BIMERR

RENOVATION 4.0

Project Acronym: **BIMERR**
Project Full Title: **BIM-based holistic tools for Energy-driven Renovation of existing Residences**
Grant Agreement: **820621**
Project Duration: **42 months**

DELIVERABLE D3.3
BIMERR evaluation methodology

Deliverable Status: **Draft**
File Name: **D3.3 - BIMERR evaluation methodology - v1.0.docx**
Due Date: **31/10/2019 (M10)**
Submission Date: **31/10/2019 (M10)**
Task Leader: **UOP**

Dissemination level	
Public	
Confidential, only for members of the Consortium (including the Commission Services)	X

This project has received funding from the European Union's Horizon 2020 Research and innovation programme under Grant Agreement n°820621

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Revision Control

Version	Author	Date	Status
0.1	UoP	30.07.2019	First Draft
0.2	UoE, KONKAT, UoP	20.09.2019	Research and innovation projects, Overview of methodologies
0.3	UoE, KONAT, BX	03.10.2019	• Restructuring of section 3. • Additions ○ Last planner system ○ Location-Based management system methods added.

0.4	BX, UoP, FER	08.10.2019	• Additions: ○ Cost estimation in Poland, ○ Termomodernizacja calculations ○ Assessment of User Acceptance (existing methodologies) ○ Prototype flat (PRENDE project) • UoE list of references incorporated into the entire document
0.5	UoP	13.10.2019	Additions: • Text in 4.1 • KPIs for cost-time (4.1.4) • KPIs for user acceptance (4.2)
0.7	UoP, all partners	25.10.2019	Additions: • KPIs for H&S • Tools performance assessment • BIF assessment • LCA
0.8	UoP	27.10.2019	Ready for internal review
0.10	UoP	30.10.2019	Comments from reviewers (UBITECH, EXE) as well as SUITE5, HYPERTECH, XYLEM
1.0	UoP	31.10.2019	Submission to the EC

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AC	Actual Cost
ARIBFA	AR-enabled In-situ Building Feature Annotation
BAC	Budget at Completion
BEM	Building Energy Model
BIF	BIMERR Interoperability Framework
BIM	Building Information Modeling
BOQ	Bill of Quantities
CAPEX	CAPital EXpenditures
CBA	Cost-Benefit Analysis
CIP	Competitiveness and Innovation project
CO	Carbon Monoxide
CO2	Carbon Dioxide
CPI	Cost Performance Index
CPM	Critical Path Method
CV	Cost Variance
DHW	Domestic Hot Water
DOA	Description of Action
EAC	Estimate at Completion
ECM	Energy Conservation Measure
ETC	Estimated to Complete
EV	Earned Value
EVA	Earned Value Analysis
FEMP	Federal Energy Management Program
GERT	Graphical Evaluation and Review Technique
GHG	GreenHouse Gas
H&S	Health & Safety
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IPMVP	International Performance Measurement and Verification Protocol
KPI	Key Performance Indicator
LBMS	Location-based Management System
LBS	Location Breakdown Structure
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing
LPS	Last Planner® System
M&V	Measurement and Verification
NPV	Net Present Value
OPEX	OPerating EXpenses
PERT	Program Evaluation and Review Technique
PMV	Predicted Mean Vote

PPC	Percent Plan Complete
PPD	Predicted Percentage Dissatisfied
PV	Planned Value
PWMA	Process & Workflow Modelling & Automation
RES	Renewable Energy Sources
RNC	Reasons for Non-Completion
ROI	Return on Investment
SPI	Schedule Performance Index
SUS	System Usability Scale
SV	Schedule Variance
SWOT	Strengths, Weaknesses, Opportunities and Threats
TAM	Technology Acceptance Model
UA	User Acceptance
UC	Use Case
UTAU	Unified Theory of Acceptance and Use of Technology
VOC	Volatile Organic Compound
WBS	Work Breakdown Structure
WHO	World Health Organization
PM	Particulate Matter

1. EXECUTIVE SUMMARY

The performance measurement and verification methodology for the assessment and evaluation of the impact of a project is a critical process that needs to be generic as well as able to be tailored to the specifics of the project. This document contains the work relative to task T3.3 'Development of Evaluation Methodology for the Impact of BIMERR Tools on Real Renovation Works'. The objective of this task is to develop a holistic methodology that describes how the BIMERR outputs will be evaluated, including KPIs and their calculation methods.

The BIMERR evaluation methodology has been based on breaking down the tools and components of the BIMERR platform that need to be assessed. It has been designed using well-known and well-established methodologies and protocols of the International and European scheme, reviewing the current status and relevant BIM projects, reviewing relevant renovation works and expertise from the constructor partners in the BIMERR. This way, the BIMERR methodology creates a robust framework that enables the definition of adequate BIMERR Key Performance Indicators (KPIs) to assess the results achieved by BIMERR.

The use of the BIMERR tools in real renovation works in the context of the use cases proposed in D3.1 is considered along the four major impact KPIs, as described in DoA, i.e. reduction of renovation process duration, reduction of the renovation process cost, improvement of user acceptance and increase in energy efficiency. For each of them a list of complementary KPIs is also provided along with the necessary input parameters and the required calculations, as well as ways are identified in order to capture this information during the piloting activities (e.g. historical data, sensor measurements, tool user feedback via the provided purpose made questionnaires, manual measurements, visual inspection results).

In order to assess how the BIMERR tools can accelerate the renovation rate of the building stock or the long term benefits on sustainability, social welfare and environmental impact, the evaluation methodology goes a step further than the mere assessment of the performance and accuracy of the BIMERR tools, and also considers KPIs that reflect the wider socio-economic, sustainability and environmental issues.

2. Objectives of the report

One of the main objectives of WP3 is to develop a methodology that describes how the BIMERR outputs will be evaluated, including KPIs and their calculations methods (MS13). This is part of the BIMERR holistic evaluation methodology that includes steps for the

i) elicitation of stakeholder expectations from tools (D3.1)
ii) definition of the business scenarios and use cases that will be implemented during the pilot activities (D3.1)
iii) development of an appropriate methodology for the evaluation of the necessary data from measurements, software outputs, building plans/models, sensor data, stakeholder opinions, etc. (D3.3)
iv) extensions and refinements of the evaluation methodology in terms of chosen use cases and KPI assessment for the specific test cases that will be selected to be evaluated per pilot building (D9.1)
v) analysis of the collected information and stakeholder opinions after the demonstration activities in order to assess the BIMERR tools (D9.4)

Deliverable D3.3 aims to establish the basis for the BIMERR evaluation methodology and define the most important Key Performance Indicators to fully characterize the performance of the BIMERR tools by combining and extending existing methodologies, previous expertise and recent results from relevant EU projects, in order to meet the requirements of the BIMERR stakeholders.

For the definition of these KPIs, the five business scenarios for BIMERR and the user requirements, as defined in Deliverable D3.1, were taken into account.

A main aim of the evaluation methodology is to assess the impact of the BIMERR tools on the renovation time and the corresponding cost, also accounting for the entire life-cycle aspect of the project. Benefits are expected to stem mainly from the facilitation of BIM creation and usage as well as the overall renovation process coordination and optimisation. BIMERR also aims to streamline the use of BIM from the model creation to the model utilisation across tools and promises to deliver tools for the automated creation of the necessary building models as well as an interoperability framework for seamless and effortless exchange of information. As a consequence, evaluating this tool requires the definition of appropriate Key Performance Indicators (including their calculation methods), the establishment of the correct baselines and the measurement of key metrics of the renovation process in order to quantitatively assess the BIMERR impact.

Another important purpose of the evaluation methodology is assessing user acceptance of the BIMERR tools. User acceptance is a necessary pre-condition for the exploitation of the tools and their proliferation in the construction industry, which is the second key impact the project aims at.

The evaluation also looks at the wider socio-economic picture and assesses how these tools can accelerate the renovation rate of the building stock or the long term benefits on sustainability, social welfare and environmental impact.

As a consequence, the considered KPI categories comprise:

- Renovation process duration
- Renovation process cost
- User acceptance
- Energy efficiency
- Occupants comfort and air quality
- Sustainability issues
- Economic issues

Each KPI presented in the above categories, is briefly described along with the calculation or the corresponding tool responsible for its calculation.

The definition of the evaluation methodology and the selected KPIs presented in this document correspond to the methodology for the BIMERR framework.

3. Existing Assessment Methodologies

3.1 Assessment of Renovation Time and Cost Requirements

Time and consequently cost savings can be achieved at each of the activities involved in the renovation of existing building assets, as well as at the interface between these activities and the various stakeholders they involve. As reported in the following, cost and time savings are primarily evaluated for activities performed prior to the delivery of a building (design and construction stages).

This section reviews current industry practices employed to measure time and cost performance. Specifically, in section 3.1.1 current project management techniques that are used to evaluate construction projects performance regarding time and cost are presented; while sections 3.1.2 and 3.1.3 focus on BIMERR's pilot-specific strategies and case studies based on real renovation/retrofitting projects. Section 3.1.4 completes the analysis for the renovation cost-time requirements by presenting a short literature review based on research publications.

3.1.1 Current Industry Practice

In the construction sector, the proper evaluation of a project performance has traditionally gained considerable attention. In [1] has been proposed an integrated framework for overall evaluation of a construction project's performance, and the performance of eight objectives is also quantified: cost, time, billing or cash flow, profitability, safety, quality, project team satisfaction and client satisfaction. However, in common practice, most companies focus on measuring only cost and schedule performance indices, overlooking the overall project performance.

The Earned Value Analysis (EVA) ([2]) and the Critical Path Method (CPM) ([3]) are widely used methods to evaluate the time and cost performance. Frequently, EVA is applied to evaluate the project cost performance and predict the project's cost at completion, while CPM is used to evaluate project schedule (time) performance and predict the completion time.

Prerequisites for applying CPM and EVA are the following:

1. definition of a list of activities required to complete the project by breaking it down into work activities
2. determination of duration and cost for the different activities
3. determination of logical dependencies between activities
4. definition of logical endpoints such as milestones or deliverable items

Having addressed these prerequisites, EVA and CPM calculations can then be performed.

The decomposition of a renovation project to activities, according to the traditional approach, has been presented in D3.1 ([4]), where a renovation process is shown to consist of seven phases and their corresponding steps: (1) building auditing; (2) architectural design of renovation; (3) permissioning; (4) executive design of the renovation; (5) construction and renovation project implementation; (6) validation; (7) building operation and maintenance. A thorough description of each phase and the corresponding steps can be found in [4].

Having decomposed the whole project into phases and steps, the next thing to do is to assign duration and cost to each of them (note that in most renovation projects, duration is calculated in workdays). This information can be provided based on data or experience available from previous projects, considering at the same time uncertainties/contingencies due to weather conditions, design complexity, etc..

In the same manner, information about the logical dependencies between activities is obtained from project managers based on their expertise. It is worth mentioning that logical dependencies and project constraints must not coincide. A logical dependency occurs when the start of an activity

requires the end of another, while a project constraint emerges when even two activities can be performed in parallel and one must precede the other due to resource limitations.

Having addressed the aforementioned prerequisites, a graphic representation of the renovation project can be drawn and the CPM calculations can be performed. Two main approaches for activities representation are used in practice: Gantt charts and logic networks.

The Gantt chart method ([5]) is the most frequently used technique to display and report timing of a renovation project. On the other hand, it suffers from lack of logical representation (dependencies), a prerequisite for the CPM calculations. For instance, why an activity started on a certain date; the reason could be a logical dependency or a resource constraint; however a Gantt chart cannot provide an answer to this question.

In contrast, networks consist of logical and graphic representations of the renovation project's activities that are used to answer such questions. There are two types of networks: arrow networks and node networks. In arrow networks, activities are represented by arrows, connected through nodes. Tail and head of an arrow represent the start and the end of an activity, respectively. The length of the arrow depicts and is often proportioned to the duration of an activity. Information about the predecessors of each activity is required. In node networks, activities are represented by nodes, connected through arrows which represent dependencies between activities. Examples of an arrow and a node network are depicted in Fig. 1.

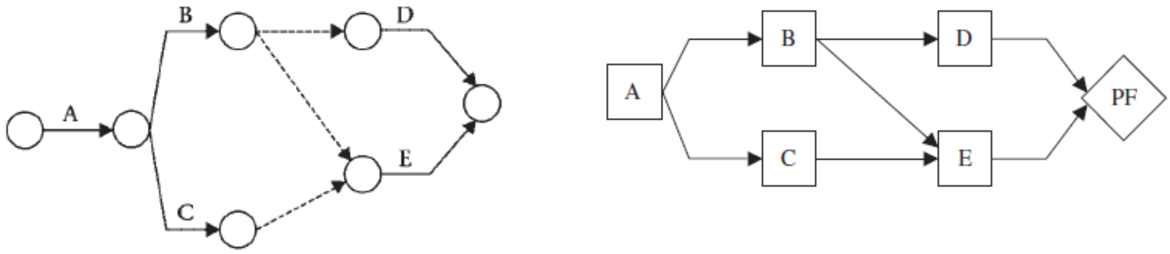

Fig. 1: An arrow network (left) and an node network (right) representation for the same project ([6])

Networks have strengths and weaknesses over Gantt charts. Networks represent dependencies between activities, while Gantt charts do not; they can better represent large and complicated projects; they can estimate, or predict, the completion date of a project, or other dates, on the basis of mathematical calculations of the CPM and the EVA, while Gantt charts predict the completion of the project, or other dates, on the basis of the user's skills. On the other hand, Gantt charts are time-scaled (i.e., the length of the activity bar represents the time duration of the activity), while networks, are not; Gantt charts are simple to prepare, can be easily explained, and as such they are more acceptable for presentations, especially for field people and people who are unfamiliar with the CPM and EVA calculations.

3.1.1.1 The Critical Path Method

CPM ([3]) is the state-of-the-art technique for scheduling/timing a project and evaluating its time performance. The main target of CPM is to calculate the critical path of the project: the longest path of planned activities to logical end points or to the end of the project, and the earliest and latest that each activity can start and finish without making the project longer. Its calculation defines activities that belong to the longest path (critical activities) and activities that can be delayed without making the project longer (activities that have float).

To find the critical path, the process that CPM follows consists of four steps: (1) draw the logic network; (2) identify all paths in the network diagram; (3) find the total duration of each path; and (4) find the maximum value of durations calculated in step 3 and the respective path; that path comprises the critical path.

The CPM calculation process is as follows ([7]):

- Phase 1 – Forward Pass: during this phase, the early start and early finish values are estimated; initially, the estimation process sets a zero value in the early start of the first activity of the logic network and a value that equals its duration in the early finish, while the early start and the early finish of the rest of the activities are estimated by considering that the early start equals the highest early finish value of precedent activities that are directly linked with the activity; early finish = early start + duration of the activity.
- Phase 2 – Backward Pass: during this phase, the late start and late finish values are estimated; starting from the last activity, its late finish value equals its early finish and its late start value equals its late finish minus its duration; next, the late finish and late start values of the rest of the activities are estimated: late finish = lowest early start value of next activities that are directly linked with the activity; late start = late finish – duration of the activity.
- Phase 3 – Float Calculations: float values indicate how long each activity can be delayed before affecting next activities; float values are calculated as follows: total float = late start – early start of the activity; free float = lowest early start value of next activities that are directly linked with the activity – early finish of the activity.
- Phase 4 – Critical Path definition: during this phase the critical activities are determined; critical activities are activities that have zero total float and free float values.

An illustrative example of a logic network after performing the aforementioned phases is depicted in Fig. 2.

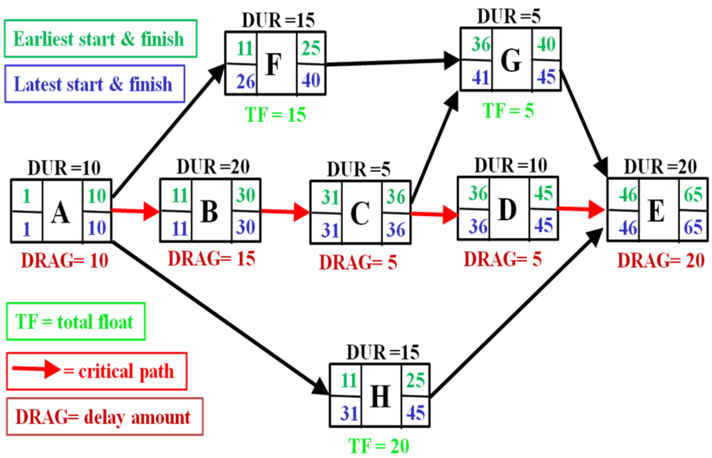

Fig. 2: Critical Path Method's results on a node network ([8])

Similar methods to or improvements of the CPM have been developed, but not gained industry's attention mainly due to their complexity. The program evaluation and review technique (PERT) is an event-oriented network analysis technique that is used to estimate the duration of a project when individual activity duration estimates are highly uncertain. PERT applies the CPM to a weighted-average duration estimate and is considered a stochastic method. Like the regular (deterministic) CPM, PERT uses logic networks to calculate the completion date of a project or the date of any other event in a schedule. In PERT, a probability (likelihood) is associated with any event date. This probability depends on uncertainty in the durations of the activities that lead to the desired event (e.g., project completion). PERT realizes that actual durations vary from those assigned, so it attempts to compensate for this variation with a "time range" during which activity durations may realistically occur. The graphical evaluation and review technique (GERT) is a network analysis technique that allows for conditional and probabilistic treatment of logical dependencies (i.e., some activities may not be performed). GERT is similar to PERT but considers both deterministic and probabilistic branching. It

incorporates both in the network analysis. GERT allows additional branching features that are not provided by CPM or PERT.

3.1.1.2 Earned Value Analysis

EVA ([2]) is the standard method for evaluating the cost performance of a renovation project. For an EVA cost performance evaluation, indicators such as Schedule Variance (SV), Cost Variance (CV), Schedule Performance Index (SPI) and Cost Performance Index (CPI), to name a few, are estimated based on three key metrics:

- the Planned Value (PV), (also known as the Budgeted Cost of Work Schedule) is the portion of the project budget planned to be spent at any timestep of the project
- the Actual Cost (AC), (also known as the Actual Cost of Work Performed) is defined as the total cost upon completion of the activity; in other words, it is the money spent for the work accomplished at any timestep during the project
- the Earned Value (EV), (also known as the Budgeted Cost of Work Performed) is defined as the estimated value of work that has actually finished and can be estimated by multiplying the percentage of project completion at any timestep of the project's duration with the total budget of the project.

At each timestep, values of SV, CV, SPI and CPI are calculated by the following equations:

$$CV = EV - AC, \quad SV = EV - PV, \quad CPI = EV/AC, \quad SPI = EV/PV$$

In timesteps where project cost performance is below the plan, the CPI value is less than one and the CV value is negative, and vice versa. Moreover, in timesteps where more work has been accomplished than was planned, the SPI value is greater than one and the SV value is positive; but the other way around does not hold in this case. An SPI value greater than one does not always mean that we are ahead of schedule, since it could be a result of accomplishing activities that do not belong to the critical path. Hence, for time/schedule performance evaluation, SPI and SV values must be further investigated by checking the critical path derived by the CPM.

PV, AC and EV metrics are commonly plotted to estimate the cost and time performance and it varies in time, providing the possibility to visually track project progress during execution (see Fig. 3).

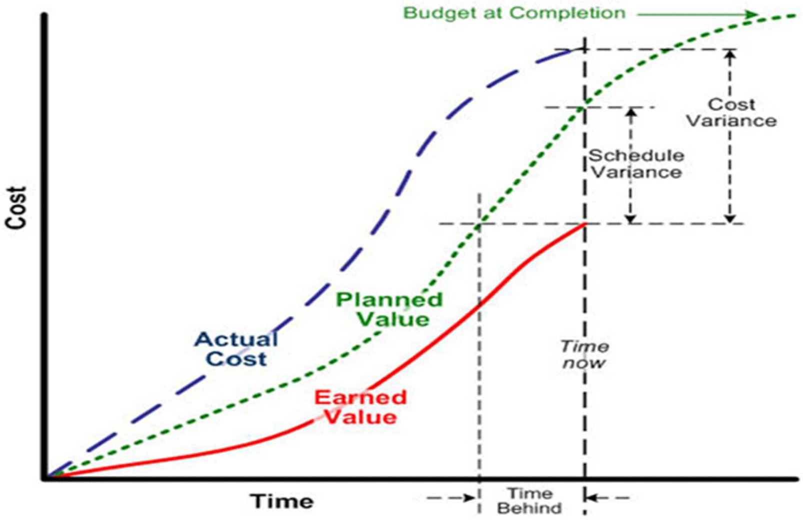

Fig. 3: Earned Value and Actual Cost plotted against the Planned Value ([2])

To account for risks on the estimated durations and costs of project activities, recent advancements in EVA have enhanced its capability for more accurate evaluation of time and cost performance by incorporating project uncertainty analysis. To this direction, Monte Carlo simulations are frequently

used to provide three curves for each EVA's metric, minimum, mean and maximum. Moreover, tolerance limits are introduced to the EVA indices.

Another strength of the EVA method is its capability to predict the final project cost at each timestep of the project's duration. To do so, three new terms are introduced: the Estimated to Complete (ETC), defined as the expected additional cost needed to complete the project; the Estimate at Completion (EAC), defined as the predicted final project cost; and the Budget at Completion (BAC), defined as the total approved budget that could include project contingencies [9].

3.1.1.3 The Last Planner® System

The purpose of the Last Planner® System (LPS) is to produce predictable workflow and rapid learning through conversations, clear communication, better coordination and commitment based planning. It aims at both increasing schedule reliability, smoothening flow of work and reducing cost and project delivery. The LPS focuses more on the collaboration processes of planning and task commitment on the construction site. LPS engages all project participants to ensure the achievement of agreed goals.

