: Stratigraphic analysis and identification of the different stratigraphic units on the building drawings

The available drawings have to be integrated with the stratigraphic analysis. The different typologies of each stratigraphy detected along the building, including the facades to be retrofitted, have to be integrated with different analysis and information to refine the data about the construction technologies and the stratigraphic units. Information to be integrated with the stratigraphic analysis are the following:

- all available information on the building typologies;
- thermal surveying and mapping;
- on-site inspections.

The stratigraphic units identified on the Test Façade building, have been represented in the available drawing, as shown in the following figures.

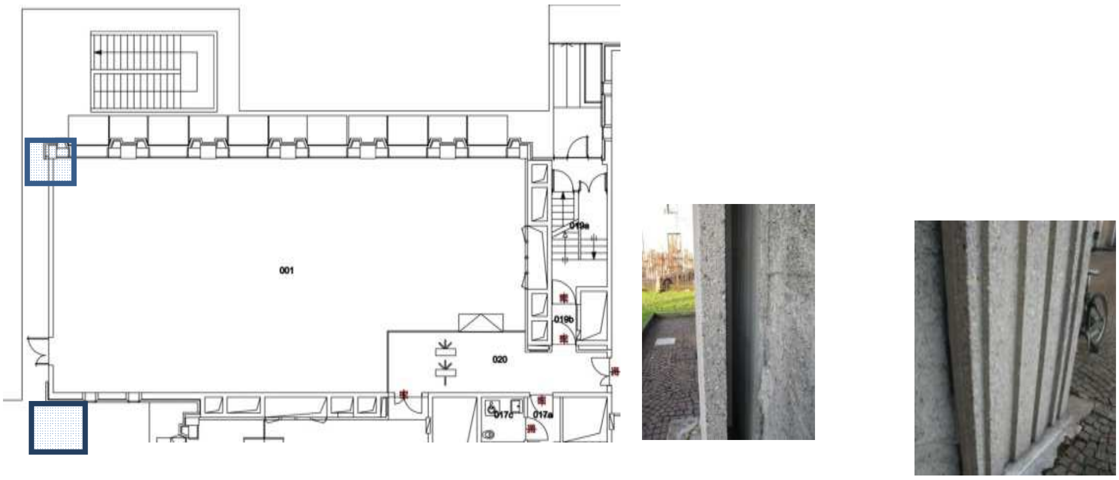


Figure 14: Stratigraphic analysis and its identification on the drawings. Ground floor: two details of the old outer retrofitting envelope covering the 2 corner (Left and Right Corner) of the test façade and the orthogonal facades

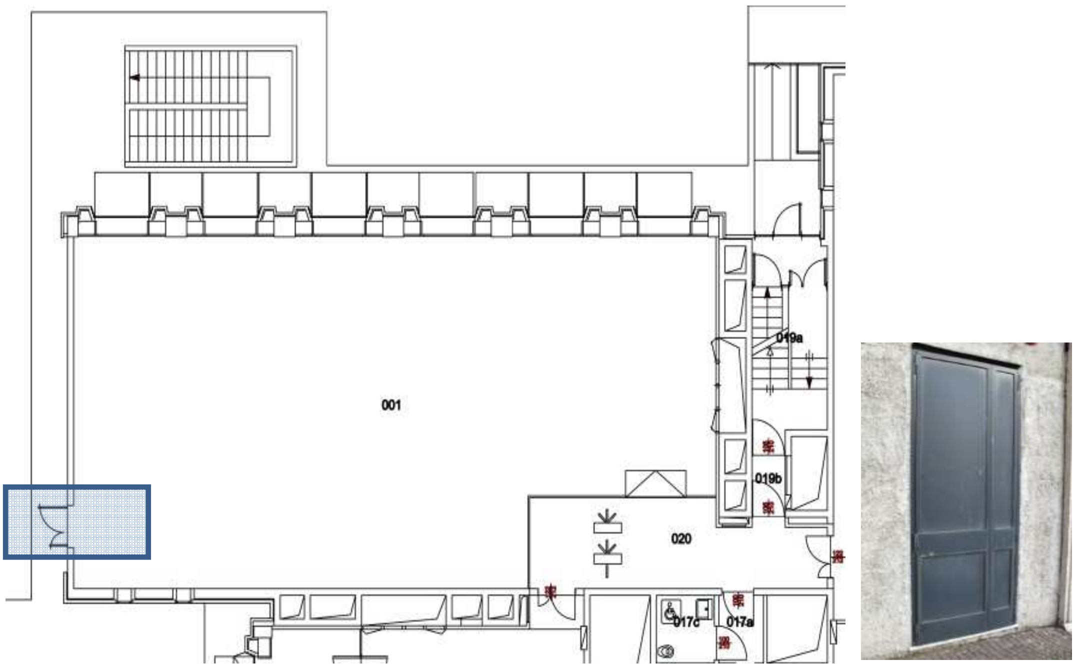


Figure 15: Stratigraphic analysis and identification on the drawing files. Ground floor: the detail of central part of the Façade (the concrete continuous wall), realized without any insulation panels and the front door

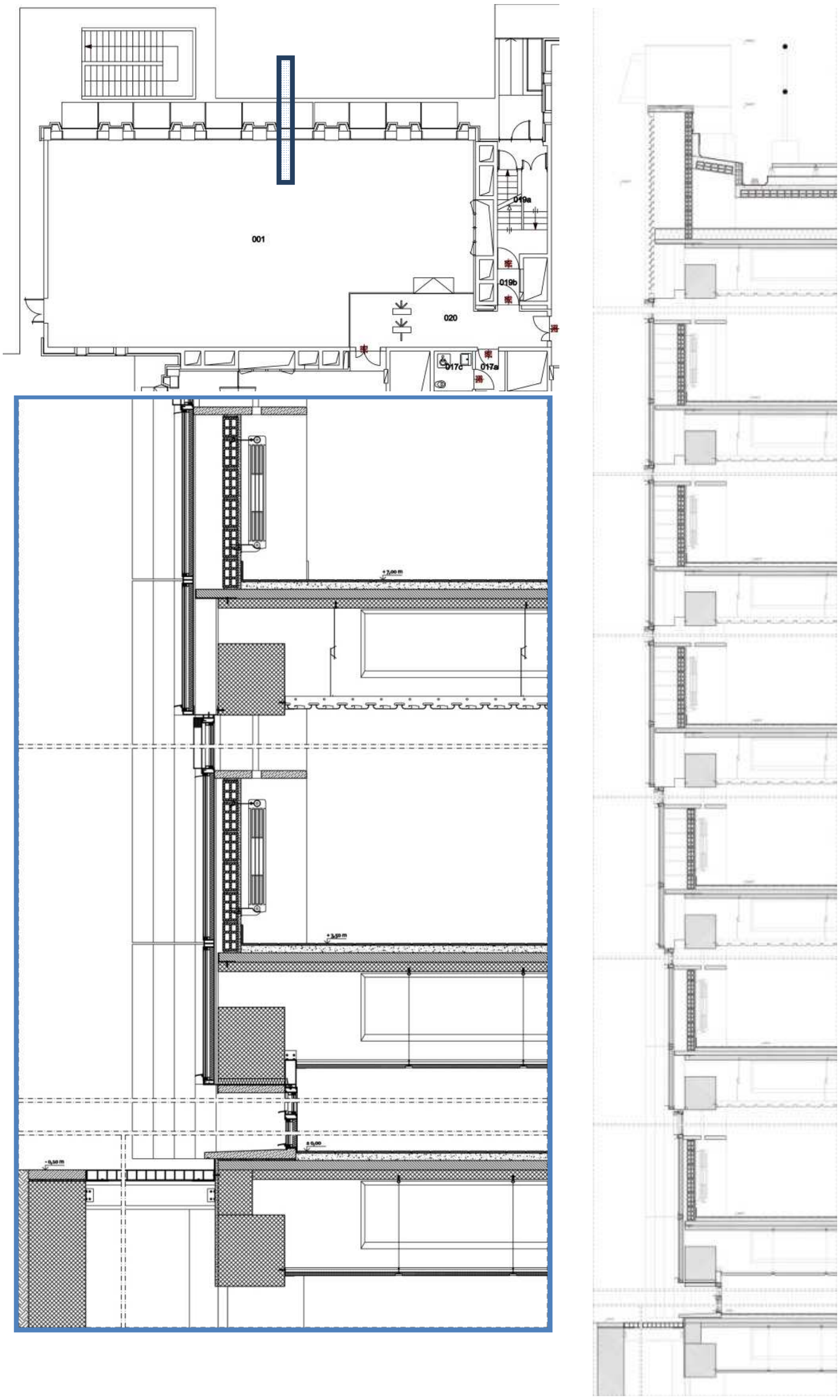


Figure 16: Stratigraphic analysis and identification on the drawing files carried on the vertical section for the detection of constructive components (pillars, slabs and structural beam elements)

5.4.4 Step 4: From Point Clouds and CAD drawing to 3D Model Object Modelling (RHINO)

Two models have been generated beginning from the same data entry (Cad drawing and point clouds): (i) a simplified model for the insulation evaluation and <VE> tool implementation and (ii) a detailed model devoted to support the Design planner development (Figure 17).

The global model of the building generated to support the thermal assessment and the <VE> Tool data implementation, takes into account the stratigraphic analysis carried out in the previous phase, the available drawings and the geometric surveying carried out with the support of the Laser Scanning and Image Block acquisition described in the previous chapter.

The global building's plans and sections (dwg format) are absorbed, where reliable, analyzed and integrated with the Laser Scanning Point clouds of the façade, and in general of the fronts or parts to be retrofitted, by using Rhino Modeler to generate a 3D Object Model Based representation of the building. This model is devoted to the assessment and management within <VE> tool development. The modelling process begins from the rooms that compose the building and operates with a high level of simplification of the structure according to the requirement given by the <VE> tool developer.

The point clouds were integrated with the available plan and sections, by using this software and its related plug in (Pointools), in order to compare, acquire data and assimilate all the geometrical information which result from the laser point clouds and the CAD drawings (i.e. slabs, vertical objects not belonging to the part of the façade to be retrofitted, since they've been already retrofitted, as in the case of the test façade).

The Rhino modeling generation/creation follows accurately the laser data along the façade. This allows:

- the reshape of the outline/sketch, both in the map and in the section form;
- the files cad import and the different layers' cleaning;
- the realization of solids in 3D;
- the import and generation of high resolution mesh and their reduction to simplified object model;
- the reshape of objects and surfaces , also the complex ones (NURBS) in the building test façade to generate the object models of each room/building component (pillar, wall, slab, beam, …);
- most important thing, the related final conversion of the file generated for parametric software like Archicad and Revit, as can be seen in the following images.

The result of the simplification process is shown in Figure 18.

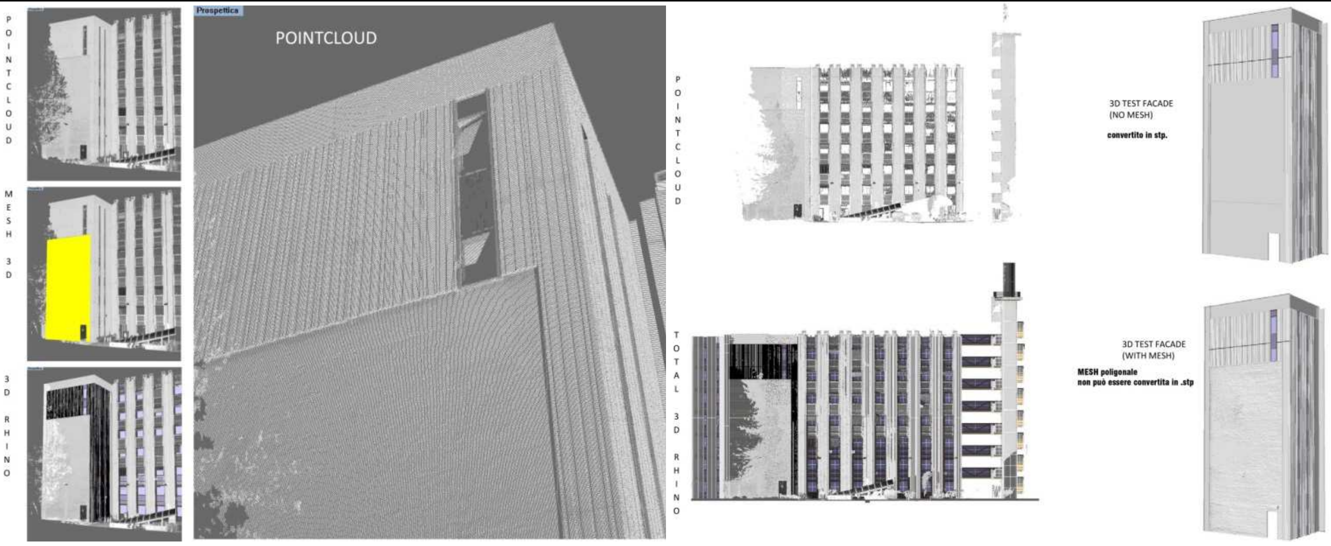


Figure 17: The two different models developed within Rhino beginning form the clouds and the CAD drawing: the simplified one, that's without the mesh generation and the one generated taking in account the richness of the point clouds

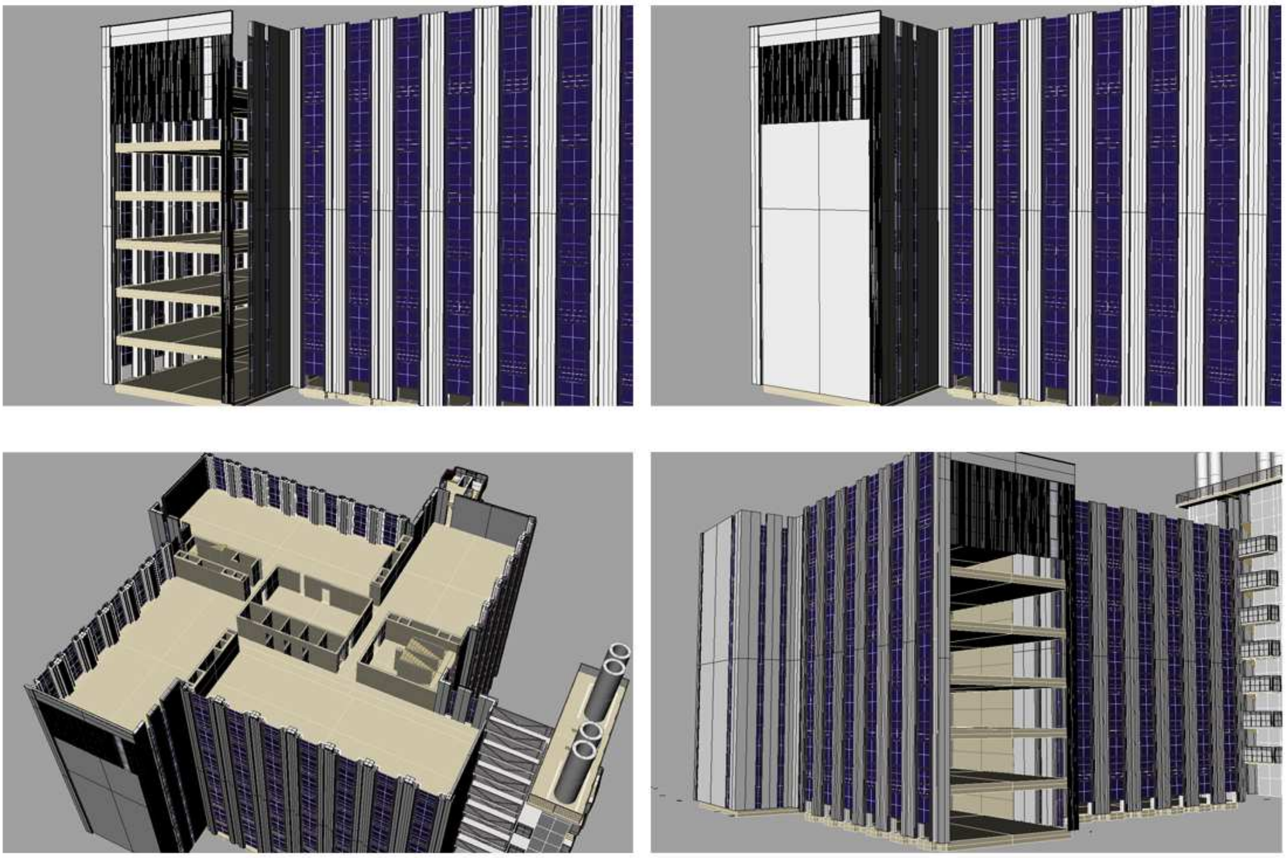


Figure 18: The Rhino simplified 3D model obtained generating for each element an Object model

5.4.5 Step 5: Simplified BIM Data management of the 3D Object Model and its component (REVIT)

Once obtained the global Model generated within Rhino, all the Object elements have been imported within REVIT BIM environment.

One of the REVIT key functionalities is that it can generate, in a very easy way, tridimensional models starting from simple files in cad design. In addition, it is also possible to import and recognize the object model generated in other software (i.e. in this case Rhino) and to expand the tridimensional model with a great number of related available information, regarding the object family, architectural, structural elements, as well as materials.

The integration of the Plan within the BIM environment and the room zone recognition is shown in Figure 19.

It's important in this phase to check the correct adjacency of the elements and the possible warning, as shown in Figure 20.

