SMARTeeSTORY

D3.2

Modelling Handbook

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Project Acronym	SMARTeeSTORY
Project Title	Integrated, interoperable, smart and user-centred building automation and control system for better energy performance of non-residential historic buildings coupling physics & data-based approaches
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Deliverable Lead Partner	TECNALIA
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List of Abbreviations

Acronym	Description
AMR	Automatic Meter Reading
BEPS	Building Energy Performance Simulation
CDD	Cooling Degree Days
CVRMSE	Coefficient of Variation of Root Mean Square Error
D	Deliverable
EC	European Commission
EU	European Union
FEMP	Federal Energy Management Program
HDD	Heating Degree Days
HVAC	Heating, Ventilation, and Air Conditioning
IPMVP	International Performance Measurement and Verification Protocol
KPI	Key Performance Indicator
MBE	Mean Bias Error
RMSE	Root Mean Square Error
T	Task
TMY	Typical Meteorological Years
WP	Work Package

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Executive Summary

This deliverable presents a modelling handbook considering the requested model quality and available information in real buildings The created methodology is tested against the demonstration buildings of SMARTeeSTORY project. The handbook aims to define a common modelling framework adaptable to various levels of data availability and applications for developing a linked group of multi-domain building performance models.

As mentioned above, this modelling handbook has been developed in the context of the SMARTeeSTORY project. However, it is expected that it will serve as a reference for any project related to the implementation of energy efficiency and/or digitalization measures. An integral modelling methodology is explained considering model quality definition, building and energy model, assessment, and calibration. Furthermore, the data gathering process and the applicability to case studies are included.

This deliverable has been developed by TECNALIA.

1 Introduction

The present report corresponds to D3.2 as result of the activities performed within T3.1 of SMARTeeSTORY project, aiming to develop physics-based models and its early-stage calibration. In this context, the content of this document describes the requested model quality and available information in real buildings, by considering the context in which this project takes place.

1.1 Purpose and scope of the document

The purpose of this document is to develop a handbook which defines a common modelling framework adaptable to various levels of data availability and applications for developing a linked group of multi-domain building performance models. The proposed methodology serves as a reference for any project related to the implementation of energy efficiency and/or digitalization measures. The modelling handbook takes into account model quality definition, building and energy model, calibration, and assessment. The defined procedure is applied to the demonstration buildings of SMARTeeSTORY project.

1.2 Relation to other activities in the project

Table 1 depicts the relation of this deliverable to other activities in the project.

Activity (Deliverable Number)	Description
D3.1	Physics-based models and early-stage calibration

Table 1. Relation to other activities in the project

2 Overall approach

This deliverable presents a modelling handbook considering the requested model quality and available information in real buildings. The defined methodology is tested against the demonstration buildings of SMARTeeSTORY project.

2.1 Objectives and expected impact

Main objective of this deliverable is related to one of the main scientific and technological objectives of the SMARTeeSTORY project i.e., developing accurate models for forecasting short and long-term buildings energy performance. In this sense, the present modelling handbook is one of the main outputs of WP3 due to the need for physic-based models that generate synthetic data to calibrate in the early stages of the project the long- and short-term prediction models used in following tasks.

Moreover, the present modelling handbook aims to define a common modelling framework adaptable to various levels of data availability and applications for developing a linked group of building performance models (multi-domain: energy performance, thermal comfort, indoor air quality, lighting).

As mentioned above, this modelling handbook has been developed in the context of the SMARTeeSTORY project. However, it is expected that it will serve as a reference for any project related to the implementation of energy efficiency and/or digitalization measures. As part of the project, it serves as a guide for generating building models that contribute to further activities:

- Development and calibration of physics-based digital twins (using architectural data and available energy data) for generating virtual energy measurements to initially (before monitoring campaign at demo sites starts) train Deep Learning algorithms (e.g., LSTM, ANN, RNN, GRP) combined with statistical and traditional time series for accurate prediction of short term (1-12h) building multi-domain performance.
- Application of data pre-processing techniques (Hybrid approaches: Singular Spectrum Analysis, Convolutional Neural Networks) and continuous (up to weekly) training and calibration for ensuring data-based model's robustness and accuracy.
- Definition of low bias models for long-term assessment of building performance, to be used throughout the pre-intervention energy assessment and target setting process as well as performance assessment along the operation of SMARTeeSTORY. To be integrated as part of the Digital Building Logbook and into energy performance contracts.
- Creation of an emulation environment to test control logics and algorithms before their deployment at real building level.

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3 Modelling Handbook

Building Energy Performance Simulation (BEPS) models are playing a significant role in recent years by assessing and predicting the energy consumption and performance of buildings. There are several types of BEPS models depending on the focus and level of detail. In this sense, this deliverable presents a guidance for generating whole-building energy models integrating an overall assessment of a building's energy performance taking into account the main building characteristics (geometry, construction materials, HVAC systems, lighting, dynamic envelope, occupancy, etc.). Furthermore, the following procedure is intended for physical models based on architectural and engineering data, and further calibrated with real consumption data.

