OptEEmAL

OPTIMISED ENERGY EFFICIENT DESIGN
PLATFORM FOR REFURBISHMENT
AT DISTRICT LEVEL

Optimised Energy Efficient Design Platform for Refurbishment at District Level
H2020-WORK PROGRAMME 2014-2015 – 5. Leadership in enabling and industrial technologies
H2020-EeB-05-2015: Innovative design tools for refurbishment at building and district level

D4.4: Requirements and design of the simulation model input generator module

WP4, Task 4.3

August 2016 (m12)

Deliverable version: D4.4, v1.0

Dissemination level: Public

Author(s): D. Rovas[1], G. Giannakis[1], G. Lilis[1], K. Katsigarakis[1], G. Hernandez [2], A. Martin[2], L. Mabe[3], M. Pousse[4], A. Escudero[4], A. Sicilia[5], P. Moreno[6], H. Ridouane[7], L. De Tommasi[7], C. Ozturk[7] G. Mameli[8]

([1]TUC, [2]CAR, [3]TEC, [4]NBK, [5]FUNITEC, [6]ACC, [7]UTRC-I, [8]ES)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 680676

Document History

Project Acronym	OptEEmAL		
Project Title	Optimised Energy Efficient Design Platform for Refurbishment at District Level		
Project Coordinator	Miguel Á. GARCÍA-FUENTES (miggar@cartif.es) Fundación CARTIF		
Project Duration	1st September 2015 – 28th February 2019 (42 Months)		
Deliverable No.	D4.4. Requirements and design of the simulation model input generator module		
Dissemination Level	PU		
Status		Working	
		Verified by other WPs	
	X	Final version	
Due date	31/08/2016		
Work Package	WP4 – Scenarios Evaluation and optimisation according to stakeholder priorities		
Lead beneficiary	TUC		
Contributing beneficiary(ies)	CAR, TEC, NBK, FUNITEC, ACC, UTRC-I, ES		
DoA	Task 4.3 – Simulation model input generator module: requirements, specifications and design		

Date	Version	Author	Comment
01/07/2016	0.5	TUC	Final Table of Contents
22/07/2016	0.6	All	Preparation of Sections 1, 5, 6 and 7
17/08/2016	0.7	TUC	Updated Sections 1, 5, 6 and 7
25/08/2016	0.8	All	Merged partners' contributions
29/08/2016	0.9	NBK	Document's review
31/08/2016	1.0	TUC	Final version (month12) ready for submission

Copyright notices

Table of Content

List of Figures

List of Tables

Abbreviations and Acronyms

Acronym	Description
BEMS	Building Energy Management System
BEPS	Building Energy Performance Simulation
BIM	Building Information Model
CBIP	Common Boundary Intersection Projection
CM	Calculation Methodology
CS	CitySim
DDM	District Data Model
DPI	District Performance Indicator
ECM	Energy Conservation Measure
EP	EnergyPlus
FIBP	Fraunhofer Institute for Building Physics
GIS	Geographic Information System
HVAC	Heating Venting Air Conditioning
IFC	Industry Foundation Classes
IPD	Integrated Project Delivery
KPI	Key Performance Indicator
LoD	Level of Detail
OptEEmAL	Optimised Energy Efficient Design Platform for Refurbishment at District Level.

Executive Summary

This Deliverable addresses the topic of how the District Performance Indicators, defined in D2.2, are to be computed within the OptEEmAL platform. The calculation of these DPIs is a key part of the process towards the identification of the best retrofitting scenarios according to stakeholders' priorities. The unified multi-level district data model (based on the IFC and CityGML standards), provides a data repository for extracting relevant information for the setup of district-level simulation models. Interfaces are defined based on standardised communication protocols aimed at generating respective inputs, invoking relevant external tools (e.g. EnergyPlus, CitySIM, NEST) and ways of post-processing the results are investigated so that the defined District Sustainability Indicators can be computed.

Issues associated with the type and quality of the input data are considered. In addition, the analysis attempts to identify the amount of information which is necessary and sufficient for the calculation of the DPIs with an acceptable degree of accuracy. Issues that need to be addressed for the generation of the simulation models (e.g. by generation of 2nd-level boundary information). The concise analysis leads to a number of requirements related to the input data and the pre-processing required for the data to be sufficient to generate the required input. As the main premise of OptEEmAL is that these indicators will be computed automatically by the platform, a non-trivial step is the creation of models from the given data. The input file generation for a number of tools is not just a simple translation process but rather should encapsulate expert knowledge so that the models relate to reality. Issues like zoning are thus critical, and are investigated.

The first version of this deliverable was issued on M6 of the project. This is the final version of the deliverable that contributes towards the requirement collection effort and the design of the prototype. In particular issues like the definition of a district (for OptEEmAL purposes) and the way to meld building- and district-level calculations are investigated. In addition, ways to reduce computational effort by distribution of calculations to many nodes is investigated. The final output is a specification of components to be detailed and developed in following stages of the project.

1 Introduction

1.1 Purpose and target group

This report summarises activities undertaken as part of the work in Task 4.3 titled "Simulation model input generator module: requirements, specification and design." The task concerns the development of the simulation model input generator module.

The approach followed in this task is aligned with the General Project Methodology used to define the OptEEmAL requirements, which is presented in the following Figure.