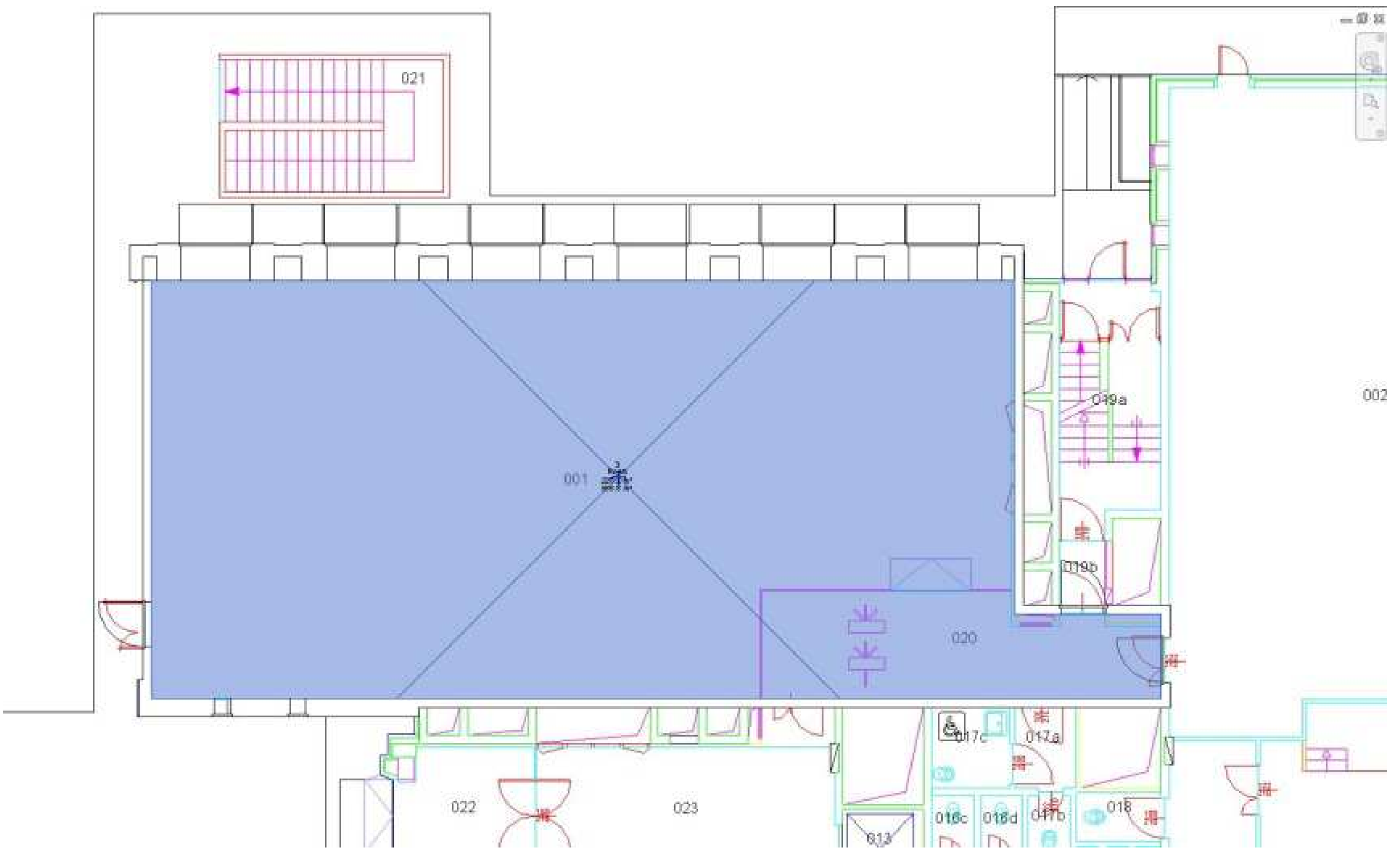


Figure 19: BIM Data Management and simplification process of the plan shape and external profiles. The integration of the Plan (Ground Floor) within the BIM environment and the room zone recognition for <VE> TOOL implementation (REVIT)

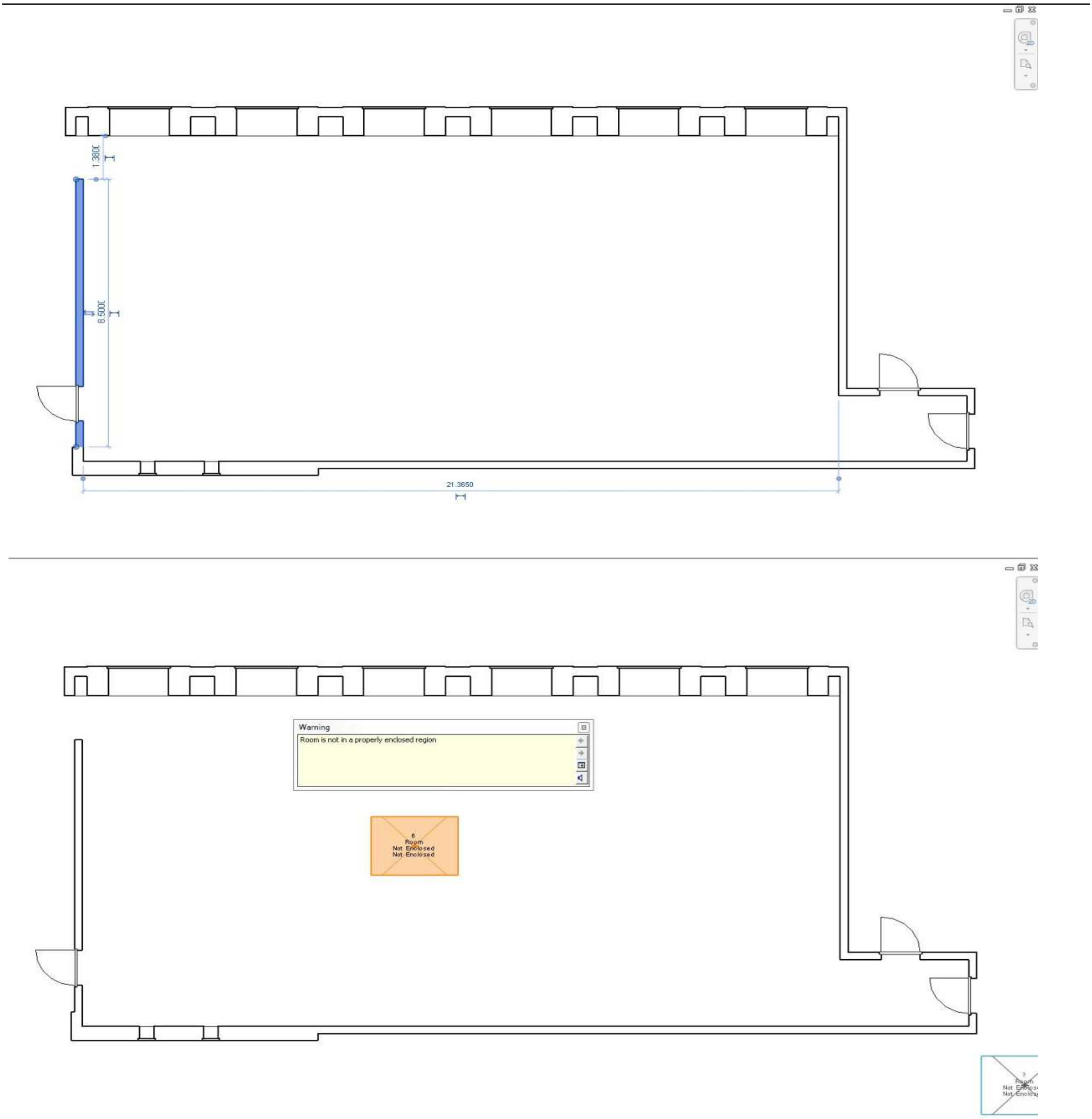


Figure 20: BIM Data Management. The integration of the Plan within the BIM environment and the room zone recognition. The example shows how in case of not well closed adjacent elements, the Room/Zone isn't recognized and the Warning that appears in case of error

Particularly it has been identified and generated, by using each Rhino object model element, every single architectural element composing the building room: pillars, slab, continuous wall, door and windows, etc. At the end of the process all the elements composing the considered room inside the building have to be recognized to generate a unique zone to extract the area and volume information. In order to ensure their aggregation the adjacency condition and geometrical congruence have to be verified in the simplification process without leaving any hole.

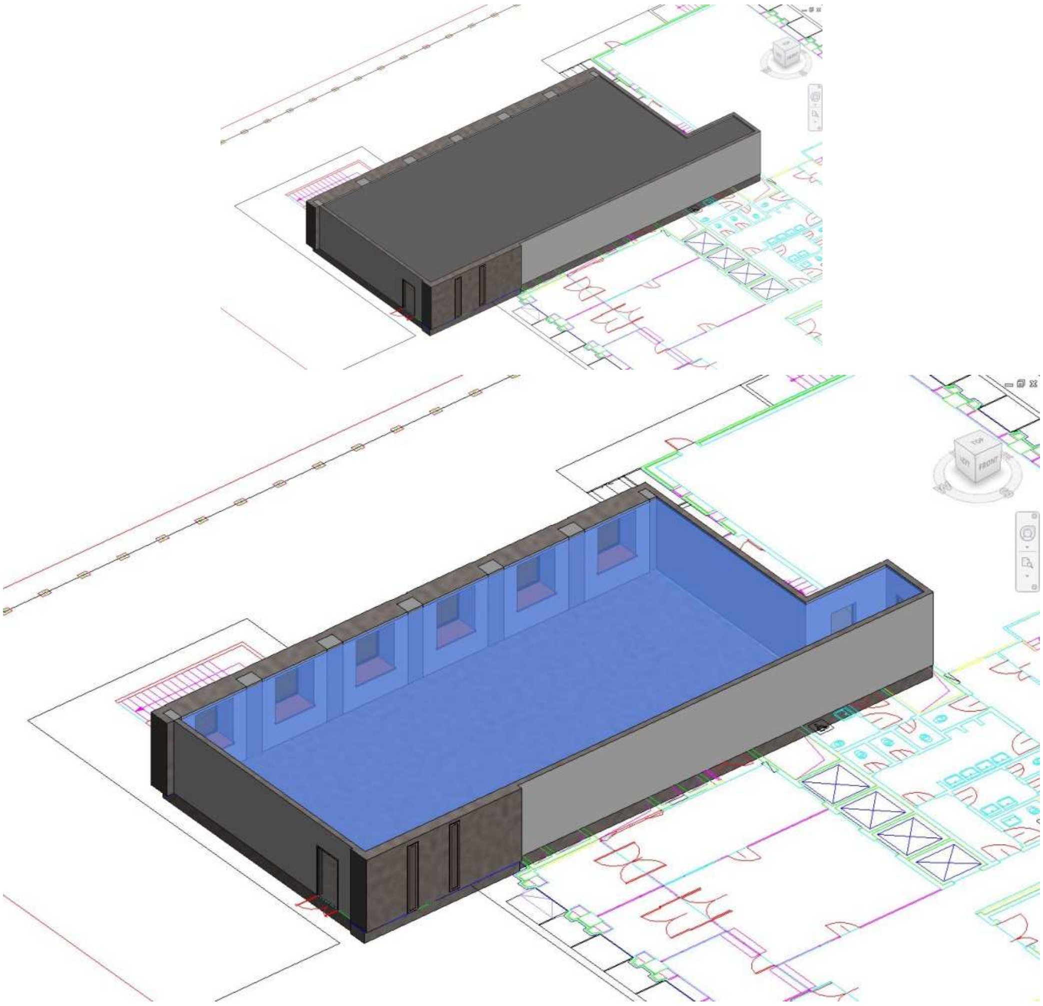


Figure 21: BIM Building Room Data Management BIM Model Generation of the room model in the final step, highlighting the recognition of the zone element of the considered room

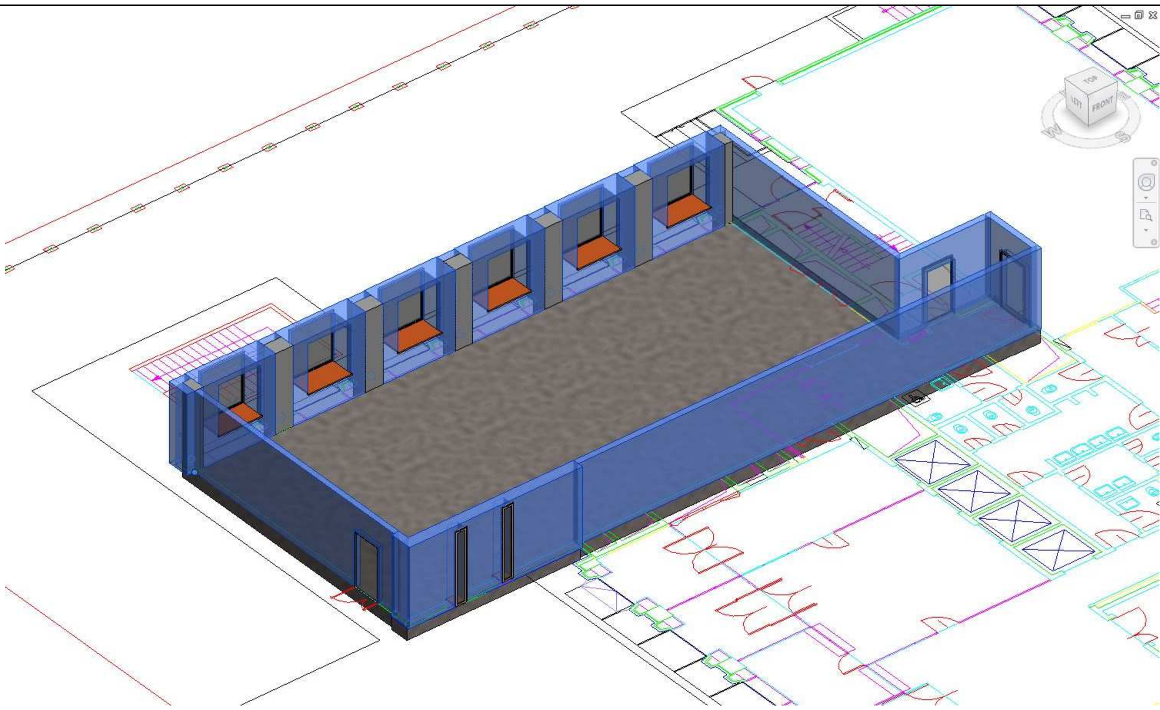


Figure 22: BIM Building Room Data Management the external continuous wall object generation and the internal ones that subdivide the building room distribution

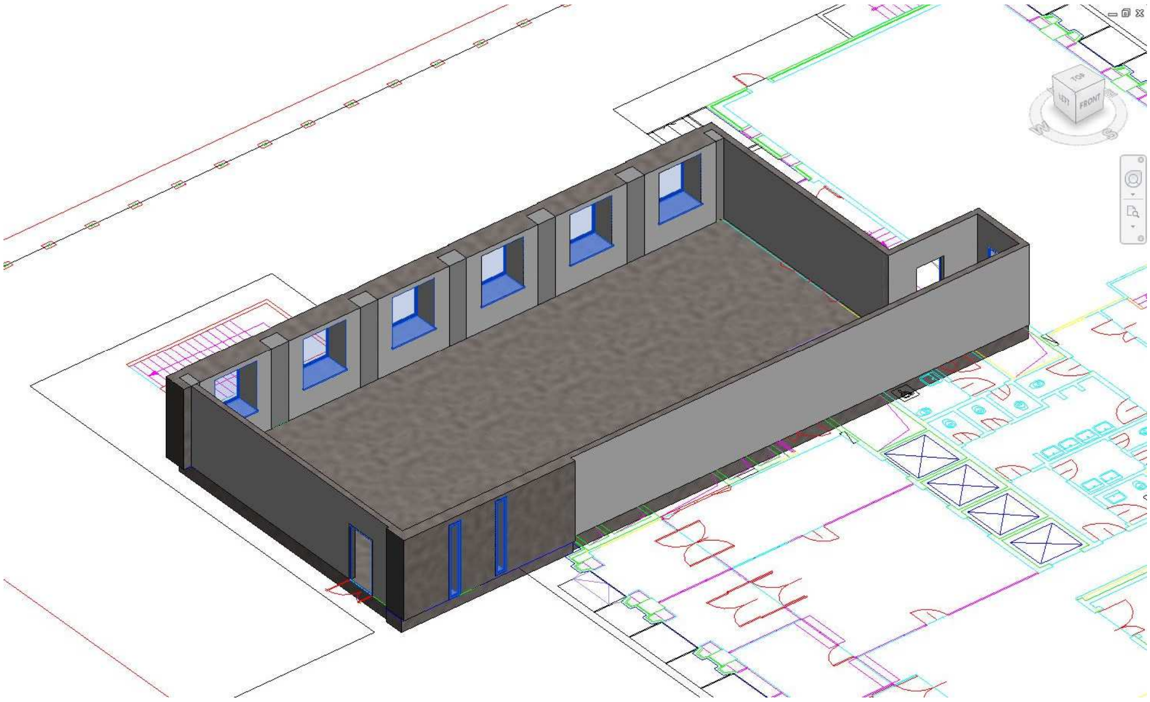


Figure 23: BIM Building Room Data Management BIM Model Generation of the window and doors generated by using the available libraries

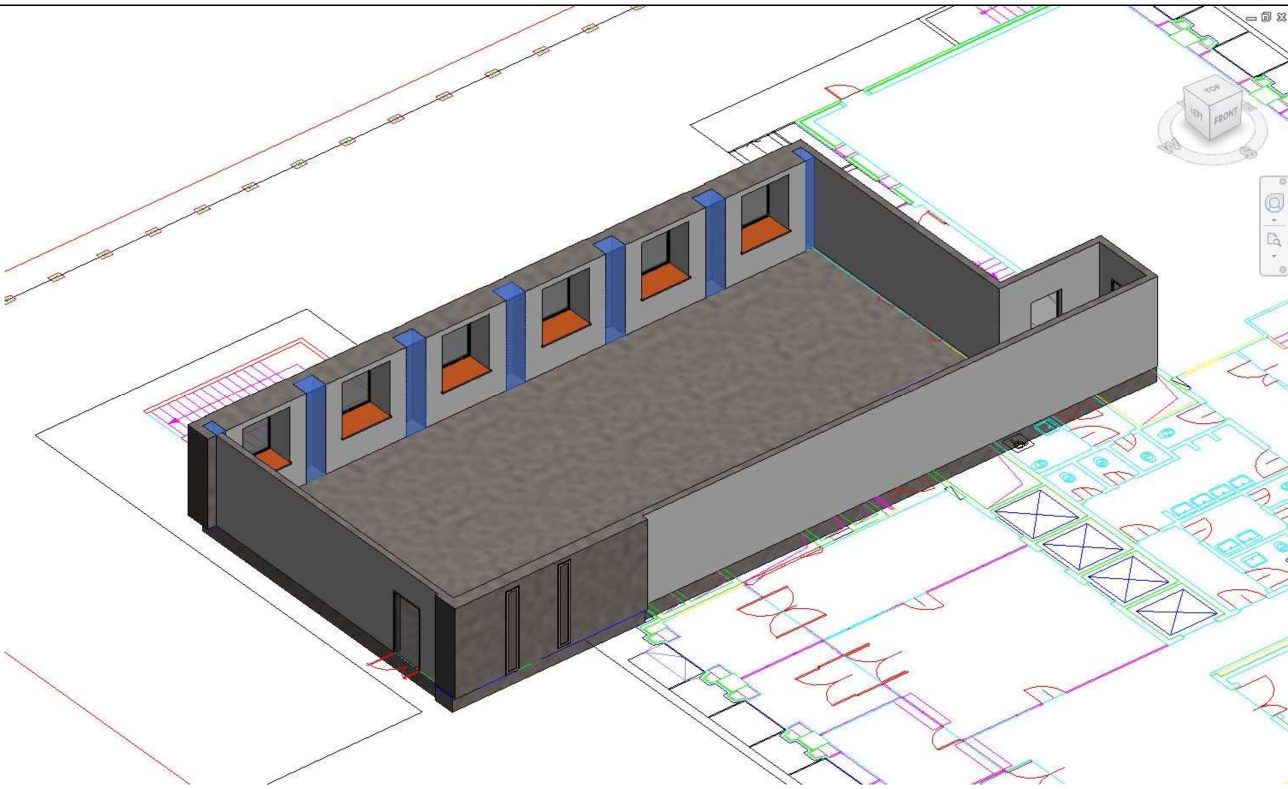


Figure 24: BIM Building Room Data Management BIM Model Generation of the punctual structural elements such as the pillars along the façade detected by the thermal camera and by the information coming from the available drawing of the project

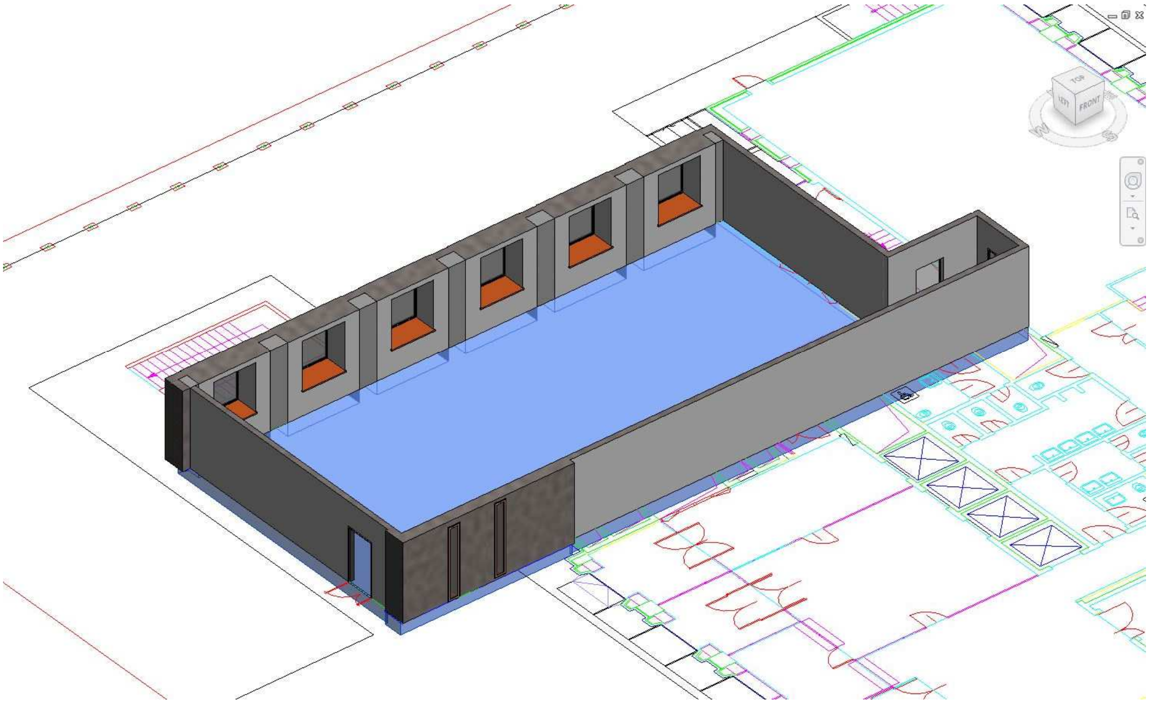


Figure 25: BIM Building Room Data Management REVIT Room Zone recognition

5.4.6 Step 6: BIM export for Design Planner

The detailed model devoted to support the retrofitting planning, is then shared with the Retrofitting Planner trough the STL format. The STL format has been chosen for the easier data entry of the CIM-MES EASEE Editor, capable to maintain the complexity of the shape modeled by the laser scan points, due to the simply way of managing 3D complex model vector data generated within the most common and sophisticated modeler, such as in this case Rhino, within the EASEE Editor itself, as described in the following chapters.