Physic-based models (also known as white-box models) solve mathematical equations based on physical laws to characterize the energy behavior of buildings under different external and internal conditions. These are models which require exhaustive information about the building and are usually mathematically complex. Even so, when properly calibrated, these models show high accuracy even under conditions that differ from those captured in the dataset used during the calibration. In order to state the equations of the model, there are various standards for the calculation process of the interactions between supply and demand, where both are dynamically coupled to predict the various energy and mass flows within the building and with the outside environment on a defined time basis. Some of them are listed below:

- ISO 15927 1-6:2009 Hygrothermal performance of buildings – Calculation and presentation of climatic data – Part 6: Accumulated temperature differences (degree-days) [1].
- ISO 13790:2011 Energy performance of buildings – Calculation of energy use for space heating and cooling [2].
- ISO 52000-1:2019 Energy performance of buildings – Overarching EPB assessment – Part 1: General framework and procedures [3].
- CIBSE Guides [4].
- ASHRAE Handbook – Fundamentals (2021) [5].

In order to automatize this process, there are several advanced software tools, which are extensively utilized by researchers and engineers, that can be used to build an energy model. Some of them are DesignBuilder, EnergyPlus, TRNSYS, Modelica and APACHE, among others. The first three are the most commonly used. DesignBuilder is a three-dimensional building modelling software which provides a user-friendly interface. The software enables users to create complex geometries and to model, analyze, and simulate various aspects of building performance, including energy consumption, thermal comfort, daylighting, and HVAC systems, by using EnergyPlus as motor engine. EnergyPlus, when used on its own, is a more detailed and powerful software program used for building energy simulation. It creates virtual models of buildings and predicts how much energy they consume based on factors like weather, materials, and HVAC systems. Similarly, TRNSYS is a comprehensive simulation tool for modelling dynamic energy systems and buildings, which can simulate complex systems and transient behavior.

Hereafter, an overall modelling pipeline is proposed, where a common model framework is adapted to various quality levels and applications. Even if the described procedure could easily be extrapolated to any other modelling tool, from here onward the methodology considers EnergyPlus as the reference simulation engine.

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This section introduces an overall approach to the modelling process in order to assess the building energy performance. First of all, the building modelling process is presented in order to define its significance and the general inputs that might be needed in order to characterize the building energy behavior, and the different methods to compensate the possible lack of sufficient available data. As a second step, a calibration process of the model is described considering different references such as ASHRAE and International Performance Measurement and Verification Protocol (IPMVP) methodologies. Finally, a set of Key Performance Indicators (KPIs) is presented to evaluate building energy performance and the impact of implementing solutions (e.g., energy efficiency and digitalization solutions).

3.1 Model Quality

The starting point of any modelling process is to define the required quality and accuracy of the models to be created, which depend on the expected functionalities and objectives of the project. From a general point of view, transient energy models of buildings are commonly developed in a simulation environment. Models must be able to represent different aspects affecting the behavior of the internal ambient temperature and indoor environmental quality parameters. In general, these parameters can be classified as: i) external weather conditions; ii) thermo-physical characteristics of the envelope; iii) occupancy patterns; iv) energy transformation, transmission, and emission components; v) ventilation system components and appliances.

In the context in which this handbook takes place, the building energy models aims to represent the real systems of the demo buildings and emulate their real behavior for different purposes which must be considered to define the model quality. These purposes can be summarized as below:

- To assess the potential performance of project interventions.
- To inform and integrate data driven models for short- and long-term predictions.

To create an emulation environment to test the control logics before their application in the real environment.

3.2 Building Model

The creation of building models follows a common outline most of the times. A general approach is presented by the methodology detailed in the EnergyPlus guideline [6], which highlights four essential steps:

1. Planification.
2. Zoning the building.
3. Preparation to construct the building model:
    a. Determine heat transfer and heat storage surfaces.
    b. Define equivalent surfaces as desired.
    c. Specify construction elements.
    d. Compile surface and surface information.
4. Compilation of internal space gain data.

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The first objective of creating an energy model is to represent the building's geometry in as much detail as possible. For example, in Figure 1, a real picture and the virtual building model of a case study building can be observed. This requires drawings and measurements of the building structure with sufficient architectural description. Internal partitioning and zoning are another key point that needs to be correctly added to the model. In some cases, the project scope could only cover a limited area of intervention. However, it is advisable to include minimum specifications of the whole building in the geometrical model and not only the intervention part in order to consider the thermal inertia of the building.