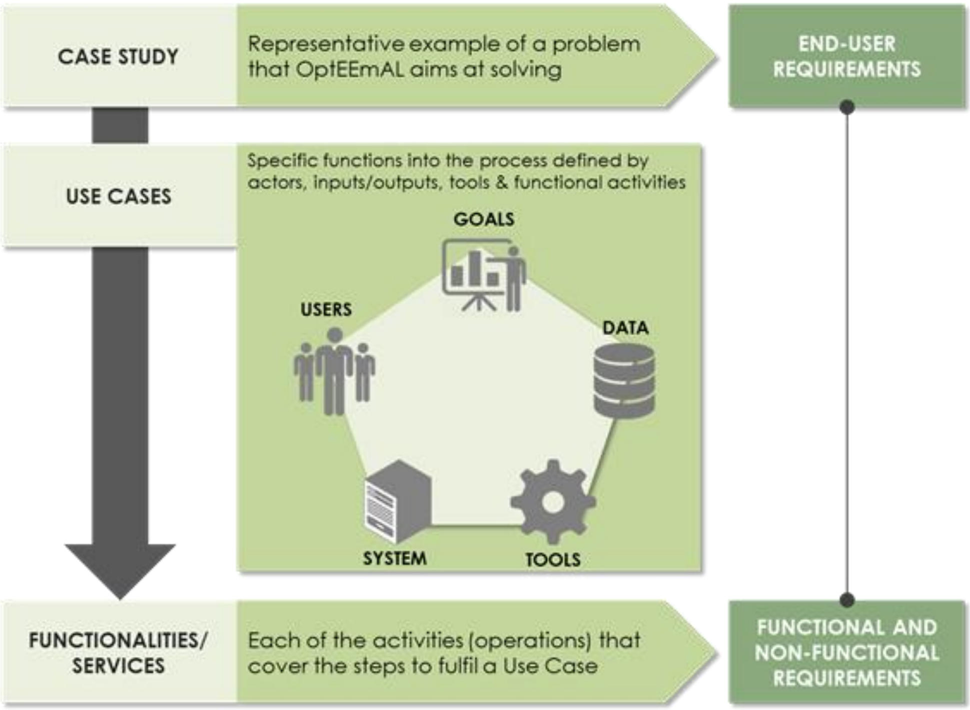

Figure 1: OptEEmAL project methodology

The methodology for OptEEmAL requirements identification is based on the following steps (for more details, see OptEEmAL D1.2 [01]):

- Step 1 – Definition of the case studies by the identification of the real problems that the OptEEmAL Platform aims at solving (based on the 6 case studies and 3 demo cases in the project).
- Step 2 – Identification of the use cases by means of specific functions that the tool will have to cover and defined in terms of actors, inputs/outputs, tools, goals, etc. for each of the case studies.
- Step 3 – Aggregation and normalisation of the use cases once defined the complete list to identify those use cases that are included in various case studies.
- Step 4 – Identification of functionalities that the OptEEmAL platform will have to cover in order to address each of the use cases identified.
- Step 5 – Identification and definition of requirements for each of the functionalities of the OptEEmAL Platform.

This requirement collection has been undertaken on a number of deliverables (see Section 1.3). Here the focus is on the invocation of tools for the calculation of relevant District Performance Indicators (DPIs).

1.2 Contributions of partners

The following Table 1 depicts the main contributions from participant partners in the development of this deliverable.

Table 1: Contribution of partners

Participant short name	Contributions
TUC	Deliverable Lead; Calculation Methodologies for Energy and Comfort; Requirements collection and module design.
CAR	Calculation Methodologies for Urban and Social DPIs, Data Processing
TEC	Definition of District Performance Indicators
NBK	Calculation methodologies for Environmental and Social DPIs
FUNITEC	Links to the District Data Model and the overall system architecture.
ACC	ECMs catalogue, link to D3.1
UTRC-I	Control ECMs and tools for simulation of HVAC systems and control design.
ES	Software architecture and links to the overall software design.

1.3 Relation to other activities in the project

The following Table 2 depicts the main relationship of this deliverable to other activities (or deliverables) developed within the OptEEmAL Project, that should be considered along with this document for further understanding of its contents.

Table 2: Relation to other activities in the project

Deliverable Number	Contributions
D1.2	This deliverable provides the overall description of the input data from the end-user perspective
D2.1	This deliverable contributes to the definition of the District Data Model and is intricately linked to this deliverable.
D2.2	This deliverable contributes to the selection of the DPIs that are used for the scenario evaluation and optimisation.
D3.1	This deliverable provides the Energy Conservation Measures Catalogue and prescribes the ECMs that should be evaluated by the tools

1.4 Outline

According to D5.2 [06], the simulation model input generator module is involved in two main processes which will be followed in the OptEEmAL platform:

1. the data insertion and diagnosis process; and

2. the scenarios generation and optimisation process.