5.4.7 Step 7: Façade map temperature generation

The thermal analysis of the building was carried out with a thermal camera installed on the UAV platform AscTec Falcon 8 (Figure 26). The Falcon 8 (70 cm x 60 cm, weight 2 kg) is equipped with 8 motors and is able to fly up to 20 minutes with a single battery. The electronic equipment includes a GPS antenna and a system of accelerometers determining the system roll, pitch and yaw. The communication system allows the ground station to receive telemetry data and video signals from the on-board sensors. Our system is equipped with a low cost high resolution FLIR TAU1 640. The camera was photogrammetrically calibrated. The main features of our camera are shown in Table 3.

Table 3: Characteristics of the thermal camera FLIR Tau 640 used

	FLIR Tau 640
Information	TIR
Focal length	19 mm
Resolution (pix)	640 x 480 pixel
Pixel size	17 µm

Figure 26: Falcon 8 UAV equipped with a FLIR Tau 640 camera and a HR RGB camera

The thermal images were acquired in a vertical strip. The orientation of these images are performed in two steps. Firstly, 14 RGB images acquired with a Nikon D700 with a 35 mm lens were registered within a bundle adjustment. In this project 10 natural points (e.g. windows and doors corners) measured with a theodolite Leica TS30 were used as GCPs during bundle adjustment. Then, using about 30 TPs measured in the RGB images, 11 IR images were included in the bundle adjustment. Statistics of the combined bundle adjustment show a final RMS of about 0.9 pixels (Fig. 5.24). This result can be considered as acceptable due to the low geometric resolution of IR images. In fact, the GSD of thermal images was about 2 cm while the one of RGB images was 2 mm, meaning one order of magnitude of difference. An important remark concerns the identification of TPs on RGB and IR images. When IR images are used the presence of repeated elements, such as windows or doors, may determine some ambiguities in the identification of tie points. For this reason, in the surveying phase some notes should be taken.

Two different campaigns were performed, the first one in winter (March 16th, 2013) the second one in summer (July 9th, 2013). The comparison of the data acquired in different campaigns will be used when the panels will be installed as per the Retrofitting Planner and the variations in thermal values due to improved insulation will be assessed.

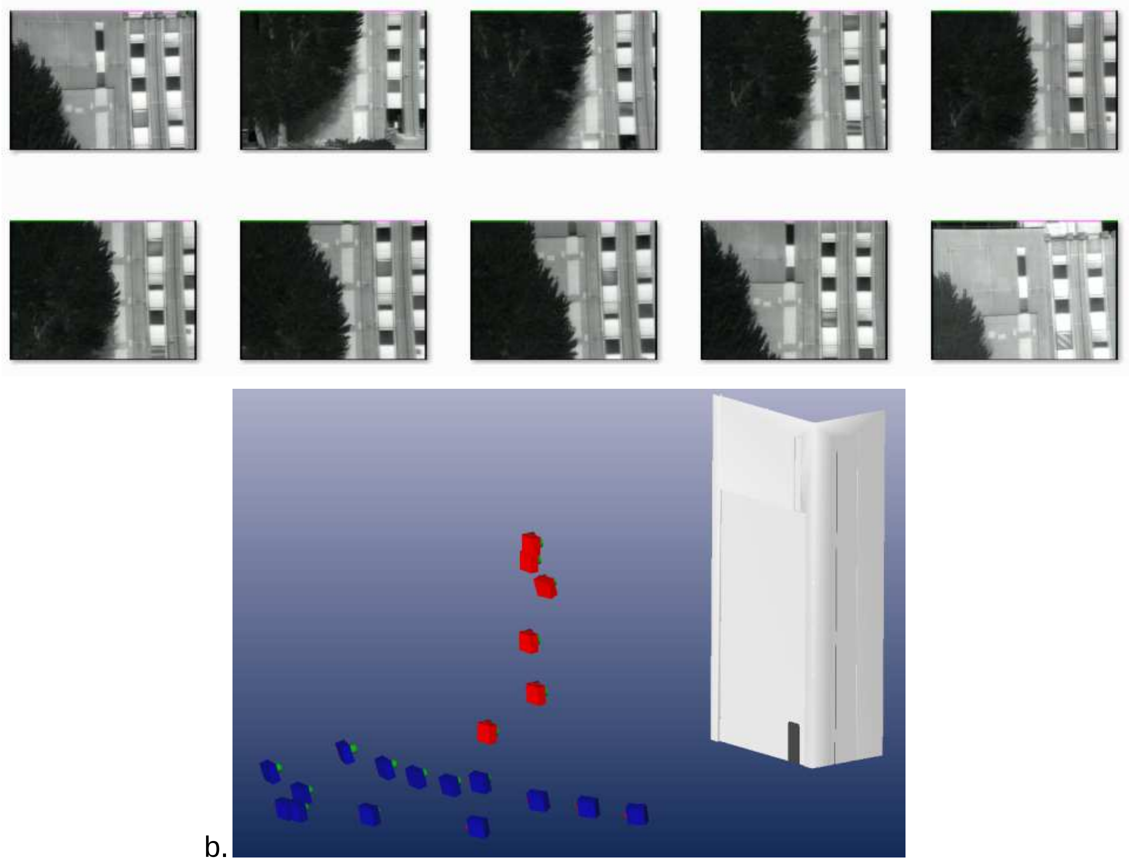
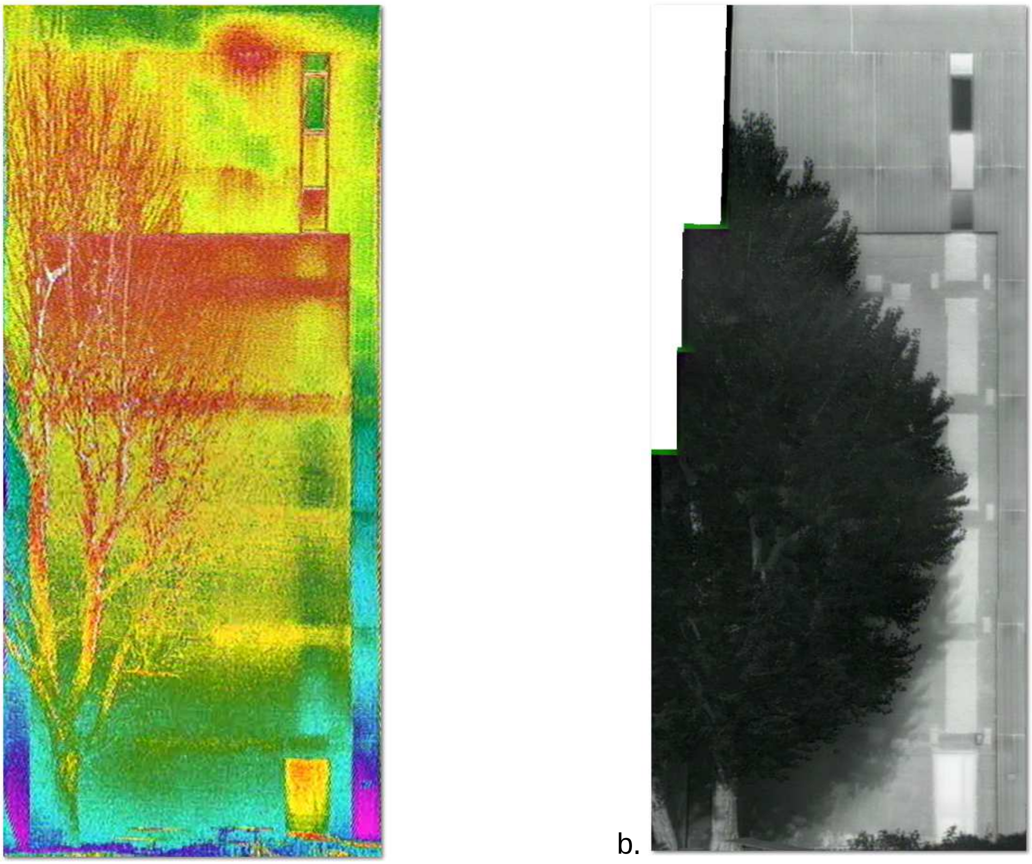

a.
b.

Figure 27: Thermal image processing: (a) thermal images acquired, (b) camera poses: red cameras IR images, blue cameras RGB images

Once IR images are registered in the same reference system of laser scanning point cloud, they can be mapped and mosaicked on the triangulated model of the façade, and then the final thermal orthoimages (Figure 27) were derived by simply projecting the data onto a plan parallel to the façade. Those orthopotos shows the presence of some thermal anomalies on the façade.

March 2013 July 2013



a. b.

Figure 28: Facade thermal orthophoto: March 2013 (a), July 2013 (b)

Figure 29: Design of the façade panels overlaid to the thermal orthophoto and the thermal anomalies positioning to support the Design of the panels and the location of the anchors avoiding the whole detected or reinforcing them

The anomalies underlined from the FLIR camera mounted by the UAV were confirmed also by the low cost low resolution camera (Figure 30). A major limitation of this camera is connected to the narrow field of view that makes more difficult to identify homologues points in a well distributed way all over the image preventing in this way a reliable orientation of these images.

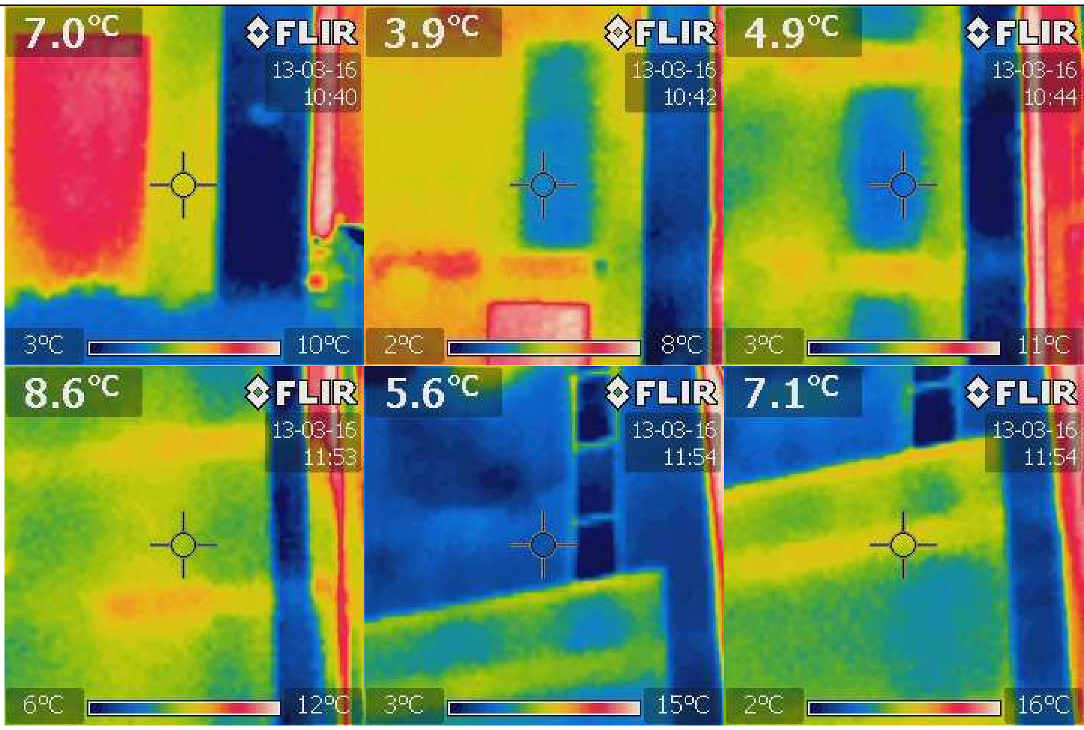


Figure 30: Thermal images acquired with a low cost low resolution thermal camera Flir i5 (160x120)

In addition, a few thermal images have been acquired with a traditional thermal camera (November 5th, 11 a.m.). The thermal in homogeneities of the façade due to geometric characteristics, technological constructive features, different materials were confirmed (Figure 31).

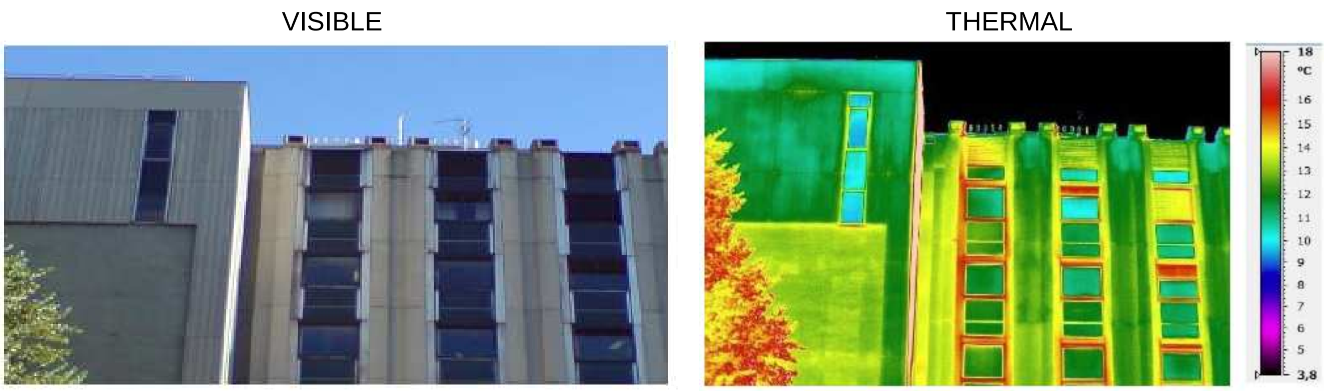


Figure 31: Thermal Images Acquired with Traditional Thermal Camera

In conclusion the availability of microDrones equipped with a thermal camera represents in the case of high rise building the best solution for thermal image acquisition. Indeed, the possibility to acquire images in orthogonal position with respect to the façade along the UAV paths allows having a constant GSD and reduces the problem of holes generally introduced by the ground image acquisition due to windows corners, balconies, etc. Micro UAV technology is still quite expensive (about 35kE) even if the continuous growing of the market will change the panorama in the next future allowing a wider use of low altitude microDrone systems for surveying purposes.

In case of using terrestrial ground measurements, it's possible to use different typologies of HR IRT cameras:

- the portable thermal, as in the case of FlirT400xseries cameras, can be used to derive surface temperature. Derived thermography can be directly processed within the common processing software;
- HR FLIR camera traditionally used for mobile equipment such as micro Drones (like FLIR Tau 640) can also be used from the ground. The main drawback in this case is the lack of surface temperature information. Indeed, since these cameras are optimized for inspections the temperature range is tuned by the system in an automatic way. This automatic adjustment cannot be disabled giving in this way thermal ranges changing from image to image. To adjust the output in an absolute referring range the possibility to use a white panel to synchronize all the images, thus obtaining a common comparable range, can be tested. However its practical application in real surveys is quite difficult for non-expert operators. A second opportunity tested is the integration with a low resolution camera to retrieve temperature information.

6 SOFTWARE TOOLS CREATED AS A RESULT OF T5.2 (D5.2)

This section outlines the work that has been completed as part of Task 5.2 “Holistic evaluation of a façade/building envelope option“. A number of software tools were developed which act as the core engine for the Retrofitting Planner. These tools are now described including a summary of the software development process.

6.1 Software development process

The diagram below outlines the software development process that IES followed to develop the tools for Task 5.2; this ‘lifecycle’ process adopts an iterative corrective procedure where one would revert back to software coding if any observations are identified during testing; and in some rare cases may even revert back to a specification stage to alter the direction of the tool if a crucial flaw is identified during testing.

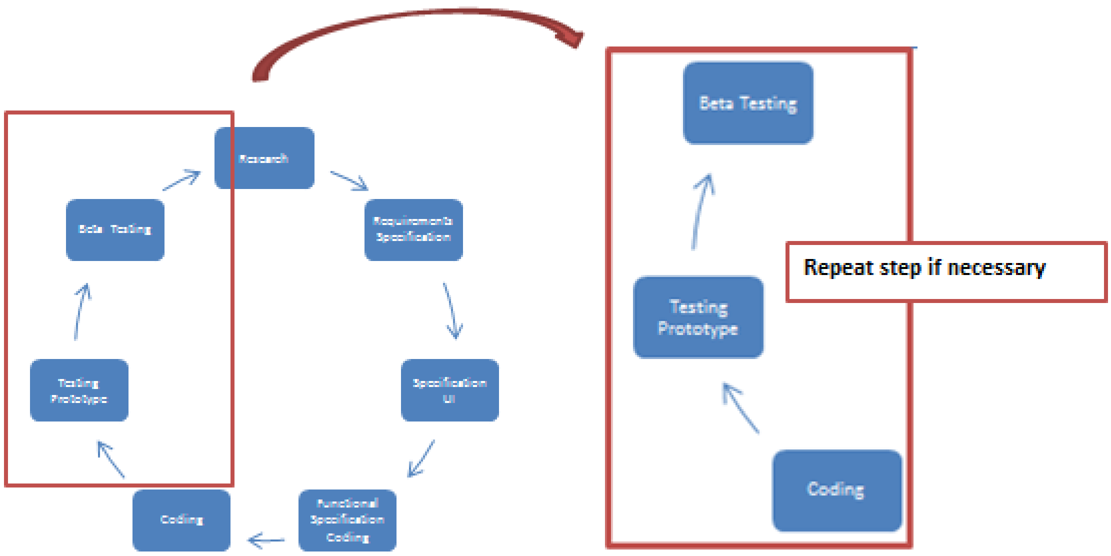


Figure 32: Software Development Workflow

Each of the stages within the diagram above are now described below:

- **Research**

  The first stage of the process takes form of a soft analysis, investigating subjects and solutions in order to meet the objectives of the DOW; some elements of this research will follow an iterative process using a trial and error method until the solutions are valid. This process will involve not only communication with project partners but with current customers (using focus groups) and other stakeholders. This stage is of particular importance to the overall development of the project as the output from this stage will inform later stages of development.
- **Requirements Specification**

  Next a requirements specification is written. This is when the output from initial research is crystallised into a software perspective. This can be either web based or application based. The process will involve investigating data needs and data sets for software development.
- **Specification UI**

Following this, another important step in the process is writing the specification for how the User Interface (UI) will look, again this can be web or application based. It is imperative that we understand the target user market when considering the UI, such things like usability and terminology will change with different markets so we must ensure the UI is constructed perfectly to meet the needs of the desired target market.

- **Functional Specification Coding**

  Once the requirements and UI have been defined, the next step in the process is the response to the requirements specification from the software developers. This document will be of a technical nature, describing in code how they will meet this specification; essentially a "DOW" for software development.

- **Coding**

  Now coding can begin involving the physical writing of the software. Once complete it will be peer reviewed, and alpha tested to ensure quality is of a high standard.

- **Testing Prototype**

  During the coding phase a number of 'milestone builds' are released for in-house testing. This stage of testing involves non-developers (internal IES staff), the testers role is to ensure that what the software is doing meets the initial requirements specification; any issues raised are highlighted to the software developers for review and amendment.

- **Beta Testing**

  Finally once the software has been tested in-house, beta testing involving external people (typically IES customers) is conducted. Their role is to ensure that what the software runs smoothly and being potential end users supply feedback to IES for review and potential amendment.