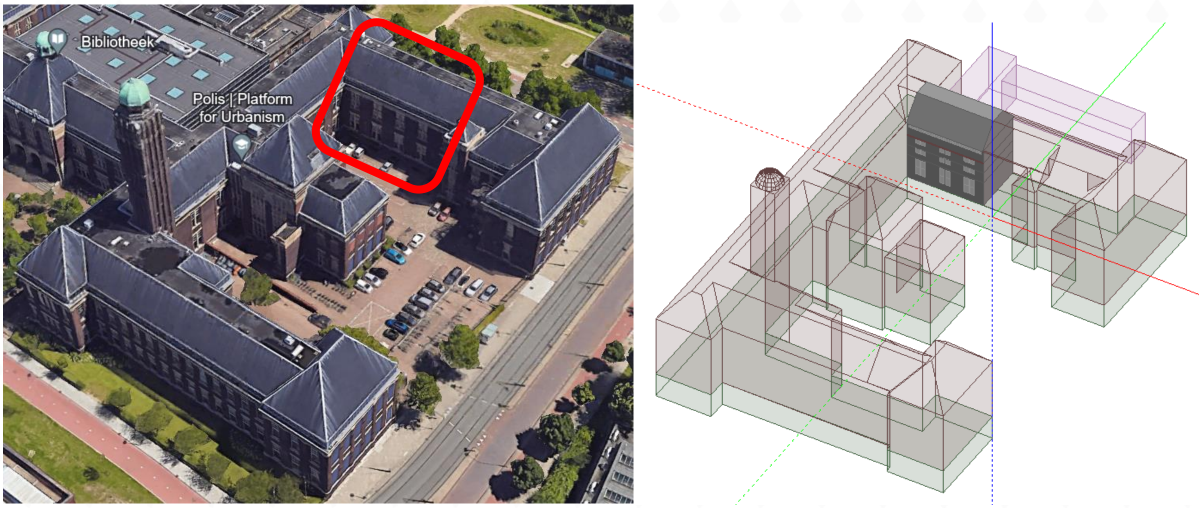

Figure 1. Real picture of a building demonstrator, where the intervention area has been highlighted(left) and virtual 3D building model of the intervention area (right).

Once the geometric information has been correctly included into the model, building characteristics and loads need to be introduced to reflect the current state of the building to assess its energy performance in further steps. This includes:

- Building wall U-values based on real data or bibliography.
- Shading from surrounding infrastructure or local shading.
- Data on building envelope air tightness based on qualified estimation.
- Window performance (U-values and g-values).
- HVAC systems characteristics (capacity, performance…).
- Data on internal heat loads from users, lighting and appliances, and the schedules associated.
- Local climate data for a normal year (or specific year for historic validation) including temperature, solar radiation and wind velocity and direction (obtained from a standardized database or in-situ weather station).
- Ventilation flows and heat recovery efficiency.
- Domestic hot water use.

3.3 Data Gathering

As stand below, physic-based models rely on the availability of data, so its accuracy is highly dependent on the data gathering process. First step within this process should consist of determining the availability and accuracy of data (geometrical, energetical, operational, etc.). In this sense, Table 2 presents a list of detailed data required for generating a highly accurate BEPS model. A checklist format has been employed aiming to facilitate data collection by building managers.

As a second approach, a technical visit to the demonstration building is highly recommended to verify the operation of the building and its appliances, and recollecting data from building users (e.g., occupancy patterns and user behavior).

In parallel, it is recommended to have ongoing discussions with the technical team in charge of the maintenance and energy management of the building in question in order to clarify doubts during the process. Notice that in some cases, new monitoring systems could be necessary to capture data that was not initially available, not only for the generation of the BEPS model but for its calibration or KPIs evaluation.

Table 2. Demo site data checklist

Building Data Checklist	Required?	Example
General building information		
Contact person (name, email, etc.)	Yes	*e.g. Name Surname, contact@gmail.com*
Construction year	Yes	*e.g. 2002*
Building hours of use (Morning & Evening)	Yes	*e.g. 9am - 5pm Mon-Fri*
Annual operation/occupancy calendar	Yes	*Bank holidays, non working days, telework, etc. e.g. building remain closed during August and Christmas holidays*
Building type	Yes	*e.g. Office*
Building address, including coordinates and altitude	Yes	*e.g. Office, Block 1, Street Name, XXN XXW, 200m*
Fuel utilised for heating / cooling / DHW / AHU	Yes	*e.g. Gas for heating and DHW*
Construction type (e.g. Concrete frame, wooden frame, etc)	Yes	*e.g. Wooden frame construction*
HVAC type (e.g. heating/ cooling / natural ventilation, etc)	Yes	*e.g. Radiators for heating & Natural ventillation for both cooling and IAQ*
EPC (Energy Performance Certification) level (please if this is a national certification, provide document explaining how this works)	Yes (if available)	*e.g. B3 (eventually attach pdf with EPC description)*
Site photographs	Yes (could be included in plans)	*e.g. jpeg, png files... of building, equipments, etc.*
Is the building listed (protected)?	Yes	*e.g. yes/no and comment with details (eventually provide national regulations on what can/cannot be done)*
Is there any applicable digitalization regulation?	Yes	*Please list any local or national regulation or policy in the term of building digitalization which may apply to this building. Good practices in this context could also be useful*