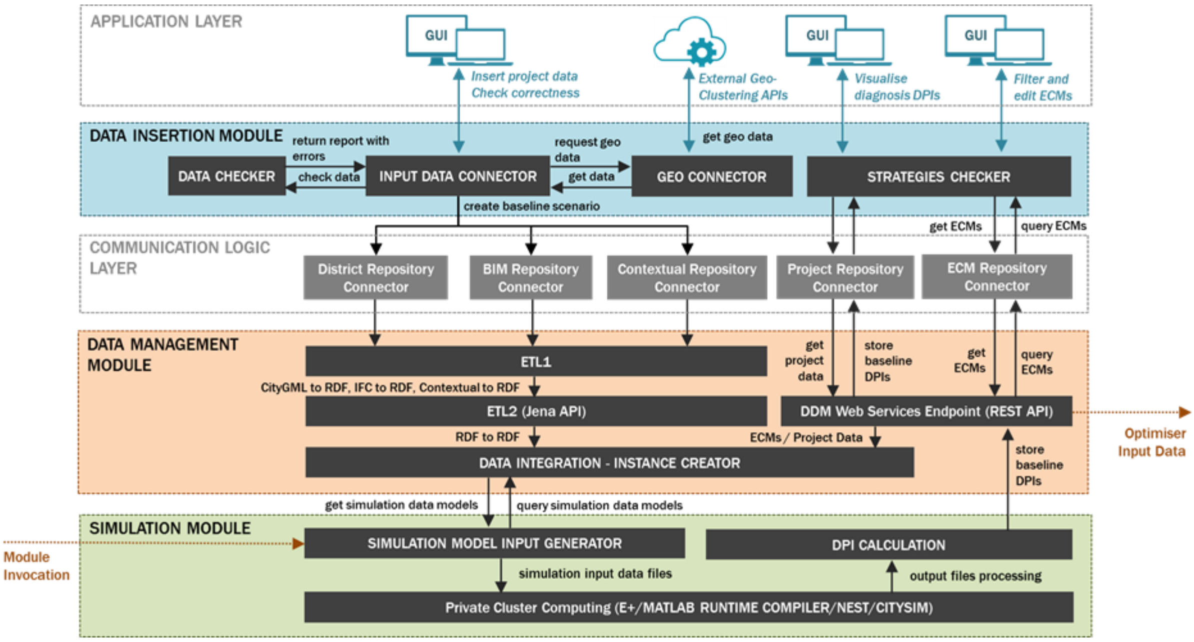

Figure 2: Data insertion and diagnosis process [06]

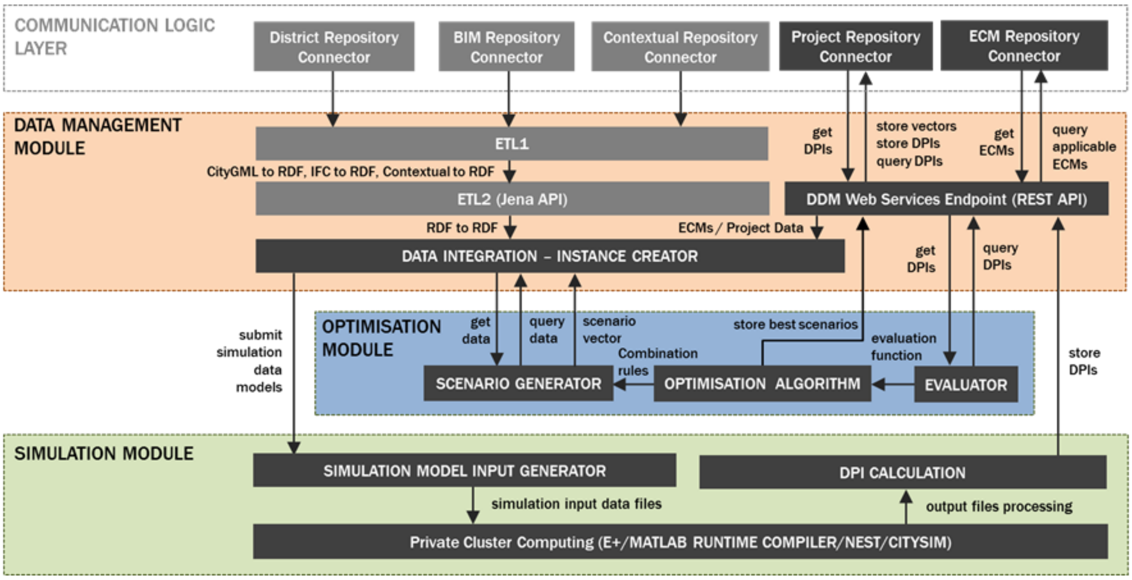

Figure 3: Scenarios generation and optimisation process [06]

In both processes, the simulation model input generator module retrieves information from the District Data Model, transforms these data to proper simulation files and launches respective simulation tools to calculate DPIs as a result. The results are directed to the data management module to be stored in the Project repository.

Towards achieving the data retrieval, the data transformation and the respective simulation tools launch, simulation model input generator module's requirements arise, while our attempt to address these requirements expressly stem from the answers to the following questions:

1. Which are the DPIs that will be calculated for the ranking of different retrofitting scenarios?
2. Which calculation methodologies and corresponding simulation tools are congruent with their calculation?
3. Since optimization process is a computationally expensive task, which will be the selected trade-off between accuracy and simulation runtime?

4. After the selection of proper simulation tools, which are the input data requirements and how will they be retrieved from the DDM?
5. Do the retrieved data require processing before their transformation to simulation input files?
6. How the retrieved data are transformed to simulation input files?
7. How the simulation tools are launched?

Answering to the first question, the District Performance Indicators which will be evaluated for the ranking of different retrofitting scenarios can be classified into seven categories:

- **Energy (ENE).** This category includes DPIs which estimate the demand and consumption of energy resources within the district.
- **Comfort (COM).** Comfort DPIs evaluate the quality of the conditions of the internal building spaces with respect to users' affordable living demands.
- **Environment (ENV).** Environmental DPIs are used to estimate the environmental impact of the districts over their whole life cycle in terms of greenhouse emissions and primary energy consumption.
- **Economic (ECO)**. Economic DPIs are used in order to asses in monetary units any investment related to district refurbishment scenarios.
- **Social (SOC).** Social DPIs asses the financial ability of the district inhabitants to cover the cost of energy consumption.
- **Urban (URB).** Urban DPIs measures the percentage of buildings complying with energy EU standards.
- **Global (GLO).** Global DPI evaluates the archived energy reduction of a selected retrofitting scenario related to its cost.

For more details, concerning the involved DPIs, their description, category, scale (building, district) and respective, please refer to D2.2 [03].