6.2 The software tools for T5.2

The EASEE Retrofitting Planner is made up of individual tools (software based) offering multiple functionalities to meet the requirements of the Description of Works and most importantly to meet the needs of the end user. The aforementioned tools built into the Retrofitting Planner have the important role of integrating the retrofitting solutions into the VE software for virtual testing of performance.

These 'tools' will be integrated directly into the IES <VE> software; for the purpose of this section of the report and to apply meaning we have summarised the tools below and included a workflow diagram.

Figure 33: WP5 Workflow Diagram

- **Master Templates** – One of the first tools developed for EASEE, Master Templates, enables the EASEE Agent to create simple models (and/or use common thermal attributes) using common building typologies (such as: office, hospital, school, supermarket, & more).
  Master Templates is particularly advantageous as the EASEE Agent can quickly apply a Master Template (containing the relevant thermal attributes) to the model brought in from POLIMI (or alternatively use the master templates to assist modelling a building from scratch). This will significantly reduce the modelling time, particularly for existing buildings. Over time as more buildings use the EASEE Retrofitting Tool the library of Master Templates will grow.
- **Search & Replace** – Following Master Templates came the Search & Replace tool, an intuitive yet seemingly simple concept (without underestimating the complex development that went into the tool) taking an element of a building and replacing with another i.e. 'replace all windows with a U-value of >3 to 1.3'. This tool significantly reduces user time being able to literally search and replace existing panels with retrofitted solutions. Originally, the user would have had to manually change each element individually which was a time consuming process.
  This simple concept can however become rather cumbersome when replacing or changing multiple elements which could result in dozens of simulations to take place which in turn takes time; to tackle this issue we developed the Parametric Batch tool (see below).
- **Parametric Batch** - The Parametric Batch Tool was developed specifically for Deliverable 5.2, the purpose of this tool is to collate all the chosen solutions, simulating them in a sequential order in 'batches'. This significantly reduces user time for the EASEE Agent saving him/her having to manually launch simulations.
- **Deft** – The final tool developed for the EASEE Retrofitting Tool was Deft, this tool is essentially a value choice tool displaying the optimised results in a comprehensive manner that allows the user to weigh up his decision for the solution best suited to him.

The following sections will now demonstrate the workflow of the Retrofitting Planner using a sample model initially; then the Gdansk demonstration building in the second workflow.

6.2.1 EASEE retrofitting planner – worked example pre D5.2

6.2.1.1 Worked example (extracted from D5.2)

Note: For the purpose of demonstrating iterations following feedback and testing, the following section has been directly extracted from D5.2; this reports the state of the tool prior to changes following testing.

This section illustrates a worked example using the various tools that make up the Retrofitting Planner within the VE software, and as described in prior sections of this report.

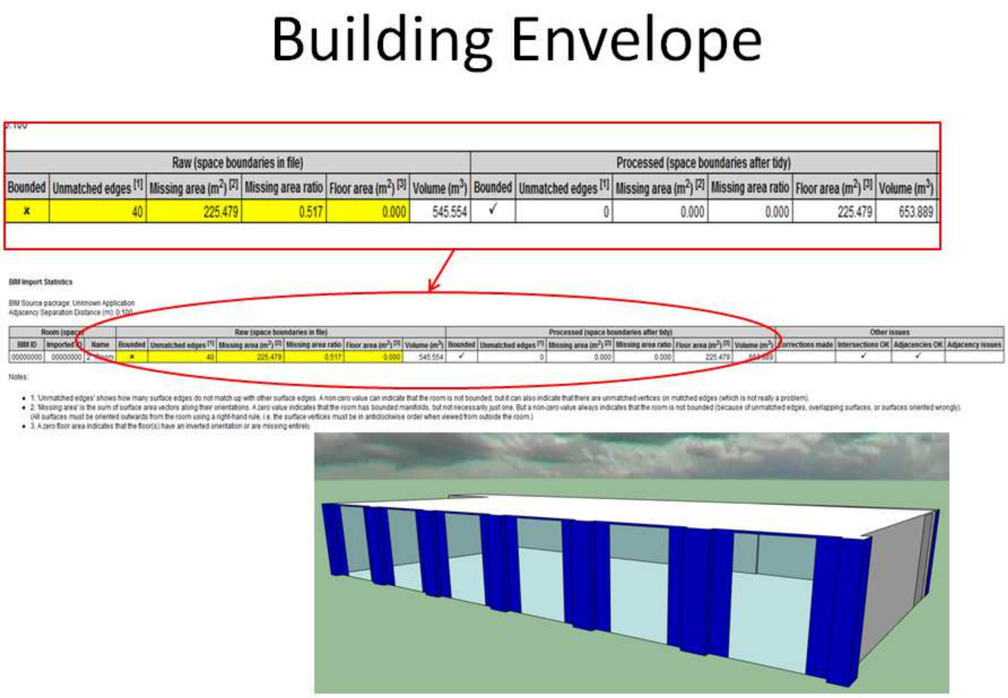


Figure 34: Building Envelope

The building envelope (or geometry) is gathered by point cloud and imported to the <VE> in IFC format. Figure 35 shows the building information model import statistics report which shows unmatched edges and missing area in the raw space boundaries in file and how these edges and areas have been successfully corrected during the import. At present construction information only comes through to the <VE> if imported as gbXML rather than IFC. So for the purposes of this demonstration the gbXML was imported so the as-built construction data could be used to create the baseline constructions on the IFC import model.

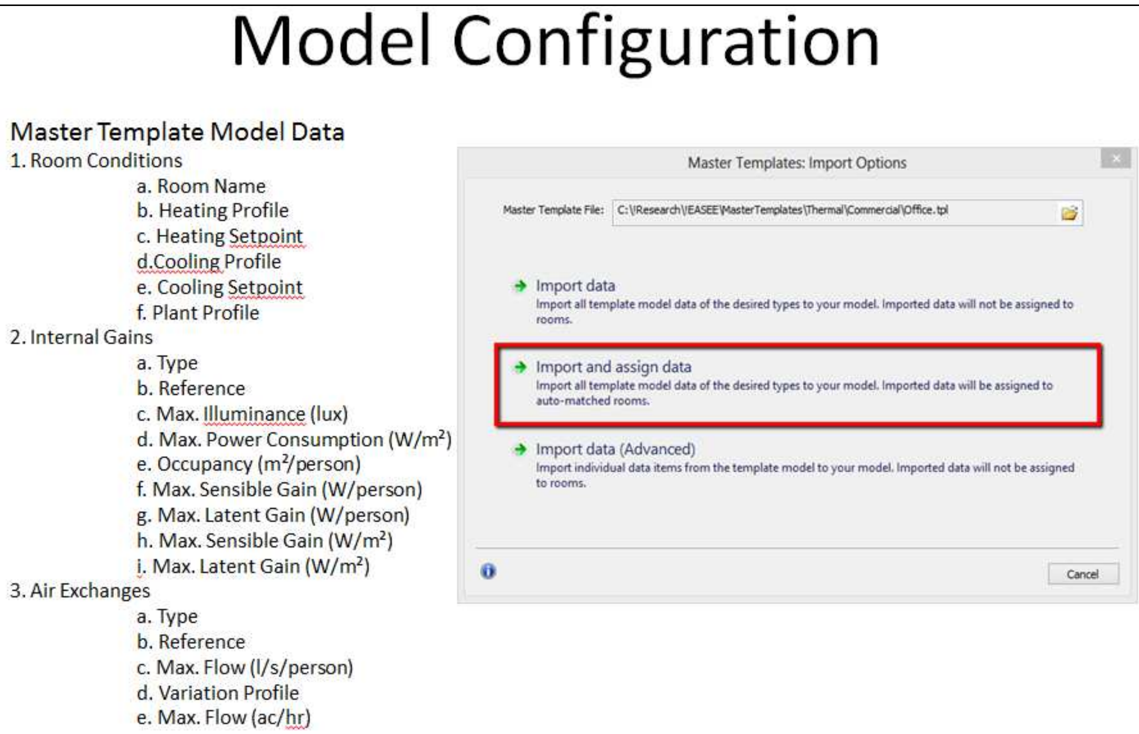


Figure 35Model Configuration

Then the site location detail and the thermal properties of the model shall be configured.

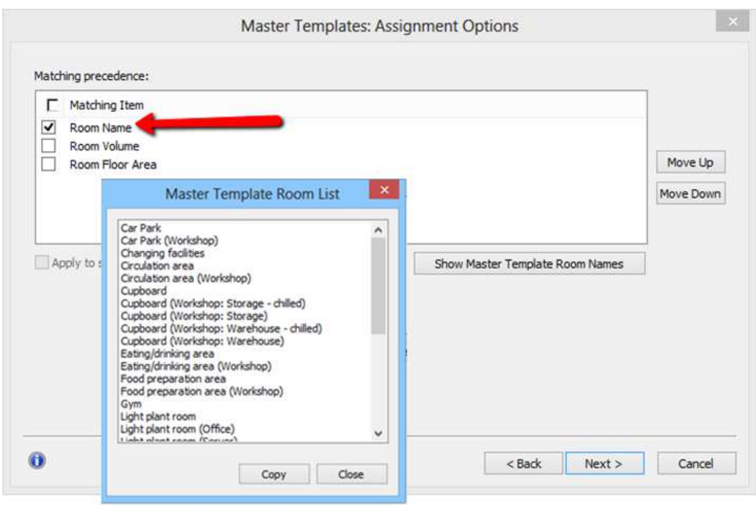
In this case the site location and orientation was present in the IFC file and was present in the model from the import. The "building" is actually just one room from a building on the Leonardo Campus of Politecnico di Milano ("PoliMi"). So the model was adjusted that internal surfaces were now adiabatic.

Every room in the model must have a space activity template assigned which defines the thermal properties of the room.

The Master Templates tool is used to import and assign these properties. Model data has been used to create Master Templates which are specific to building typologies including domestic buildings, commercial buildings, educational buildings, healthcare buildings, industrial buildings and also some miscellaneous model data.

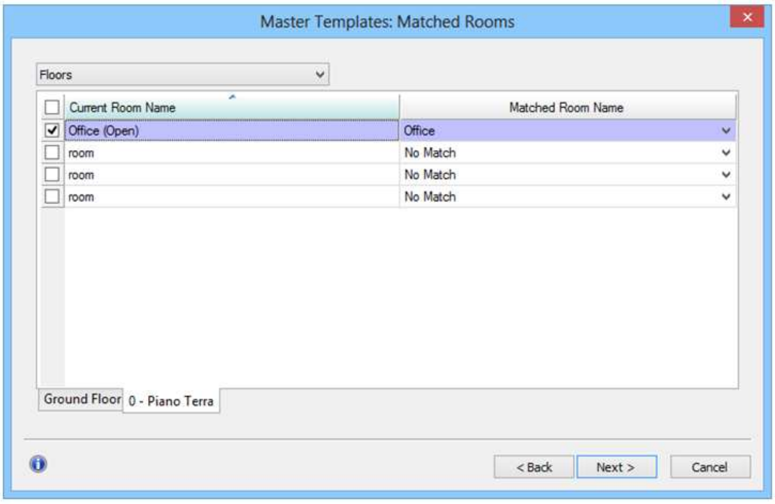
The steps provided and described in the table below are then performed.

Table 4: Steps to be performed for the Model Configuration

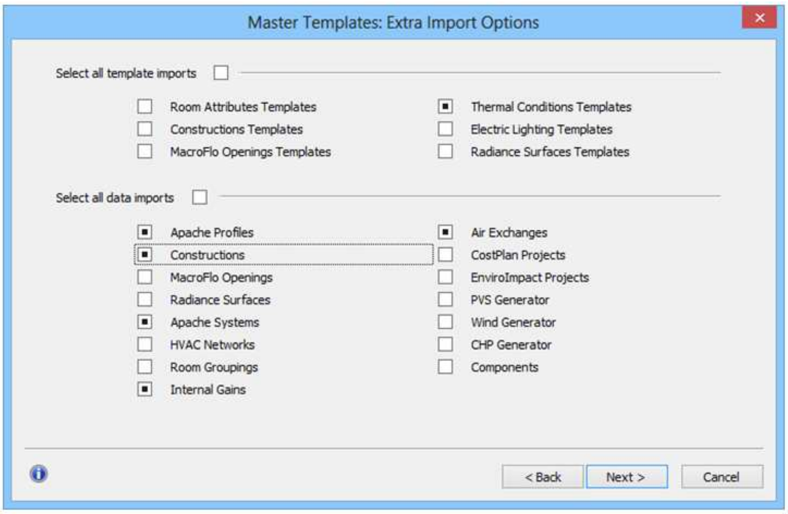


The "Import and Assign" option automatically matches the room with the model data depending on room name, area or volume.

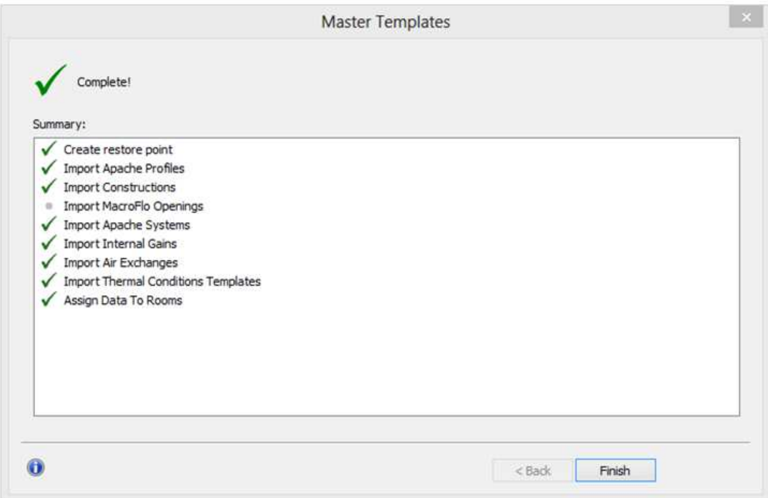
The building type in question is a university and the room in question has been assumed to be an office space. So the third level master template was selected and the imported model room name was changed to "Office (Open)" to correspond with the Master Template Room List.



The Master Template tool now provides a selection of the “best-fit” room names.

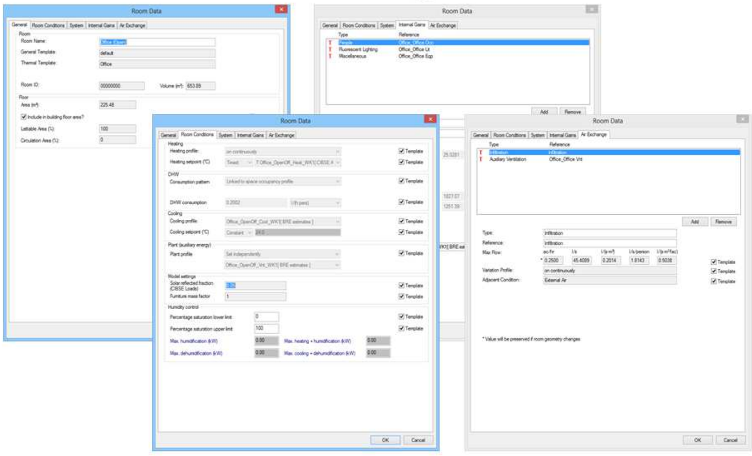


The following options are provided but for this demo only the thermal data will be considered.

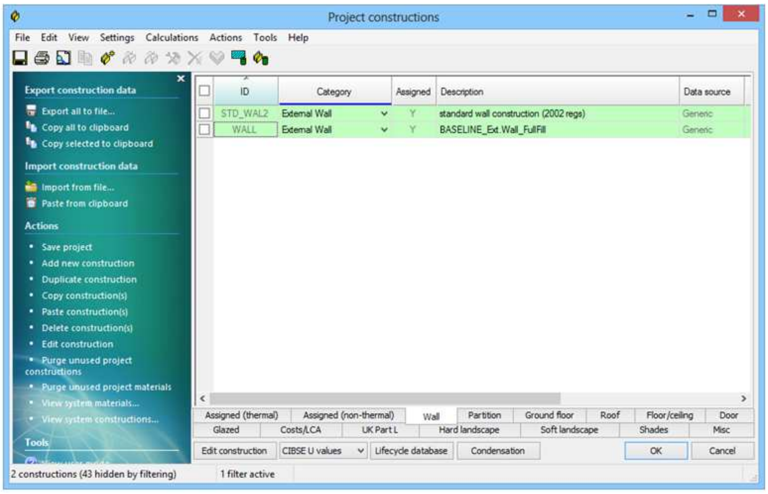


The master template tool imports and assigns the selected data to the model.

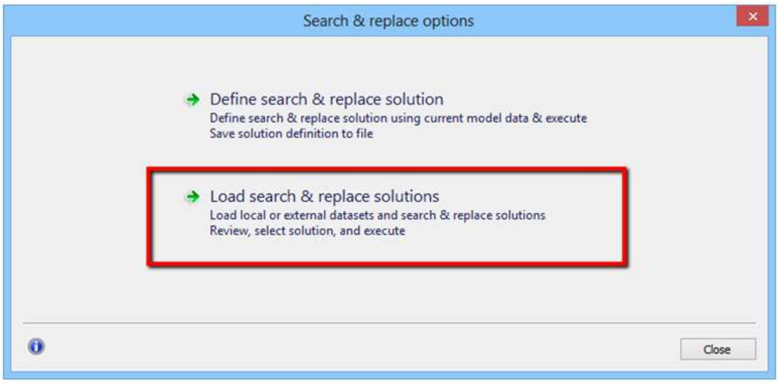
Model Configuration



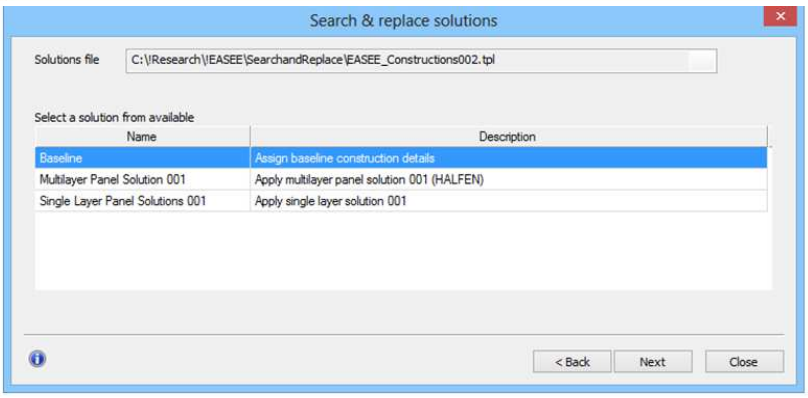
The master template tool imports and assigns the selected data to the model.



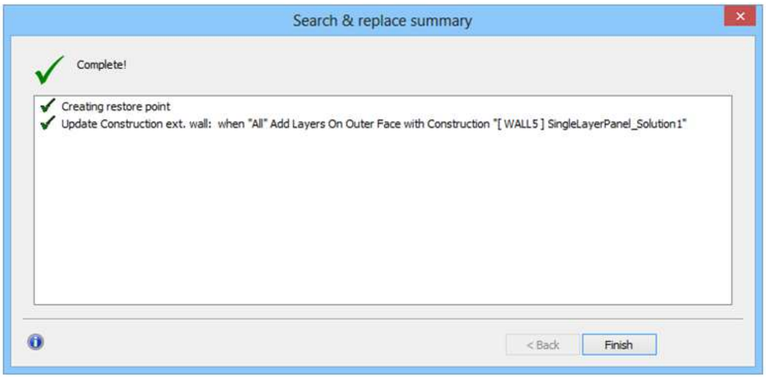
This analysis aims at including insulating panel solutions being fixed onto the existing building.