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Climatic zone and climate	Yes	*e.g. Eastern Europe, continental climate*
Available weather data from local weather station	Yes (if available)	*e.g. local weather station recording outdoor temperature, relative humidity, wind an solar radiation*
Is the intervention area delimited?	Yes (if applicable)	*Fill in the data in the table according to the intervention area and also the whole building (for that purpose, please identify each item with "Building" or "Building Area". Please define which is the intervention area).*
Automatic Meter Reading data and energy costs information		
Fossil Fuel Yearly (kWh)	Yes	*e.g. 2250 kWh gas*
Electricity Yearly (kWh)	Yes	*e.g. 1862 kWh electricity*
DHW consumption (l/y)	Yes	*e.g. 2000 l/y water (other volumetric units could be used)*
Electricity bills	Yes	*Total energy costs for electricity, or break down of month energy bills in kWh / cost e.g. Jan - 100kWh, €60 feb - 120kWh, €70 etc...*
Fossil fuel bills	Yes	*Total energy costs for fossil fuel, or break down of month energy bills in kWh / cost e.g. Jan - 100kWh, €60 feb - 120kWh, €70 etc...*
Construction / Building envelope (with U-values)		
External wall	Yes	*U-Values / construction details. E.g. Timber cladding with 200mm wood fibre insultation board, 90mm crosslam timber, 60x60mm counter battens, 60mm service zone and clay plaster lining board . U-Value of 0.3W/m²K*
Internal partition	Yes	*U-Values / construction, to same detail as above*
Internal ceiling/floor	Yes	*U-Values / construction, to same detail as above*
Ground floor/ roof	Yes	*U-Values / construction, to same detail as above*
Window %, type, frame and thermal characteristics (U-value, g-value and SHGC value)	Yes	*e.g. Double glazed window, gas filled, with 10% frame. WWR 20% W, 10% E, 0% N, 25% S. U-Value of 1.2W/m2K, g-value of 0.5 and SHGC value of 0.4*
Infiltration rate - Property air tightness (poor, basic, good)	Yes	*e.g. poor (if available, specify n50 value or blower door test results)*
Infiltration rate - Any External Vents Present?	if applicable	*e.g Yes or No, and number/ position*
Latest improvements	if applicable	*e.g. List the latest improvement and the year of application*
Building layout drawings and models		

Footprint area	Yes	*e.g. 578 m²*
Floor area (GIFA / Net)	Yes	*e.g. 1987 m2*
Floor plans	Yes	*pdf, dwg, dxf files*
Zone - Descriptions/end use (i.e. meeting room, labs, etc...)	Yes (could be included in plans)	*Please, identified the intervention area. e.g. meeting room.*
Zones - HVAC/Lighting/Equipment drawings	Yes	*e.g. ME drawings*
Elevations	Yes	*pdf, dwg, dxf files*
Sections	Yes	*pdf, dwg, dxf files*
Fenestration	Yes	*e.g. 345 m²*
Shading devices	Yes	*e.g. external louvres*
Adjacent buildings	Yes	*e.g. any relevant building which might affect analysis - such as very tall building which shades the addressed building most of the time*
Building orientation	Yes	*e.g. degrees from North (clockwise - take front façade as reference)*
3D Model (BIM, IES-VE, Revit, SketchUp, Rhino etc.)	if available (highly desirable)	*e.g. any available model (current or past)*
Schedules per Zone/Room		
Number of people + hours of occupancy	Yes	*Please state the number of people per room if known, but at minimum, the number of people occupying the building. E.g. 20 people, occupy building from 9am-5pm mon-fri, taking an hour for lunch at 1pm.*
Lighting Gains best-guess schedules	Yes	*Please estimate the lighting gains in W/m2 based on lighting type. E.g. Room 1, 2 and 3 each have 20 fluorescent light bulbs with power of 12W/m2. Room 4 and 5 have 15, etc. Types of lighting / specifications would be helpful to estimate gains and lux levels.*
Equipment Gains best-guess schedules	Yes	*Please list the types of equipment used in each room, and the power consumption in known (or a best guess on what this might be) e.g. Room 1 has five desktop computers consuming 85W when on (same hours as occupancy), along with 15 laptops consuming 45W when in use. Desktop computers and Laptops typically in sleep mode from 1pm-2pm, consuming 2W and 4W, respectively. All machines are turned off outside of office opening hours*