Figure 4 depicts the outline of this document. Here, motivated by the analysis of the case studies and definition of use cases – see D1.2 [01] – we take a thorough look into the tools that can be used for the evaluation of the DPIs discussed above. Three major considerations are the guiding principles in our analysis:

(i) more than a single tool can be used to compute a single DPI, therefore there is a selection process regarding the tools that have to be supported within the OptEEmAL platform;
(ii) even for a specific tool different modelling approaches can be utilised depending on the available data, therefore there is a selection process regarding the modelling detail within each of the tools that will be supported within the OptEEmAL platform; and,
(iii) for calculation of the various DPIs there are interdependencies in the calculation, with one DPI known as a prerequisite (input) in another DPI calculation, so for each of the scenarios there has to be a specific sequence where the DPIs are computed.

In the following Sections, these three considerations are made more explicit. In Section 2, our analysis focuses on the calculation methodologies – and respective tools embedding those methodologies -- available for the DPIs calculation, focusing on the Energy and Comfort, the most challenging DPIs to be computed. Various tools are analysed and categorised with important modelling aspects, concluding to the simulation tools that are selected to be used within OptEEmAL. Section 2 concludes that the DPIs calculation process within OptEEmAL involves multiple tools which operate in a cascade manner in order to perform the actual calculation. Section 3 briefly presents these simulation tools and their input/output format files.

In Section 4, an analysis of data required for the generation of the selected simulation inputs files is performed. This discussion is intricately linked with the work in D2.1, which aims at encoding these requirements in the definition of the District Data Model (DDM). Important issues like the distinction between 1st- and 2nd-level space boundaries are made, as well as the need for definition of the zoning using an automated procedure. These technical aspects are highlighted in the description and will be addressed as part of the work in WP4.

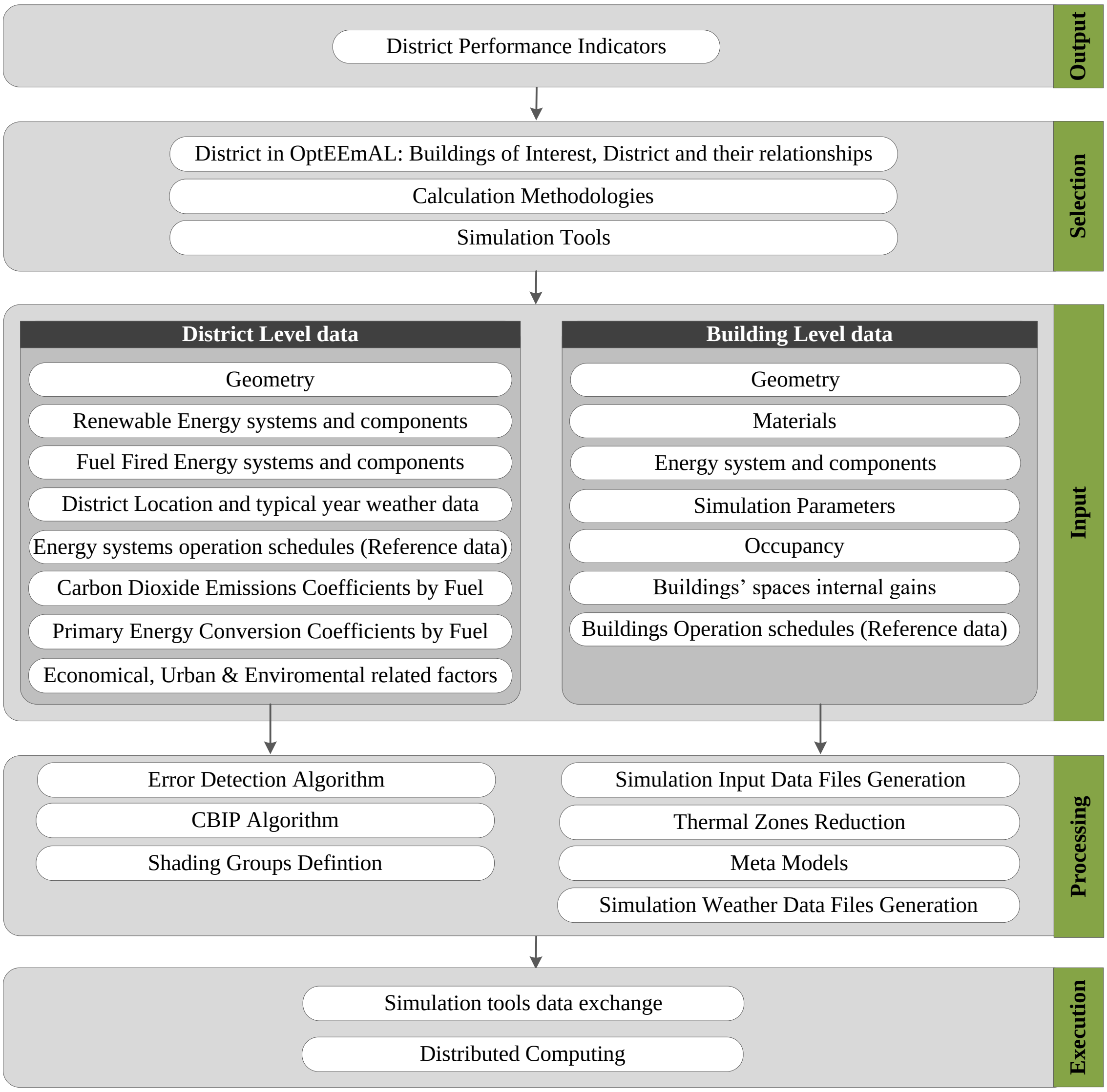

Figure 4: Outline of D4.4: Requirements and design of the simulation model input generator module

Based on the level of detail of the available data it is possible to construct simulation models of increasing quality. A fundamental question that needs to be answered is:

What is the level of detail in the information so that the relevant DPIs can be computed with an accuracy which is sufficient for the decision-making process that the OptEEmAL tool is meant to support?