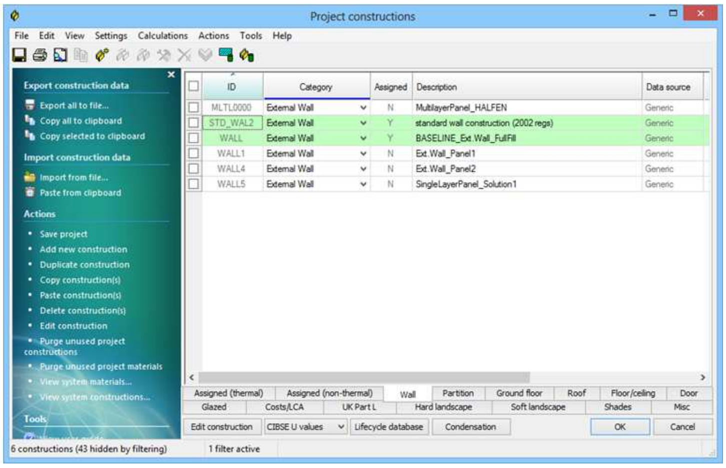
Then, in order to simulate these solutions behaviour, the existing constructions and panel solutions have to be defined. To this aim, the "Search & Replace" tool will be used to apply the panel solutions to existing constructions in the model and the <VE>.



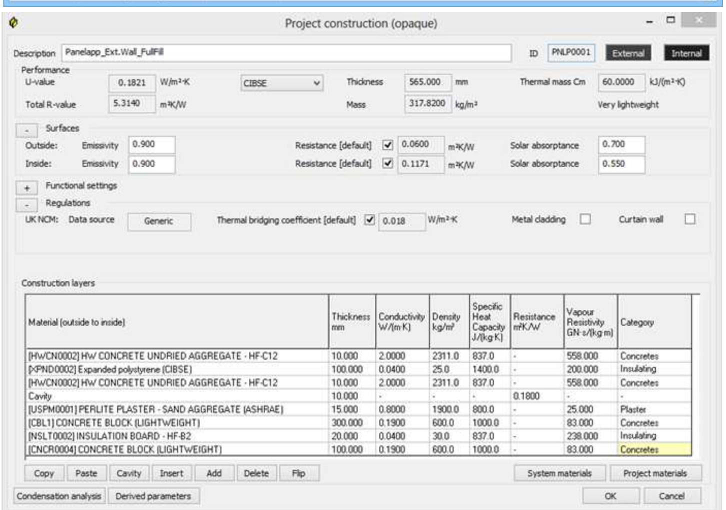
"Search & Replace" solutions have been set up to include the retrofitting panels and their thermal properties. This list can be expanded the more manufacturers include/provide information available on retrofitting solutions. For this report Search & Replace solutions have been set up using the panel solution data from Deliverable D2.1– "Report on preliminary evaluation and selection for the best panel design".; it should be noted though that the panel specifications may be updated following submission of D2.4 in Month 32.



The "Search & Replace" tool adds the panel solution construction detail layers onto the other face of the existing construction creating a new construction.



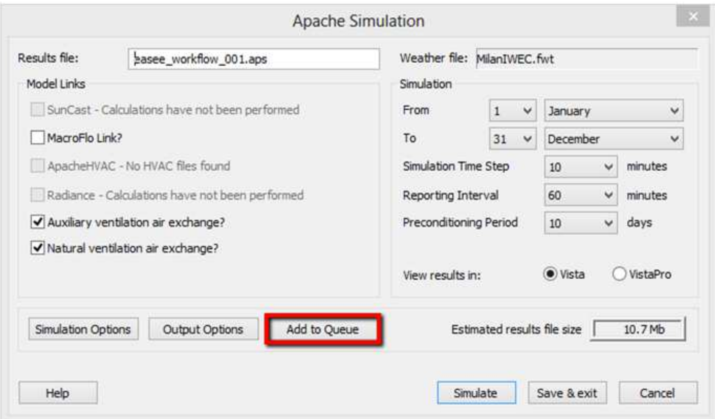
Continuation of above process.



The construction database shows the list of the constructions in the project including the baseline construction, the panel solutions and the altered construction which is baseline+panel. The "Search & Replace" tool adds the panel solution construction detail layers onto the other face of the existing construction creating a new construction.

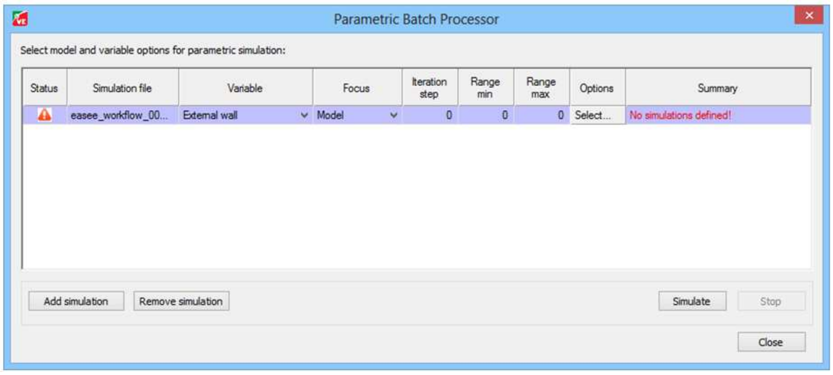
This is a view of the altered construction broken down into material layers. Both the baseline construction materials and the panel construction materials can be seen here.

Parametric Simulation/Analysis

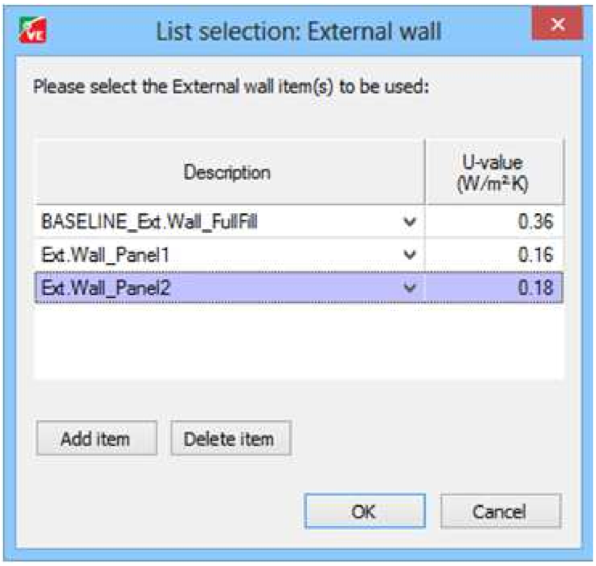


Then a parametric simulation analysis is performed. This tool allows multiple variants of a model or independent models to be created automatically and simulated with a single changing variable in a batch queue for multiple models.

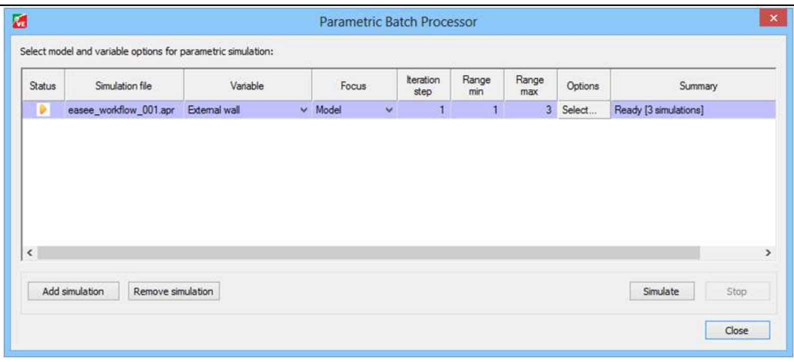
Parametric Simulation/Analysis



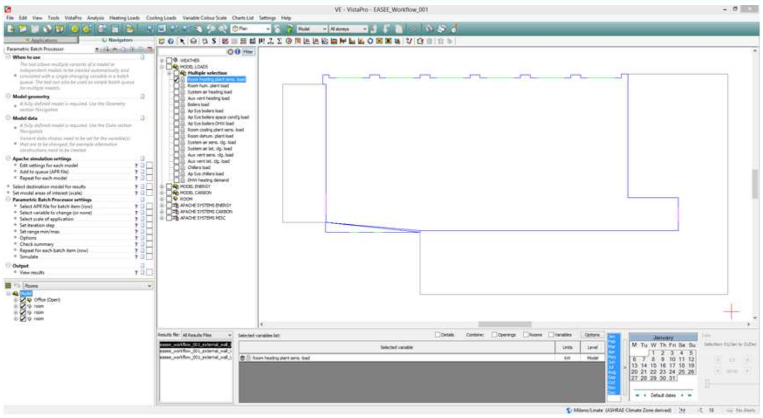
In the case of this example this tool will be used on the model to which the thermal model data and the variant "External Wall Construction" have been applied.



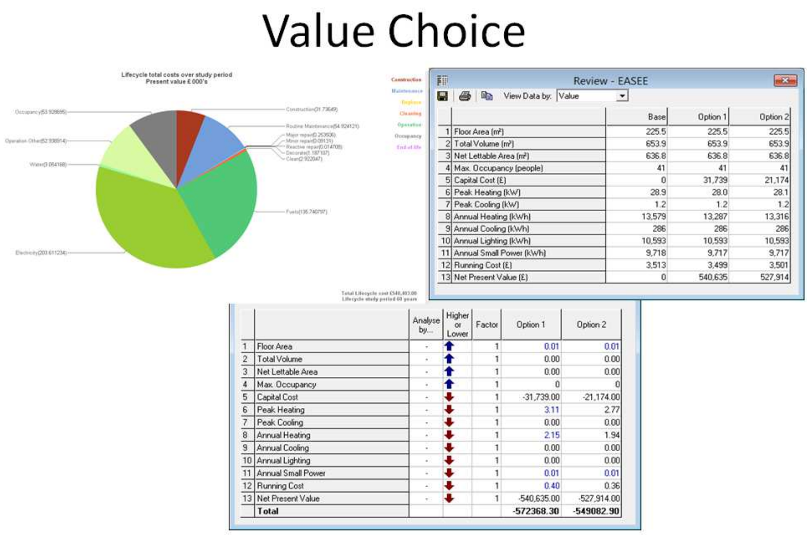
The external wall construction variations used are the baseline along with the two baseline panel solution combination constructions which were created using “Search & Replace”.



The model and the variants are set, 3 simulations will be lined up for execution.



The simulation results files are all viewable together in the <VE>.



Then the user will be able to evaluate the best choice to be performed. To this aim the Deft tool has been created. It is a unique Value Engineering software tool, since there are no similar products currently available in the marketplace. Indeed, Deft enables the user to compare building options based upon variables such as capital cost and thermal performance. The basic concept associated with Deft is that it can calculate key performance indices. These performance indices can be weighted to enable the effects of different building design changes to be compared more effectively and will allow the people involved in the decision making to do so based upon accurate information. Life cycle analyses for buildings looks at the trade-off the impact of capital and operating costs of a building. Cost Plan is a general purpose software product allowing the user to estimate costs.

6.2.2 EASEE Retrofitting Planner – worked example (improvement after D5.2)

Since submitting D5.2, the EASEE Navigator of workflow has been produced; this allows the EASEE Agent to navigate with ease through the steps required in order to produce a thermal model and a report demonstrating the improvements achieved through the use of the panel solutions. An example of the new workflow including the revisions to the original workflow are detailed below.

Note that the improvements made to the EASEE Retrofitting Planner were made following feedback from the IES internal consultancy team. Indeed, the IES internal consultants are expert users of the VE and were best placed to provide meaningful feedback in relation to the use of the tool; furthermore these consultants have been the primary users of the EASEE Retrofitting Planner (EASEE Agents).

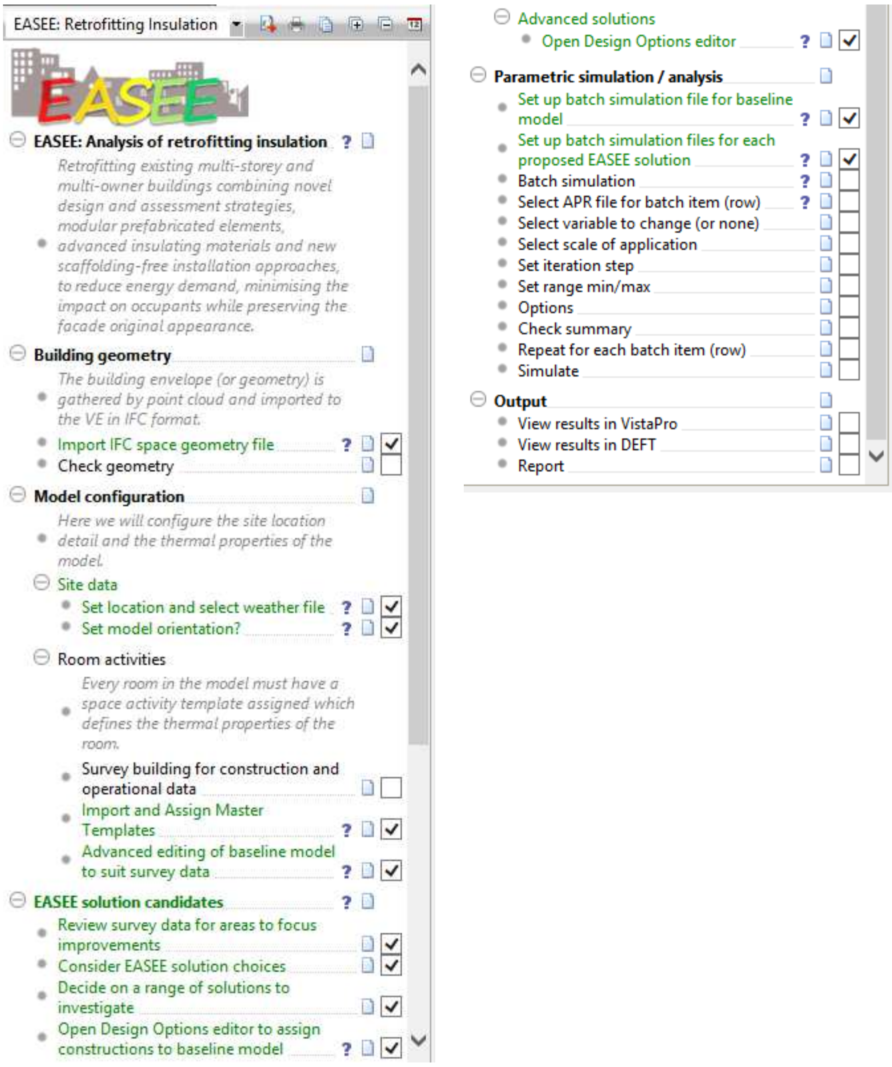


Figure 36: EASEE Navigator

6.2.2.1 Building geometry

Within this practical example the following notes have to be taken into account:

- IFC import is still the same as the previous workflow (as reported in D5.1 and D5.2)
- the EASEE demonstration sites have been built using drawings (within the VE software)
- For this improved workflow example the Gdansk model has been used

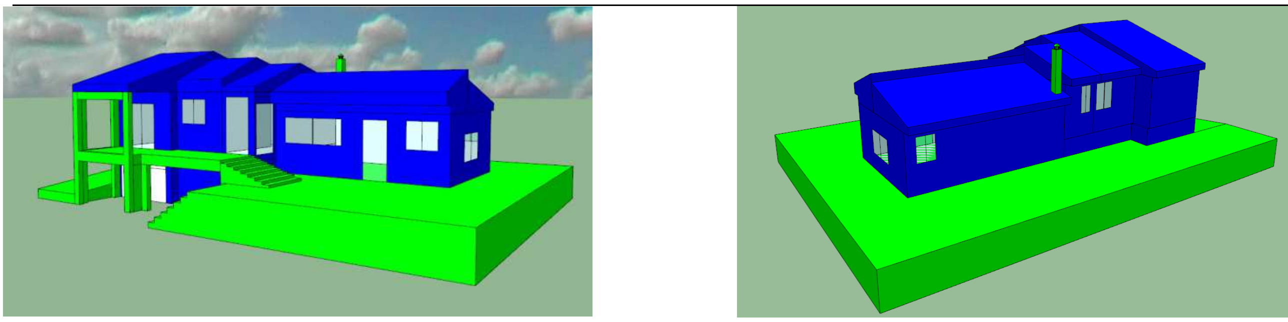


Figure 37: Madrid Model

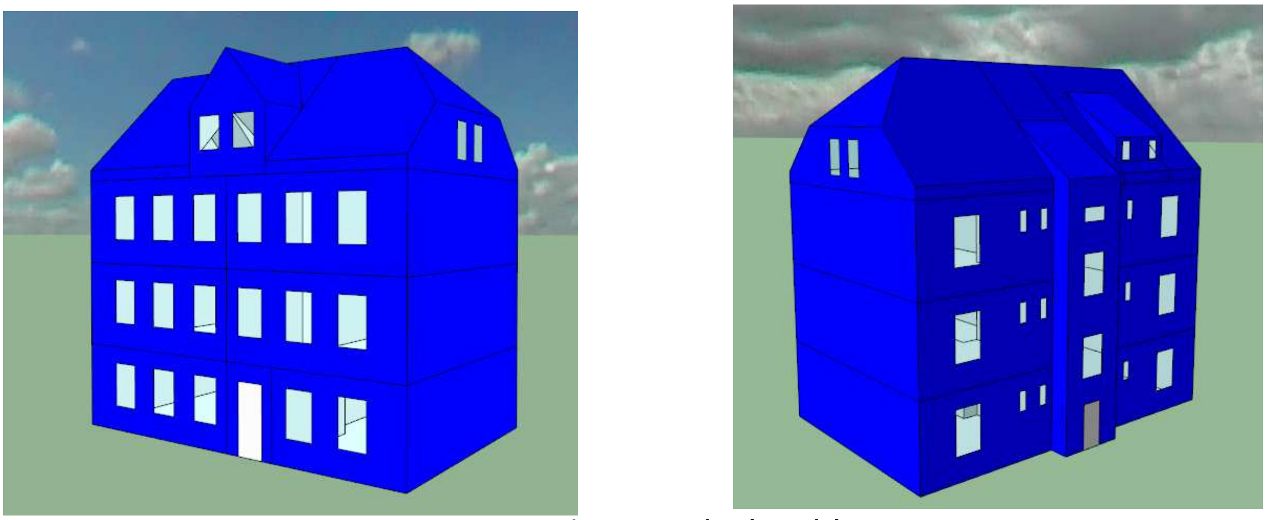
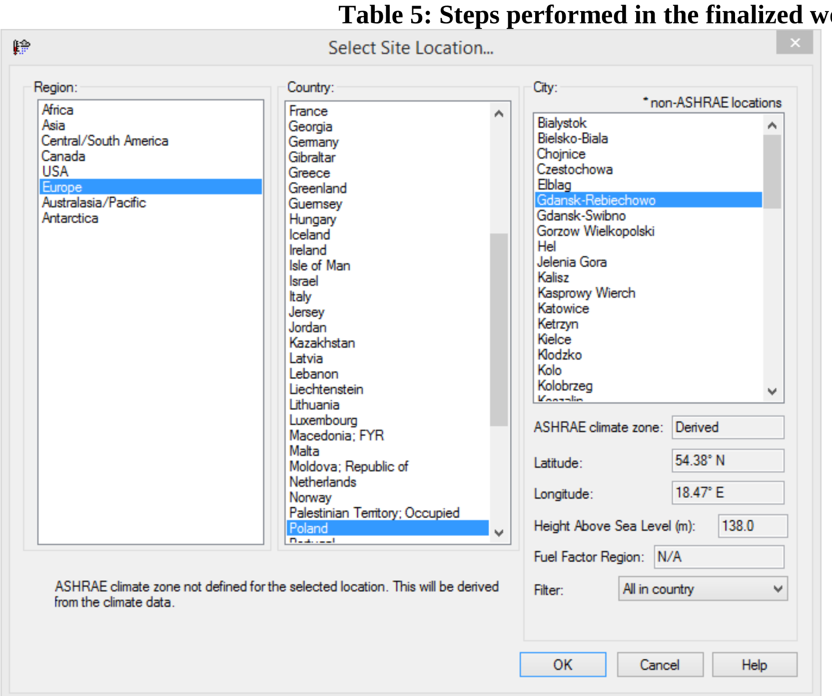