Equipment submetering data log	if possible	*e.g. any document stating the submetering data of different appliances*
Individual Zone/room set points heating & cooling	Yes	*Please specify the use of each room, along with the setpoint temperatures of each. E.g. Open plan room (room 5) has heating set point of 20°C and cooling of 23°C. Kitchen has heating set point of 19°C and cooling of 23°C, etc*
Lighting Systems per area		
Current lamp type	Yes	*e.g. fluorescent bulbs*
Number used in different areas	Yes	*e.g. 4 bulbs in room 1, 8 in room 2..*
Wattage of each lamp type	Yes	*e.g. 15 W bulbs*
Document any automation control on the light system (i.e. schedule control, daylight sensor, motion sensor control etc.)	Yes	*e.g. motion control in toilets, no control in office area*
Parasitic power of occupancy sensing, emergency signals, etc.	if possible	*e.g. occupancy sensors 2W constant standby power*
Submetering data log	if possible	*e.g. any document stating the submetering data of different lighting systems*
HVAC - Heating		
Document the heating system	Yes	*e.g. describe the system and attach datasheets if available*
Heating type, fuel, and system age	Yes	*e.g. radiators & heat pumps*
Seasonal efficiency (sCOP)	Yes	*e.g. 2.7*
Operational temperature	Yes	*e.g. 50°C*
HVAC - Cooling		
Document the cooling system	Yes	*e.g. describe the system and attach datasheets if available*
Cooling type and system age	Yes	*e.g. air conditioning*
Seasonal efficiency (SEER)	Yes	*e.g. 13*
Operational temperature	Yes	*e.g. 50°C*
HVAC - Others		
Document the hot water system	Yes	*e.g. describe the system and attach datasheets if available*
Hot water system: energy source	Yes	*e.g. electricity*
Hot water system: delivery efficiency	Yes	*e.g. 0.95*
System storage type, volume, loop length, pump power, time switch, flow rate	if possible	*e.g. 1000 L storage, 20m, 0.2 kW ..*
HVAC – AHU/FCU		
Design airflow rates or ac/h per room	Yes	*e.g. office 3 ach/h (or l/s), toilets 15 ac/h, kitchen 25 ac/h*
Heat recovery effectiveness (if any)	Yes	*e.g. 0.38*

Fan types and sizes	if possible	*e.g. centrifugal fans, 70mm*
Air supply temperature (document proportional control strategy)	if possible	*e.g. 25 °C - specify if different room by room and during heating/cooling period*
Document if room condition (temperature and humidity) is maintained in each area	if possible	*e.g. one specific area constantly above set point temperature*
Document any demand control ventilation strategy implemented	if possible	*e.g. modulate fresh air damper according to room sensor CO2 concentration*
Coil characteristics and controls	if possible	*e.g. cooling coil output T controlled by indoor room T*
Document specification of the AHUs/FCUs	if possible	*e.g. datasheet of AHUs / FCUs*
BMS / sensors data		
Is there any BMS system installed? If so, please specify	if applicable	*e.g. lighting control*
Is there remote access to BMS network?	if applicable	*e.g. yes, through secured VPN*
Is there any smart sensor in the building (e.g. measuring temperature, CO_2)	if applicable	*e.g. yes, temperature sensor in bedrooms and kitchen*
Where are the data measured from the sensors stored?	if applicable	*e.g. online database*
Renewables		
Photovoltaics (PV) - area, inclination, orientation	if applicable	*e.g. 200 m² PVs, 30 degrees inclination South-East*
PV - Manufacturer's data	if applicable	*e.g. datasheet of manufacturer*
PV - electricity production	if available	*e.g. electricity production in the most recent available year (monthly/yearly)*
Solar Panels - Area, inclination, orientation	if applicable	*e.g. 200 m² solar panels, 30 degrees inclination South-West*
Solar Panels - Manufacturer's data	if applicable	*e.g. datasheet of manufacturer*
CHP - Fuel Type	if applicable	*e.g. gas*
CHP - Heat output (rated output)	if applicable	*e.g. 1000 kW*
CHP - Thermal efficiency (rated output)	if applicable	*e.g. 0.5*
CHP - Power Efficiency (rated output)	if applicable	*e.g. 0.28*
CHP - Fraction of rated heat output at minimum output	if applicable	*e.g. 0.5*
CHP - Thermal efficiency (minimum output)	if applicable	*e.g. 0.57*
CHP - Power efficiency (minimum output)	if applicable	*e.g. 0.2*
Thermal energy storage type, capacity	if applicable	*e.g. ice thermal storage, 200 MW*
Document any other renewable energy source	if applicable	*e.g. wind turbines, tidal power*

3.3.1 Methods to compensate lack of data in real case application

When working with real data it is possible that not all the required information to define every aspect of the energy model is available. This section has been included in order to provide different references and databases that can help to compensate this possible lack of data/information. It should be noted that the assumed parameters may be adjusted during the calibration process.