According to the Lean Construction Institute[1], the main objectives of LPS are:

- produce the best possible plan by involving all key stakeholders
- create the right level of detailed, useful, collaborated plans that produce safe, highly reliable work flow, high quality, on-time-every-time delivery for all construction scope
- provide a framework for teams to enable effective collaboration
- increase daily productivity within the production teams through the systematic removal of waste
- control and measure construction progress, patters and provide information to make rapid corrective decisions

To introduce LPS in a production control, the authors in [10] p. 230, suggest to:

- drop activities from the phase schedule into a 6-week (typical) lookahead window, screen for constraints, and advance only if constraints can be removed in time
- try to make only quality assignments – require that defective assignments be rejected
- track the percentage of assignments completed each plan period (PPC or 'per cent plan complete') and act on reasons for plan failure

Ballard in [11] defined three components for the LPS: a) lookahead planning, b) commitment planning and c) learning. He also provided a framework of the production control with LPS, which is shown in Fig. 4. This framework presents the different actions that should be taken during the Last Planner planning cycle to establish a reliable workflow.

[1] **Lean Construction Institute**, Last Planner® System: https://www.leanconstruction.org/media/docs/chapterpdf/israel/Last_Planner_System_Business_Process_Standard_and_Guidelines.pdf

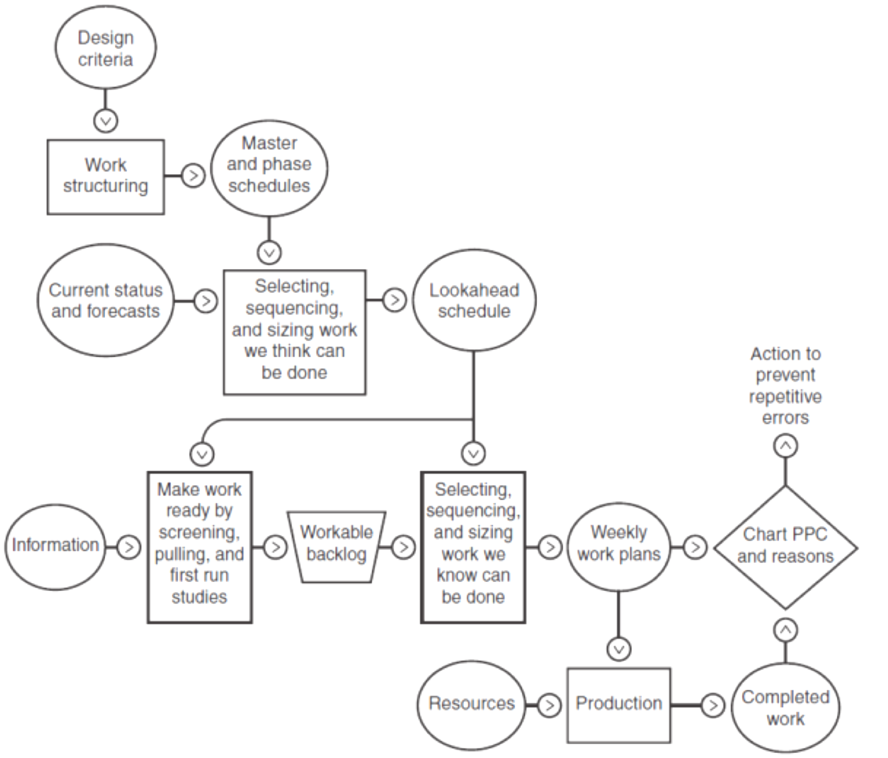

Fig. 4: Last Planner System Planning cycle according to Ballard in [11].

In LPS every construction task can be technically gathered into four groups during its execution phase: SHOULD-task, CAN-task, WILL-task and DID-task. This SHOULD-CAN-WILL-DID process (Fig. 5, Fig. 6 and Fig. 7) is supposed to be applied in five consecutive steps, which are characterized by corresponding plan phases with increasing level of detail:

1. **Master Scheduling**, sets up milestones and durations of the entire project. Master Schedule is a front end planning, which defines major milestone dates and it is based on CPM. CPM is the logic to determine the overall project duration.
2. **Phase Scheduling** defines construction plan involving project participants, identifies handoffs and operational conflicts. It generates a detailed schedule that evolves during the project. Phase Scheduling decomposes the master schedule into more detailed project components. Handoffs and relationships can be evaluated by using collaborative planning combined with reverse phase scheduling activity durations. It results in modifications to the CPM logic.
3. **Make-ready Planning** consists of more detailed activities on the phase scheduling with constraints analysis. It considers 4-6 week lookahead planning, i.e. a list of activities that need to be worked on over the upcoming 4-6 weeks. It is preferred in order to ensure that work is made ready for installation. The lookahead plan is updated weekly, where constraints that potentially threaten reliable workflow are analysed.
4. **Weekly Work Planning** with measured percent plan complete, which defines daily commitments to perform during the following week. It is the most detailed plan of the LPS. It directly drives the production process. A reliability plan is done by making only quality assignments and reliable promises. A detailed measurable commitment of completion is defined for each planned work. At the end of each week, assignments are reviewed based on the percent plan complete (PPC) measure. Through PPC it is possible to measure the reliability of the planning system.
5. **Learning and Improvement Planning**, which monitors progress of scheduled activities and evaluates successes and failures of the previous week's plan. At this stage, reasons for plan

failures and acting on these reasons are carried out and conclusions are drawn to make improvements in upcoming work planning. It helps to avoid mistakes in the future.

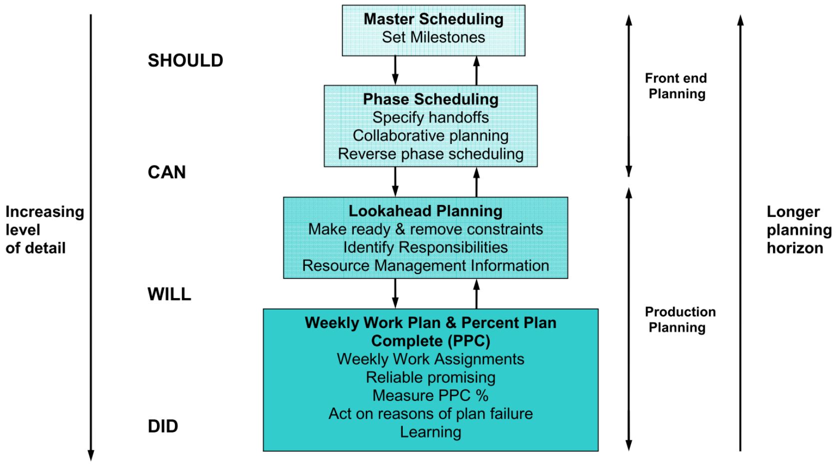

Fig. 5: LPS Planning cycle according to [12]

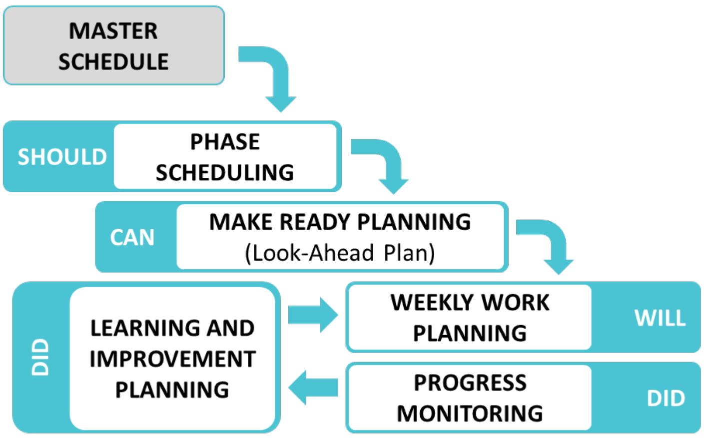

Fig. 6: LPS Planning cycle elaborated by the Lean Construction institute

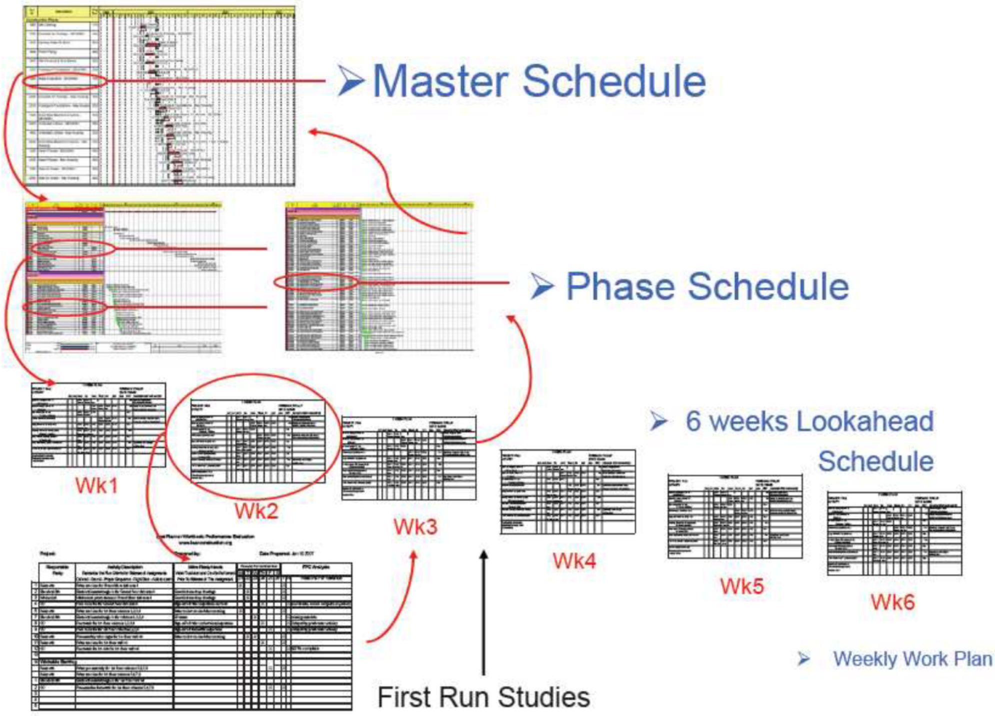

Fig. 7: LPS Planning cycle according to [12]

LPS uses a PPC value to establish how well the planning system is working in terms of completed tasks, as well as reasons for non-completion (RNC) to prevent the recurrence of errors in succeeding work plan:

$$PPC = \frac{Number\ of\ assignments\ completed\ in\ the\ planned\ week}{Number\ of\ assignments\ planned\ for\ this\ week} \quad (1)$$

For example:

Week 1	
Completed tasks	**Planned tasks**
A	A
B	B
	C
	D

$$PPC = \frac{AB}{ABCD} = 50\%$$

PPC effectively answers the question: How good a predictor of work flow are plans made two weeks in advance?

3.1.1.4 Location-Based Management System

According to [13], a Location-based Management System (LBMS) can be considered as a lean technique that focuses on production control based on pull controlling. The goal of lean production is to create a reliable workflow. The main goal of LBMS is ensuring that task can be performed without any interruption due to failure of prerequisites in locations, avoiding the associated waste like interruption, double-handling of materials, equipment of crews and reworks [13]. LBMS considers that the project is broken down to physical locations with different activities assigned. Each activity is defined according to a location hierarchy level, so-called Location Breakdown Structure (LBS). Construction activities and their controlling refer always to locations. A location-based planning system

uses location as the basic unit of planning and control and tasks are assumed to flow through locations. Tasks are structured following CPM which is augmented with the concept of locations. Organization of activities by locations provides more comprehensive information, avoids interruption between different trades, and enhances constancy of the workflow [13]. It can also increase productivity and prevent production problems which cause cascading delays and impact project durations by 10% [14]. Moreover, thanks to LBMS more appropriate predictions of material bottlenecks as well as human resource demands can be made, and correspondent actions can be taken. In recent case studies, a successful implementation of LBMS in software has been observed ([15]–[17]). In recent years, the implementation in the field of lean construction methods such as LPS and LBMS have improved construction processes, productivity collaboration between project participants, as well as have decreased waste and project variability ([18]).

A Location-Based Management System is founded on the location-based plan. Location-based planning is composed of a task and activities, where a task is understood as a sequence of activities in differing locations. In other words, a task contains work or activities in a sequence of locations, and it is performed by one or multiple crews. Tasks planned in the construction project are based on CPM to define logic and connections between activities. Moreover, for each task, duration is calculated based on quantities, allowing to distribute the location sequence and production rate in such a way to ensure the continuous production. Overall, location-based planning is an extension of activity-based logic with location-based logic. To introduce the location-based logic, locations of the construction project have to be defined by location breakdown structure (LBS). The LBS is similar to the work breakdown structure (WBS), but is refers to location hierarchy, where the highest level logically includes the lower levels of locations. Fig. 8 and Fig. 9 illustrate how the LBS can be performed on a multi-storey building. Fig. 8 shows how the building is divided both horizontally and vertically. Fig. 9 shows four-level hierarchy using a diagram, where the building is split into sections, then into two risers, then risers are split into floors and finally apartments.

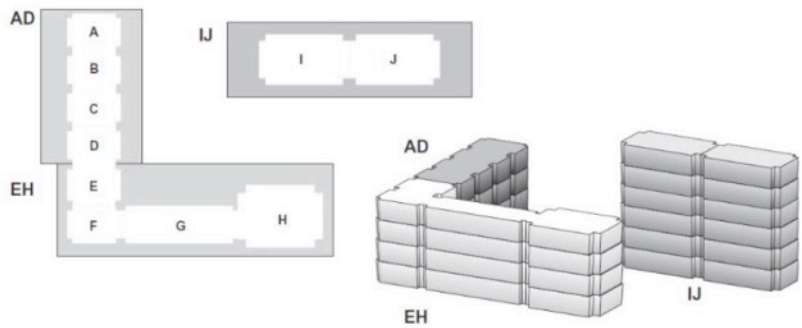

Fig. 8: Hierarchy levels according to [13]

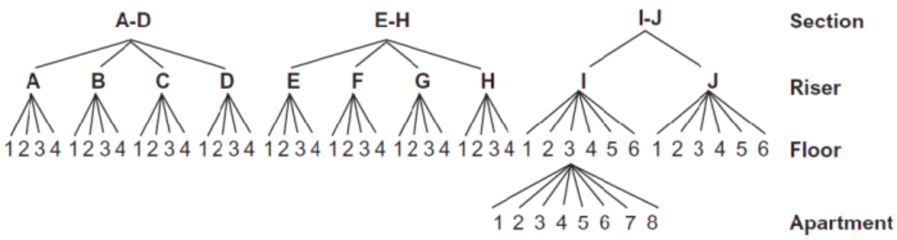

Fig. 9: LBS diagram according to [13] (p. 126)

For each location, quantities should be defined to estimate duration of activities. The bill of quantities (BOQ) defines all the work that should be done in a specific location by a crew. Once the quality of work in a location is completed, the crew can start a work in the next location. The specific BOQ should be allocated to tasks. Based on BOQ in a location, the duration of a task can be calculated by using the consumption rate, the assigned resources (crews) and the productivity data. The consumption rate indicates the amount of worker time, measured in worker hours needed to complete one production unit. The calculation of total worker hour in a specific location is:

$$\mathrm{h}^{T}{}_{j} = \sum_{i=1}^{i=n} (Q_{i,j} \times R^{C}_{i,j}) \quad (2)$$

where:

$\mathrm{h}^{T}{}_{j}$ = Total hours for the location *j*

$Q_{i,j}$ = The quantity of item *i*, in location *j*

$R^{C}_{i,j}$ = The production rate for item *i* in location *j*

and there are *n* items *i* being grouped into a single task.

The production rate can be found in productivity databases. This calculation is required for each location of each task.

The duration of a task in a specific location can be calculated based on quantities and crews assigned to it. The following steps may be followed to calculate the duration:

1. Calculate the quantity of worker hours (h^{T}_{j}) needed to complete the quantity of an item in a location
2. Divide the result by the sum of production factors of the selected resources to get the duration in hours
3. Divide by the shift length to get the duration in shifts
4. Multiply the duration (shifts) by the difficulty factor

These steps can be expressed in the following equation:

$$\mathrm{D}^{S}{}_{j} = \left(\frac{\mathrm{h}^{T}{}_{j}}{\sum_{i=1}^{i=n} P_{i,j}}\right) \div h^{s} \times d_{j} \quad (3)$$

where:

$\mathrm{D}^{S}{}_{j}$ = Duration in shifts for the location *j*

$\mathrm{h}^{T}{}_{j}$ = Total hours for the location *j*

$P_{i,j}$ = The productivity for item *i* in location *j*

h^{s} = Shift length (hours) for the task

d_{j} = The difficulty in location *j*

This information can be used to create the flow-line of a task, as shown in Fig. 10. In this figure, the Location Breakdown Structure is shown on the left and the time line is shown horizontally. Each task is shown as a diagonal line. The slope of the line signifies the production rate of the task. The flow-line slope represents quantity variation between locations, considering that the difficulty factor of each location is the same. Work sequence can be read horizontally, when several flow-lines are designed. Empty areas between flow-lines indicate wasted time between tasks.

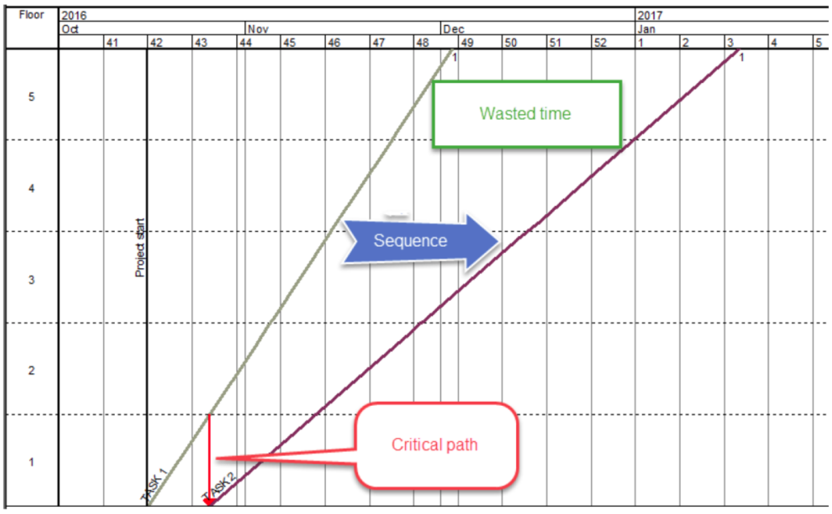

Fig. 10: Example of flow-line graph of two tasks according to [14].

Location-based controlling

Controlling in LBMS monitors status of locations and labour on site to calculate actual productivity, visualizing status in control charts and flow-lines. This information enables the forecasting of progress based on actual production rates. LBMS requires that there is an early warning mechanism that can inform on upcoming problems. For this purpose, a double-loop learning model [19] can be used, which first considers forecasting progress and afterwards detailed plans (lookahead plans), as shown in Fig. 11.

The progress of scheduled tasks is monitored by measuring task start and finish time or competition rates in each activity in a specific location. Actual production rates for each activity can be calculated from this, and if actual resources are known, the actual resource consumption rate can be calculated ([13], p. 257). Therefore, a weekly or daily progress reporting is required. Beyond activity start and finish dates, actual information about crew sizes, quantities in locations and days on which tasks were suspended, have to be recorded in order to calculate productivity accurately.

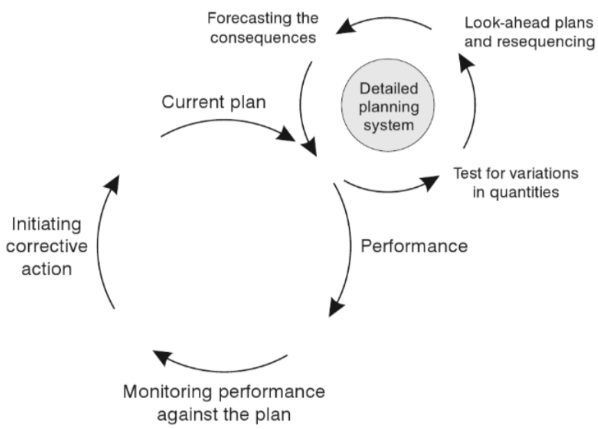

Fig. 11: Double-loop control cycle according to Stacey in [19].

3.1.2 Cost calculations based on estimates

In this section the steps for cost estimation that refer to the Polish methods are analyzed, since Poland is one of the two pilot countries for BIMERR.

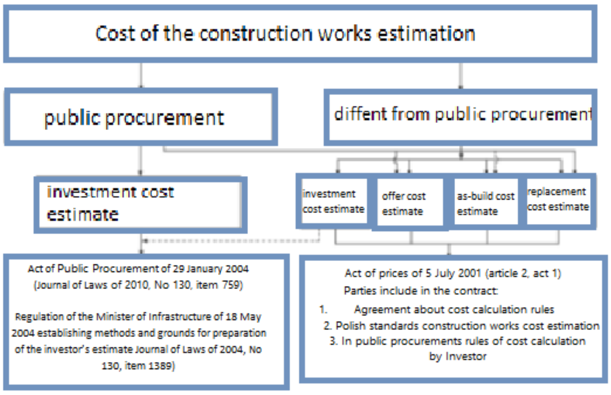

Fig. 12: Polish approach on cost estimation

The formulas used to estimate costs are based on [20] and include:

1. Elaboration of conceptual, architectural and executive project, and
2. Execution of construction works.

3.1.2.1 Cost estimation for the elaboration of architectural and executive project

These calculations refer to the Architectural and Executive Design of renovation process, i.e. phase 2 and 4 of the renovation process presented in D3.1, [4].