The answer is not clear, and in fact requires careful consideration of the various data that might be available. To answer this question and determine the level of information that should be sufficient, in Section 5 and in the Annex I, we analyse for each possible DPI different scenarios and rank them according to the perceived accuracy. The result of the analysis can help determine the amount of information in describing the district to ensure that simulation models of sufficient accuracy can be constructed. This analysis also helps address point (iii) above regarding the sequence of calculation of the various DPIs.

Having selected the level of detail in the information so that the relevant DPIs can be computed with an accuracy which is sufficient for the decision-making process that the OptEEmAL tool is meant to support, certain processing stages, which are described in Section 6 and analysed in D4.5 [05], are prerequisites towards the simulation input files generation.

DPIs computation is analysed in Section 7. Here, data exchange requirements between the individual simulation tools are defined. Moreover, since DPIs calculation is a time consuming process and given that during the optimization process a plethora of candidate scenarios will be evaluated, a distributed computation approach for the Energy DPIs calculation is proposed.

Finally, in Section 8, conclusions and future work are discussed.

2 Calculation Methodologies

2.1 Modelling and simulation

To avoid ambiguity, we use the term *calculation methodology* to describe a clearly-defined procedure (however complex it might be) toward performing a calculation for one (or more) DPI of interest (e.g. energy demand). Oftentimes mathematical *models* are used to represent components of the system in consideration; the use of such models can form part of this calculation methodology. *Simulation* refers to the implementation and execution of the calculation methodology. In this text, the terms *calculation methodology, simulation, and simulation models*, are used synonymously, understanding the (admittedly small) risk of ambiguity.

In OptEEmAL, simulation is used for evaluation of the baseline conditions (definition of the current state) but also for comparative evaluation (benchmarking) of the various retrofitting alternatives. As the OptEEmAL platform is to be used as an integrated decision support tool, the accuracy requirements are relatively high from the calculation methodologies that will be adopted (at least when compared to early-design or compliance calculations). As far as decision support is concerned, the issue of definition of the baseline model is particularly critical; a first-principle modelling approach of such complex systems like the ones discussed here is always subject to uncertainties and disturbances. To ensure that the baseline model captures reality correctly, the availability of factual (monitored) data, along with a proper calibration methodology can be exploited and actively used to bridge the “simulated” and “real” worlds [07].

In this Section, the various possible calculation methodologies are investigated and, following a concise analysis a set of requirements are identified (in Section 4) to guide the design of the OptEEmAL DPI calculation component of the platform. The discussion is split in two parts: building- and district-level calculation methodologies, along with the input data requirements.

For *building-level tools* we start, in Section 2.2, with an investigation on the calculation methodologies that should be supported within the OptEEmAL application domain: these may range from “standard” zonal-type approaches and quasi-steady methods to purpose-built simulation models obtained from model-reduction or simplified calculation methodologies. The exposition of available tools is completed in Section 2.3 with presentation of methodologies for district-level calculations.

2.2 Building-level Calculation Methodologies

The complexity of building simulation stemming from the multitude of intertwined parameters along with the many and varying typology of energy-influencing and consuming elements makes the development of accurate simulation models a challenging and oftentimes formidable task. It is becoming quite common, especially during the design (or subsequent retrofitting) phases of a building lifecycle, that simulation models are employed to prognosticate energy performance and help identify salient problems with respect to energy design. The calculation methodologies used can range from “simple” quasi-steady-methods, as defined in ISO 13790:2008 [08] and related standards; to dynamic, implemented in energy-performance simulation zonal-type software like EnergyPlus [09] or TRNSYS [10]. Each calculation method supports different use cases and, as such, the modelling assumptions and the associated inputs can vary greatly in the levels of detail and information that has to be provided. In an attempt to rationalize the medley approaches one could use multiple classification criteria: the resolution of the spatial and temporal discretization, the mathematical structure of the models used, whether these models are created from data or using first-principles, etc.[1]

2.2.1 Calculation Methodologies – Temporal Classification

In general model-based building thermal and energy simulation programs use mass and energy balances [11] as a basis for estimation of the evolution of the values of parameters referring to internal conditions (temperature, humidity, CO_2 concentration, luminance) and energy needs (total energy, maximum power demands) of building interiors. Energy conservation laws are used to investigate thermal energy transfers and exchanges among building elements, spaces, and systems, while mass conservation is used for evaluation of vapour-water transfers (humidity). Implicit in all the methodologies is the discretization of the pertinent conservation equations over pre-determined time intervals. Based on time-resolution criteria calculation methodologies can be classified into two categories:

- *Static or quasi-static calculation methodologies.*

  These methods assume average parameter values for a long period of time (typically a month or a season), and account for dynamic effects using empirical correlations and averaging correction factors. These types of calculation methods are especially useful for estimation on energy performance on an annual basis.

- *Transient calculation methodologies.*

  Transient calculation methodologies take a more granular approach using a time resolution which is comparable to the time-scale of time-varying effects that are being modelled. Consequently, these methods are capable of capturing transient phenomena such as weather changes, occupancy variations, thermal loading effects, or the effects of building energy management systems.