Figure 38: Gdansk Model

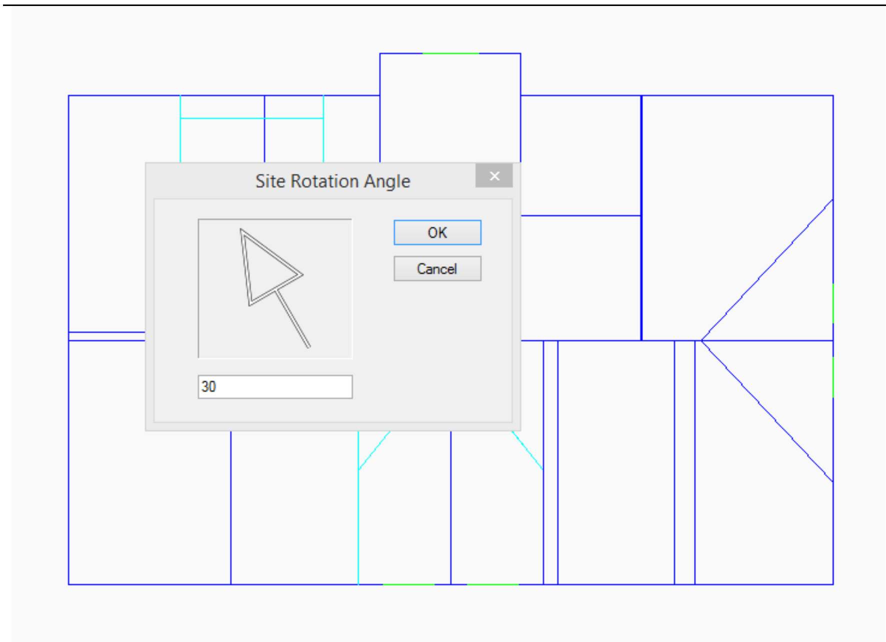
In this framework the following steps have been performed:

Table 5: Steps performed in the finalized worked example



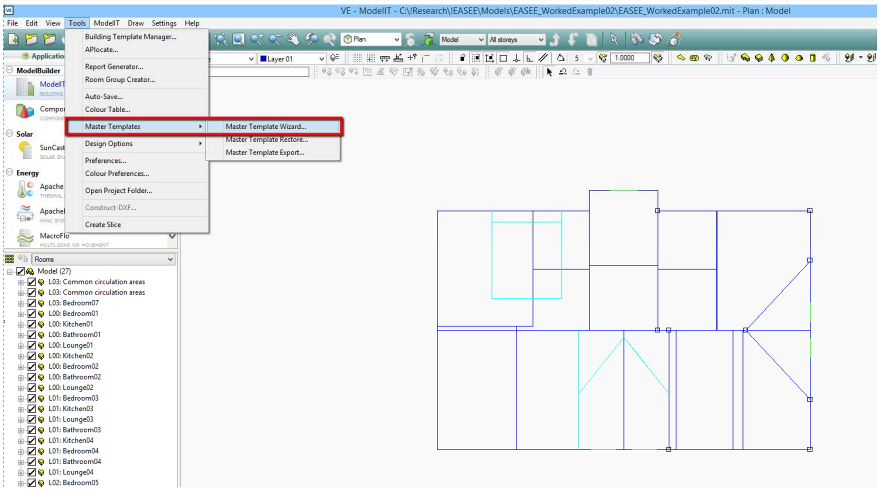
Model configuration:

Site data



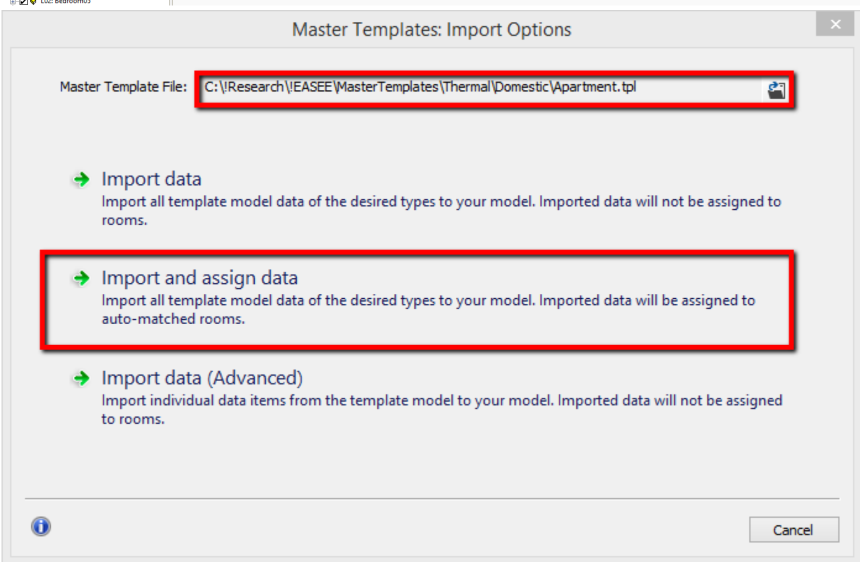
Model configuration:

Location and orientation of building set within the VE.

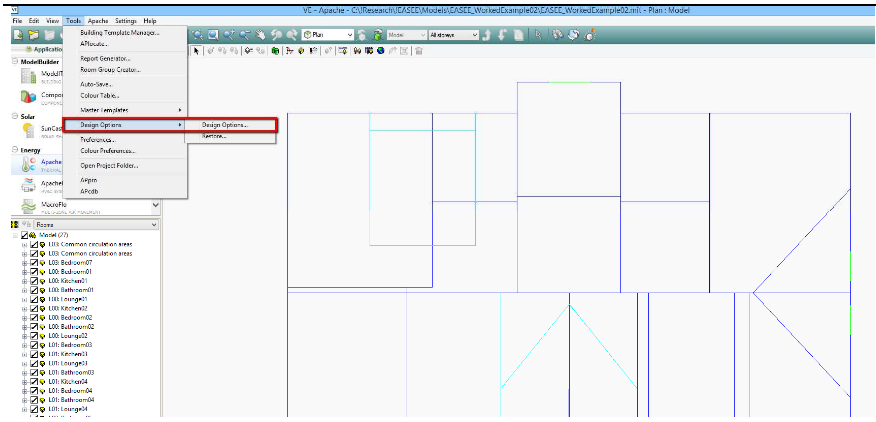


Room Activities:

Import and assign data from master templates, as was done in the previous workflow.



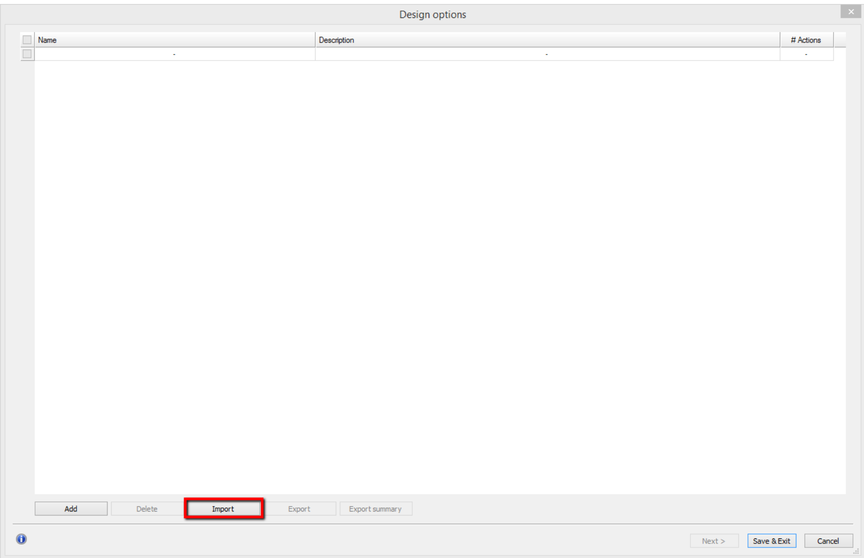
From now on the steps already performed in previous paragraph shall be performed.



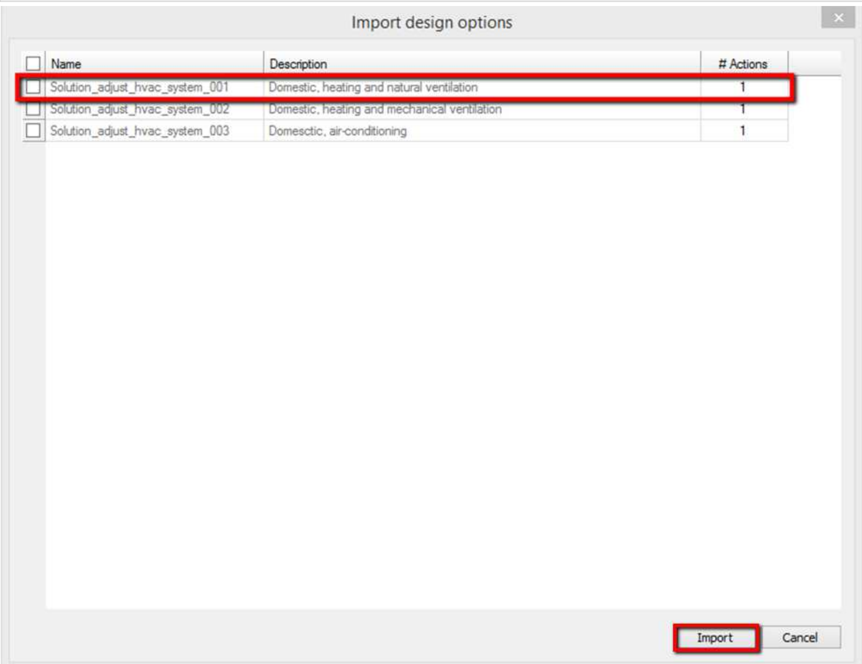
Advance Editing of Baseline Model:

This may be carried out by the consultant manually in the VE or Design Options (previously known as Search & Replace) may be used. In this example design options is used to change the system assigned to the building.

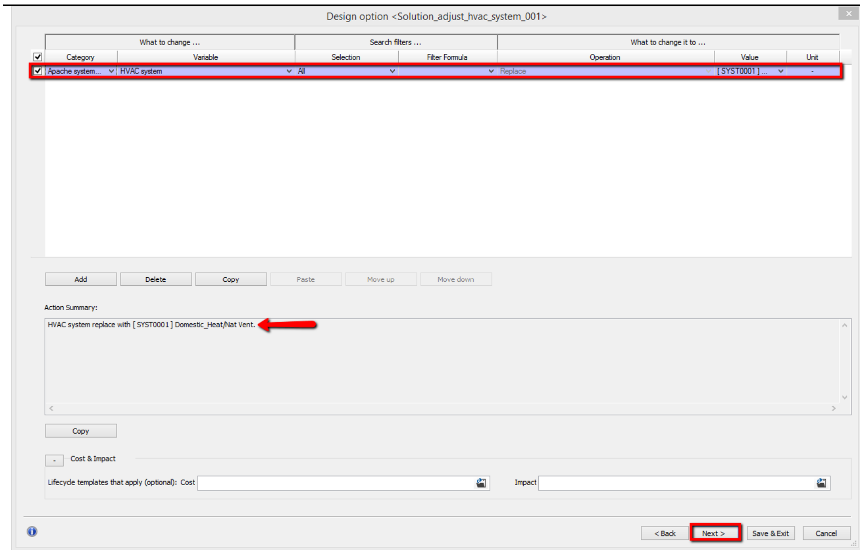
Design options is now accessible from the ‘Tools’ tab dropdown under Master Templates.



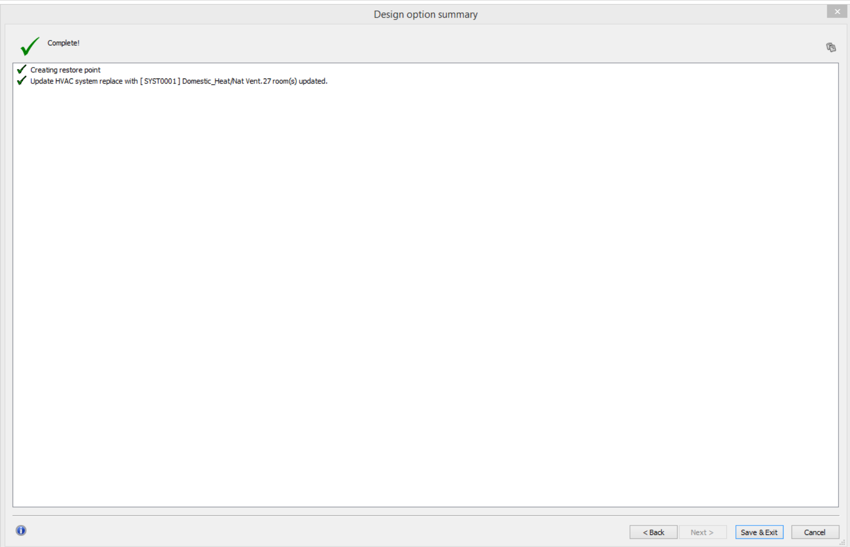
Design Options Interface has improved on the search & replace tool.



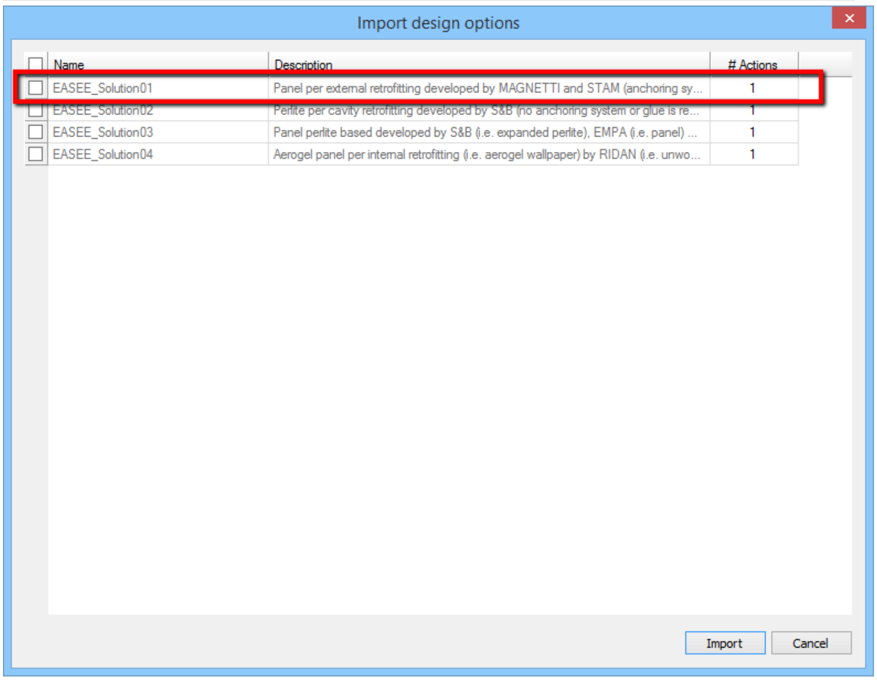
Quickly and easily predefined solutions can be used to configure the model.



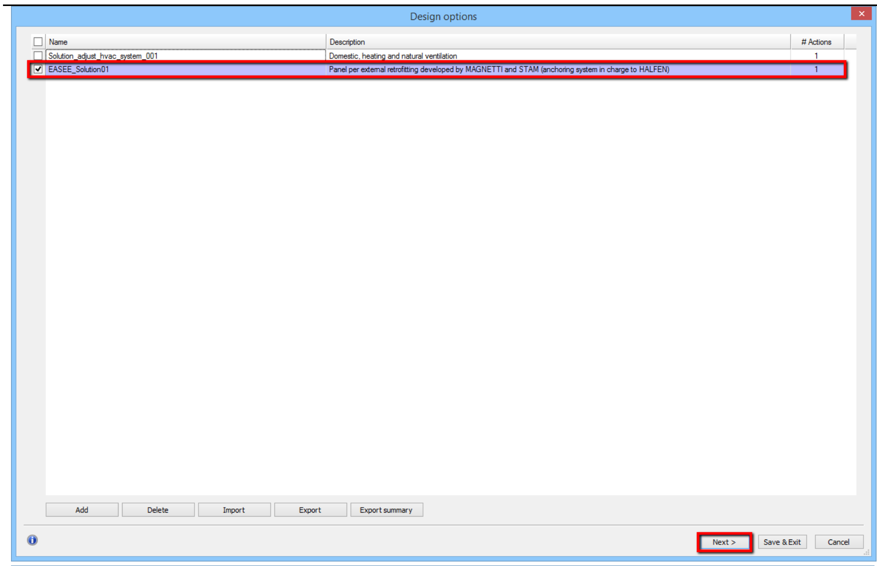
The system data for 'Heating and Natural Ventilation' has been imported into the model along with the action that Design Options will use to assign the data to the current model.



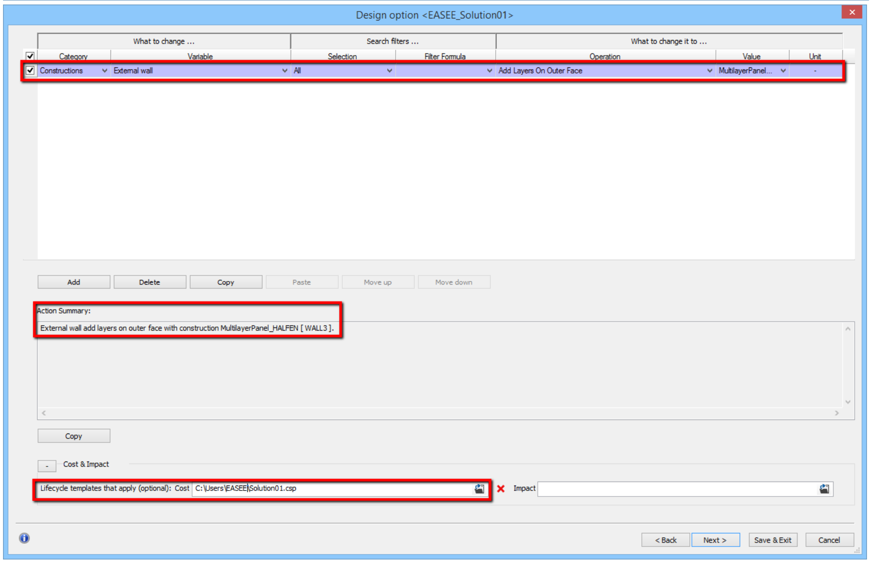
The system has been successfully replaced in the model.



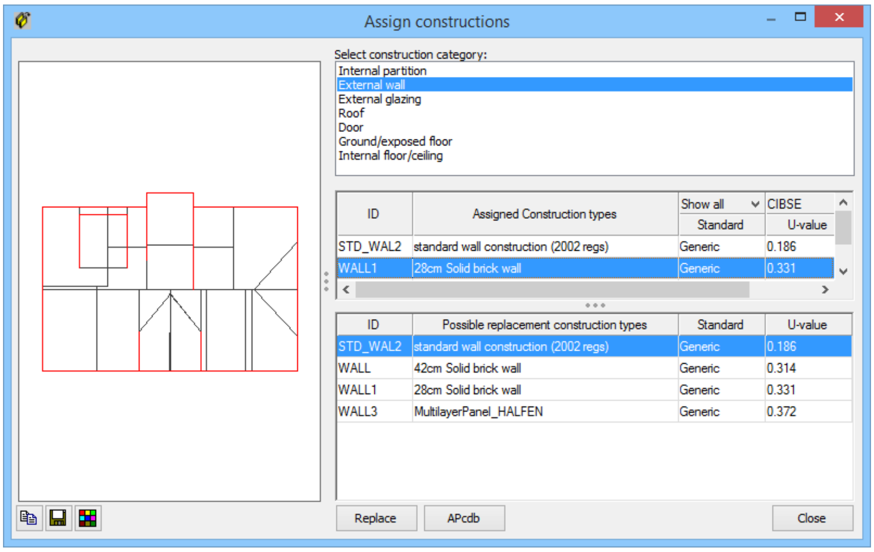
Design Options have also been set up to include the manufactures panels and their thermal properties. This list can be expanded to include more manufacturers and solutions when the information becomes available.