Planned costs of design works are calculated according to the formula:

$$W_{PP} = W_{\%} \cdot W_{RB} \tag{4}$$

where:

W_{PP} – is planned costs of design works
W_{RB} – is planned costs of construction works
$W_{\%}$ – is percentage ratio

W_{PP} excludes:

- obtaining a legal map, preparing a map for project purposes
- preparation of geological and engineering documentation (ground and water research)
- preparation of environmental protection operators
- inventory of objects, land development
- inventory and valorization of vegetation

In W_{PP} the following percentages of design stages are considered:

- Conceptual design: 7-15% of W_{PP}
- Architectural design: 30-45% of W_{PP}
- Execution design: 40-60% of W_{PP}

The sum of the component values of the design stages, calculated as a percentage, is 100%.

The percentage ratio $W_{\%}$ used to calculate the value of the design works of W_{PP} shall be determined according to Table 1, depending on the category of construction and assembly works, which shall be determined according to Table 2.

Cost of planned construction works in k PLN	W %					
	Categories of compelxity					
	I	II	III	IV	V	VI
Up to 200	3,50	5,00				
500	3,25	4,60	5,95			
1 000	3,00	4,20	5,45	7,55		
2 000	2,80	3,90	5,00	6,90	8,65	
5 000	2,60	3,60	4,55	6,25	7,85	9,40
10 000	2,40	3,30	4,20	5,90	7,10	8,50
20 000	2,25	3,00	3,80	5,20	6,45	7,70
50 000		2,80	3,50	4,70	5,85	7,00
100 000		2,55	3,20	4,30	5,30	6,30
200 000			2,90	3,90	4,80	5,70
500 000			2,70	3,55	4,40	5,20

Table 1: Cost calculation (W_{PP}).

Groups	Function	Categories					
		I	II	III	IV	V	VI
1	Basic one level single family building (without basement and garage), summer house		*	**			
2	Single family building with garage, semi-detached house, full season summer house.			*	**	**	
3	Single family building with individual requirements				*	**	**
4	The highest standards residence						*
5	Single family with compact build-up (terraced house)				*	**	**
6	Multifamily building up to 12m without basement and garage			*	**		
7	Multifamily building different from group 6, 8 and 9				*	**	
8	Multifamily building more than 55m					*	**
9	The highest standards multifamily building						*
** classification in case of basic requirements for the building*							
*** classification in case of higher than basic requirements*							

Table 2: Category of construction and assembly works.

The values of $W_{\%}$ given in Table 1 refer to the design of construction works for new buildings. In the case of renovation, e.g. volume extension, substantial changes, renovation works, the $W_{\%}$ value increases by 15-30%, depending on the complexity of the works being designed. In the case of extension (horizontal, not requiring any interference in the functional system, structure or installations of the existing facility), the value of $W_{\%}$ increases by 5-15%, depending on the degree of complexity of the planned works.

In order to determine the value of $W_{\%}$ of objects with intermediate planned costs of construction works in relation to those included in the table, linear interpolation should be applied.

Categories of complexity for buildings are as follows:

1. category I - the simplest open or semi-open buildings, shelters and single-space, single-storey buildings without installation equipment (except for the simplest electrical and gravitational ventilation installations) and technology buildings not intended for human habitation.
2. category II - simple single-storey buildings with and without basement, equipped with the simplest installations (plumbing, central heating, electrical installations, gravitational ventilation), with the simplest technological equipment.
3. category III - low level buildings with a low level of difficulty, with a simple homogeneous function, with basic installation and technological equipment.
4. category IV - buildings with complex functional, installation and technological requirements of medium difficulty, not included in categories 5 and 6.
5. category V - multifunctional buildings and buildings with very complex functional, installation and technological requirements, requiring special engineering solutions, high-rise buildings.
6. category VI - buildings with the highest degree of functional, installation and technological complexity, with built-in complex engineering structures, unique installations and equipment, buildings with the highest requirements as to the standard of finish and prestige.

3.1.2.2 Cost estimation for the execution of construction works

The calculations herein refer to cost estimation of actual renovation works, i.e. Step 5.12 of the renovation process presented in D3.1, [4].

In Poland it is acceptable to elaborate on 2 types of cost estimation for the execution of construction works: the Simplified and Specific methods. However, only the Simplified method is presented here since the Specific method is considered out of the scope of this deliverable.

No.	Type of work	Quantity [m^2]	Unit price [zł/m^2]	Price [zł]
1	KNR 2-02 0115/01 Walls of multi-storey buildings made of 1-layer brick with lime or cement-lime mortar	45,600	233,26	10636,82
2	KNR 2-02 0115/02 Walls of multi-storey buildings made of 1 and ½ -layer brick with lime or cement-lime mortar	67,54	345,23	23316,58

Table 3: Simplified method parameters

The construction cost estimation is calculated as:

$$C_k = \sum L \times C_j \times P_v \tag{5}$$

where:

$$C_j = R_j + M_{nj} + S_j + K_{pj} + Z_j \tag{6}$$

or

$$C_j = R_j + M_j + S_j + K_{zj} + Z_j \tag{7}$$

where:

C_k – price estimation of construction works,
L – number of units for bills of quantities for the assumed level of work aggregation,
C_j – unit prices for bills of quantities (Table 3),
P_v – VAT tax (23% in Poland),
R_j – labour costing value per pre-defined units,

M_{nj} – price estimation for materials per pre-defined unit considering also purchase costs,
M_j – price estimation for materials per pre-defined unit without considering purchase costs,
S_j – price estimation for equipment per pre-defined unit,
K_{pj} – indirect costs per pre-defined unit,
Z_j – profit per pre-defined unit
K_{zj} – price estimation for purchasing costs (transportation costs)

3.1.2.3 Cost estimation for other services related to the renovation project

There are other costs related to a renovation project that do not fall into the previous categories defined in sections 3.1.2.1 and 3.1.2.2. These costs come from specific services such as on-site surveys, audits, etc. Usually companies estimate these costs as follows:

3.1.2.3.1 **Building survey** (traditional techniques)

The price depends on the complexity of the building and its size and functionality. This corresponds to steps 1.1, 1.3 and 1.4 of the renovation process [4].

Companies can calculate it differently:

- price per m^2 of the building for auditing. Usually the price will increase with the floor area of the building, e.g. up to 200 m^2 it is X€/m^2, above 200 m^2 it is Y€/m^2
- Cost is calculated based on the kind of documents that will be elaborated and on how detailed the survey will be (see Table 4)

Floor plan	**Price [PLN/m^2]**
Basic survey	2,5
Simplified survey	3,5
Detailed survey	4,5
Elevations	
Basic survey	0,9
Simplified survey	1,2
Detailed survey	2,4
Cross-sections	
Basic survey	4
Simplified survey	5,6
Detailed survey	8
Flat roof top	
Basic survey	0,3
Simplified survey	0,4
Detailed survey	0,5

Table 4: Prices for building survey per m^2.

3.1.2.3.2 Survey with laser scanning

This refers to step 1.3a of the renovation process [4]:

- Survey done by 3D laser scanning : price/m^2 of the building
- prepare CAD drawings based on 3D laser scanning: price/m^2 of the building

- prepare BIM model based on 3D laser scanning: : price/m^2 of the building

Sometimes the unit can change to price/number of rooms.

3.1.2.3.3 Energy auditing and certification

The cost of energy auditing, i.e. step 1.5 of the renovation process, depends on the floor area of the building: e.g. up to 7500 m^2 it is X€, above 7500m^2 it Y€.

The cost of certification, i.e. step 6.2 of renovation process, is a flat price defined by the person who will perform the certification; it starts from 250€.

3.1.2.3.4 Thermal imagining

It can be a price for the whole building which depends on the building size or it can be calculated as €/apartment. Additional cost for report elaboration can also be considered.

3.1.2.3.5 Blower door test

A typical cost estimation for such a test is 295€ for 200 m^2. However, the price increases with the area: 10% for each additional 100 m^2 of usable area. Furthermore, the cost calculations depend on:

- the number of tests/measurements
- the size and type of building / facility / premises construction, etc.
- the form and the details of report
- the time required for preparations of the object for testing (if applicable)

3.1.3 Calculations based on real renovation/retrofitting works

Focusing on BIMERR's objectives for reducing the cost and time of renovation, a background study was performed by the pilot partners in order to gather relevant information of past renovation/retrofitting projects. Therefore, processed data for both time and cost from past projects have been produced, grouped and presented in Table 5 and Table 6.

Spain-Poland	Time (days)	Cost (€/m^2)
Phase 1 (Auditing) **Phase 2 (Architectural Design)** **Phase 4 (Executive Design)**		10 €/ m^2
Phase 1 (Auditing)	30 days or (50min/ m^2)	
Step 1.1 (inspection)	1 day/250 m^2	400 €/day
Phase 2 Architectural Design) **Phase 4 (Executive Design)**	90 days	
Phase 3 (Permissioning)	180 days	
Step 5.1 (Site Utilization Planning)	30 days	
Phase 5 (Construction and Renovation Project Implementation)	180 days	241 €/ m^2
Phase 6 (Validation phase)	180 days	10 €/m^2 Architect

Step 6.1a	8-10 €/m^2

Table 5: Time and cost requirements from previous renovation projects in Spain-Poland.

Greece	Time (days/m^2)	Cost (€)
Step 1.1 (inspection)	1 day/200 m^2	200 €/day
Step 2.1	5 days/100 m^2	300 €
Step 2.2	15 days/100 m^2	200 €
Step 2.3	15 days/100 m^2	250 €
Step 2.4	15 days/100 m^2	200 €
Step 4.1	10 days/100 m^2	100 €
Step 4.2	10 days/100 m^2	100 €
Step 4.3	7 days/100 m^2	180 €
Step 5.13	1 days /200 m^2	200 € for PM to be involved

Table 6: Time and cost requirements from previous renovation projects in Greece.

3.1.4 Research State-of-the-art for time and cost estimations

A number of papers deals with the evaluation of the actual impact of projects adopting BIM in the construction world. A comprehensive overview of the proposed methods can be found in [21]. However, the most difficult part concerning these studies are the necessary comparisons with previous approaches/technologies so as the actual gain could be derived.

Arguably, time and cost performance are tightly linked through the (simplified) formula:

$$cost = time \times unit\_of\_time\ cost \quad (8)$$

where $unit\_of\_time\ cost$ is the hourly, daily, etc. cost of the resources allocated to conduct the work. Traditionally, Life Cycle Cost (LCC) calculations have been made to evaluate different alternatives and make cost-effective decisions along the investment, operation and maintenance phases of a building ([21]-[22]). Note that operational costs can be divided into energy-related and non-energy [24]. In parallel, the payback period and the Return on Investment (ROI) are parameters widely used in construction projects [23], [25]. And more recently, innovative software solutions have been developed to integrate cost monitoring, estimation and planning information into BIM models as summarised in [26]. As a result of the increasing use of BIM in construction projects, new KPIs arise related to the creation of digital models and the subsequent digital management of projects ([26]-[27]). For example, Won and Lee in [27] propose metrics to evaluate the impact of the additional cost for BIM implementation; and another indicator called BIM ROI [28], grounded on the avoidance of costs of design errors by using BIM, measures the savings (in both direct and indirect costs) after hiring BIM coordinators for a project.

While innovation is applied to processes to reduce costs, this may be achieved in two different ways: first, by reducing time allocated to tasks using faster processes (e.g. semi or fully automating tedious and repetitive tasks); and second, by reducing the $unit\_of\_time\ cost$ by changing the type and size of resource involved in the new process. Note that, in many cases, the proposed changes to the process focus on improving the productivity of the existing resources.

Furthermore, it is noteworthy that, while the costs of design, construction and operation processes can involve various types of resources (that can change according to the selected process), labour costs generally account for a large share of overall costs. For construction works, which arguably involve large non-labour costs, labour costs still typically account for significant share, for example 40% in the case of housing construction costs[2].

These remarks suggest that, notwithstanding the importance of non-labour costs, improvements in process costs in construction projects are mainly achieved through improvements in the efficiency of the process alone by reducing human resource requirements through automation. This observation tacitly underpins most of the works that can be found in the literature, that report mainly time performance but not cost performance. Yet, it is also observed that, even works that 'report' time performance, often do it without comparison with current practice. For example, most works on as-is BIM modelling focus on developing new algorithms aimed at automating the processing of reality capture data to generate BIM models in order to speed up that process ([29], [30]). While they often report some time performance of their automated process, they typically do not report how these compare against the time performance of current (typically manual) processes. And this should take into account the additional time required by an expert to correct the automated process errors to bring those to the same level of quality as would be obtained using current processes. There is thus a gap in knowledge around time-cost performance in that particular renovation process stage.

Nonetheless, we note some recent relevant results have been published by the P2ENDURE H2020 project (see Section 4.9 below) that attempt to compare the time reduction enabled by their BIM-based deep renovation of building envelopes and technical systems using prefab solutions [31]. They identify five main renovation stages (As-built data collection; Renovation design; Engineering; Renovation works; Maintenance), that are suitable for any type of renovation project (not just prefab or energy-related) and report quantitative results that compare their approach to traditional practice. Their framework constitutes a good basis upon which to build.

Yet, a remaining important challenge in conducting and reporting meaningful time and cost analysis of process is the lack of benchmark case studies/datasets. As a result, all projects and publications that attempt to report on renovation efficiency (e.g. P2ENDURE) typically do so for their own case studies/datasets. Only in the case of entirely digital processes can benchmark datasets be created. Yet, even in such cases, benchmark datasets are not very common.

In the case of Scan-to-BIM, we note the existence of the *Indoor Modelling Benchmark* [32] and more recently the *Benchmark on Indoor Modelling* ([33], [34]).

3.2 Assessment of User Acceptance

Nowadays the use of information technologies in organizations and companies has been increased. A big amount of capitals is provided for investment in information technology. However, the technologies that are used for improving productivity, have to be accepted and used by employees in organizations. User acceptance of new technologies is one of the most developed research areas in the modern information systems literature. Research in this area has resulted in several theoretical models, with roots in information systems, psychology, and sociology, that routinely explain over 40% of the variance in individual intention to use technology [35].

Companies must develop implementation methods to include user feedback and user acceptance testing for use-cases as they are developed. Developing applications and services alongside user feedback enables an organization to predict user acceptance of new systems and functionalities ahead of launch dates, increasing overall user acceptance of services provided and increasing overall business

[2] https://homeguide.com/costs/cost-to-build-a-house#labor

https://www.nahbclassic.org/generic.aspx?genericContentID=248306

https://www.constructionbusinessowner.com/accounting/accounting-finance/construction-labor-costs-5-percent-factor

value of the applications within the company intranet. This is significant due to the fact that when a system has low user acceptance, it becomes under-utilized within an organization and the resources invested into it are effectively negated [36].

Adapting user-centered design into an implementation process provides an important framework for optimizing a product or service around how users would naturally interact with the system rather than requiring users to adapt their behavior to facilitate the product. A user-centered design approach to product implementation keeps the user’s needs and requirements at the center of design and development decisions throughout the development lifecycle. A product developed around a user’s needs substantially increases user acceptance and subsequent system utilization, thus providing greater return on investment resources allocated to the product [37].

Davis et al. in [36] suggested that user acceptance is necessary for system use and important to successful implementation. Usability is defined from International Standard Bodies (ISO 9241-210:2010 for Human-centered design ([38]) as “extend to up where a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in specified context of use”. The usability of a system is important because it affects the system-user acceptance. Effectiveness in usability is defined as the degree to which an interface facilitates users in accomplishing tasks and goals.

Various models [35]that measure the user acceptance of a system/service include aspects such as perceived usefulness, perceived ease of use, performance expectancy, effort expectancy, social influence and facilitating conditions. The collection of data that are used for measurement and evaluation of user acceptance is done through questionnaires. Two widely known models for evaluation of user acceptance are TAM (Technology Acceptance Model) [36] and UTAU (Unified Theory of Acceptance and Use of Technology) [35].

TAM is used to predict information technology acceptance and usage on the job and is applied to various systems and technologies. The most significant determinants of TAM are Perceived Usefulness – the degree to which a person believes that using a particular system would enhance his/her job performance, and Perceived Ease of Use – the degree to which a person believes that using a particular system would be free of effort. Perceived usefulness is a key parameter for user acceptance of a system/service because it affects the user's intention to use it, e.g. [39] describes how wearable devices would improve the user’s job performance.

Two more parameters that are parts of TAM are the Attitude Towards Using a technology and Behavioral Intentions to Use. Attitude towards using a technology is the user’s evaluation of desirability using a specific information system (application). Behavioral Intentions to Use is the measure of the likelihood to use the technology. These four parameters can considerably affect each other [36], [40], [41]. The following figure shows the influences between the four factors of TAM. Note that the external variables shown in the figure could be social, cultural, political or economic factors.

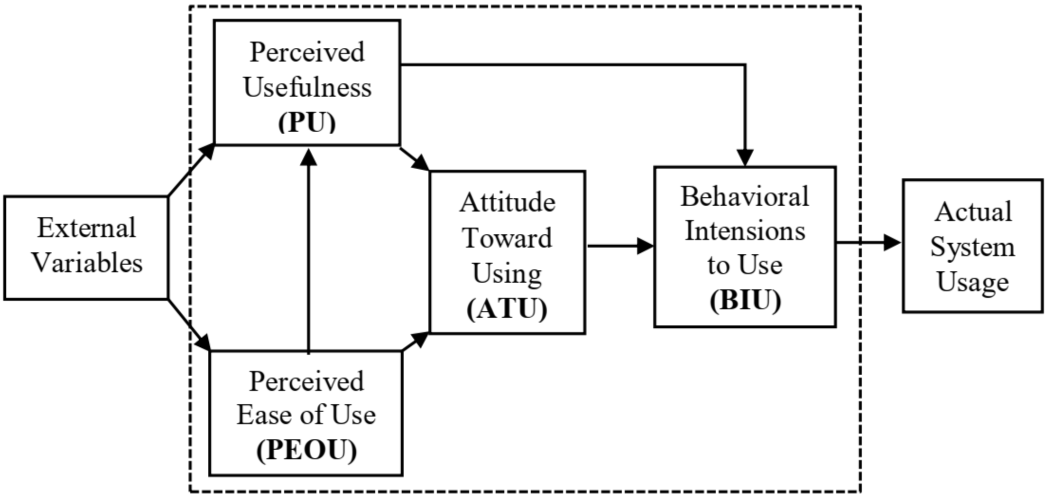

Fig. 13: the TAM model

The UTAU model theorizes that the intention to use a technology is influenced by Performance Expectancy, the measure to which a user thinks that using the system would improve his/her job performance, Effort Expectancy – the degree of easy associated with the use of the system, Social Influence –the degree to which an individual perceives that important others believe he/she should use the new system, Facilitating Conditions - the degree to which an individual believes that an organizational and technical infrastructure exists to support use of the system.

The following figure shows the influences between the key elements of UTAU and moderators such as gender, age, experiences and voluntariness.

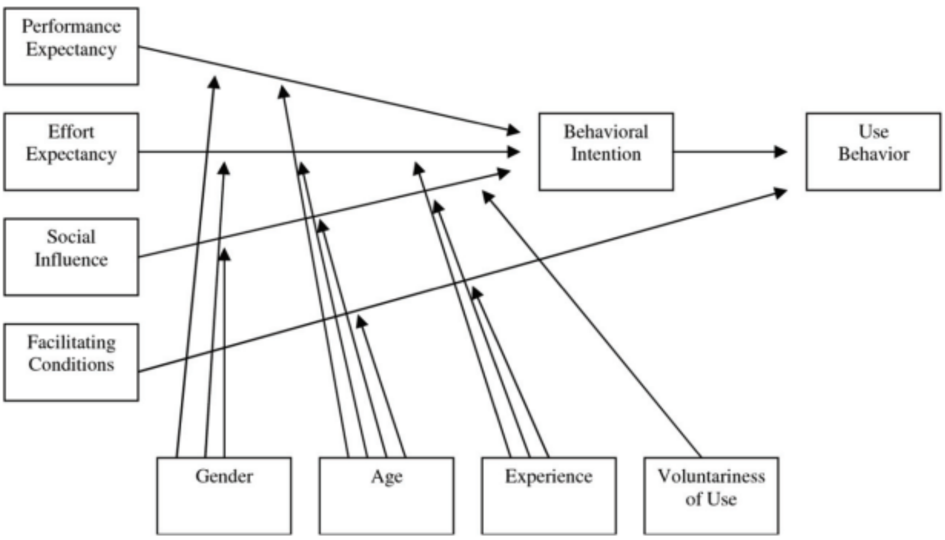

Fig. 14: the UTAU model ([35]).

User acceptance is a critical factor that needs to be taken into consideration especially today that information technology has greatly evolved and has shown innovations. In [42] a study of user acceptance of innovative technologies is presented while in [43] the factors that could influence the acceptance of new technologies in the workspace are examined. In general, user acceptance reflects whether a system is sufficiently compatible with the characteristics of the users and the characteristics

of the task to be executed. User acceptance is an indicator for successful user support by an information system.

3.3 Assessment of Energy Efficiency

The focus of the BIMERR project is the development of an ICT-enabled Renovation 4.0 toolkit to support the AEC community throughout the energy efficiency renovation process of existing buildings. In order to evaluate the outcome, the renovation projects under the BIMERR umbrella will be also assessed in terms of the energy performance of the renovated buildings. For this purpose, methods similar to the ones used in projects dealing with the energy efficiency of buildings will be used, and hence, the assessment will be based on the International Performance Measurement and Verification Protocol (IPMVP) ([44], [45]) that dominates the energy evaluations in the European projects, as well as criteria used by European directives for the energy performance evaluation of renovated buildings ([46]–[48]).

3.3.1 The IPMVP protocol

IPMVP is sponsored by the Efficiency Valuation Organization (EVO) [45]. EVO has published the IPMVP to increase investment in energy and water efficiency, demand management and renewable energy projects around the world. IPMVP presents common principles and terms that are widely accepted as basic to any good Measurement and Verification (M&V) process. According to [44], "Measurement and Verification" is the process of using measurement to reliably determine actual savings created within an individual facility by an energy management program. IPMVP does not define the M&V activities for all applications, rather each project must be individually designed to suit the needs of all readers of energy savings reports. This individual design is recorded in the project's M&V Plan and savings are reported as defined therein.