The monthly-based calculation methodology described in ISO 13790:2008 is a prime example of a quasi-static calculation methodology. This fully-prescribed[2] calculation methodology has been adapted – in the context of activities for the implementation of the EPBD [12] – by many EU member states to form at a national level an accepted calculation methodology for computing energy performance. In Annex H of the standard the accuracy of the calculation methodology and the sensitivity to errors in the input data is discussed. In certain conditions, the calculation methodology can be validated against reality and relatively small deviations can be observed for annual predictions, but on the monthly scale these deviations can be significant. The sensitivity to input data is also discussed: uncertainties in the estimation of thermal properties or other input parameters can contaminate the results, and the propagation of these errors can yield sizable deviations in the end results. For this reason, in many cases, the calculation methodology is used to establish an ordering relation, that allows for meaningful comparisons[3] (and thus establishing the rating system used in many countries), but with lesser expectations with regards to prognostication of real performance – this is often referred to as (code) compliance modelling.

2.2.2 Quasi-static Calculation Methodologies

A basic modelling assumption used here is the multi-zonal paradigm: dividing the volume of the building into disjoint regions (zones), each with the basic variables (say, temperature) assumed to be spatially constant. The evolution in time of the zonal parameters is evaluated from the solution of a

---

[1] Some of this analysis for the building-level tools has been initially performed on a different context within the FP7 BaaS project. Here it has been extended and adapted to the requirements of the OptEEmAL project.

[2] and to a certain extent "unambiguous,"

[3] e.g., the concept of a reference building

system or algebraic and/or ordinary differential equations. Zones in that sense form the basic spatial component for performing the calculations. The selection of zoning is in essence the spatial discretization of the building. As it typical in other domains (e.g. the numerical solution of partial differential equations), the resolution should be granular enough to be able to discern all basic effects that are being modelled. So, in effect, the calculation methodology, and in particular the level of modelling detail employed by that methodology, govern the spatial discretization to be used.

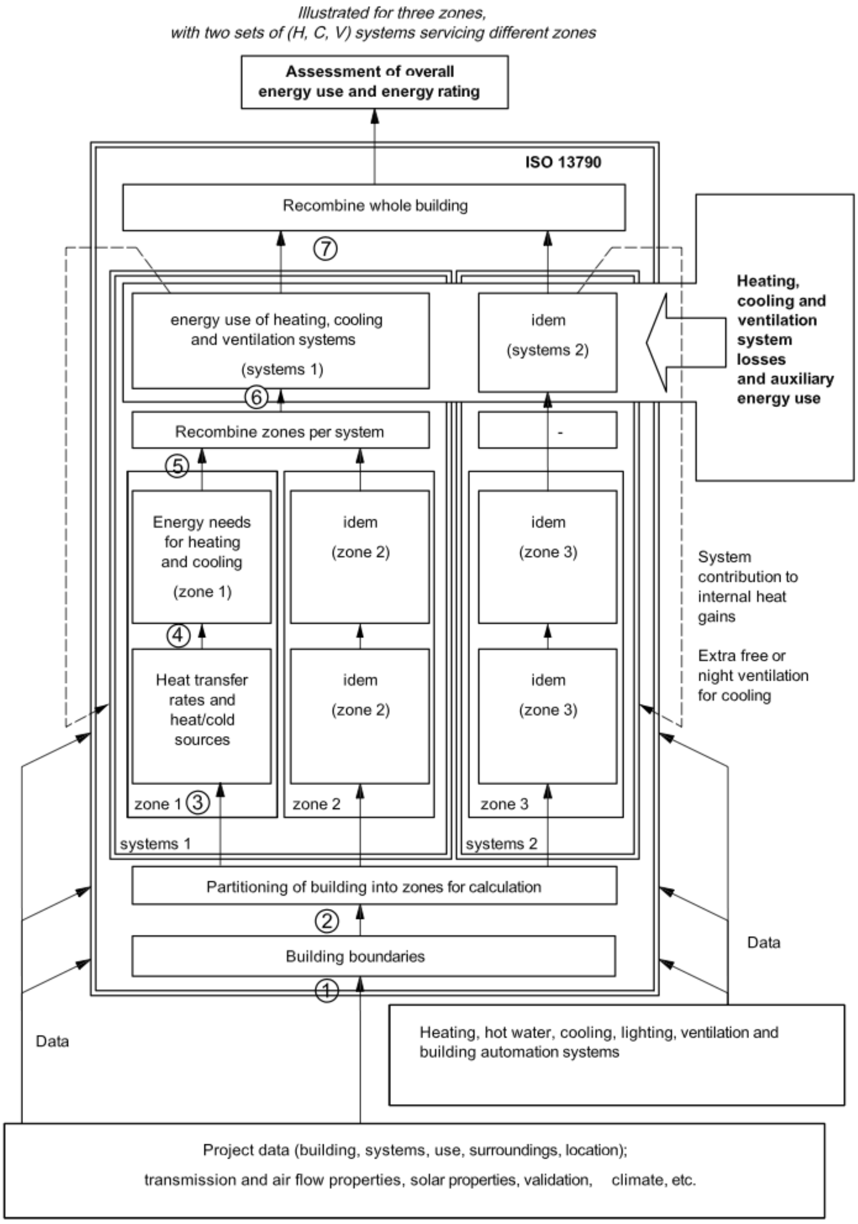

Figure 5: Schematic of the ISO 13790:2008 calculation methodology [14]

As we will see later, for more detailed modelling approaches, as the ones used in simulation software like TRNSYS and EnergyPlus, the approach taken to zoning should be different to conform to the higher level of modelling detail employed. Implicit in the choice of discretization is the balance between accuracy and complexity[4]. An overly fine discretization can lead to many input requirements and increase disproportionately the effort required in setting up the calculation. Too coarse of an

[4] Complexity here refers to the number of inputs that have to be specified, which scale linearly to the number of zones, and also to the computational complexity which also increases as the number of zones increase.

approximation, implies low complexity but also large approximation errors might be introduced invalidating the obtained results. Obviously selecting the zoning to strike a proper balance between accuracy and complexity is a critical consideration in setting up the simulation, and is something that requires careful selection to strike a proper balance between accuracy and effort.