With respect to the type of data required to build an energy model there are mainly two categories: building data/information (physical structure, characteristics of the different systems, internal gains, etc.) and weather data.

Typically, the lack of data concerns the first category: the envelope components and user behavior. To ensure the model's accuracy, reference values from public databases or local building policies could be utilized as a valid alternative when no information of the real building is available, based on the know-how of the team, as those proposed in Table 3.

Table 3. Reference documents and database with reference values for building modelling.

Database / Reference document	Content
iNSPiRe (EU project) [7]	Average parameters of residential and office building stock in different European countries: o U-values by country and climate region for walls, window, roof, floor. o Calculation through overall consumption data per country (kWh/m^2·a). o Energy consumption and demand by end use, country, and climate region. o Energy use by fuel type. o Fuel consumption for space heating and DHW by country. o Structural and façade material per construction period. o Country overview.
TABULA WebTool (EU project) [8]	Typology approach for residential building stock energy assessment for 13 European countries. Online calculation of the exemplary buildings from different countries. o Energy related features o Possible energy savings by implementing refurbishment measures o Calibration of the calculated energy use to the typical levels of actual consumption o Reference values for national minimum requirement, improved standard and NZEB (constructive materials and U-value) for roof, wall, floor, window o Reference energetic systems for national minimum requirement, improved standard and NZEB (heating

	system, ventilation system, DHW system and additional system)
EUROSTAT [9] and Office of Statistics for each country	Usually provides statistical information on the building and energy sector for each country o Energy balances o Supply, transformation, and consumption per energy source o Disaggregated final energy consumption o Energy indicators o Cooling and heating degree days
Energy Agency for each country	Various energy-related parameters based on local statistics
Building Technical Code for each country	Minimum standards for building constructive details or energy related aspects, including aspects related with occupancy
EnergyPlus / DesignBuilder	Availability of templates for each component / element

In the case that the weather data is the one missing, Table 4 shows two possible references that can be used to solve this.

Table 4. Reference documents and database for climate data

Database / Reference document	Content
Meteonorm [10]	Typical Meteorological Years (TMY) and historical time series of weather data
BizEE [11]	Degree Days calculator for locations worldwide

TMY are derived from hourly observations at a specific location by the national weather service or meteorological office. These datasets typify one year of hourly climate data extracted from at least 10-year records. It is remarkable that when using TMY as weather input of the model is mandatory to normalize the energy consumption obtained from the model. The most common method to achieve this is to use the Heating Degree Days (HDD) and Cooling Degree Days (CDD).

$$Q_{met,norm}[kWh] = Q_{met} \cdot \frac{HDD_{mod}}{HDD_{real}}$$

This normalization allows a like-for-like comparison between the outdoor conditions of a typical year used in the building simulation, and real measured outdoor data. Whenever measured weather data is available for the monitored periods, the TMY climate file should be substituted to include recorded outdoor temperature, solar radiation, and relative humidity.

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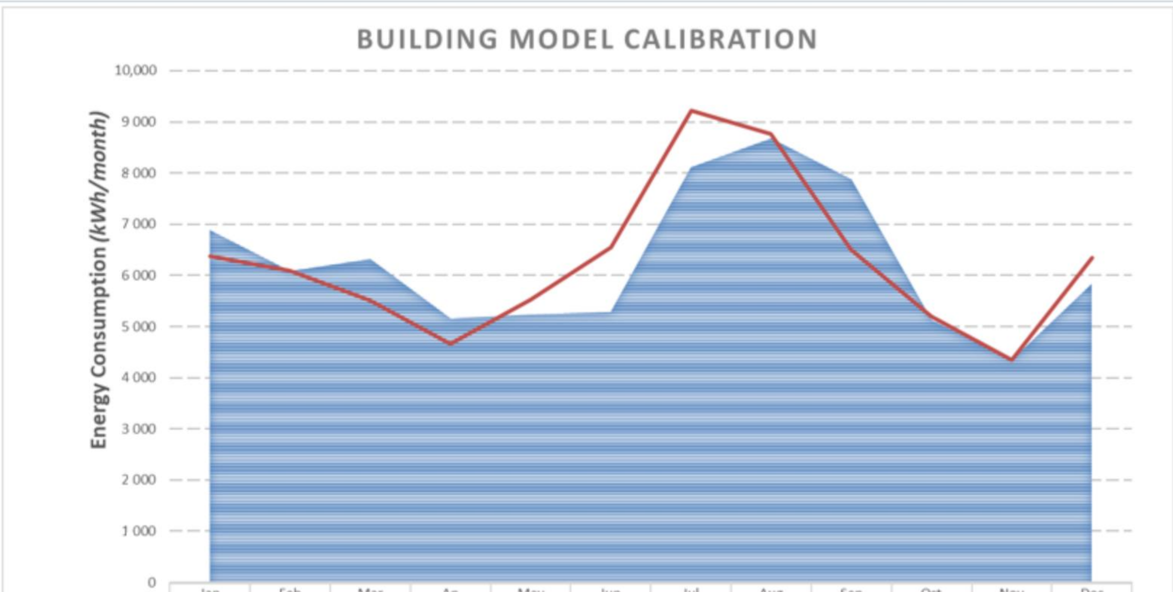
3.4 Calibration