M&V activities consist of some or all of the following:

1. meter installation calibration and maintenance
2. data gathering and screening
3. development of a computation method and acceptable estimates
4. computations with measured data
5. reporting, quality assurance, and third party verification of reports

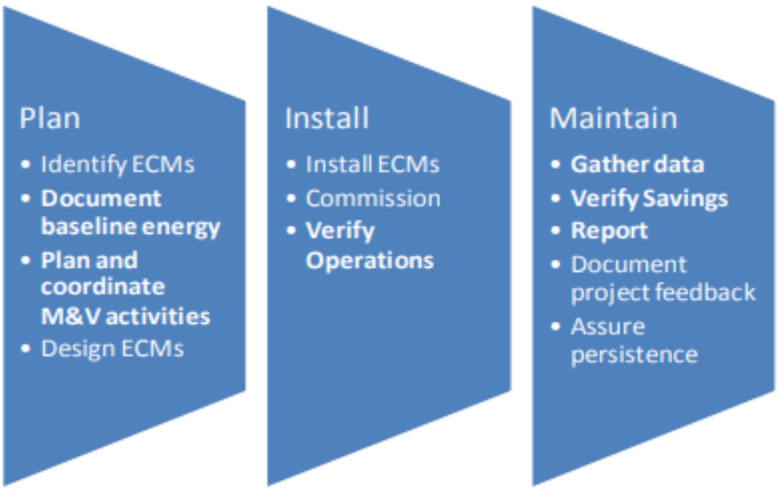

Fig. 15: Process Timeline (M&V activities in bold) [44].

Since savings cannot be directly measured, they are determined by comparing measured use before and after implementation of a project, making appropriate adjustments for changes in conditions. The saving or 'avoided energy use' is the difference between the adjusted-baseline energy and the energy that was actually measured during the reporting period. It is necessary to segregate the energy effects of a savings program from the effects of other simultaneous changes affecting the energy using systems. The comparison of before and after energy use or demand, should be made on a consistent basis, using the following equation:

$$Savings = (Baseline\_Period\_use\_or\_demand - Reporting\_Period\_use\_or\_demand) \pm Adjustments \quad (9)$$

Two types of adjustments are possible:

- Routine Adjustments – for any energy-governing factors, expected to change routinely during the reporting period, such as weather. A variety of techniques can be used to define the adjustment methodology. Techniques may be as simple as a constant value (no adjustment) or as complex as several multi-parametric non-linear equations each correlating energy with one or more independent variables. Valid mathematical techniques must be used to derive the adjustment method for each M&V Plan.
- Non-Routine Adjustments – for those energy-governing factors which are not usually expected to change, such as the facility size, the design and operation of installed equipment, or the type of occupants. These static factors must be monitored for change throughout the reporting period.

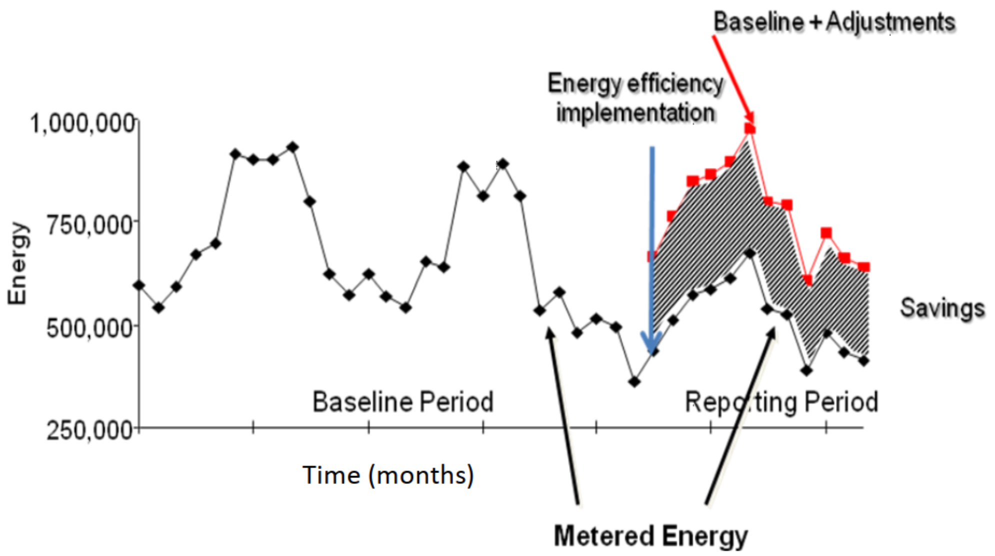

Fig. 16: Energy savings example [49].

IPMVP provides four options for determining savings: A, B, C and D. The choice among the options involves many considerations. If it is decided to determine savings at the facility level, options C or D may be favoured. However, if only the performance of the Energy Conservation Measure (ECM) itself is of concern, a retrofit-isolation technique may be more suitable (option A, B or D).

IPMVP Option	How Savings Are Calculated	Typical Applications
A. Retrofit Isolation: Key Parameter Measurement *Savings* are determined by field measurement of the key performance parameter(s) which define the *energy* use of the *ECM*'s affected system(s) and/or the success of the project. Measurement frequency ranges from short-term to continuous, depending on the expected variations in the measured parameter, and the length of the *reporting period*. Parameters not selected for field measurement are *estimated*. *Estimates* can based on historical data, manufacturer's specifications, or engineering judgment. Documentation of the source or justification of the *estimated* parameter is required. The plausible *savings* error arising from *estimation* rather than measurement is evaluated.	Engineering calculation of *baseline* and *reporting period energy* from: ○ short-term or continuous measurements of key operating parameter(s); and ○ *estimated* values. *Routine* and *non-routine adjustments* as required.	A lighting retrofit where power draw is the key performance parameter that is measured periodically. Estimate operating hours of the lights based on *facility* schedules and occupant behavior.
B. Retrofit Isolation: All Parameter Measurement *Savings* are determined by field measurement of the *energy* use of the *ECM*-affected system. Measurement frequency ranges from short-term to continuous, depending on the expected variations in the *savings* and the length of the *reporting period*.	Short-term or continuous measurements of *baseline* and *reporting-period energy*, and/or engineering computations using measurements of proxies of *energy* use. Routine and non-routine adjustments as required.	Application of a variable-speed drive and controls to a motor to adjust pump flow. Measure electric power with a kW meter installed on the electrical supply to the motor, which reads the power every minute. In the *baseline period* this meter is in place for a week to verify *constant* loading. The meter is in place throughout the *reporting period* to track variations in power use.

IPMVP Option	How Savings Are Calculated	Typical Applications
C. Whole Facility *Savings* are determined by measuring energy use at the whole *facility* or sub-*facility* level. Continuous measurements of the entire *facility's energy* use are taken throughout the *reporting period*.	Analysis of whole *facility baseline* and *reporting period* (utility) meter data. *Routine adjustments* as required, using techniques such as simple comparison or regression analysis. *Non-routine adjustments* as required.	Multifaceted energy management program affecting many systems in a *facility*. Measure energy use with the gas and electric utility meters for a twelve month *baseline period* and throughout the *reporting period*.
D. Calibrated Simulation *Savings* are determined through simulation of the *energy* use of the whole *facility*, or of a sub-*facility*. Simulation routines are demonstrated to adequately model actual *energy* performance measured in the *facility*. This Option usually requires considerable skill in calibrated simulation.	Energy use simulation, calibrated with hourly or monthly utility billing data. (Energy end use metering may be used to help refine input data.)	Multifaceted energy management program affecting many systems in a facility but where no meter existed in the *baseline* period. Energy use measurements, after installation of gas and electric meters, are used to calibrate a simulation. *Baseline* energy use, determined using the calibrated simulation, is compared to a simulation of *reporting period* energy use.

Table 7: Overview of IPMVP Options [44].

The selection of an IMPVP option is a decision that is made by the designer of the M&V program for each project, based on the full set of project conditions, analysis, budgets and professional judgment. Fig. 17 outlines the common logic used in Option selection.

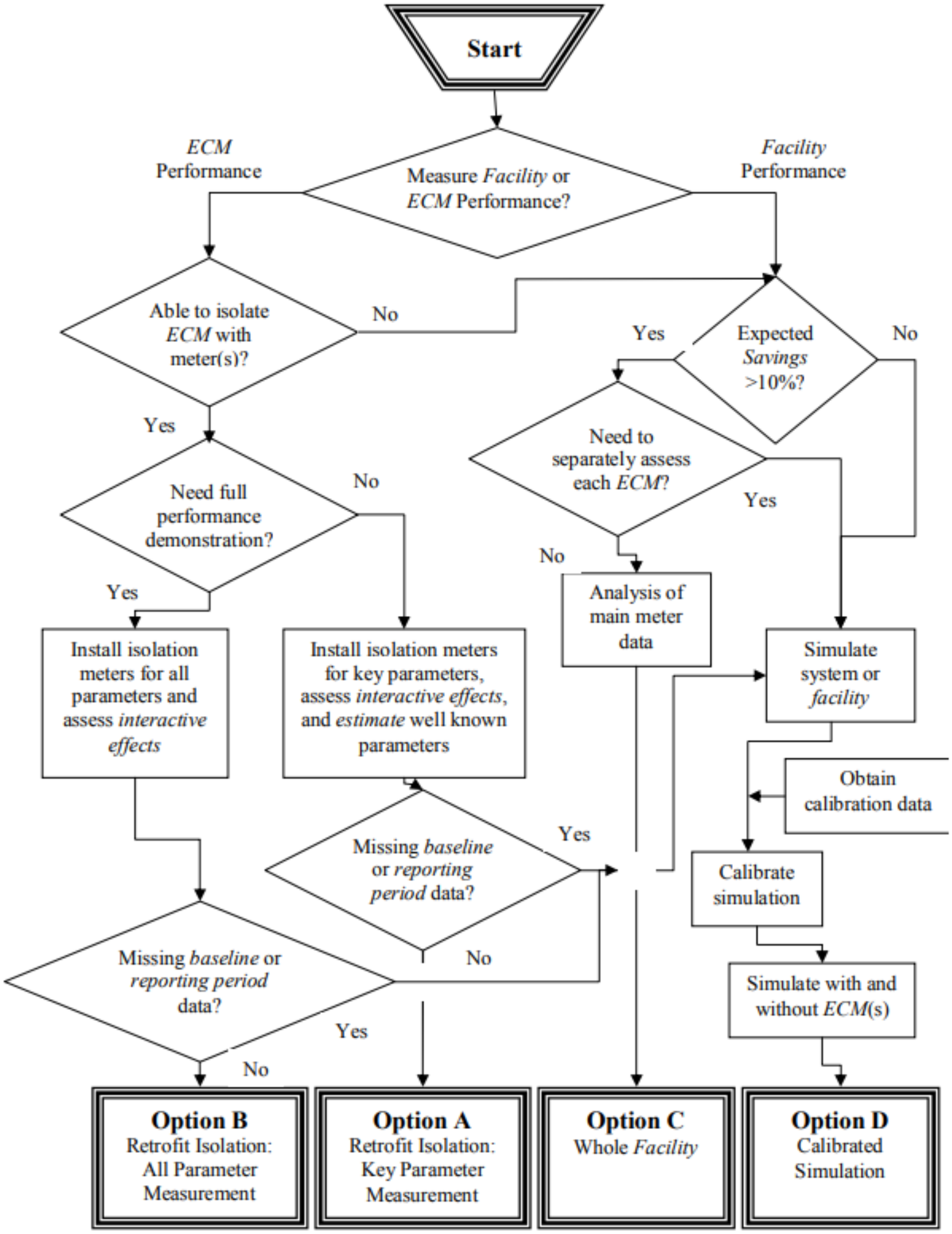

Fig. 17: Simplified IPMVP option selection process [44].

The renovation performance can be compared with reference to:

- The baseline period, i.e. the actual performance of the building measured in the period before the renovation.
- The predictions obtained from the simulation models, in order to assess the gap between predicted and actual performance.

The design of the M&V and reporting process must run in parallel to the ECM design and implementation process and the following issues need to be considered:

• When the focus is on the overall cost control, Whole-Facility methods are most suited, i.e. options C and D. On the other hand, when the focus is on particular ECMs, Retrofit Isolation techniques are most appropriate, i.e. options B and D. In large renovation projects, option A is not applicable.

• While developing the ECMs, the IPMVP option that best suits the ECMs, the needs for accuracy and the budget for M&V has to be selected. Furthermore, based also on the input data availability, it has to be defined whether adjustment of all energy quantities will be made to the reporting period conditions or to some other set of conditions, and also the duration of the baseline and the reporting period.

3.3.2 Development of the BIMERR M&V Plan

The first steps for the performance analysis consist in the collection of the necessary data to completely characterize the energy performance of the building:

- Define the type of measurement and data requirements
- Gather relevant energy and operating data from the *baseline period* and record them in a way that can be accessed in the future
- Identify significant energy uses

After these initial steps and depending on the results, an M&V Plan is prepared defining the subsequent steps.

3.3.2.1 Definition of the baseline

A first analysis must be carried out in order to establish the current performance of the building, before the implementation of any renovation action. This state of the building is defined as the Baseline, and its current energy consumption must be reported, in order to be able to evaluate the effect introduced by the deployment of renovation measures and compare the performance of the system before and after the introduced changes ([50]–[52]). Thus, to enable the thorough validation of the BIMERR framework, an ex-ante evaluation of the project pilot sites will take place before deployment to create a realistic and reliable performance baseline.

For the analysis of the energy performance of a building with a specific configuration, user behavior and equipment operation, it is necessary to ensure proper collection of data followed by a thorough analysis of this data to get a full characterization of the energy performance of the building. Therefore, it is necessary to define suitable Key Performance Indicators before the implementation of the BIMERR framework.

3.3.2.2 Analysis and comparison

In case of lack of adequate input data for the baseline definition, simulation model results are required to be used instead of real measurements. A model must be developed considering the collected data in the previous phase at each pilot site, constituting the Building Information Models. The Baseline, obtained before any intervention from BIMERR with current building state and configuration and energy performance, will be used as reference data for comparing the final results after implementing the BIMERR framework in the area of deployment.

The energy baseline characterization (measured or simulated) will include the following elements:

• Analysis of the energy consumption over a sufficient period of time (about one year) and with sufficient resolution (hourly if possible) to identify variations in consumption.

• Estimated breakdown in energy consumption according to use (e.g. hot water, heating, etc.).

• Independent and fixed variables that affect the energy consumption and the relevant values (i.e. degree days for heating or cooling, number of occupants for hot water, etc.). This data must be measured at the same time as the energy consumption data.

As indicated before, it is then necessary to determine adequate Key Performance Indicators that reflect the parameters needed for the assessment of the energy performance.

After the definition of the Baseline and the BIMERR project-specific M&V plan, the next actions will aim to design, install, calibrate and commission any special measurement equipment that is needed under the defined M&V Plan. Thus, for the approach and implementation of the monitoring system, we need to a) Identify the systems to measure, b) Specify the metering points, c) Track the energy consumption data. All the sources of energy delivered to the building by a utility company must be identified including all the renewable and nonrenewable sources of on-site energy generation.

Metering points and sensors required for performance verification, and the number, type and location of all the meters has to be specified. If multiple sources of energy are considered additional meters may be required. The location of primary building-level meters for each energy source has to be identified. If utility meters are shared with other buildings or the energy efficiency of a specific building area is considered (e.g. the building entrance hall), the installation of sub-meters will be required to provide the required data. The chosen M&V may use a single meter at the utility entrance or multiple sub-meters that account for whole building energy use in aggregate.

The measurement and recording of the energy consumption must be done with a time granularity that can vary depending on the needs (from real-time monitoring to time aggregation as day or month). Tracking of the building occupancy, use, and maintenance has to be considered in order to provide the context for the energy consumption data and the usage patterns.

However, it must be underlined here that BIMERR deals with the pre-commissioning stage and hence, any analysis or comparison will be performed only in the case that a renovated building enters the operational stage during the implementation of the project.

Finally, one of the least-cost and most efficient solutions in reducing emissions and energy demand is the development of modern (climate-resilient and low-carbon) district energy in cities ([53]). Modern district energy systems combine district heating, district cooling with combined heat and power, thermal storage, heat pumps and/or decentralised energy. Optimizing the interaction of buildings with urban systems (electricity, heating, etc.) needs to be addressed in urban planning processes. At district level, not only the individual buildings comprising the district should be considered, but also the energy generation plants and distribution grids [50]. Energy KPIs will characterize the performance of the elements inside the district boundary and the energy flows at the boundary with the exterior. Herein, at district level all the energy KPIs considered at building level will be considered as an aggregation of all the individual buildings, e.g. assuming a uniform building distribution in the district along with the building density in the area.

3.3.3 Occupants comfort and indoor air quality

The aim of the BIMERR project is to consider the role of building occupants as an active element of the building renovation process. The renovation design is adapted to the actual building use, as well as to the needs, schedules, comfort requirements and preferences of the occupants for better living quality. Following the definition of User Acceptance KPIs for the Occupants, where the usability of the BIMERR tool is assessed, one of the main objectives is to enhance the BIMERR performance evaluation framework with KPIs about occupants' preferences. Hence, special interest is on the occupants' response with respect to HVAC operation associated with air quality, as well as temperature and humidity.

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. Because there are large variations from person to person, it is difficult to satisfy everyone in a space. Thus, the environmental conditions required for comfort are not the same for everyone ([54]). Human's thermal sensation is mainly related to the thermal balance of the body as a whole. This balance is influenced by physical activity and clothing, as well as environmental parameters such as air dry bulb temperature, surrounding surfaces radiant temperature, air speed and humidity. The first two

factors are characteristics of the occupants, and the remaining four factors are conditions of the thermal environment. These parameters are combined in thermal models defined in bibliography to express thermal comfort and discomfort settings.

The topic of Indoor Air Quality (IAQ) is rather overlooked or simplified to a set of designed minimum air flow rates. This is partly due to the inability of the occupants of a building to quantify their discomfort due to reduced IAQ, compared to thermal perception, e.g. it is much easier to understand the effect of a cold, hot, too humid or too dry space to our thermal sensation. Nevertheless, many studies have tried to correlate the effect of reduced IAQ to a cost-related index, such as office productivity, with tangible results.

3.3.3.1 Indices for occupants comfort

Numerous indices for the assessment and design of thermal comfort conditions have been developed during the past 50 to 60 years. The IPMVP protocol through concepts and practices for Improved Indoor Environmental Quality, defines guidelines for thermal comfort related aspects. The protocol identifies ASHRAE thermal comfort models ([54]) as the ones to be addressed during the evaluation process. The most commonly adopted thermal model indicators ([55]) are the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD).

The PMV index is determined based on the estimated metabolic rate and the clothing insulation, and additional environmental indicators such as measured or predicted air temperature, mean radiant temperature, relative air velocity, and air humidity. It integrates the effects of the two personal parameters and the four environmental parameters on the thermal balance, and it predicts the mean thermal sensation on a seven-point thermal sensation scale. Table 8 presents the seven-point thermal-sensation scale, which serves as a basis for the predicted mean vote.

PVM Index	Thermal Sensation
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table 8: PMV Indicator Value

Measurement of the thermal parameters of the environment should be made in occupied zones of the building at locations where the occupants are expected to spend their time. Olesen (1995) [56], ISO 7726-2005 [57], and ASHRAE 55-1992R [54] provide detailed descriptions of the requirements for the measuring instruments and for thermal comfort measurement procedures.

On the other hand, the PPD index is derived from the PMV index and predicts the percentage of thermally dissatisfied persons among a large group of people. Occupants of buildings are not alike, and therefore the individual thermal-sensation votes of the occupants of a given environment will be scattered around the mean. The PPD index predicts the number of people likely to feel uncomfortably warm or cool. Typically, a 10% dissatisfaction criterion for thermal comfort is used for the determination of acceptable thermal conditions [58]. This corresponds to a PMV in the range -0.5 to +0.5. Note that the minimum attainable PPD is 5%, even when the result is a neutral thermal sensation (PMV = 0). Because of inter-individual differences, it is not possible to satisfy everyone. The next figure presents the PPD index curve:

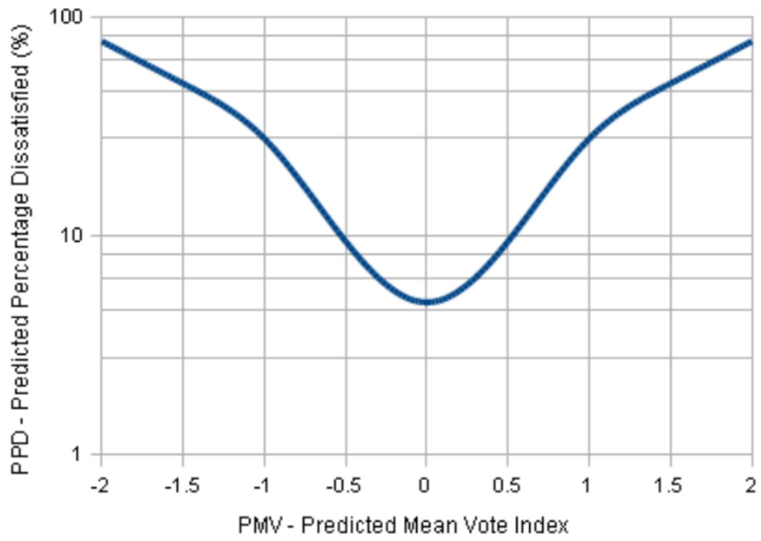

Fig. 18: Predicted Percentage Dissatisfied Indicator

The next equation provides the relation between PPD and PMV:

$$PPD = 100 - 95\exp\left(-(0.3353PMV^4 + 0.2179PMV^2)\right) \quad (10)$$

The PMV index has been validated as a predictor of thermal sensation in numerous comprehensive field studies. The next table shows the corresponding PMV and PPD values, considering indicative input parameters.