In the calculations described in the standards the desire for transparency and reproducibility, push toward coarser zoning definitions – for the quasi-steady calculation methodology discussed so far the interested reader could refer to [13],or other similar standards on a clear set of guidelines. But for more detailed modelling and realistic results, zoning is the single most important assumption that can separate a properly conducted simulation that closely reflects reality from a nonsensical one. The multitude of ways that the spatial discretization can be defined, with the concomitant effects it has with respect to the quality of the simulation, and the ambiguity in its definition esp. for complex building geometries, makes the entering threshold for whole-building simulation quite high. Once the spatial discretization has been established, at a second level the interactions between zones need to be prescribed: in most cases inter-zone exchanges should be enforced, but to simplify the calculation in certain cases (when there is presumed weak thermal coupling) adiabatic boundary conditions can be enforced thus simplifying the calculation. Once the spatial discretization has been established a connectivity graph can be created to represent the interactions between zones.

In Figure 5, a schematic of the calculation methodology for a building split into three zones is illustrated. Quoting the Standard [14], once the zoning has been established, the basic energy interactions that have to be accounted for in forming the energy (heat) balance at the building zone level include the following terms:

- transmission heat transfer between the conditioned space and the external environment, governed by the difference between the temperature of the conditioned zone and the external temperature;
- ventilation heat transfer (by natural ventilation or by a mechanical ventilation system), governed by the difference between the temperature of the conditioned zone and the supply air temperature;
- transmission and ventilation heat transfer between adjacent zones, governed by the difference between the temperature of the conditioned zone and the internal temperature in the adjacent space;
- internal heat gains (including negative gains from heat sinks), for instance from persons, appliances, lighting and heat dissipated in, or absorbed by, heating, cooling, hot water or ventilation systems;
- solar heat gains (which can be direct, e.g. through windows, or indirect, e.g. via absorption in opaque building elements);
- storage of heat in, or release of stored heat from, the mass of the building;
- energy need for heating: if the zone is heated, a heating system supplies heat in order to raise the internal temperature to the required minimum level (the set-point for heating);
- energy need for cooling: if the zone is cooled, a cooling system extracts heat in order to lower the internal temperature to the required maximum level (the set-point for cooling).

The basic energy calculations involving the terms described before, are performed at each zone and then combined to estimate the energy use for heating, cooling and ventilation systems. The whole process is repeated in an iterative manner. Upon recombination from the zones to the whole building energy-use indices are computed for the whole building. Boundaries to the calculation are the presence of systems for heating, hot water, cooling, lighting, ventilation and building automation systems – all possible considerations within the OptEEmAL project. Their presence and concomitant calculation methodologies modelling their effects are stipulated in other standards and should be used together with the building model.

2.2.3 Transient Calculation Methodologies

In the case where dynamic effects are important the temporal resolution of a month is not sufficient to capture all relevant dynamics. In this case, smaller time steps are required and a different approach is essential. This has obvious benefits: certain physical effects like transfer of heat from building thermal masses or the dynamic effects of the operation of active climate control HVAC components happen on a time-scale which is comparable to the simulation time-step. It is then possible to use more detailed models that capture these dynamic interactions and there is no longer the need for averaging or the use of correlations and other averaging factors. On the other hand, the need for defining boundary conditions, at each time step means that in many cases the problem definition has to be more detailed (at each time step) requiring, at this level of detail, information which may not be available.

An example of such model is the dynamic one described in [14]. Here a zone is represented as a thermal circuit with 5 thermal resistances and 1 thermal capacitance (5R1C). The thermal capacitance is used to model thermal storage effects in the zone. The mathematical formulation of the problem in this case is an Ordinary Differential Equation to model the evolution of the temperature θ_m as a function of time. Upon discretization of the equation using a finite-difference scheme, e.g. an implicit scheme like the Crank-Nicolson method, one gets the equations for the evolution in time of the relevant temperature parameter. One obvious benefit of the model above is the ability to model the temperature in the walls and therefore it becomes possible to have estimates of thermal comfort (as the radiant temperature is an important parameter for thermal comfort). In a multi-zone configuration one needs to set individually for each of these nodes the thermal system and combine it to form the overall thermal network. The number of capacitances in this case is proportional to the number of zones, and a system of Ordinary Differential Equations has to be integrated in time. In ISO 13790 such a methodology is described and the boundary conditions are selected to ensure compatibility between the monthly and dynamic models.

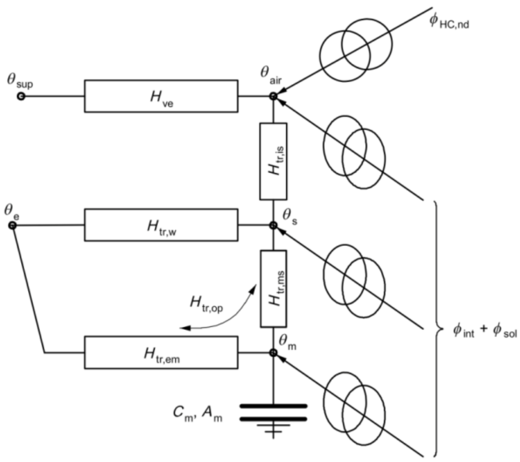

Figure 6: 5R1C Representation of a zone [14]