Calibration process consists of reducing the performance gap of the building model, which is related to discrepancies between model outputs and real data, and it is a key process to achieve more accurate and reliable results. In this sense, the IPMVP is commonly used as a reference guide for this issue. The IPMVP consists of a standardized framework for accurately measuring and verifying energy and water savings resulting from energy efficiency projects. It offers various options for data collection and analysis, emphasizing baseline and reporting periods, accurate measurement, and clear reporting and it provides four options for determining savings. Based on the calibration process detailed by Option D of IPMVP [12], the following steps can be followed:

1. Assume input parameters and document them.
2. Verify that the simulation predicts reasonable operating results such as space or process temperature/humidity.
3. Compare simulated energy and demand results with metered data, on an hourly or monthly basis. Use actual weather data when conditions vary significantly from average year weather data. Assess patterns in the differences between simulation and calibration data. Bar charts, monthly percent difference time-series graphs and monthly x-y scatter plots give visual presentations which aid the identification of error patterns.
4. Revise assumed input data in step 1 and repeat steps 2 and 3 to bring predicted results reasonably close to actual energy use and demand. More actual operating data from the facility may also be needed to improve the calibration.



	Jan	Feb	Mar	Ap	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity Meter	6880	6080	6320	5160	5240	5280	8120	8680	7880	5120	4360	5840
Simulation Data	6368.71	6096.68	5515.69	4665.40	5525.18	6548.61	9220.67	8761.90	6504.20	5190.89	4346.63	6339.83

Figure 2. Calibration of a simulation model with utility bills. Source: [13]

There are different levels of calibration depending on the available data. In any case, utility bills are essential for any calibration, where the most commonly used are 12 monthly utility bills. The requested information for this process consists mainly of energy consumption and demand data and can be used to make some adjustments to some parameters that were previously estimated, until the performance gap is reduced to within a small percentage error. Other building input data that could enhance the accuracy of the calibration process are as-built data, site visit or inspection, detailed audit, and short and long-term monitoring. Similarly, further operating data from the facility (fluid flow, temperatures, etc.) can be used as part of the simulation process when focusing on facilities performance.

As further explained in section 3.3.1, the use of reference data could also be an option to avoid data shortages during the calibration process. However, the most appropriate option is to calibrate the BEPS model using monitoring data, the more relevant period could be enough (e.g., the heating period in cold climates). The use of monthly data instead of hourly data is usually less time consuming during the calibration process, although the latter generates less error.

Hereunder, some current approaches to BEPS calibration are listed in accordance with those classified by Clarke et al. [14] and adopted by Reddy et. al [15]:

- Manual calibration based on iterative and pragmatic intervention.
- Graphical-based calibration.
- Calibration based on special tests and analytical procedures.
- Automated calibration based on analytical and mathematical methods.

In order to validate the calibration process of the BEPS model, some statistical indices are commonly used in order to evaluate the performance gap:

- **Mean Bias Error (MBE) (%):** it is a good indicator of the overall bias in the model. It is calculated as the sum of errors between measured (m_i) and simulated (s_i) data points, (usually energy consumptions) for each model instance (i) at the calculation time intervals (p) of the considered period (N_p). The difference is then divided by the sum of the measured data (m_i). It must be noticed that positive bias compensates for negative bias generating a cancellation effect.

$$MBE\ (\%) = \frac{\sum_{i=1}^{N_p}(m_i - s_i)}{\sum_{i=1}^{N_p}(m_i)}$$

- **Root Mean Square Error (RMSE) (%):** it is a measure of the variability of the data, by evaluating the sample deviation of the differences between the measured vales (m_i) and the simulated values (s_i) of the model. In this case, each error is calculated and squared and then the sum of squares errors is added for each model instance (i) at the calculation time intervals (p) of the considered period (N_p) and divided by the number of points in the total period (N_p). Then, the square root of the result is calculated as the RMSE.

$$RMSE\ (\%) = \sqrt{\frac{\sum_{i=1}^{N_p}(m_i - s_i)^2}{N_p}}$$

- **Coefficient of Variation of Root Mean Square Error (CVRMSE) (%):** it is calculated as the RMSE normalized to the average of the measured values ($\bar{m}$). It allows to determine how well the model fits the data as it specifies the overall uncertainty in the prediction of the building energy performance. It does not suffer from the cancellation effect.

$$CV\ RMSE\ (\%) = \frac{\sqrt{(\sum_{i=1}^{N_p}(m_i - s_i)^2)/N_p}}{\bar{m}}$$

- The consideration of both MBE and CVRMSE are the most commonly implemented as it allows preventing errors compensation. The validation process of BEPS models is based on compliance with standard criteria for these two statistical indices as shown in Table 5.