Run no.	Air temperature °C	Mean radiant temperature °C	Air velocity m/s	RH %	Metabolic rate met	Clothing insulation clo	PMV	PPD
1	22,0	22,0	0,10	60	1,2	0,5	–0,75	17
2	27,0	27,0	0,10	60	1,2	0,5	0,77	17
3	27,0	27,0	0,30	60	1,2	0,5	0,44	9
4	23,5	25,5	0,10	60	1,2	0,5	–0,01	5
5	23,5	25,5	0,30	60	1,2	0,5	–0,55	11
6	19,0	19,0	0,10	40	1,2	1,0	–0,60	13
7	23,5	23,5	0,10	40	1,2	1,0	0,50	10
8	23,5	23,5	0,30	40	1,2	1,0	0,12	5
9	23,0	21,0	0,10	40	1,2	1,0	0,05	5
10	23,0	21,0	0,30	40	1,2	1,0	–0,16	6
11	22,0	22,0	0,10	60	1,6	0,5	0,05	5
12	27,0	27,0	0,10	60	1,6	0,5	1,17	34
13	27,0	27,0	0,30	60	1,6	0,5	0,95	24

Table 9: PMV and PPD Values (ISO 7730: 2006- Annex D)

3.3.3.2 Indices for IAQ

In contrast to thermal comfort, IAQ definitions include long lists of different pollutants accompanied by reference value guidelines for each of them. Many standardisation efforts have been undertaken, often providing different views and categorisations of the various substances. The World Health Organization (WHO) air quality guidelines [59] are issued for the protection of public health from health risks due to a number of chemicals commonly present in indoor air. The guidelines are based on a comprehensive review and evaluation of the accumulated scientific evidence by a multidisciplinary group of experts studying the toxic properties and health effects of

these pollutants and they have been adopted by several European Projects in an effort to provide a unified KPI framework (e.g. [60])

Measuring all the proposed substances at high spatial granularity seems an exaggeration for a simple indoor residential environment and hence, in an attempt to balance the trade-off between ensuring acceptable IAQ and minimizing the associated sensing infrastructure cost, a small set of IAQ KPIs, is considered [50]: Carbon Dioxide (CO2), Carbon Monoxide (CO), Particulate Matter (PM) and Volatile Organic Compounds (VOCs). However, each building is unique and is subjected to different disturbances affecting indoor air quality. Hence, the initial selection of the evaluation metrics should be performed by the building Stakeholders based on the particularities of each target building. In case IAQ proves to be inadequate (e.g. by direct complaints from the occupants), more KPIs can be measured and calculated either for the entire building either targeted to specific spaces that are identified as problematic.

CO2 at very high concentrations (e.g. greater than 5000 ppm) can pose a health risk. However, in most buildings, concentrations almost never rise to these levels, but CO2 concentrations can be used as an indicator of occupant odours (odorous bioeffluents) and occupant acceptance of these odours. In addition, CO2 concentrations can serve as an appropriate air quality measurement because of the potential to predict the amount of outdoor air supplied to a space.

Carbon monoxide is identified as an appropriate air quality measure because of the significance of the health effects and associated risk and liability of this contaminant. Sources of carbon monoxide are carbon based fuel sources. A carbon monoxide indicator would assist towards identifying any IAQ problems in buildings with fuel-based heating systems and smoking areas, as well as buildings that are near traffic and parking areas.

Particulates are defined as suspended mixtures of solid of liquid particles. They include asbestos, silica dust, coal dust, bio-aerosols, smoke, and fumes. The toxicity of particles is related to the size and nature of the particle. Smaller particles are deposited further into the lungs and the removal processes at this location are slow. It is important to minimize airborne particles as much as possible using more routine means such as good housekeeping practices, upgrading filters, maintaining a positive pressure relative to the outdoors and having proper exhaust design.

According to the European Decopaint Directive (2004/42/EC): “VOC is any organic chemical with boiling point below 250 °C at a standard atmospheric pressure of 101.3 kPa”. VOCs may have effects ranging from odour perception and irritation of the mucous membranes of the eyes, nose and throat to acute and/or systemic effects and long-term effects. This also includes effects on the nervous system, allergenic or allergy-promoting and, in particular, carcinogenic, mutagenic or reprotoxic properties

Once again it must be noted that the choice of indoor air quality indicators will be determined by building stakeholders and the project partners taking into account the characteristics of the pilot sites.

3.3.4 Energy cost aspects

The running energy costs include all costs arising from the use of energy sources (oil, gas, solid fuels, district heating, electricity) in the building. The determination of the running energy costs should be based on the results of the calculations for the final energy demand consisting of space heating, water heating, auxiliary energy, lightning and HVAC. This comprises the total amount of costs, including the variable costs for electricity/gas/district heating used and the corresponding fixed costs for services. The calculations of the running energy costs are Electricity energy costs, Gas energy costs and District heating costs. The estimated costs should be based on the real price level from the respective European country.

The Pay-Back Time and Return on Investment (ROI) are specific KPIs that will define the business framework for retrofitting activities, comparing the investment costs with the economic savings achieved due to the energy conservation measures introduced in the retrofitting.

Pay-back Time refers to the period of time (in years) required to recover the funds expended in an investment. The payback period is considered a method of analysis with limitations since it does not account for the time value of money, but it is easy to use. It is calculated according to the equation:

$$\text{Payback Time} = C_{INV}/S \qquad (11)$$

where

C_{INV}: Investment costs

S: Yearly savings in running costs energy

Energy measures for buildings (retrofitting, maintenance) are efficient if the energy savings caused by these measures over the whole life cycle exceed the total investment costs for the measures. The Return on Investment is a very important issue for decision-makers to evaluate the economic efficiency of energy measures. It assesses the ROI of energy measures for the whole building by using the overall investment costs and the saving in running costs energy. The indicator only relies on the costs and savings from measures that are directly affecting the energy demand in the use stage over a defined period of consideration.

The calculation of Return on Investment (%) is calculated as follows:

$$ROI = \frac{S * \sum_{j=0}^{t}(1+Z)^{t}}{C_{INV} * (1+i)^{t}} * 100 \quad (12)$$

where

S: yearly savings in running costs energy [€].

$$S = Energy\ running\ costs_{original} - Energy\ running\ costs_{after\_measure} \quad (13)$$

C_{INV}: energy measures [€]

i: The total investment costs for the discount rate

z: energy price changing rate

t: period considered

Additionally, two other economic indicators usually considered for renovation are the Increase in Rental Rate of building, i.e. the percentage of rental rate increase of the renovated building and the Increase of Resale Rate of building, i.e. the percentage of resale rate increase of the renovated building.

3.3.5 Life Cycle Costs (LCC) & Sustainability perspectives

Life Cycle Costs is also a specific KPI that defines the business framework for retrofitting activities, but in a more complex form than the PayBack time since this KPI compares the investment costs with the economic savings achieved due to the energy conservation measures introduced in the retrofitting. LCC analysis considers all cash inflows and outflows over the useful life of the project, reducing each flow to its present value.

The LCC approach is an economic method to assist in the decision making process and to identify cost effectiveness of different design options and sensitivity of the cost resulting of the prices evolutions for products, services, energy and human operation. When two or more mutually exclusive alternatives are being evaluated, the one with the lowest life-cycle cost should be selected. That alternative will represent the lowest cost when expressed in net present value (NPV) terms. This indicator supports the European Commission objective to increase the consideration for life-time costs of buildings rather than just the initial costs, including construction and demolition waste.

The calculation of LCC is presented in different standards:

- EN ISO 15686- 5 introduces main principles and list of costs/benefits related to the buildings ([61]).
- EN 15459 describes more precisely the Global costing for the construction and operation stages. This standard provides a calculation method for the economics of heating systems and other systems that are involved in the energy use of the building (building envelope, ventilation, etc.) and applies to all types of buildings ([62]).
- EN 15643-3 presents the framework for development of LCC methodology applicable to buildings.
  Assessment shall be carried out at any time of the building life cycle (form inception to end of life) ([63]).

The LCC indicators are based on the modular approach from inception to the demolition of the building/end of life of equipment. The calculation of the Life cycle costs has to take into account the following Life Cycle Stages according to EN 15978:

- Construction Process Stage. The definition and quantification of the products used for the building construction and retrofitting are aligned with these defined for the calculation of the environmental indicators as presented in the European standards developed by CEN TC 350 ("EN 15978:2012; Sustainability in construction works – Environmental performance of buildings. Calculation method" [64] and "EN 15643-4: 2011 Sustainability in construction works. Assessment of buildings. Part 4 Framework for the assessment of economic performance" [65]).
- Use Stage. For consistency with the Directive on Energy performance of buildings the incomes due to energy sales are introduced (as a negative cost). Costs for maintenance shall be aligned with the management system of the building.
- End of life Stage. The costs for disposal are introduced in the calculation as a percentage of the buildings products costs.

The observation period (estimated life cycle of a building) will cover 50 years.

The considered costs in the LCC calculation include two aspects: the determination of investment costs for retrofitting measures and the determination of running energy costs.

The NPV factor is used to adapt the future costs to the moment when the economic assessment is performed. The NPV sums the discounted cash flows. It integrates and converts at the same time amounts of money (incomes, expenses, etc.) of various time periods. The formula that is used for the determination of the NPV is:

$$NPV = -C_0 + \sum_{t=1}^{n} \frac{F_t}{(1+p)^t} \quad (14)$$

where

t is the time period, usually a year

F_t the net cash flow for year *t*:

$$F_t = B_t - C_t \quad (15)$$

B_t is the benefit (inflows) for year t

C_t the cost (outflows) for year *t*

C_0 reflects the initial investment

p the cost of capital

n is the number of years of the investment's lifetime

It is assumed that the various net cash flows are collected at the end of the time periods, i.e. at the end of years. An investment should be realised only if *NPV > 0*, while in case alternative investments are compared, the best of them would be the one with the higher *NPV*.

3.3.5.1 Sustainability and Environmental aspects

Sustainability and environmental awareness is fast becoming an important renovation decision making parameter for many people, especially the most energy-conscious ones. A key challenge for the renovation sector is to enhance the sustainability and environmental performance of the building sector, to comply with relevant EU and national directives, while achieving optimization objectives that refer to the life-cycle of buildings and the materials/ components used, as well as other related aspects such as decommissioning and recycling. LCC can take into account a wide variety of metrics to estimate the holistic environmental impact of the building renovation using popular LCA methodologies with

concrete steps, i.e. life cycle inventory to reveal and analyse all the inventory and relevant flows followed by a life cycle impact assessment. In this context, several indicators can be considered such as acidification potential of soil and water, depletion potential of the stratospheric ozone layer, eutrophication potential etc., as well as aggregated indicators such as water pollution for the amount of water required to dilute toxic elements emitted into water or soil, air pollution for the amount of air required to dilute toxic elements emitted into air, environmental cost that effectively aggregates all the relevant environmental impacts into a single environmental cost, representing the environmental shadow price of a product or project.

3.3.5.2 Building level and district level

All the above economic and energy related KPIs are to be considered concurrently at both building and district level. At a building level, costs and savings will be considered until the building boundary, while at district level they will be considered as an aggregation of the individual building costs and savings. Hence at district level, all the KPIs considered at building level will be considered as an aggregation of all the individual buildings, e.g. assuming a uniform building distribution in the district along with the building density in the area.

4. RELEVANT EU PROJECTS

A research literature review is carried out in this section in order to identify performance assessment methodologies and possible benchmarks that could be leveraged by BIMERR.

4.1 EEMEASURE

The eeMeasure software [66] enables ICT PSP projects to calculate and record energy saving results using a consistent methodology. The idea was that it would enable the European Commission and other interested parties to produce a quantitative analysis of the energy savings potential of ICT based solutions in residential and non-residential buildings.

4.2 3E-HOUSES

3e-Houses is an EU Competitiveness and Innovation project (CIP) that finished in 2013 and targeted ICT for energy efficiency in social housing. The concept was energy conservation through the modification of tenants behaviour towards energy. Appropriate equipment was installed in pilot houses to monitor electricity and gas, and the collected results were available to tenants via a web interface.

The 3e-Houses developed its own M&V protocol and as comparison the eeMeasure methodology provided by EC was also used [67]. Small differences in the approaches were mainly attributed to the different regression models, i.e. linear for eeMeasure, quadrature for 3e-Houses. Its M&V protocol was based on the IPMVP but adaptations were required [68] since the project targeted residential end users rather than industrial, as in IPMVP.

3E-houses, eSESH and BECA are three EU projects that worked in parallel under the umbrella of ICT for energy efficiency in social housing. Their contributions ended up with a common deliverable regarding the methodology for measuring energy savings in the residential sector [49].

4.3 BECA

The *Residential Methodology* is a common deliverable from several ICT PSP projects [49]. The *Non-Residential Methodology* is a deliverable from the eeMeasure project [69]. Both methodologies are based on the International Performance Measurement and Verification Protocol (IPMVP). They are both developed from the experience of ICT PSP projects which include approximately 10,000 social dwellings and 30 public buildings (e.g. hospitals, schools).

The Non-Residential Methodology is closely aligned to the eeMeasure software. It can be used for any property type (including residential) and can be used with any data frequency. The methodology is based on the IPMVP and ICT PSP project types. A process flow is defined which directs projects to monitor appropriate variables and to create an accurate model, and also, a description of the underlying mathematical statistics can be found in [69].

The Residential Methodology was presented in [49] on April 2012. In response to the fourth Call for Proposals under the ICT PSP Work Program 2010, Objective 4.1 – "ICT for energy efficiency in social housing", three project consortia were asked to continue work on the development of a methodology for energy saving measurement. The outcome [49] represented the third version of the methodology, based on the second version provided by eSESH1 in September 2011 [4], while the first version was delivered by 3e-HOUSES2 in September 2010 [5]. It is applicable only to dwellings and generally assumes a monthly measurement period. The document introduces the IPMVP and discusses the four IPMVP Options and the use of basic statistical analysis. Measurement periods are suggested for different types of project and the evaluation of social and behavioural changes is considered. The document proposes a consumption analysis matrix and also discusses survey questionnaires.

The original basis for savings calculations within the ICT-PSP projects was a modified version of the EVO (www.evo-world.org) International Performance Measurement & Verification Protocol (IPMVP).

One early adaptation of IPMVP to ICT PSP was to attempt to reduce costs of measurement in line with the dramatically lower scale of energy consumption, by suggesting the use of larger time intervals for measurement and the use of less sub-metering. In addition, there were parameters such as demand response and avoided CO2 emissions which were not taken into account in the IPMVP protocol and extensions were required.

By assessing the IPMVP options in the context of ICT PSP for the residential sector, it was concluded that an assumption of constant demand (Option A) or cyclically predictable demand (Option B) or another demand structure which could be fully modelled (Option D), could not usually be made. In particular, none of these assumptions applied to projects aiming to change the resident behaviour – i.e. change demand – as a key way in which the intervention took effect, such as many interventions had been piloted in the ICT PSP projects. The approach offered in IPMVP as Option C was certainly applicable in an ICT PSP context. This option did not assume constant energy demand or that energy demand variation could be accurately modelled. Option C was a before-after comparison. The IPMVP approach in Option C still carried the notion of fully repeated cyclical variation in demand, i.e. an "operating cycle", however with some adjustments the approach was still applicable to ICT PSP pilots. The ICT PSP methodology also allowed for a control group approach, not defined in IPMVP. Where no baseline energy consumption data were available, the control group approach would be the only alternative. Also the control group approach could be used to evaluate behavioural changes (demand response).

4.4 MOEEBIUS

MOEEBIUS (Modelling Optimization of Energy Efficiency in Buildings for Urban Sustainability) was part of the H2020-EeB-2015 call in the topic: *New tools and methodologies to reduce the gap between predicted and actual energy performances at the level of buildings and blocks of buildings*. MOEEBIUS introduces a Holistic Energy Performance Optimization Framework that enhances current (passive and active building elements) modelling approaches and delivers simulation tools which deeply grasp and describe real-life building operation complexities in accurate simulation predictions that significantly reduce the "performance gap" and enhance optimization of building energy performance.

In general, the development of the Measurement and Verification (M&V) methodology in the MOEBIUS project has been based on the IPMVP [44] and FEMP [70]. Options A and B of the IPMVP are for the retrofit isolation method, i.e. for the evaluation of isolated energy conservation measures and consider only the affected equipment or system, independent of the rest of the facility. Options C and D are for the whole facility method, they consider the total energy use and de-emphasize specific equipment performance. FEMP [70] indicates the following six steps to measure and verify savings:

1. Allocate Project Risks and Responsibilities
2. Develop a Project-Specific M&V Plan
3. Define the Baseline
4. Install and Commission Equipment and Systems
5. Conduct Post-Installation Verification Activities
6. Perform Regular-Interval M&V Activities

The six steps defined in FEMP [70] to measure and verify savings are organized in the MOEEBIUS methodology in three phases: ex-ante analysis, implementation and M&V. Furthermore, an additional step is considered in the Ex-ante analysis phase, comprising the analysis and comparison of the defined baseline.

For the MOEBIUS framework, KPIs have been incorporated to assess the results achieved, i.e. the optimization of the energy performance at both building and district levels, addressing energy and economic savings, but always under user comfort conditions, (the complete list of MOEEBIUS KPIs can be found in [50]):.

- Energy KPIs

- Demand Response KPIs
- Occupants Comfort KPIs
- Indoor Air Quality KPIs
- Economic KPIs
- Predictive Maintenance KPIs
- MOEEBIUS Simulation system Performance KPIs

4.5 OrbEET

OrbEEt started on March 2015 and ended on February 2018 and focused on providing new ICT-based solutions for energy efficiency. It managed to associate energy consumption with specific business processes, office uses and organization entities instead of focusing only on the traditional "energy consumption of a building".

Comparing OrbEET to BIMERR, it should be noted that it is clearly not a renovation/construction project and its focus is on energy conservation via changing the occupants behaviour, rather than energy efficiency. In addition, it targets office buildings that are occupied by business, organization entities, etc. , when BIMERR is mainly focused on residential buildings.

The M&V methodology followed by OrbEEt was a combination of IPMVP Options D and C, [71]. Specifically, simulation and measurements were used for the baselining and reporting periods, respectively.

With respect to KPIs, OrbEEt delivered performance indicators in four axes, i.e. Energy Performance, Business Performance, Human Comfort and Users Engagement. However, herein, from the OrbEEt KPIs library, we provide a short description and the relevant calculation formulas only for the KPIs dealing with *Energy and GHG emissions* delivered by the project.

Category	Name	Description	Units	Formula
Energy	Energy Consumption	Total energy consumption is the sum of electrical energy, over a given time period T	KWh	Integral of the electric energy over time
Energy	Primary Energy Consumption (Monthly, Daily, Time-period)	Total primary energy consumption taking into account the source of energy	KWh	Energy Consumption * Primary Energy Indicator
Energy	CO2 emissions (Monthly, Daily, Time-period)	Total CO2 emissions taking into account the CO2 emissions ratio and energy consumption	$kg\ CO_2$	Energy Consumption * CO2 emissions ratio

Table 10: Energy and GHG emissions KPIs from Orbeet [51]

It is also worth noticing that the OrbEEt energy performance reporting offered granularity in four axes, i.e. spatial (per area, room type, etc.), temporal (per day, per week, etc.), occupancy related (per occupant role, per business process, etc.) and related device.

4.6 FLEXCoop

FLEXCoop is an EU project that started on October 2017 and focused on the smart management of the European electricity grid. It built upon the concept of an open Demand Response optimization framework where consumers are able to modify their electricity needs. At the prosumers' side, the energy devices installed in a building were able to control their operation (anticipate/delay/cancel) providing flexibility in energy consumption, allowing cooperative aggregators to sell the aggregated flexibility.

Comparing FLEXCoop to BIMERR, it should be noted that it is clearly not a renovation/construction project and its focus is on energy conservation (demand response of residential users) rather than energy efficiency.

FLEXCoop M&V methodology [52] cannot be entirely based on the IPMVP options. It is however loosely related to Options B and D, but with much sorter baseline/reporting periods since parameters such as human actions and occupancy are considered as dependent measurable variables.

FLEXCoop deals with six KPI categories, i.e. Energy, DR and Flexibility, Comfort, Economic, System Reliability, Security and Privacy, however, in Table 11 we provide a short description only for the KPIs measuring the *Energy and Economic Savings*.

Category	Name	Description	Units	Formula
Energy	Energy Saving	Quantifying the difference between measured and reference consumption data within a predefined period	KWh	
Energy	(Buildings) Final consumption	Quantifying the total amount of energy consumed in a building (or in a part of it) within a predefined period	KWh; KWh/m2	
Economic / Cost	CAPEX - CAPital EXpenditures	Summing up all upfront investment required to purchase, manufacture, install and put in operation the required equipment of FLEXCoop	Euro; Euro/m2	CAPEX = C1+C2+C3 where C1:cost of all materials and manufacturing, installation and put in modules, batteries, inverters, etc. C2 and C3: the cost of all sensors and control units of the IMCS and the OEMS
Economic / Cost	Return on Investment	Evaluating the economic efficiency of energy measures for the whole building by using the overall investment costs and the saving in running costs energy	%	$ROI = \frac{Revenue\ - Investment\ Costs}{Investment\ Costs}$

Table 11: Energy and Economic KPIs from FLEXCoop [52].

4.7 UtilitEE

UtiliEE is an EU ongoing project that started on November 2017 and targets energy efficiency through consumers' behavioural change. It proposes an ICT ecosystem that engages users in changing their energy-hungry activities though meaningful feedback, while at the same time focuses on automatically preserving users' comfort as well as engendering a healthy indoor environment. Taking this a step further, UtilitEE introduces new business models that exploit the potential of new services that consumers flexibility offers.