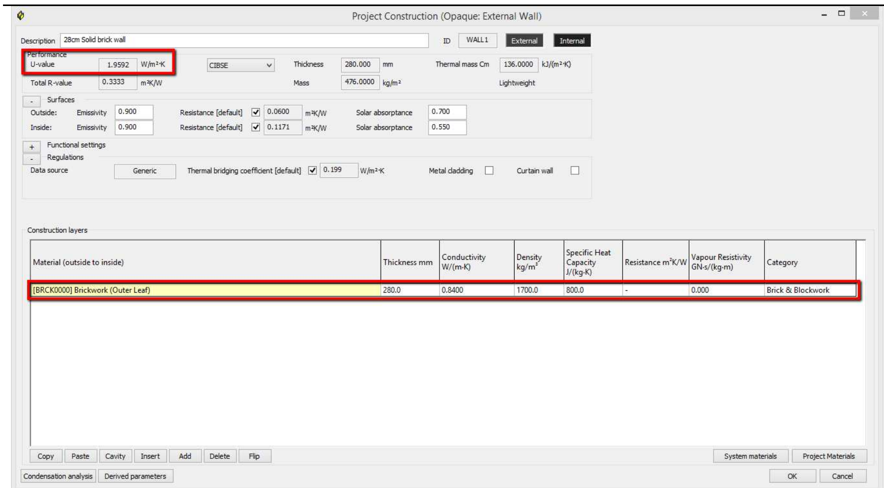
As before design options import the data, in this case the construction detail of the panel solution into the model and also the action required to assign the construction to the model.



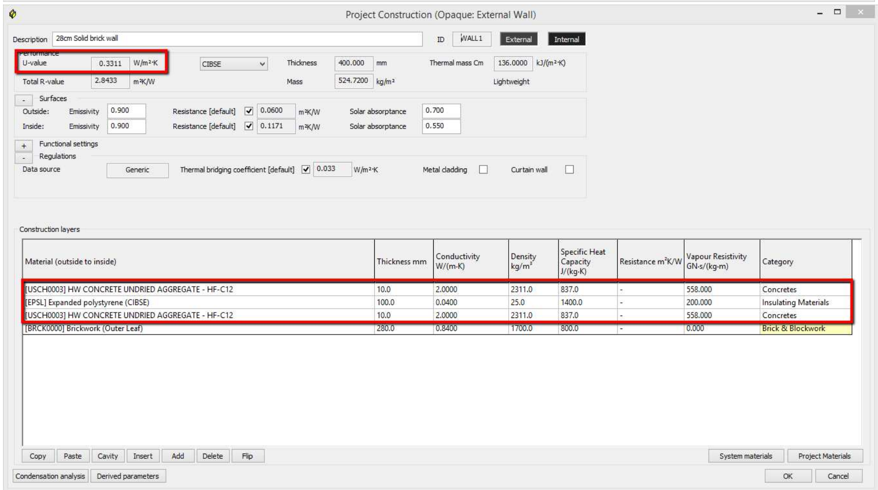
The design options tool adds the panel solution construction detail layers onto the other face of the existing construction creating a new construction. Design options also add the cost template for the relevant solution in this case solution 01 to the model.



The external wall construction assigned to the building is '28cm solid brick wall'.



The makeup of the wall prior to the solution01 being added is detailed.



The properties of the wall with solution01 added to the exterior of the construction is displayed.

Note that the Parametric Batch Processor and DEFT tool are currently in final testing stage and will be shown in detail within the demonstration deliverable D8.2 "Performance assessment of the 4 demo buildings"; the features and functionality will be as previously reported.

7 DESIGN TOOL ROLE WITHIN THE EASEE HOLISTIC APPROACH

In the framework of WP5, the Design Tool represents the link between the building numerical model (derived both from the building geometrical assessment performed within Task 5.1 and the results from the Retrofitting Planner Task 5.2) and the reconfigurable mould, developed within WP6 in order to manufacture the insulating panels for the building retrofitting.

Indeed, the geometry and thermal model of the building, required for the panels to be dimensioned accurately and passed to the manufacturers for production, are passed to the Retrofitting Planner as simple geometry and to the Design Tool as detailed geometry. The thermal model of the building is built within the Retrofitting Planner, and analysis is performed to allow the building owner to make an informed decision with respect to the insulation option he would like to implement. These results are then manually sent to the Design Tool and used together with already received detailed geometry file. Both data is used to define the various panels sizes and positions onto the various facades and then to send this information to the manufacturer of the panels, ready to go to production. Therefore the main functionalities of the Design Tool software are:

- The optimization of the panels number and size according to the specific facade
- The capacity to virtually place panels on the 3D building model
- The capacity of data export in the format that can be read by the numerically controlled reconfigurable mould.

7.1 Design tool: Input/Output

As shown in the figure below, the Design Tool software takes in the Retrofitting Planner results file (from IES) and the detailed building geometry (from POLIMI). Then the software developed will dimension the panels according to the façade and to the chosen insulation option. This is then sent as a results file to the manufacturers of the panel for the production of the options for retrofit.

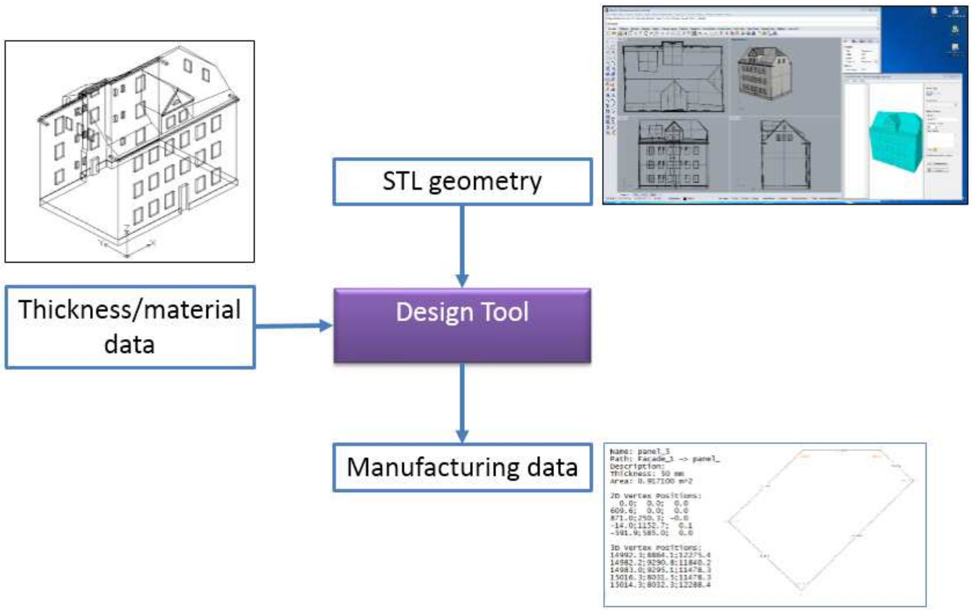


Figure 39:Scheme of the Design Tool Input / Output

The main Input / Output are briefly described below:

- **Input – top branch in the figure above**
  Software is capable of importing building model in a STL format, both text and binary. This feature is implemented on purpose, to avoid more complicated native formats of different commercial software tools. Extremely simple syntax of STL format allows to avoid any uncertainties and to flawlessly import building model from wide range of engineering tools. Since STL format doesn't contain any information about features such as windows, walls etc., Design Tool utilizes feature recognition algorithm for edges/faces detection.
- **Input – left branch in the figure above**
  Software is capable of importing data related to the building and in particular to "thickness/material data" that is in fact one of the Retrofitting Planner results. Indeed, for planning panel's distribution, most important data is material chosen for the insulating panels and thickness of the insulation designed for each specific façade.
- **Output – bottom branch in the figure above**
  As output, the Design Tool provides the complete distribution of the insulating panels on the building façade, in a form of 3D model. There are different possible ways of exporting panel distribution:

  - STL 3D model;
  - Text file, containing information such as panel name, material, geometry, etc;
  - Image (PNG file) containing technical drawing of the panel, with 3D preview of panel location on the façade.

  Additionally it is possible to create an HTML file allowing for an easy access to exported files. Example of such file is shown in **Figure 40**, where technical drawing of each panel, preview of the panel's position on the building model and information about each panel (dimensions, material, and additional description) are shown. All this information can be accessed through the hyperlinks menu available on top of the page.

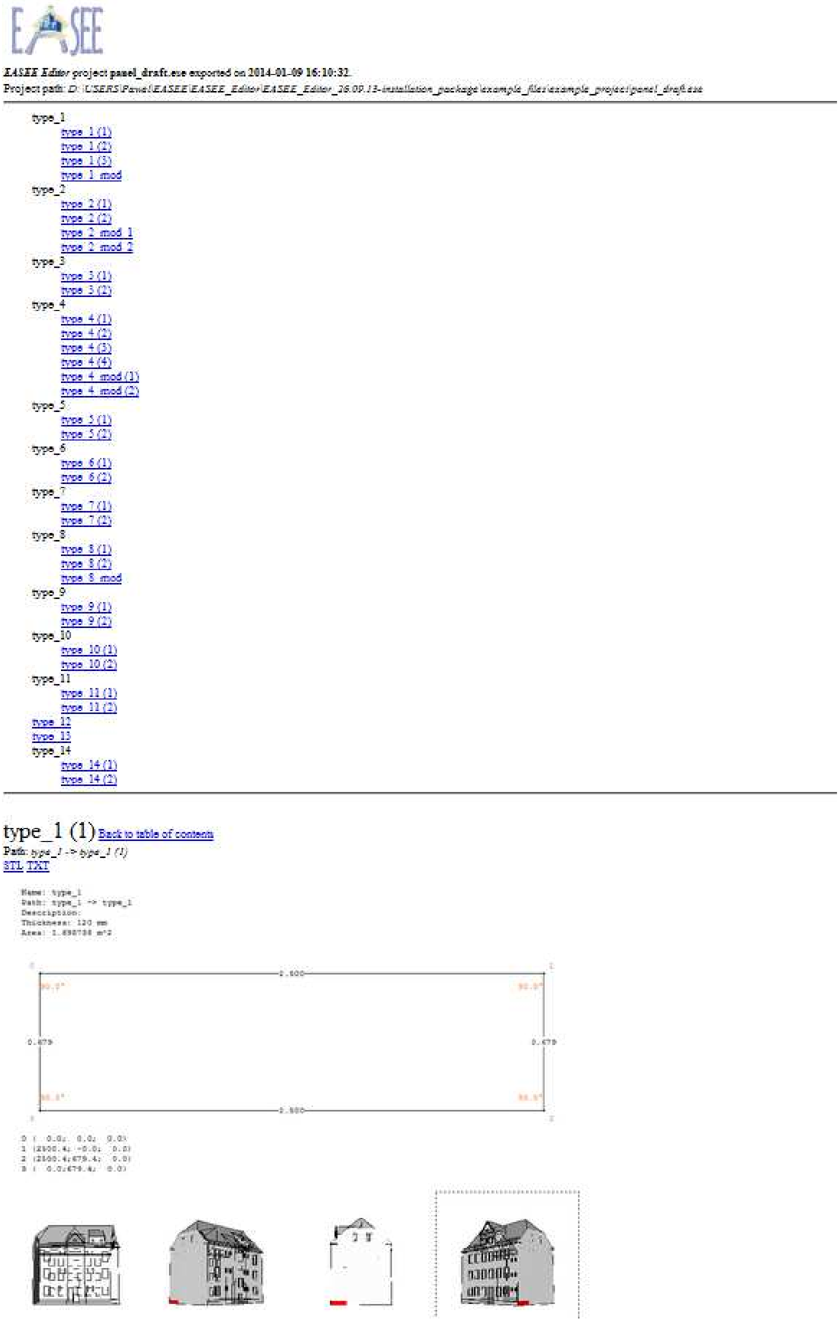


Figure 40:Example of a HTML file exported from the Design Tool

7.2 End-user identification

The Design Tool is an integrated part of the retrofitting holistic approach developed within the EASEE Project. Together with EASEE novel insulation systems, building owner (or administrator) gets set of tools and services, which includes assessing building geometry, thermal simulation, planning a panel design (done with Design Tool), and finally manufacturing and installation of the panels. Although the panels' distribution planning on the façade is not a difficult task, the following different constrains have been identified:

- **Architectural constraints** – panels' distribution/design on the facade needs to be planned with respect to all architectural features that characterize the building façade and that might be maintained after the retrofitting process. Indeed, buildings considered within the EASEE project target might be also under the care of heritage conservator, therefore preserving their original aesthetic is essential.

- **Mechanical resistance constraints** – each building envelope, according to its structure and materials is made of, may have different mechanical resistance and therefore may withstand different loads applied per square meter of wall. Since considered buildings are mostly old existing constructions, weight limits for the panels may be significant criterion crucial for choosing insulation technology.
- **Anchoring constraints** – depending on building material and construction type (concrete/steel reinforcements etc.) maximum size of panel and optimum anchors location on the façade have to be chosen wisely.
- **Tolerances constraints** – panels have to be placed taking into account proper tolerances, (gap among each panels) in order to avoid mounting problems that can occur in case of positioning inaccuracy. Size of expansions joints may vary according to the facade and to the different panels' material and manufacturing technology.
- **Manufacturing constraints** – because of certain manufacturing process, limited shapes of panels can be used, and number of panel types can strongly affect cost of the manufacturing. Therefore, one has to be aware of manufacturing techniques during planning panel distribution on the façade.

Due to the complexity of the task (optimization of the panels' distribution on the facade), actual end-user of the software should be **an architect**, or **structural engineer** responsible for the whole retrofitting process.

7.3 Worked example

Process of planning panels' distribution on the building façade was tested on the Gdansk demo building. As an input, 3D mesh model was used – it was reconstructed from the laser scan of the demo building (shown in the picture below).

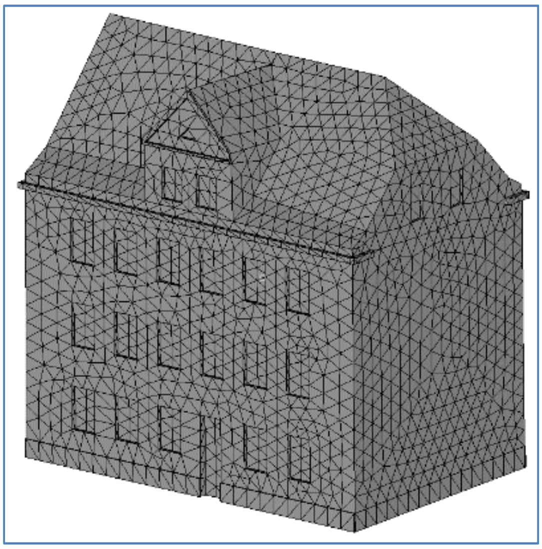


Figure 41: Mesh model of the building

Purpose of the test panels' layout was to check, how many types of panels need to be manufactured for quite insulating simple rectangular façade, with trapezium near the roof, two ledges and two windows. Conservative assumptions were made: whenever possible, panels are rectangular or triangular, fitted without (or with minor) dilatation. Results are presented in the figure below.

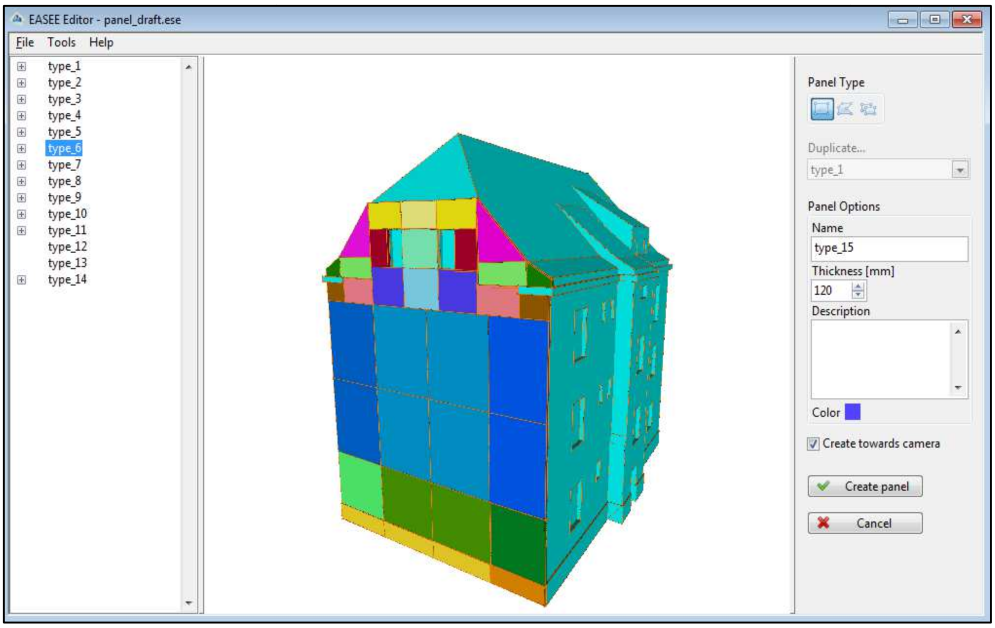


Figure 42: Example layout of panels

Summary: total 35 panels of 14 types were generated. This number can be easily decreased by adding dilatation between the panels – in such case. each rectangular surface can be insulated with one type of rectangular panel. Additionally, manufacturing technique utilizing reconfigurable mould is flexible, so idea of producing panels of non-regular shape can also be considered. Choosing solution to be applied depends on the capabilities of the manufacturing process and accuracy of the 3D model considered.
In the figure below, piece of the HTML output file is presented:

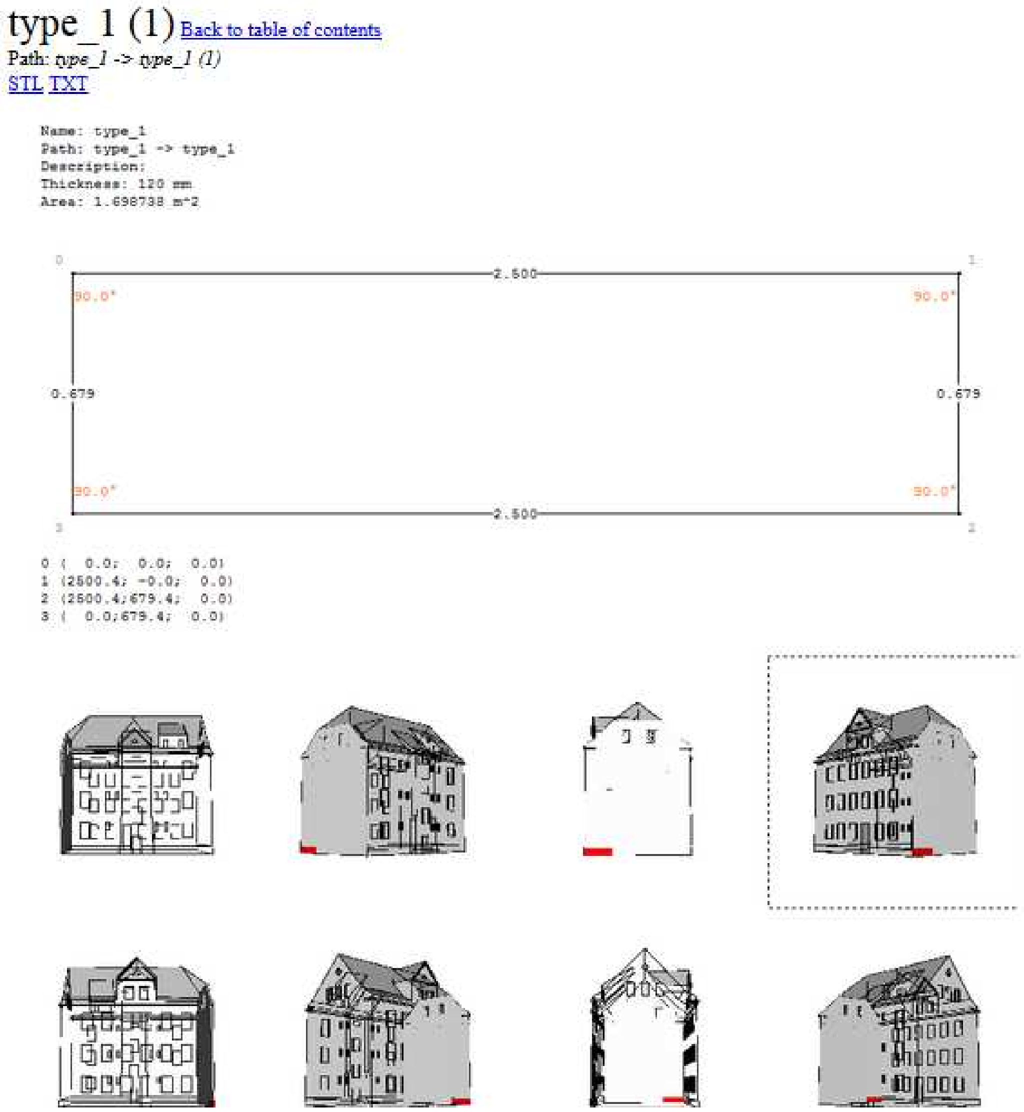


Figure 43: Piece of an output file from the Design Tool

Data stored in the output file was reviewed and accepted by the partners responsible for manufacturing,

8 LESSONS – KNOWLEDGE SHARING

8.1 Objective

Task 5.4 Retrofitting planner integration, testing and evaluation specifically states:

"To accelerate the benefits that would accrue from this project the results of the assessments should be lodged in a web based database held by IES"

We see the purpose of this web based database being to engage with the wider community, namely: architects, engineers, designers, building managers, owners and more. Through this online database, potential users can see at first hand the benefits of implementing retrofitting solutions; additionally they can view independent feedback from past customers of the service.