Table 5. Acceptance criteria for calibration of BEPS models.

Standard/guideline	Monthly criteria (%)		Hourly criteria (%)	
	MBE	CVRMSE (monthly)	MBE	CVRMSE (hourly)
ASHRAE Guideline 14 [17]	5	15	10	30
IPMVP [12]	20	-	5	20
FEMP [18]	5	15	10	30

Once the model is calibrated and validated, a simulation is run to calculate the KPIs before and after the solutions are implemented.

3.5 Key Performance Indicators

KPIs are commonly used in order to assess the energy savings achieved in the demos before and after implementing any modification. In this sense, the IPMVP [12] is widely implemented. KPIs must be selected depending on project scope, although they normally include energy and economic indicators as the focus is on the analysis of the energy performance of the building. Some examples are listed above:

- Produced energy.
- Final energy consumption.
- Primary energy consumption.
- Greenhouse gas emissions.
- Fossil fuel consumption.
- Comfort (temperature, humidity, CO_2, light, etc.).
- Payback period.
- Internal return rate.

4 Application to SMARTeeSTORY case

The Modelling Handbook methodology described in the previous sections has been applied in SMARTeeSTORY case. The project has three demonstrators located in different climatic zones: Delft (The Netherlands), Granada (Spain) and Riga (Latvia). Information from buildings has been collected in the way presented in Table 2 for each demonstrator. Afterwards, the models have been built using DesignBuilder and EnergyPlus software by introducing the gathered information. In cases where lack of data has been identified, the methodology developed to compensate this gap has been implemented as defined in section 3.3.1. Once the building model is defined, the calibration process will be performed as mentioned in section 3.4 by considering the data collected during the monitoring campaign that take place in each of the demonstrators.

The physic-based models developed in the mentioned software include most of the services related and some domains related with the SRI, as one of the objectives of SMARTeeSTORY project is to develop control logics and other solutions which help increasing the SRI value of demonstrators. The building model simulations allow simulating the effect of this solutions in terms of energy performance, such as:

- Detailed schedules of heating and cooling systems that allow simulating smart thermostats.
- Schedules dependent of other items that allow simulating intelligent lighting (i.e., lights are on only when the room is occupied).
- Detailed schedules of other systems such as ventilation, local shading, DHW, etc.

The detailed definition of the SRS of the demonstrator buildings pre- and post-intervention is necessary in order to implement these services and domains in the models where possible, allowing an accurate performance assessment of their use.

After the application of the developed methodology to SMARTeeSTORY buildings, the following lessons learned can highlighted:

- The lack of architectural and physical data brings inaccuracy and lack of reliability of the models.
- Developing physics-based models is time consuming. In the absence of information or the delay during the gathering process, the time of the modelling process increases. In any case, communication with facility managers or other people who are familiar with the building and its facilities is essential.
- When modelling small areas of intervention of a whole building as in SMARTeeSTORY case, the description of the boundary conditions (i.e., the surrounding rooms) are of major importance.
- The objectives and functionalities of the model must be well defined from the beginning:
    a. General performance assessment of the building, i.e., sizing of the HVAC system, envelopes or glazing comparison, first stages of design, etc.
    b. Specific element performance assessment or control, i.e., smart shading, control strategies, etc.

  In this regard, discussions with partners responsible for the intervention packages within SMARTeeSTORY have been essential to understand the need for the models to address.
- Monitoring data are essential as the lack of real data (consumption, indoor temperature, weather data, etc.) brings inaccuracy and lack of reliability of the models.

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5 Conclusions

Physic models are a useful tool to simulate the energetic behavior of buildings. This document defines the methodology to build a white box energy model of a building and the required data and information to do so.

As it is common with all type of models, the data/information quality is what defines the accuracy of the model. Due to this reason, the modelling handbook remarks the importance of having data as detailed as possible.

This deliverable defines the step to follow when building a model after obtaining the necessary data and describes the possible difficulties that may arise during the process. In order to resolve these problems, some commonly used reference documents and resources are listed, as well as methods to normalize the available data.

Software tools can simulate the energy performance of buildings through the direct application of different energy calculation methodologies. There are a wide variety of modelling tools on the market with different specifications. The correct tool should be chosen according to the quality and characteristics required by the model.

Once the model is built, it must go under a calibration process which is normally based on some measurement and verification protocols such as the IPMVP.

Once calibrated, the model is ready to be used for the following purposes among others:

- To assess the potential performance of project interventions.
- To inform and integrate data driven models for short- and long-term predictions.
- To create an emulation environment to test the control logics before their application in the real environment.

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