UtilitEE is clearly not a renovation/construction project, with focus on energy conservation via occupants' behavioural change.

The UtilitEE M&V protocol [72] followed a two phase approach based on Option C and B, respectively. The first phase (Option C), lacking sub-metering data, involved a top down approach with annual billing information along with adjustments for baselining that built upon a) occupancy data collected during building auditing and b) weather information. In the second phase, sub-metering data was available and a bottom up approach was implemented. The baseline period was decided separately for each type of device that was included in the sub-metering. For instance, HVAC systems are weather-dependent, so a year lasting baseline period is proposed, but for the rest of the energy consumption systems, such as DHW systems, a week-long baseline period is sufficient.

Regarding KPIs, the preliminary list includes both energy related metrics (usage and cost savings), and indoor environment quality metrics (such as percentage of satisfied occupants regarding thermal comfort, lighting, etc.).

4.8 DURAARK

This is an EU funded project [73] within the 7th Framework Programme. Its main objective is the preservation of 3D models for reuse. This is achieved by means of the design of algorithms for data ingestion, management, storage and access. Additionally, an important effort in geometric/semantic enrichment of 3D/BIM models is made (Scan-to-BIM). Validation aspects are mostly related to the

comparison of manual and automated (proposed) methodologies/pipelines for the generation of BIM models.

Amongst the performance evaluation processes and KPIs proposed to validate the Scan-to-BIM approach, some examples are:

- Quality control of new and existing BIM models, by means of
  - Deviation of produced BIM from physical world (i.e. planar deviation of facades)
  - Measuring the difference between point clouds and IFC generated models based on the nearest distance from points to geometry
  - Precision in registration
  - Percentage of properly reconstructed BIM elements (e.g. doors and windows).
  - Confusion matrices to show the performance in the recognition of electrical appliances
- Time comparison between traditional and DURAARK process (reduced by 31%), by measuring
  - Time consumed for manually generating BIM models
  - Time consumed for a semi-automated generation of BIM models with point clouds as a base
- - Quantitative parameters for the evaluation of data enrichment processes and entity retrieval.

4.9 P2ENDURE:

This ongoing four-year project [74] is framed on building renovation and it deals with prefabrication solutions, mainly envelope and Heating, Ventilation and Air Conditioning (HVAC), for renovation processes. Besides energy performance analysis, P2ENDURE proposes BIM-based software tools for parametric modelling of prefab components and asset management. The project is monitoring ten live demonstration pilots in different EU countries and partners will potentially engage with at least fifty real-estate clients, end-users, policy makers and industrial partners. Regarding validation procedures, the project measures time, cost and energy performance, claiming 15% of budget reduction, 60% of energy savings and 50% of installation time reduction. Additionally, the partners consider the welfare of inhabitants (from the point of view of both environmental hazards and disturbance) during renovation.

Regarding energy efficiency, the partners evaluate energy consumption after and before renovation, by means of Building Energy Models (BEMs) or manually.

- Pre-renovation: energy audits, bills, energy models, transmittance, temperature and time pattern of indoor usage, existing BIM/BEM.
- Post-renovation: energy simulation after renovation. Renovation tasks include improving window glazing, insulation, solar panels, etc.

With respect to budget and time reduction, partners provide three indicators:

- Life Cycle Cost (LCC) that is 15% less than the traditional comparative cost of deep renovation.
  - Comparing: maintenance without renovation, traditional renovation, renovation with P2ENDURE
  - CAPEX: renovation costs per m^2 envelope or units
  - OPEX: Current/expected maintenance after renovation, energy and other costs (e.g. water)
- Payback time for P2ENDURE approach is estimated less than 3 years.
  - Return on Investment
- Decrease of the installation time by 50% in comparison with available renovation solutions and decrease of the overall renovation time. The analysed operations include:
  - As-built data collection
  - Renovation design
  - Engineering

- Renovation works
- Maintenance

  Note that, regarding installation procedures, maintenance time has not been evaluated/compared, yet. Generally, renovation is the time-saving operation.

Finally, different indicators are utilised to measure the welfare of the building occupants, mostly by means of qualitative surveys. These include:

- Safety sensation
- Noise and vibrations
- Time for construction activities
- Surface occupied
- Generation of waste

Dust emissions is the only quantitative indicator related to neighbours wellbeing.

4.10 EEEMBEDDED:

Finished in 2017, this project [75] is part of the 7th framework program. It is focused on the development of an energy system simulation model to support an integrated information management framework for designing energy-efficient buildings and their optimal energetic embedding in the neighbourhood. The project is framed on the building design stage, and its performance on two pilot projects is validated by means of Cost-Benefit Analysis (CBA) and Strengths, Weaknesses, Opportunities and Threats (SWOT), delivering qualitative results.

However, one of the main objectives of this project that can be of interest for BIMERR is the development of a control and monitoring system based on KPIs. KPIs proposed in this project are related to energy and emissions, socio-cultural aspects (thermal comfort and air quality), and investments and operational costs. Amongst the KPIs related to energy, relevant examples are:

- Cooling and heating demand (net energy): solar gains, heat losses, peak loads
- Energy consumption: overall efficiency, percentage of thermal energy demand covered
- Heat balance outputs: thermal gains and losses, enthalpy
- Emissions: global warming potential, ozone depletion potential, acidification potential

Regarding investments and operational costs:

- Life Cycle Costs: investment, operation, maintenance
- Payback

And with respect to socio-cultural aspects:

- Comfort conditions: physiological equivalent temperature, air flow rate, shading
- Indoor climate class: min/max temperatures, CO2 concentration, humidity

4.11 OPTEEMAL

This Horizon 2020 project [76] finished on February 2019 and deals with energy retrofitting at district level. Its main goal is the development of decision support tools to assist district renovation/refurbishment/reconfiguration planning, integrating the needs of inhabitants, authorities and investors. To do this, partners have integrated stakeholders needs into a single software environment, analysing different scales and time frames. The proposed tools assess costs and benefits, environmental and social impact.

4.12 BUILT2SPEC

This ongoing project [77] is part of the H2020 programme. The project is focused on the construction of new buildings (although partners also mention retrofits) according to specifications and standards. A number of technologies and developed tools are connected to a virtual management platform for inspection and quality measures, considering EU energy efficiency targets, and building standards and policies.

Amongst the aspects considered for quality checking, the following can be highlighted:

- With respect to energy efficiency:
    - Thermal performance is estimated by calculating the heat transferred from indoors to outdoors (or vice versa). Key indicators to measure the thermal bridging of the external envelope are the percentage of areas below the critical surface temperature or the global U-value.
    - Regarding air tightness, the energy loss through cracks and gaps is evaluated by means of parameters such as leakage rate or permeability.
- Other indicators are utilised to measure the wellbeing of neighbours:
    - Indoor air quality is measured through the evaluation of pollutant concentration.
    - Acoustic performance is also evaluated.
- Regarding 3D (re)construction, geometric information is acquired by means of reality capture technologies to evaluate:
    - Verticality, horizontality and angles of structural components
    - and location of other elements

  which are compared with as-designed or as-is BIM models.

5. BIMERR BASELINING METHOD

The baselining methodology considers the BIMERR impact in terms of major KPIs such as the renovation cost and time reduction and energy savings where a *before-after* comparison is required. User acceptance, which is also a major impact category of BIMERR and is evaluated according to section 6.2, does not participate in any comparison assessment, so no baselining approach is required.

5.1 TIME AND COST BASELINING METHOD

In order to assess the BIMERR impact on the time and cost performance of a renovation project, a baselining method must be defined, i.e. a way to determine what the duration and cost of a renovation project is when the traditional renovation approach is followed.

Reviewing the assessment methodologies followed by the industry and described in section 3.1.1, both the CPM method, i.e. activity-based planning, and the LBMS method, i.e. location-based planning, satisfy our requirements for time and cost baselining. Both can analyse complicated construction projects and provide efficient project management. CPM is a far more established method, already implemented by typical project management packages such as Microsoft Project and Primavera, however, CPM fails to implement current concepts and construction trends such as workflows, uninterrupted management and use of resources, crew efficient balancing. A hybrid solution can be considered as the obvious solution, i.e. an extension of CPM that will adhere to the lean construction benefits offered by LBMS.

It should be pointed out that the renovation process will be modelled in detail in T6.1 where the different phases and steps will be broken down into specific activities and assigned to a specific location. In turn, such Business Process models of the renovation process will be transformed into workflow models establishing all the necessary connections and dependencies between them (with special consideration given to time-relevant inter-dependencies between activities and prerequisites for the initiation of a specific activity) , and leading to an adaptive renovation process. Therefore, the exact adaptation of the renovation process into a possible CPM-LBMS hybrid model will be delivered as part of the task 9.1, when all necessary information will have been collected and properly analyzed, reflecting both the existing process, along with the re-designed/ optimized process delivered in WP6.

Simulations will be used for providing the necessary baselining metrics which will be used for assessing the cost and duration reduction (%) offered by BIMERR-enabled renovation process. Simulations will consider historical data provided by the demo partners, along with data collected through surveys (interviews/focus groups) so as to quantify and take into account observations and valuable empirical knowledge coming from hands-on experience of the construction actors from previous projects.

5.2 ENERGY BASELINING METHOD

For energy performance, energy efficiency, energy costs and occupants' comfort baselining, we will rely on the IPMVP protocol, following a hybrid approach to be supported by the BIMERR Building Energy Performance Estimation module. This means that in order to perform a sound baselining we will collect all the available data and combine them with simulated results for those aspects that data are missing from the real buildings. These simulations will be adjusted/calibrated by utilizing the actual data that are available, while appropriate normalisation techniques will be applied (considering degree days variations and occupancy diversity) to ensure objective comparisons between the pre-renovation and post-renovation building performance, thus being able to accommodate diverse weather conditions within different years and alternative occupancy patterns caused by different use of specific spaces/ zones. Given the nature of the project, it is expected that comparison of the achieved energy performance at post-renovation phase with the baselining and impact assessment will be mostly based on accurate results delivered through the BIMERR Building Energy Performance Estimation Tool, since it is not expected that renovated buildings will have entered the operational phase until the end of the

project. Needless to say, in case that we do have the building in operational phase during the project, then, we can do the evaluation based on actual data.

A similar approach will be followed for the occupants' comfort impact assessment and gains achieved between the pre- and post-renovation phases, utilizing the relevant functionalities of the BIMERR Building Energy Performance Estimation Tool to calculate in an accurate manner the relevant KPIs (PMV, PPD). Again, if the building enters operational phase during the project, assessment of comfort will be done based on actual data measurements, in combination with appropriately designed surveys, to collect valuable insights on user acceptance with regards to comfort preservation in the post-renovated built environment.

5.2.1 Baseline comparison

The savings in energy costs are the difference between the running energy costs of the building after the deployment of energy renovation measures in order to achieve energy savings and the running energy costs that the original building would have had at the same time period. The running energy costs that the original building would have had are considered to be equal to the running energy costs of the original building measured during the baseline period but with the appropriate adjustment. Care should be taken in selecting the period of time to be used as the baseline period and the reporting period. Strategies for both periods are discussed in IPMVP [44]. The baseline period should be established to:

- Represent all operating modes and conditions of the facility. This period should span a full operating cycle from maximum energy use to minimum. Whole-building energy use can be significantly affected by weather conditions. Typically, a whole year of baseline data is needed to define a full operating cycle.
- Include only time periods for which all fixed and variable energy-governing facts are known about the facility. Extension of baseline periods backwards in time to include multiple cycles of operation requires equal knowledge of all energy-governing factors throughout the longer baseline period in order to properly derive routine and non-routine adjustments after ECM installation.
- Correspond to the period immediately before the application of the energy measures. Periods further back in time would not reflect the conditions when energy measures were taken and may therefore, not provide a proper baseline for the specific ECMs.
- ECM planning may require study of a longer time period than is chosen for the baseline period. Longer study periods assist the planner in understanding facility performance and determining the actual length of a normal cycle.

The user of the savings reports should determine the length of the reporting period. The reporting period should encompass at least one normal operating cycle of the facility, in order to fully characterize the savings effectiveness in all normal operating modes. The length of any reporting period should be determined with due consideration of the life of the ECM and the likelihood of degradation of originally achieved savings over time.

As already discussed in section 3.3.1, the Routine and Non-Routine Adjustments shown in Equation (9) should be computed in order to compare in similar conditions if the initial conditions (governing the energy performance) have changed. Appendix B of IPMVP [44] offers some guidance on assessing the validity of mathematical methods. Applicable methods and the corresponding mathematical expressions can also be found in [78], to adjustment factors such as the weather conditions and the occupancy level. Therefore Equation (9) can be expressed more fully as:

$$Savings = (Baseline\_energy - Reporting\_period\_energy) \pm Routine\_Adjustments \pm Non\_Routine\_Adjustments \quad (16)$$

The adjustments terms in Equation (16) are used to express both pieces of measured energy data under the same set of conditions. The mechanism of the adjustments depends upon whether savings are to be reported on the basis of the conditions of the reporting period, or normalized to some other fixed set of conditions. The adjusted-baseline energy is normally found by first developing a mathematical model which correlates actual baseline energy data with appropriate independent variables in the baseline period. Each reporting period's independent variables are then inserted into this baseline mathematical model to produce the adjusted-baseline energy use.

Apart from actual measurements, we can use the results of calibrated simulation which involves the use of computer simulation software to predict the facility energy for one or both of the terms in Equation (9). A simulation model must be calibrated so that it predicts an energy pattern that approximately matches the actual metered data. Calibrated simulation is useful where:

- Baseline energy data do not exist or are unavailable
- Reporting-period energy data are unavailable or obscured by factors that are difficult to quantify
- It is desired to determine the savings associated with individual ECMs

Savings can be determined using calibrated simulation results representing the baseline energy and/or the reporting-period energy. For projects with a physical baseline, the two calibrated models include one with the ECMs and one without them. For projects with a hypothetical baseline, calibrated models may include the hypothetical baseline and the as-built (reporting period) conditions, but measured data will only be available for calibration under as-built conditions. In either case, both models and measured energy data must be under the same set of operating conditions.

Furthermore, presuming that the calibration error equally affects both baseline and reporting period models, then savings can be estimated as:

$$Savings = Basiline\_energy\_from\_the\_calibrated\_model[hypothetical\ or\ withoud\ ECMs] - Reporting\_period\_energy\_from\_the\_calibrated\_model\ [with\ ECMs] \quad (17)$$

One of the model-derived energy terms in Equation (17) may be replaced by the actual measured energy. However, one must adjust the calculations for the calibration error for each month in the calibration period, using the following Equation:

$$Savings = Baseline\_energy\_from\_the\_calibrated\_model\ [hypothetical\ or\ without\ ECMs] - Actual\_calibration\_period\_energy \pm Calibration\_error\_in\_the\_corresponding\_calibration\_reading \quad (18)$$

In the BIMERR framework, calibrated simulation is going to be used in order to predict the energy performance of the building after the renovation, unless the renovated building is in operational mode during the project. Accurate computer modelling and calibration to measured energy data are the major challenges associated with Calibrated Simulation.

6. KPIs for BIMERR Assessment

6.1 Renovation time and cost assessment

This section presents the KPIs for evaluating cost and time of a BIMERR enabled renovation. The approach followed is based on the SLAM goal-driven method that can be found in [27]. At this point it should be pointed out that the KPIs introduced herein are primarily performance indicators for the tools that will be developed in the framework of BIMERR and will support the entire renovation process; from the initial inspections to construction and up to the finalization of the as-built project documentation. Most of the KPIs that will be presented in this section are already established in the construction industry and tracked by construction companies, so any improvement on their measured value is directly associated with the increased accuracy and performance enhancement of the BIMERR tools that will be replacing the traditional approaches. Furthermore, when the pilot details are known then it will be possible for the overall accuracy and performance improvement to be specified exactly, (probably in a cumulative manner), as already described in the DoA in T9.1.

In order to evaluate the time and cost reduction in the renovation process the following methodology was followed:

1. Analysis of BIMERR goals/objectives
2. Analysis of what causes delays and cost over-runs in a typical renovation project [79]
3. Analysis of BIMERR use cases; this work was conducted in the framework of T3.1, [4]
4. Association of use cases to phases - and steps when possible (Fig. 19), since the BIMERR project targets all phases of renovation process from auditing to construction (up to the as-built documentation)
5. Production of preliminary list of KPIs for time and cost
    5.1. Involving measuring directly time or parameters that can be translated into time/cost requirements. For this step we need to be clear about what kind of delay (e.g. delay due to design errors, due to wrong quantity orders, etc.) the BIMERR tool involved in the use case is supposed to minimize, so as to associate it with parameters that can be measured.
    5.2. For each KPI the following information is provided:
        - name
        - description, i.e. why it is important to have the specific KPI in the evaluation framework of BIMERR
        - the renovation phase (and step when possible) where it will be measured
        - the use case it is associated with
        - a short analysis considering its calculation method; either a calculation formula is provided or the software tool (BIMERR or otherwise) that will be used for the calculation.
        - an indication whether or not it is related directly to the performance assessment of the tools that will be developed under the BIMERR framework.
6. The preliminary list of KPIs is reviewed by the pilot partners in order for specific aspects such as measurability, collectability and comparability of the proposed KPIs to be examined.
7. The first list of KPIs is circulated among the partners for review comments

Fig. 20 presents the methodology for the production of the list of candidate KPIs.

The final list of KPIs is presented in section 6.1.1 and consists of two categories: a) state indicators and b) impact indicators; with the second category to be directly related to the BIMERR impact in renovation duration and cost. Note that this categorisation is also used for the Energy KPIs. It should be pointed out that although CT28-CT30 are in essence Health & Safety metrics, they are included in

the table since they are also directly associated with the time and cost performance of any renovation project.

For reasons of comparison between the traditional renovation approach (baselining) and the BIMERR approach, historical data have already been collected by the pilot partners as shown in section 3.1.3. However, if more data is required, interviews and surveys with members of the living lab will be considered for providing estimation on reference values.

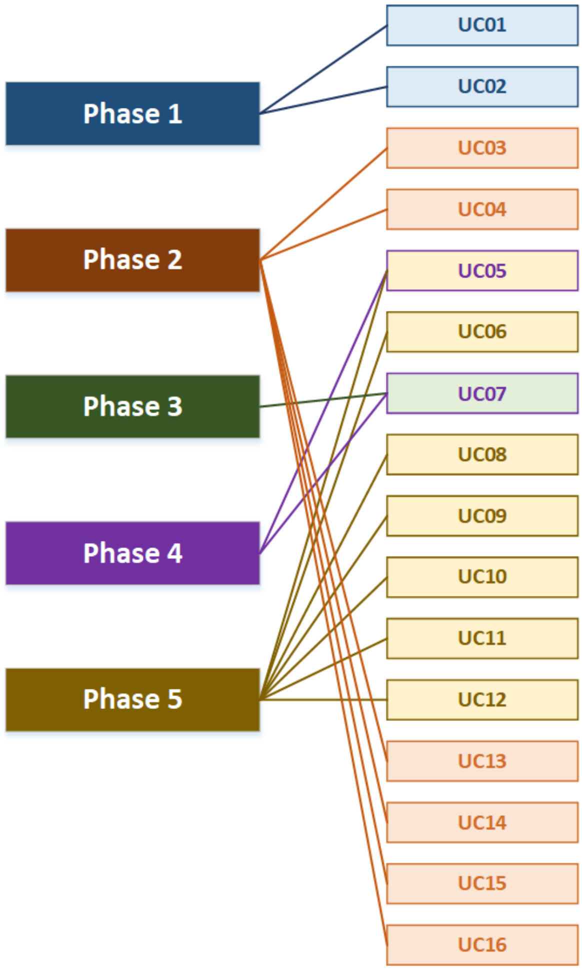

Fig. 19: Renovation phases mapping to BIMERR use cases

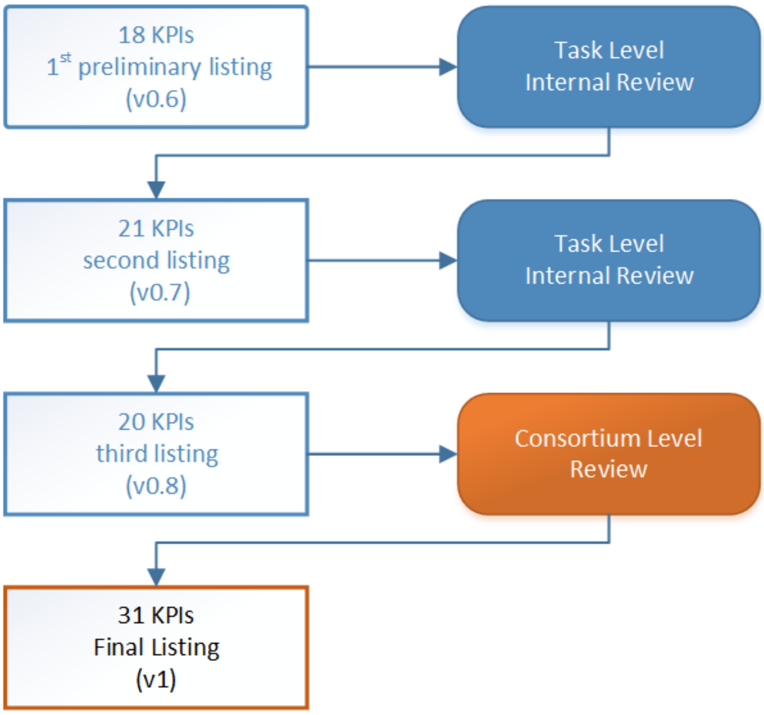

Fig. 20: Methodology for the production of the list of candidate KPIs

6.1.1 *KPIs for assessing time and cost performance of renovation*

6.1.1.1 State indicators

KPI	Name	Renovation Phase (Steps)	UCs	Description	Calculation	Performance/Accuracy
CT1	Time required to complete the as-is model of the building to be renovated (geometry only). (days)	**1** (1.1, 1.3)	UC1 UC2	BIMERR Scan-to-BIM solution provides a (semi-) automatic approach to produce as-is geometric models of the buildings under renovation. This process is expected to be faster than traditional manual approaches used for the generation of 3D models.	The process starts with scanning (T_{start}) and is completed (T_{end}) with creation of the BIM model. BIMERR tools: Scan-to-BIM, BIM Platform	✓
CT2	Time required to update the as-is model with complete building information (systems, energy equipment, hidden installations).	**1** (1.4, 1.5)	UC2	With BIMERR HMD-AR and ARIBFA (AR-enabled In-situ Building Feature Annotation) app the as-is model is accurately updated with energy related equipment, their characteristics and other related hidden components within the building. Some components can be detected automatically through the AR sensors and geometrically modelled and positioned automatically in the BIM model, so that the user only needs to focus on entering any other object information that cannot be obtained visually with the AR cameras. For the traditional process this is done during the technical survey of the building with visual inspection of the building, and subsequent transcription into the project model.	The process starts with the identification of the building equipment (T_{start}) and is completed (T_{end}) with the update of the BIM model. BIMERR tools: ARIBFA, Smart Glasses, BIM Platform	✓
CT3	Number of simulations performed	**4** (4.3, 4.4) **5** (5.1, 5.2,5.3, 5.4, 5.5, 5.6, 5.10, 5.11)	UC5	With the BIMERR Renovation Process Simulation and Formal Verification tool the Project Manager can simulate the planning process and optimize the efficiency of different parameters like time and cost via multiple iterations. In the traditional construction approach, there is no such option available.	BIMERR Tool: Renovation Process Simulation and Formal Verification tool	✓
CT4	Number of total issues detected during the first phase of the planning process (before finalizing	**4** (4.3, 4.4) **5** (5.1, 5.2,5.3,	UC5	With the BIMERR Renovation Process Simulation and Formal Verification tool, the Project Manager can detect potential issues (like deviations from time and cost projections) during the planning phase of a project. These issues	BIMERR Tool: Renovation Process Simulation and Formal Verification tool	