The Work Package 5 partners agreed to utilize an output from a prior UK funded project called "Lessons"; "Lessons" supplies users with easy access to the knowledge gained and lessons learnt by construction professionals from their previous building design experience. Intuitive and easy to use, "Lessons" allows for both novice and expert user. The knowledge outputs empower building designers, allowing them to draw on the experiences and insights of past designs. The results are better informed decisions even when dealing with less familiar or new technologies.

"Lessons" meets the requirements of the EASEE project; it provides an online interface so that either the client themselves or the EASEE agent can share the experience of using an EASEE retrofitting solution.
The user interface is broken into **two sections**; one for a standard user sharing their experience of using a product and the other for product manufacturers to upload information about their products to eventually be 'tagged' to a case study. The screen shots below highlight the main features of "Lessons":

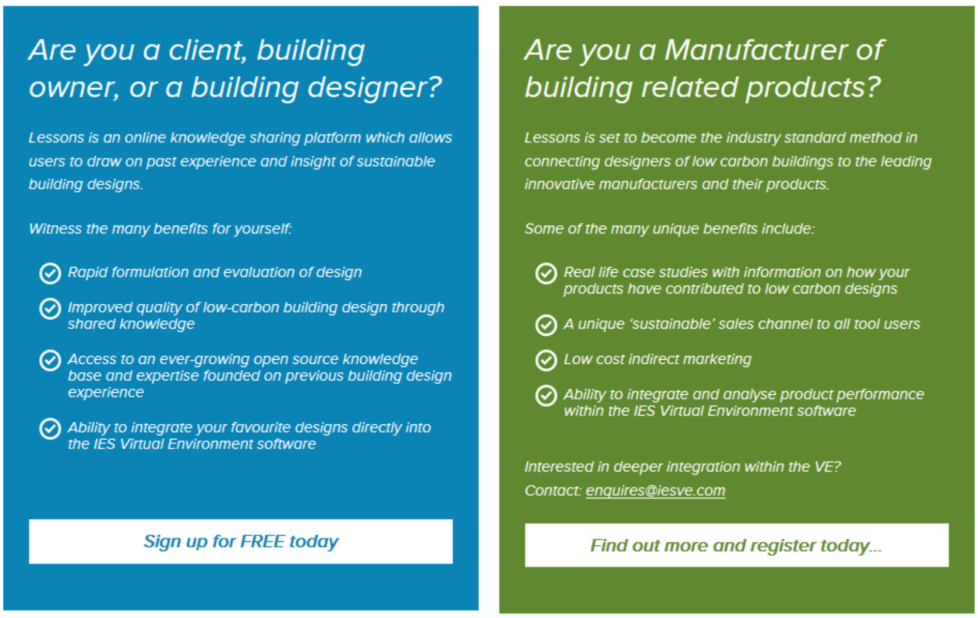


Figure 44: Lessons Homepage (extract)

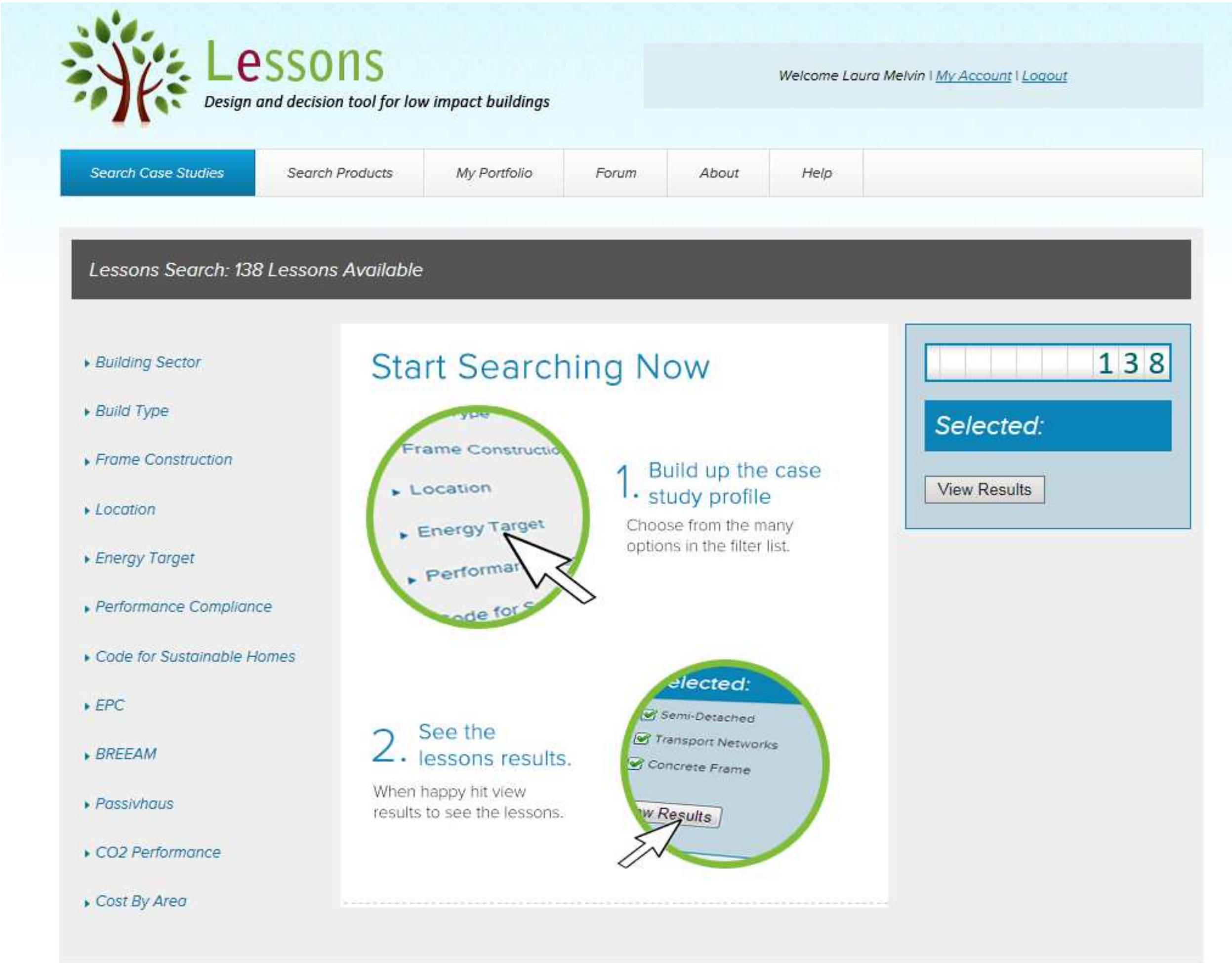


Figure 45: Case Study Search

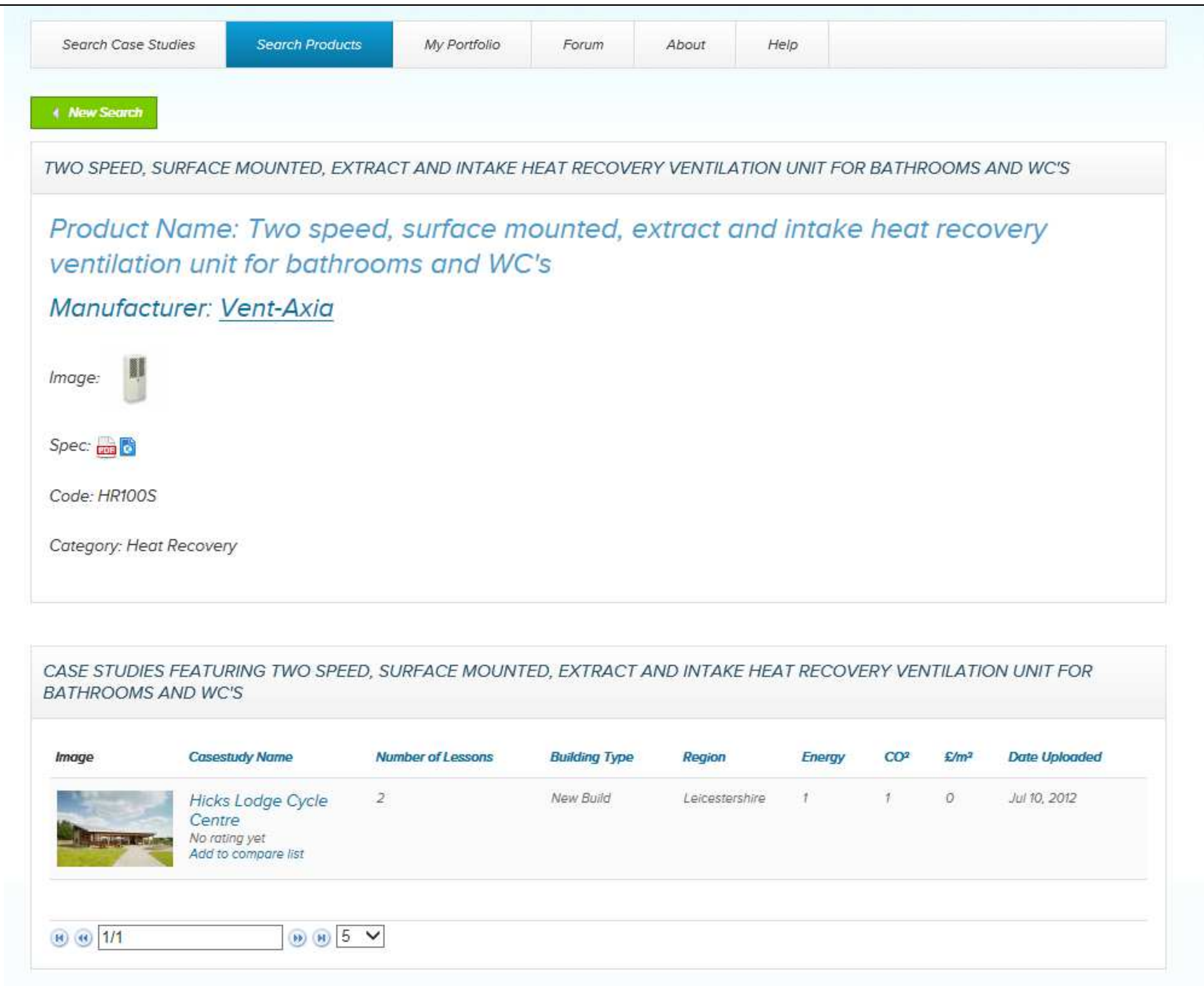


Figure 46: Product Page (tagged to case study)

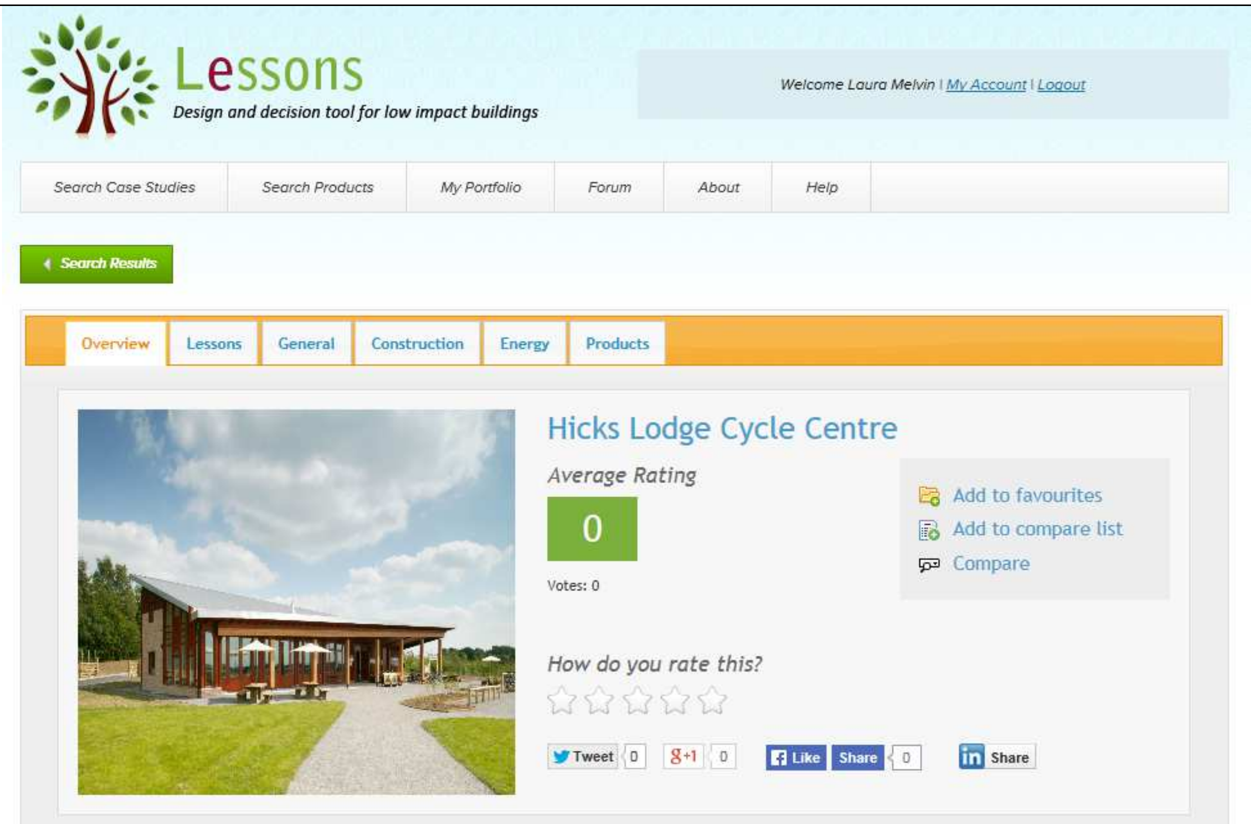


Figure 47: Case Study

To respect the end user's privacy, permission to upload material must be granted prior to uploading to "Lessons".

9 CONCLUSIONS

This deliverable has outlined the software tools that have been developed to allow for an analysis of the various insulation options, which could be applied to an existing building. These tools allow the various parameters and features of the insulating retrofitting solutions to be added to a Dynamic Simulation Model of the existing building in order to assess the expected performance of the panel over the life of the building. The user can then understand what are the benefits of each panel with respect to energy consumption, carbon use, capital cost, life cycle cost, return on investment etc. and make an informed decision on which option best suits their individual requirements.

As a result, four different software features have been developed and added to the existing IES suite of tools, these are (i) Master Templates, (ii) Search and Replace, (iii) Parametric Batch and (iv) DEFT Value Choice Tool. These form a core part of the EASEE Retrofitting Planner. The model will be created using the point cloud data from POLIMI (D5.1), the IES suite of tools will then allow the user choose which option they would like to apply (D5.2) and the CIM-MES software will then specify how the panels will be applied to the building and sends these instructions to the manufacturer for development (D5.3). These tools are integrated together through a consulting service to form the final EASEE Retrofitting Planner and Design Tool.

The Retrofitting Planner was developed using the IES in-house process for software development. This involves a number of steps and stages to complete the development. These steps include initial research into the software followed by a requirements specification which describes in detail the functions of the tool that is to be developed and what the purpose of the tool will be. In addition, a User Interface (UI) specification is written which describes what the interface will look like within the software. These are then passed to the IES developers to write a functional specification, which details how the tool will be coded in the IES <VE>. Once these steps are complete, coding can begin. The tool is tested at various points (or milestone builds) during the process with a final beta prototype ready for testing at the end of the development period.

The first tool that was developed was Master Templates. Master Templates enables the EASEE Agent to create simple models (and/or use common thermal attributes) using common building typologies (such as: office, hospital, school, supermarket, & more). These allow for a model to be created quickly instead of starting from scratch each time.

The next tool developed was Search and Replace (now known as Design Options)(. This is an intuitive yet seemingly simple concept (without underestimating the complex development that went into the tool) taking an element of a building and replacing with another i.e. 'replace all windows with a U-value of >3 to 1.3'. Currently within the IES <VE>, if you want to change a part of the envelope, this has to be changed for each zone of the building; this tool allows this process to take place automatically, significantly improving the speed of altering/enhancing a model for the end user.

In order to allow for multiple simulations to take place at once and allow for many different configurations of the various insulation options to be analysed, the Parametric Batch tool was developed. The purpose of this tool is to collate all the chosen solutions, simulating them in a sequential order in 'batches'. This significantly reduces user time for the EASEE Agent saving him/her having to manually launch simulations.

Finally to allow the user understand the options that are available to him/her, a value choice tool called DEFT was developed. This allows for the various options to be displayed to the user in a comprehensive manner, allowing them to make the decision that best suits their individual needs and requirements.

A worked example of how the tool would be used with the various insulation options is described in detail. The worked example goes through how the Master Template was created and various Search and Replace solutions applied. These solutions were then run using the Parametric Batch tool and the results displayed using the DEFT Value Choice Tool. The actual UI that has been developed is shown in this worked example.

Additionally, Polimi developed a methodology for the generation of the 3D model which takes into account geometrical aspects, structural aspects and thermal aspects has been developed both for the Retrofitting Planner and the Design Planner. Two methods of data format were examined: traditional CAD tools and new BIM tools for transfer of the model between software's. . It is recognised that BIM tools are a new technology and currently have inherent problems associated with them, however BIM is the methodology of the future and to allow a tool that can be commercialised for long-term benefit, allowing for the data import using BIM functions such as .IFC is important to the commercial success of the EASEE project.

In addition to the geometrical assessment, thermal mapping was carried out to assess the quality of the structure at this stage before any retrofitting has been applied to the façade. Two types of cameras were used to create the thermal image of the 3D envelope, and these technologies are well described, the two types of camera are: a traditional thermal camera and a UAV camera.

The purpose of Task 5.3 was to create a software tool (developed by CIM-MES), which "(…) provides the manufacturers of the prefabricated elements the technical specifications for the customized component fabrication". The Design Tool (also called "EASEE Editor" within the project) satisfies this requirement. Indeed, the software is able to import 3D building model (which is an outcome of building assessment procedure) and to help the user to virtually plan panels' distribution according to the specific building envelope, taking into consideration also potential constraints (such as constraints from the heritage conservation supervision, etc). Moreover, when planning panels' distribution, all material and geometrical constraints which are results of simulations (performed within the Retrofitting Planner) can be taken into account. Finally, Design Tool exports documentation of the designed panels, in both text format (that can be easily interpreted by the numerically controlled reconfigurable mould) and HTML/PNG format, which is in fact technical documentation for each panel, as well as the assembling documentation.

Finally, to convey the success (or perhaps non-success) of a particular solution on a building we will upload (with the user's permission) a case study to www.buildinglessons.com; a project previously funded by the UK TSB fund.

This deliverable has shown how these tools will significantly contribute to the overall Retrofitting Planner which will then encourage and incentivise building owners as well as other stakeholders to choose the options available to them and help improve the overall sustainability of the built environment.