This project has received funding from the European Union's Horizon 2020 Research and innovation programme under Grant Agreement n°820621

	the project scheduling), $N_{iss,pl}$.	5.4, 5.5, 5.6, 5.10, 5.11)		would otherwise emerge during the construction phase and would increase the project's duration and actual cost. In the traditional approach, the proper planning of a project's construction phase is based only on the Project Manager's professional experience and good practices. *Possible association to time/cost gain:* If we consider that currently there is no issue detection software available for the planning phase of a project, the gain is straightforward: $\frac{N_{iss,pl}}{N_{iss,ref}} \times 100\%$, where $N_{iss,ref}$ is the average number of total issues that arise due to poor planning during the construction phase of a similar project.		
CT5	Number of orders placed and managed in an automated manner during planning process	**5** (5.6, 5.7, 5.9, 5.15)	UC6 UC7	With the BIMERR workflow automation tool orders are sent to different vendors/manufacturers in an automated manner. Considerable time/cost savings compared to the traditional approach where this task is handled by the project manager and his/her team.	BIMERR tool: PWMA Toolkit	
CT6	Number of orders delivered Just-in Time, $N_{OR,JIT}$.	**5** (5.7, 5.9, 5.11)	UC8 UC9	BIMERR enables the simulation and monitoring of the construction process. This way information on when ordered materials should be installed can be determined in advance with precision. This information can then be transferred to the manufacturer enabling the Just-in Time (JIT) method and avoid unnecessary delays. The calculation will be based on the ratio $$\frac{N_{OR,JIT}}{N_{OR,total}} \cdot 100\%$$ where $N_{OR,JIT}$ is the number of orders delivered JIT during construction and $N_{OR,total}$ is the total number of orders placed during planning.	BIMERR tool: Process Modelling Tool of the PWMA Toolkit	✓
CT7	Number of automated RFIs (Request for Information) sent during planning process	5 (5.6, 5.7, 5.9, 5.15)	UC6 UC7	With BIMERR workflow automation the RFIs are sent in the different stakeholders in an automated manner.	BIMERR tool: PWMA Toolkit	✓

CT8	Number of adjustments to the project schedule during planning process (after project scheduling is finalized)	5 (5.6, 5.7, 5.9, 5.15)	UC6 UC7	The project manager (or the person responsible for orders, logistic planning etc.) receives alerts for issues that could lead to re-scheduling of the project/workflow; thus optimizing the route of project implementation.	BIMERR tool: PWMA Toolkit	
CT9	Response time (averaged over the RFIs sent).	**3** (all) **4** (4.3, 4.4)	UC6 UC7	BIMERR semantic interoperability provision simplifies processes and eliminates the need of paperwork; thus, time savings in the delivery of requested data are expected due to the efficient, high performing and mainly reliable exchange of information.	BIMERR tool: PWMA Toolkit	
CT10	Time for uploading data to the BIF	**1**(1.1, 1.3)**,** 3, **4** (4.3, 4.4)	UC01 UC02 UC07	BIF (BIMERR Interoperability Framework) is a crucial part of BIMERR functionality since will allow the communication of different systems owned by different stakeholders. Practically throughout the renovation process, stakeholders need to upload infromation to the BIM platform; the semantically enhanced BIM model is uploaded to the BIM Platform during building auditing phase, all the necessary documents for permisionning are also uploaded and information produced after the executive design, such as drawings etc., are also uploaded during permisionning and planning phases. Thus, time required for uploading data is an important KPI.	BIMERR tool: BIF	✓
CT11	Number of errors encountered in data received	**1**(1.1, 1.3)**,** 3, **4** (4.3, 4.4)	UC01 UC02 UC07	During renovation process practically all stakeholders get to upload some kind of information to the BIM Platform. This information however is received by other stakeholders (internal or external), therefore tracking the errors encountered in received data is an improtant KPI.	BIMERR tool: BIF	✓
CT12	Time needed to fine-tune the semantic mapping	**1**(1.1, 1.3)**,** 3, **4** (4.3, 4.4)	UC01 UC02 UC07	The communication between systems owned by different stakeholders is based on semantically interoperable mechanisms, so this KPIs will measure the time performance of BIF when fine-tunes the semantic mapping.	BIMERR tool: BIF	✓
CT13	Number of errors encountered in the semantic mapping of data	**1**(1.1, 1.3)**,** 3, **4** (4.3, 4.4)	UC01 UC02 UC07	The communication between systems owned by different stakeholders is based on semantically interoperable mechanisms, and semantic mapping of data may be subject to errors.	BIMERR tool: BIF	✓
CT14	Number of connectivity issues observed, leading to process delays	**1-5**	all	All stakeholders need to access the BIM Platform in several situations during the renovation process. This KPI examines the connectivity issues that occurred during the renovation project.	BIMERR tool: BIF	✓
CT15	Number of incidents allowing unauthorized access to data	**1-5**	all	BIMERR provides the Building Information Secure Provisioning Tool that is used in order for specific data access policies referring to the access rights of each stakeholder to the building information available in the BIM Platform to be defined. As a result, each time a stakeholder tries to build a query regarding building information the aforementioned access polices need to be respected.	BIMERR tool: BIF	✓

CT16	Time spent in successfully completing the setting up and delivery of orders.	**5** (5.6, 5.7, 5.9)	UC6 UC7	The automated execution of the processes workflow provided with BIMERR will lead to reduced durations of the relevant steps of the renovation process.	Project Management tool	✓
CT17	Number of reworks during construction process	5 (5.12, 5.13)	UC8	Detailed context-aware information (instructions, drawing, BIM model, etc.) will be available real time in working crews' smart equipment reducing errors during construction works that traditionally lead to reworks, i.e. possible cost and time overruns.	Project Management tool	✓
CT18	Number of automated tasks assigned to working crews during construction works.	5 (5.12, 5.13)	UC8	Traditionally, the construction manager/site manager updates the working crews on the daily activities/tasks during a morning session and during the day. BIMERR provides automated task assignment and notification to working crews.	Project Management tool	
CT19	Number of RFIs sent from working crews to site manager	5 (5.12, 5.13)	UC8	Typically in traditional construction approaches working crews experiencing difficulties with their assigned tasks request guidance from the site manager, who has to search the relevant information, visit the crew on site and offer the necessary explanation. With BIMERR, assigned tasks will be accompanied with all needed information such as drawing, instructions etc. This way considerable time is expected to be saved.	Project Management tool	✓
CT20	Number of workflows created by the site manager	5 (5.12, 5.13)	UC8	BIMERR with the use of PWMA tool supports workflow management and automation. During traditional construction approaches, processes involved in typical activities (such as windows installation) were analyzed into tasks on a daily basis by the site/construction manager and assigned to working crews. With BIMERR, the processes around the various construction activities will be transformed into workflows that are executed semi-automatically or automatically.	BIMERR tool: Process Modelling Tool of the PWMA Toolkit	
CT21	Number of change-orders on a process level (due to poor planning) during constructions	5 (5.12, 5.13)	UC8 UC9	Due to the optimized planning process supported by the BIMERR Renovation Process Simulation tool the number of change orders due to poor planning is expected to be reduced.	Project Management tool	✓
CT22	Number of times that the project completion was rescheduled.	5 (5.2, 5.6,5.12, 5.13)	UC8 UC9	BIMERR tools support continuous monitoring and reporting of work progress on site or critical issues that occur. So, the early detection of a critical issue allows the PWMA tool to provide guidance to the foreman/construction manager for the optimal rescheduling of construction works (or even provide automated re-scheduling of works).	Project Management tool	✓

				This way critical delays that eventually will lead to the delay of the project completion can be avoided.		
CT23	Percent Plan Complete (PPC); a measure for estimating the reliability of the current schedule	5 (5.2, 5.6,5.12, 5.13)	UC8 UC9	BIMERR supports optimal rescheduling of daily works in order to avoid critical delays. So, the continuous tracking of PPC values for construction activities will provide the site manager with information on the reliability of scheduled works for upcoming weeks. If PPC is decreasing, this KPI will inform the site manager that the current scheduling of construction activities requires some corrective adjustments.	Ratio of the number of activities completed on time to total number of activities planned for the week.	
CT24	Time spent for completing the assigned tasks	5 (5.12, 5.13)	UC8,UC9, UC10	With BIMERR HMD-AR and ARIBFA apps, workers will receive real-time detailed context-aware information (instructions, drawing, BIM model, etc.), even in the event of critical issues, for each task. This will reduce the time taken to complete an assigned task.	Project Management tool BIMERR tools: ARIBFA app	✓
CT25	Time spent for preparing the as-build project documentation.	5 (5.17)	UC10	Due to constant updating of the BIM-model with changes (suggested by workers, owners, etc.) during the construction works, the necessary corrections that are traditionally made at the end of the renovation works are now reduced or eliminated.	Its measurement follows the concept: $Days(T_{D,end} - T_{D,start})$ where $T_{D,end}$ and $T_{D,start}$ are the delivery date and preparation starting date of the as-built documentation	✓
CT26	Number of updates to the BIM model representing modifications to the original plans that occurred on site.	5 (5.13, 5.16, 5.17)	UC10	In the context of BIMERR continuous reporting, necessary modifications to the BIM model can be proposed by working crews or building occupants, approved by site managers and finally represented to the BIM model by the architect; all involved stakeholders are notified by the BIMERR PWMA toolkit. So, due to the automatic reporting of issues/changes, the final update of the model will require less time. In the traditional approach the as-built project documentation that includes all the changes that were made during the construction works along with geodesic documentation and recorded as-built geodetic measurements and data, is prepared after the end of renovation works (final step of the renovation process).	BIMERR tools: PWMA, BIM Platform	✓
CT27	Time spent for preparing (daily) reports for on-site works	5 (5.2, 5.6,5.12, 5.13)	UC9, UC10	BIMERR continuous reporting feature will facilitate keeping track of any change/issue during construction; this way the time requirement for creating reports will be reduced.	Survey/Interviews.	

CT28	Number of incidents occurred during construction	5 (5.12, 5.13, 5.14, 5.15)	UC11 UC12	In BIMERR detailed safety instructions and guidance are attached to workflows which involve installations. This way the working crews will be properly informed prior to any activity on site. Additionally, building owners (or occupants) that could potentially visit the construction site receive notification to their smart phones prior to their visit. Finally, in the BIMERR enabled renovation, construction crews are able to create H&S issues the moment they notice them and the H&S manager is automatically notified. In traditional approaches reporting and notifications is based only on direct communication/contact between persons. Therefore, a reduction in the Number of incidents occurred during construction, N_{inc}, is expected.	Survey/Interviews.	
CT29	Number of incidents avoided due to proactive information provision	5 (5.12, 5.13, 5.14, 5.15)	UC11 UC12	H&S issues around the construction site can potentially lead to incidents. Due to BIMERR proactive information provision supported by the ARIBFA app, H&S are detected by members of the construction crew and in real-time reported back to management, and automatically are shown in the BIM.	Number of incidents avoided, i.e. $N_{inc,A} = N_{inc,R} - N_{inc}$ where $N_{inc,A}$ is the number of avoided incidents, $N_{inc,R}$ is the number of H&S issues detected, and N_{inc} is the number of incidents occured during construction, i.e. CT28. BIMERR tools: ARIBFA, PWMA	
CT30	Number of lost-time injuries per million hours worked (LTIFR)	5 (5.12, 5.13, 5.14, 5.15)	UC11 UC12	BIMERR provides both guidance to actors operating on-site and prompt notifications regarding to safety issues. This way accidents on-site can be avoided.	The LTIFR is calculated with the following equation: $LTIFR = \frac{LTI}{WHr_{total}} \cdot 10^6$ where LTI is the total number of lost-time injuries during a time period and WHr_{total} is the total number of work-hours spent for the renovation project during the same period of time.	

CT31	Average time to resolve H&S risks & issues	5 (5.12, 5.13, 5.14, 5.15)	UC11 UC12	Due to a) near real-time notification of the H&S manager of any new H&S issues around the construction site, and b) the automatic representation of the issue (description and status) to the BIM model, scheduling and finally resolving of the issues is expected to be performed in a more efficient manner compared to traditional tactics. The measurement of this KPI can be implemented directly by BIMERR tools.	BIMERR tools: ARIBFA, BIM Platform	

6.1.1.2 Impact Indicators

KPI	Name	Renovation Phase (Steps)	UCs	Description	Task/Source	Calculation
ICT1	Reduction of the renovation process duration (%)	All	All	This KPI is directly associated with the target BIMERR impacts according to DoA, so its measurement is necessary.	6.2, 9.1, 9.5 PWMA	Ratio of the duration of a BIMERR enabled renovation process* to the duration of a traditional renovation process. *The renovation process (BIMERR enabled and traditional) concerns the same building category and the same type of renovation.
ICT2	Reduction of the renovation process cost (%)	All	All	This KPI is directly associated with the target BIMERR impacts according to DoA, so its measurement is necessary..	PWMA	Ratio of the cost of a BIMERR enabled renovation process* to the cost of a traditional renovation process. *The renovation process (BIMERR enabled and traditional) concerns the same building category and the same type of renovation.

6.2 User Acceptance Assessment

This section describes the BIMERR approach on assessing the user acceptance of the tools and applications that will be developed in order to support the renovation process. Section 6.2.1 summarizes the basic steps followed for defining the final list of User Acceptance (UA) KPIs which are presented in section 6.2.2

6.2.1 Methodology

The evaluation of user acceptance in the BIMERR framework follows an empirical approach that is based on the analysis of users' characteristics and project goals, while incorporating the typical constructs for perceived usefulness and ease of use [36]:

1. analysis of BIMERR end users'
    - work environment
    - daily work activities
    - needs/desires related to the improvement of their work
2. analysis of the information gathered from the requirements workshops (based on design thinking methodology)
3. analysis of the benefits that are expected to be delivered through the BIMERR project
4. definition of the factors for perceived value for BIMERR toolkit. Specifically, functionality and interoperability/compatibility, well-designed user interfaces.
5. formulation of preliminary list of KPIs to be measured during demo activities
6. mapping of KPIs to main user groups (see D3.1)
7. circulation of KPI list among partners for feedback
8. final list of KPIs that will be included in the deliverable
9. questionnaires for measuring the KPIs (see Annexes I-VII)
    - the system usability scale (SUS) approach [80] will be also used as a simple and established method for assessing usability among users

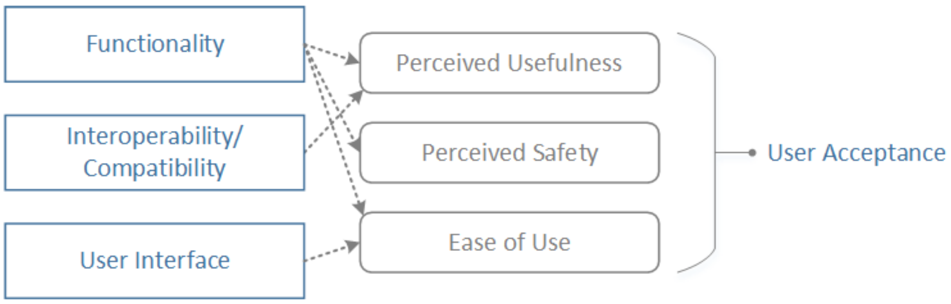

Fig. 21: User acceptance in the context of BIMERR

It should be pointed out that with respect to H&S, herein only the perception and satisfaction of working crews towards H&S management in renovation project is assessed. In order to have a complete assessment of Safety in construction in the framework of BIMERR, KPIs presented both herein and in section 6.1, i.e. CT28-CT31 should be measured.

The final list of UA KPIs consists of 20 KPIs, as summarized in section 6.2.2. Some KPIs are directly associated to enhancements derived by BIMERR, while others just measure a specific satisfaction factor. Note that all KPIs will be evaluated based on quantitative feedback, using questions with answers linked to numeric rating scale (see Annexes I-VII).

This project has received funding from the European Union's Horizon 2020 Research and innovation programme under Grant Agreement n°820621

6.2.2 KPIs for User Acceptance assessment

KPI	Definition/Description	Main User Group
Perceived Usefulness		
UA1	Productivity improvement	Architect, BIM modeller, Project manager, Site manager, Surveyor, Worker
UA2	Increase in the efficiency of task completion	Architect, BIM modeller, Project manager, Site manager, Surveyor, Worker
UA3	Improvement in decision making	Architect, Project Manager, Site Manager, Worker
UA4	Improvement in collaboration among teams	Architect, BIM modeller, Project manager, Site manager, Surveyor, Worker
UA5	Improvement in communication among peers and stakeholders	Project Manager, Site Manager, Worker
UA6	Improvement of architectural design quality due to the enriched and more accurate BIM models produced	Architect
UA7	Increase in the sense of accountability among stakeholders	Site Manager, Project Manager
UA8	Improvement in the perceived easiness in information exchange and tracking	Architect, Project Manager, Site Manager, Occupant
UA9	Improvement in the perceived accuracy in bidding estimations	Project Manager
UA10	Improvement in the perceived easiness in management of change-orders during construction phase	Project Manager, Site Manager
UA11	Reduction in the level of intrusion experienced by occupants during renovation	Occupant
UA12	Increase in monitoring capabilities offered to stakeholders during renovation works	Project manager, Site manager, Worker, Occupant
UA13	Completeness of information exchanged with the BIF	Architect, Project Manager, Site Manager
UA14	Perceived security in data accessibility	Architect, BIM modeller, Project manager, Site manager, Surveyor, Worker, Occupant
UA15	Overall added value offered through the BIF	Architect, BIM modeller, Project manager, Site manager, Surveyor, Worker, Occupant
Perceived Safety		
UA16	Improvement in perceived safety at construction site	Worker, Site Manager, Occupant
UA17	Improved safety communications in the construction site	Worker, Site Manager, Occupant
UA18	Working crews' level of satisfaction with management commitment to H&S	Worker, Site Manager

UA19	Level of annoyance due to noise	Worker, Site Manager, Occupant
UA20	Level of annoyance due to vibrations	Worker, Site Manager, Occupant
UA21	Level of annoyance caused by materials occupying surfaces	Worker, Site Manager, Occupant
	Ease of Use	
UA22	Level of difficulty in learning to use BIMERR tools	Architect, BIM modeller, Project manager, Site manager, Surveyor, Worker, Occupant
UA23	Level of intuitiveness in user interfaces	Architect, BIM modeller, Project manager, Site manager, Surveyor, Worker, Occupant
UA24	Easiness in the use of semantic mapping tools	Architect, BIM Modeler, Project Manager, Surveyor
UA25	Level of guidance comprehensiveness for facilitating semantic mapping	Architect, BIM Modeler, Project Manager, Surveyor
UA26	Easiness in the creation of queries for data search	Architect, Project Manager, Site Manager

6.3 Building energy, environmental and economic performance

6.3.1 Methodology

The evaluation of energy efficiency follows a subset of the approach presented in section 6.1 since not all steps are applicable for this criterion. Revisions, such as appropriate selection and/or grouping of KPIs, will be necessary after the pilot projects have been determined, and will be done in task 9.1 according to DoA.

Energy Efficiency is directly associated with Business Scenario 5. As described in D3.1, BS5 is about "*Construction companies and/or architectural studios to accurately predict the energy performance of renovated buildings and continuously update their predictions based on real data, towards making more attractive the energy performance contracting model*". The Use Cases which are related to BS5 are shown in Table 12:

UC ID	Use Case Name
UC-03	Adapt design to the actual building use, including accurate information about occupancy and schedules, comfort requirements/ preferences and energy uses.
UC-04	Consider new materials and technologies in any design and simulation activity through appropriately configured BIM-compliant models residing in relevant open repositories (with accurate specification of their impact in energy performance of buildings).
UC-13	Perform back-to-back simulations of alternative renovation scenarios to evaluate and select the best energy-performing renovation scenario
UC-14	Energy performance assessment to be elevated at a life-cycle perspective including relevant LCA-LCC metrics
UC-15	Energy performance simulations to assess not only energy metrics, but also accurately evaluate occupants' comfort and indoor air quality
UC-16	Assessment of energy performance to also address the district aspect and enable the consideration of interactions between buildings, but also between buildings

	and district systems in a holistic assessment framework incorporated in urban planning applications

Table 12: Use Cases associated with BS5

The main building energy, environmental and economic performance indicators (applied on the targeted operational scenario) can be classified in the following four main categories:

Energy KPIs Category	**Associated UCs**	**Comments on Performance Assessment**
Energy KPIs	UC3, UC4, UC13, UC16	The energy performance upgrade of the renovated building is in the core of BIMERR. Beyond the static components of a building, renovation for energy efficiency is also about the energy consumption of the building –why and how energy is consumed, and whether the renovation project has achieved the required level of energy upgrade of the building. Optimizing the interaction of buildings with urban systems (electricity, heating, etc.), but also between them are major issues to be addressed in urban planning processes at district level.
Occupants comfort and indoor air quality KPIs	UC3, UC15	The renovation design is adapted to the actual building use, as well as to the needs, schedules, comfort requirements and preferences of the occupants for better living quality. Establishment of built environments that can preserve high levels of human comfort and indoor air quality is a key requirement for the renovation industry since they are tightly connected to the real estate value of a building and, thus, directly affect the economics and contractual terms for the implementation of such projects.
Sustainability KPIs	UC14	A major challenge for the renovation sector is to improve the sustainability and environmental performance of the building sector as well as comply with relevant EU and national directives, while achieving optimization objectives that refer to the life-cycle of buildings and the materials/ components used, as well as other related aspects such as decommissioning and recycling.
Economic KPIs	All	Economic KPIs will define the business framework for retrofitting activities, comparing the investment costs with the economic savings achieved due to the energy conservation measures introduced in the retrofitting.

Table 13: Categories of building energy, environmental and economic KPIs.

Each category is composed by several KPIs. The goal is to select the most significant indicators and form a manageable but still meaningful set of KPIs that are sufficient for the assessment of the energy

aspects performance according to issues identified as important for BIMERR, as described in the corresponding UC scenarios.

The KPIs presented here consider not only the performance at the pilot sites of the project, but they are more general, covering a wider range of applications. As also mentioned above, the final selection of KPIs will be decided when the pilot sites are selected. Then, in task 9.1 it will be decided which of these KPIs are most appropriate to be used for the specific renovation projects.

6.3.2 KPIs for building energy, environmental and economic performance

It has to be underlined that based on the KPIs listed here it will be also possible to calculate the respective energy savings in terms of total energy, energy per carrier, energy per use, etc..

6.3.2.1 Energy KPIs

6.3.2.1.1 State indicators

KPI	Name	Definition/Description	Units
		Buildings	
EE1	Total primary energy consumption	Primary energy consumption refers to the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process	kWh/m^2/year
EE2	PENRT Primary energy non-renewable total	PENRT Primary energy non-renewable total	kWh/m^2/year
EE3	Electric energy consumption	the building's total electric energy consumed for the operation of HVAC systems, lighting and appliances	kWh/m^2/year
EE4	Natural gas energy consumption	the building's total natural gas energy consumed for the operation of HVAC systems and appliances	kWh/m^2/year
EE5	District heating energy consumption	the building's total district heating energy consumed for the operation of HVAC systems and domestic hot water equipment	kWh/m^2/year
EE6	Other fuel types	e.g. diesel, biomass energy consumption	kWh/m^2/year
EE7	Peak heating load and heating load profile	the heating power profile for a specific period of time in Watts and its maximum/peak value	Watts
EE8	Peak cooling load and cooling load profile	the cooling power profile for a specific period of time in	Watts

		Watts and its maximum/peak value	
EE9	Heating and cooling energy demand	Heating and cooling energy demand	kWh/m^2/year
EE10	Peak electricity load and electricity load profile	the electricity power profile for a specific period of time in Watts and its maximum/peak value	Watts
EE11	PV electric energy generation	the electric energy generated by photovoltaic panels installed in the building – to be discussed if pv installations will be candidate renovation measures	kWh/m^2/year
EE12	Solar thermal energy generation	the thermal energy generated by solar thermal panels installed in the building – to be discussed if solar thermal panels installations will be candidate renovation measures	kWh/m^2/year
District			
EE13	Electrical energy generated in the district and used onsite	Electrical energy generated in district and used in building	kWh/m^2/year
EE14	Energy generated on site and exported to the district.	Excess energy generated on site and exported to district.	kWh/m^2/year

6.3.2.1.2 Impact indicators

KPI	Name	Definition/Description	Units
EE15	Annual Energy Savings	Aggregate annual energy saving at premises	kWh/m^2/year
EE16	Energy Savings (percentage)	Percentage reduction of energy need	%
EE17	Reduction of peak energy load (percentage)	Percentage reduction of peak energy load	%
EE18	GHG emissions reduction (percentage)	Percentage reduction of GHG emissions	%

6.3.2.2 Occupants comfort and indoor air quality KPIs

6.3.2.2.1 Impact indicators

KPI	Name	Definition/Description	Units
OC1	Mean Vote difference for thermal comfort	Simulated with BIM tools or measured, occupants' mean satisfaction with heating,	-

		cooling, ventilation operation before and after renovation	
OC2	Heating Desired Temperature Not Met While Occupied Time	Percentage of time that the occupants' max temperature preferences where not met.	%
OC3	Cooling Desired Temperature Not Met While Occupied Time	Percentage of time that the occupants' min temperature preferences where not met.	%
OC4	Humidity Preferences Not Met While Occupied Time	Percentage of time that the occupants' humidity preferences where not met.	%
OC5	Indoor air quality preferences Not Met While Occupied Time	Percentage of time that the occupants' indoor air quality preferences where not met.	%
OC6	Percentage Dissatisfied difference with thermal comfort	Simulated with BIM tools or measured, percentage of dissatisfied occupants' with heating, cooling, ventilation operation before and after renovation	%
OC7	Mean Vote difference for indoor air quality improvement	Simulated with BIM tools or measured, occupants' mean satisfaction with indoor air quality considering humidity, CO2, CO, particular matter, VOC etc., before and after renovation	-
OC8	Percentage Dissatisfied difference for indoor air quality improvement	Simulated with BIM tools or measured, percentage of dissatisfied occupants' with indoor air quality considering humidity, CO2, CO, particular matter, VOC etc., before and after renovation	%

6.3.2.3 Sustainability KPIs

6.3.2.3.1 Impact indicators

KPI	Name	Definition/Description	Units
SU1	Global Warming Potential	Indicator of potential global warming due to emissions of greenhouse gases to air	kg CO2eq/ m2
SU2	Depletion potential of the stratospheric ozone layer	Indicator of emissions to air that cause the destruction of the stratospheric ozone layer	kg CFC-11 eq/ m2

SU3	Acidification potential of soil and water	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides	kg SO2 eq/ m2
SU4	Eutrophication potential	Indicator of the enrichment of the aquatic ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds	kg PO4 eq/ m2
SU5	Formation potential of tropospheric ozone	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.	kg ethylene/ m2
SU6	Abiotic depletion potential for non-fossil fuels resources	Indicator of the depletion of natural non-fossil resources	kg antimony/ m2
SU7	Abiotic depletion potential for fossil fuels	Indicator of the depletion of natural fossil fuel resources	MJ/ m2
Aggregated Indicators			
SU8	Water pollution	Indicator of the amount of water required to dilute toxic elements emitted into water or soil	m3/m2
SU9	Air pollution	Indicator of the amount of air required to dilute toxic elements emitted into air	m3/m2
SU10	Environmental Cost Indicator	Indicator that unites all relevant environmental impacts into a single score of environmental costs, representing the environmental shadow price of a product or project.	€/m2

****The calculation of all aforementioned sustainability indicators will be performed based on the inputs (characterization factors) included in the materials' database to be developed under T7.1 of the BIMERR project. Details on the characterization factors (and weighting of impact categories) will be provided in Deliverable D9.1, which will instantiate the calculation of all indicators based on the results of D7.1 and decisions made under the respective task.*

6.3.2.4 Economic KPIs

6.3.2.4.1 Impact indicators

KPI	Name	Definition/Description	Units
EC1	Return on Investment (ROI)	ROI assessment of energy by using the overall investment costs and the saving in energy running costs over a defined period of time	%
EC2	Payback Period	Estimated by the ratio of investment costs over the yearly savings in energy running costs	years
EC3	Increase in rental rate of building	Percentage of rental rate increase of the renovated building	%
EC4	Increase of resale rate of building	Percentage of resale rate increase of the renovated building	%

7. CONCLUSIONS

The current deliverable defines the BIMERR evaluation methodology that has been based on methodologies and standards used in the International and European level. After reviewing the relevant methodologies and assessing their applicability in the BIMERR project, the use of the BIMERR tools in real renovation works in the context of the use cases proposed in D3.1 is considered along the following categories of KPIs:

- Renovation process duration
- Renovation process cost
- User acceptance
- Energy efficiency
- Occupants comfort and air quality
- Sustainability issues
- Economic issues

For each of them a list of complementary KPIs is also provided along with the necessary input parameters and the required calculations, as well as ways are identified in order to capture this information during the piloting activities (e.g. historical data, sensor measurements, tool user feedback via the provided purpose made questionnaires, manual measurements, visual inspection results).

Overall, 31 state and 2 impact KPIs are proposed for cost and time assessment, 26 impact KPIs for user acceptance evaluation, 14 state and 4 impact KPIs for energy performance, 8 impact KPIs for occupants comfort, 10 impact KPIs for sustainability and 4 impact KPIs for economic aspects.

As mentioned in the document, extensions and refinements of the evaluation methodology in terms of chosen use cases and KPI assessment must happen when the specific test cases will be selected to be evaluated per pilot building.

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ANNEX 1: QUESTIONNAIRE FOR ARCHITECT

Please rate the following statements according to the scale:
1 (Strongly disagree), 2 (Disagree), 3 (Neither agree nor disagree), 4 (Agree), 5 (Strongly Agree)

No.	Statement	1	2	3	4	5
1	I think that I would like to use this system frequently					
2	I found the system unnecessarily complex					
3	I thought the system was easy to use					
4	I think that I would need the support of a technical person to be able to use this system					
5	I found the various functions in this system were well integrated					
6	I thought there was too much inconsistency in this system					
7	I would imagine that most people would learn to use this system very quickly					
8	I found the system very cumbersome to use					
9	I felt very confident using the system					
10	I needed to learn a lot of things before I could get going with this system					
11 UA1	I think BIMERR helps me be more productive					
12 UA2	BIMERR makes me complete my tasks more efficiently					
13 UA3	BIMERR helps me make better decisions in my line of work					
14 UA4	I think that BIMERR promotes a more collaborative work environment					
15 UA6	I think that the enriched and more accurate BIM models produced by BIMERR improve the quality of my designs					
16 UA13	I consider the information exchanged with the support of BIMERR tools (BIF) complete					
17 UA14	I think that access to building information data respects all the necessary access policies					
18 UA15	I think that there is clearly an added value in implementing BIMERR interoperability framework (BIF)					
19	Learning to work with BIMERR was easy					

UA22						
20 UA23	I find that the User Interface of BIMERR has an intuitive design					
21 UA24	Working with BIMERR's semantic mapping tools was easy					
22 UA25	I think that the guidance provided for facilitating semantic mapping was comprehensive					
23 UA26	I think that creating queries for data search was easy					

ANNEX II: QUESTIONNAIRE FOR BIM MODELER

Please rate the following statements according to the scale:
1 (Strongly disagree), 2 (Disagree), 3 (Neither agree nor disagree), 4 (Agree), 5 (Strongly Agree)

No.	Statement	1	2	3	4	5
1	I think that I would like to use this system frequently					
2	I found the system unnecessarily complex					
3	I thought the system was easy to use					
4	I think that I would need the support of a technical person to be able to use this system					
5	I found the various functions in this system were well integrated					
6	I thought there was too much inconsistency in this system					
7	I would imagine that most people would learn to use this system very quickly					
8	I found the system very cumbersome to use					
9	I felt very confident using the system					
10	I needed to learn a lot of things before I could get going with this system					
11 UA1	I think BIMERR helps me be more productive					
12 UA2	BIMERR makes me complete my tasks more efficiently					
13 UA4	I think that BIMERR promotes a more collaborative work environment					
14 UA14	I think that access to building information data respects all the necessary access policies					
15 UA15	I think that there is clearly an added value in implementing BIMERR interoperability framework (BIF)					
16 UA22	Learning to work with BIMERR was easy					
17 UA23	I find that the User Interface of BIMERR has an intuitive design					
18 UA24	Working with BIMERR's semantic mapping tools was easy					

19 UA25	I think that the guidance provided for facilitating semantic mapping was comprehensive					

ANNEX III: QUESTIONNAIRE FOR PROJECT MANAGER

Please rate the following statements according to the scale:
1 (Strongly disagree), 2 (Disagree), 3 (Neither agree nor disagree), 4 (Agree), 5 (Strongly Agree)

No.	Statement	1	2	3	4	5
1	I think that I would like to use this system frequently					
2	I found the system unnecessarily complex					
3	I thought the system was easy to use					
4	I think that I would need the support of a technical person to be able to use this system					
5	I found the various functions in this system were well integrated					
6	I thought there was too much inconsistency in this system					
7	I would imagine that most people would learn to use this system very quickly					
8	I found the system very cumbersome to use					
9	I felt very confident using the system					
10	I needed to learn a lot of things before I could get going with this system					
11 UA1	I think BIMERR helps me be more productive					
12 UA2	BIMERR makes me complete my tasks more efficiently					
13 UA3	BIMERR helps me make better decisions in my line of work					
14 UA4	I think that BIMERR promotes a more collaborative work environment					
15 UA5	My communication at work with other stakeholders has been improved with BIMERR					
16 UA7	With BIMERR the responsibility allocation among stakeholders is more transparent					
17 UA8	BIMERR makes it easier for me to exchange information with other stakeholders					
18 UA9	BIMERR helps me make more accurate estimations for bidding					
19	BIMERR makes change-order management easier					

UA10						
20 UA12	BIMERR provides better monitoring of construction works during renovation					
21 UA13	I consider the information exchanged with the support of BIMERR tools (BIF) complete					
22 UA14	I think that access to building information data respects all the necessary access policies					
23 UA15	I think that there is clearly an added value in implementing BIMERR interoperability framework (BIF)					
24 UA22	Learning to work with BIMERR was easy					
25 UA23	I find that the User Interface of BIMERR has an intuitive design					
26 UA24	Working with BIMERR's semantic mapping tools was easy					
27 UA25	I think that the guidance provided for facilitating semantic mapping was comprehensive					
28 UA26	I think that creating queries for data search was easy					

ANNEX IV: QUESTIONNAIRE FOR SITE MANAGER

Please rate the following statements according to the scale:
1 (Strongly disagree), 2 (Disagree), 3 (Neither agree nor disagree), 4 (Agree), 5 (Strongly Agree)

No.	Statement	1	2	3	4	5
1	I think that I would like to use this system frequently					
2	I found the system unnecessarily complex					
3	I thought the system was easy to use					
4	I think that I would need the support of a technical person to be able to use this system					
5	I found the various functions in this system were well integrated					
6	I thought there was too much inconsistency in this system					
7	I would imagine that most people would learn to use this system very quickly					
8	I found the system very cumbersome to use					
9	I felt very confident using the system					
10	I needed to learn a lot of things before I could get going with this system					
11 UA1	I think BIMERR helps me be more productive					
12 UA2	BIMERR makes me complete my tasks more efficiently					
13 UA3	BIMERR helps me make better decisions in my line of work					
14 UA4	I think that BIMERR promotes a more collaborative work environment					
15 UA5	My communication at work with other stakeholders has been improved with BIMERR					
16 UA7	With BIMERR the responsibility allocation among stakeholders is more transparent					
17 UA8	BIMERR makes it easier for me to exchange information with other stakeholders					
18 UA10	BIMERR makes change-order management easier					

19 UA12	BIMERR provides better monitoring of construction works during renovation					
20 UA13	I consider the information exchanged with the support of BIMERR tools (BIF) complete					
21 UA14	I think that access to building information data respects all the necessary access policies					
22 UA15	I think that there is clearly an added value in implementing BIMERR interoperability framework (BIF)					
23 UA16	Using BIMERR makes me feel safer around the construction site					
24 UA17	I think that with BIMERR, all information regarding safety in the construction site is better communicated to working crews					
25 UA18	Workplace H&S is considered to be at least as important as productivity and quality					
26 UA19	I am annoyed by the noise levels at the construction site					
27 UA20	I am annoyed by the vibrations occurring at the construction site					
28 UA21	I get annoyed by the materials occupying surfaces around the construction site					
29 UA22	Learning to work with BIMERR was easy					
30 UA23	I find that the User Interface of BIMERR has an intuitive design					
31 UA26	I think that creating queries for data search was easy					

ANNEX V: QUESTIONNAIRE FOR SURVEYOR

Please rate the following statements according to the scale:
1 (Strongly disagree), 2 (Disagree), 3 (Neither agree nor disagree), 4 (Agree), 5 (Strongly Agree)

No.	Statement	1	2	3	4	5
1	I think that I would like to use this system frequently					
2	2. I found the system unnecessarily complex					
3	I thought the system was easy to use					
4	I think that I would need the support of a technical person to be able to use this system					
5	I found the various functions in this system were well integrated					
6	I thought there was too much inconsistency in this system					
7	I would imagine that most people would learn to use this system very quickly					
8	I found the system very cumbersome to use					
9	I felt very confident using the system					
10	I needed to learn a lot of things before I could get going with this system					
11 UA1	I think BIMERR helps me be more productive					
12 UA2	BIMERR makes me complete my tasks more efficiently					
13 UA4	I think that BIMERR promotes a more collaborative work environment					
14 UA6	I think that the enriched and more accurate BIM models produced by BIMERR improve the quality of my designs					
15 UA14	I think that access to building information data respects all the necessary access policies					
16 UA15	I think that there is clearly an added value in implementing BIMERR interoperability framework (BIF)					
17 UA22	Learning to work with BIMERR was easy					
18 UA23	I find that the User Interface of BIMERR has an intuitive design					
19	Working with BIMERR's semantic mapping tools was easy					

UA24						
20 UA25	I think that the guidance provided for facilitating semantic mapping was comprehensive					

ANNEX VI: QUESTIONNAIRE FOR WORKER

Please rate the following statements according to the scale:
1 (Strongly disagree), 2 (Disagree), 3 (Neither agree nor disagree), 4 (Agree), 5 (Strongly Agree)

No.	Statement	1	2	3	4	5
1	I think that I would like to use this system frequently					
2	I found the system unnecessarily complex					
3	I thought the system was easy to use					
4	I think that I would need the support of a technical person to be able to use this system					
5	I found the various functions in this system were well integrated					
6	I thought there was too much inconsistency in this system					
7	I would imagine that most people would learn to use this system very quickly					
8	I found the system very cumbersome to use					
9	I felt very confident using the system					
10	I needed to learn a lot of things before I could get going with this system					
11 UA1	I think BIMERR helps me be more productive					
12 UA2	BIMERR makes me complete my tasks more efficiently					
13 UA3	BIMERR helps me make better decisions in my line of work					
14 UA4	I think that BIMERR promotes a more collaborative work environment					
15 UA5	My communication at work with other stakeholders has been improved with BIMERR					
16 UA12	BIMERR provides better monitoring of construction works during renovation					
17 UA14	I think that access to building information data respects all the necessary access policies					
18 UA15	I think that there is clearly an added value in implementing BIMERR interoperability framework (BIF)					
19 UA16	Using BIMERR makes me feel safer around the construction site					

20 UA17	I think that with BIMERR, all information regarding safety in the construction site is better communicated to working crews					
21 UA18	Workplace H&S is considered to be at least as important as productivity and quality					
22 UA19	I am annoyed by the noise levels at the construction site					
23 UA20	I am annoyed by the vibrations occuring at the construction site					
24 UA21	I get annoyed by the materials occupying surfaces around the construction site					
25 UA22	Learning to work with BIMERR was easy					
26 UA23	I find that the User Interface of BIMERR has an intuitive design					

ANNEX VII: QUESTIONNAIRE FOR OCCUPANT

Please rate the following statements according to the scale:
1 (Strongly disagree), 2 (Disagree), 3 (Neither agree nor disagree), 4 (Agree), 5 (Strongly Agree)

No.	Statement	1	2	3	4	5
1	I think that I would like to use this system frequently					
2	I found the system unnecessarily complex					
3	I thought the system was easy to use					
4	I think that I would need the support of a technical person to be able to use this system					
5	I found the various functions in this system were well integrated					
6	I thought there was too much inconsistency in this system					
7	I would imagine that most people would learn to use this system very quickly					
8	I found the system very cumbersome to use					
9	I felt very confident using the system					
10	I needed to learn a lot of things before I could get going with this system					
11 UA8	BIMERR makes it easier for me to exchange information with other stakeholders					
12 UA11	With BIMERR, the renovation of my residence caused me less discomfort than what is expected with the traditional renovation approach					
13 UA12	BIMERR provides better monitoring of construction works during renovation					
14 UA14	I think that access to building information data respects all the necessary access policies					
15 UA15	I think that there is clearly an added value in implementing BIMERR interoperability framework (BIF)					
16 UA16	Using BIMERR makes me feel safer around the construction site					
17 UA17	I think that with BIMERR, all information regarding safety in the construction site is better communicated to working crews					
18 UA19	I am annoyed by the noise levels at the construction site					
19 UA20	I am annoyed by the vibrations occurring at the construction site					

20 UA21	I get annoyed by the materials occupying surfaces around the construction site					
21 UA22	Learning to work with BIMERR was easy					
22 UA23	I find that the User Interface of BIMERR has an intuitive design					