A similar approach is followed in TRNSYS 16[5] [10]: TRNSYS has a modular and extensible structure where different models for the building and its systems (called Types in TRNSYS) are combined to

[5] Here and in the discussion that follows two specific simulation tools are explicitly mentioned: TRNSYS and EnergyPlus. While the examples given here use these tools for specificity reasons, it should be understood that these tools represent only a small fraction of the options available for whole building simulation. Nonetheless, the discussion regarding temporal and spatial discretization options applies irrespective of the actual implementation selected. The discussion here intends to classify simulation approaches and in no way should be construed as endorsement on the part of the OptEEmAL consortium of any of these tools. For the reader interested in exploring other tools, see [16] for a, not necessarily up-to-date, but nonetheless comprehensive comparison.

form the problem description. Type 56, for example, implements the multi-zone building model. There the geometrical and connectivity information for the zonal splitting is provided along with parameters for describing opaque and transparent building materials. The models used for the multi-zone building are more detailed than the simple RC above, including a star-shaped topology for approximating radiant exchange between zone surfaces along with the transfer function method for modelling transient conductive exchanges through walls. The integration time step can vary from 1min to 1h[6]. This higher level of simulation detail is especially useful when one considers the coupled interaction of the building and energy systems; it is for this reason, that TRNSYS has been extensively used as a simulation-aid tool for energy systems development and testing.

This modular approach which is implemented in TRNSYS is quite common in all building simulation software. While implementation details might differ among different tools, a similar approach is followed by EnergyPlus, IES and others. The modular architecture allows for easy extension with new modules (Types) when a new system or component needs to be modelled, or when a different model is introduced. This component-oriented architecture is probably best reflected in the development of the Modelica language which provides such functionalities needed in the simulation and modelling of complex systems – we discuss more regarding Modelica and its use for building simulation in the following sections.

To properly estimate comfort conditions and whether they are obtainable within buildings, accurate prediction of internal temperatures is important. This requires accurate modelling of the zones but also proper calculation of the thermal gains. The last part is particularly important in cases of buildings with high solar gains e.g. due to a high glazing-wall ratio or due to the presence of solar atriums.

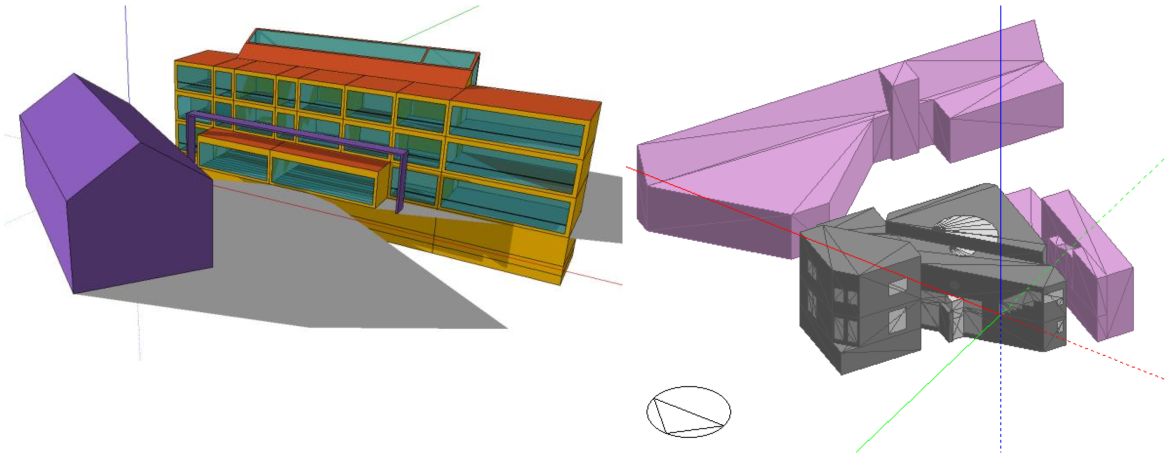

Figure 7: TRNSYS 17 Simulation Model for the FIBP Building (left);
EnergyPlus Simulation Model for the TUC Building (right) [15]

By way of example, shown in Figure 7, are the simulation models for two buildings that have been studied in the context of the PEBBLE [19] and BaaS [20] projects; on the left, the ZUB building of the Fraunhofer Institute of Building Physics (FIBP) is shown, on the right the Technical Services Building at the Technical University of Crete (TUC). In the case of the FIBP building the high glazing to wall ratio along with the proper orientation of the building allows for large solar gains through the triple glazing, effectively reducing heating demands in the winter time. Improper control of external shading devices during summer time can cause overheating due to the large thermal gains. In the case of the TUC building the presence of a solar atrium allows natural light for the building corridors,

[6] In fact, the use of double precision numbers, allows for time-steps as low as 0.01 sec, although it might be hard to justify the use of such time-steps as the time scales related to the thermal processes modelled is at least an order of magnitude slower.

but causes significant overheating especially during the summer months when the solar path is at an almost perpendicular angle with the roof.

In both cases, to compute correctly solar gains and the evolution of temperature variables, a detailed consideration of the three-dimensional building geometry is necessary. For such reasons, state-of-the-art building simulation software today, uses the 3-D information of the building elements, to define geometrically the building spaces and surfaces, and uses this information to compute in more detail radiative transfer, e.g. due to solar gains. Examples of tools which implement such calculation methodologies are TRNSYS 17 [10] and EnergyPlus [16]. Both of these tools use detailed three-dimensional representation of geometric objects-building elements, and use detailed[7] methods to compute such exchanges. At this level of modelling detail, obvious advantages are the capability to capture correctly radiant heat gains and exchanges. It also becomes possible to include the shading effects of neighbouring buildings, represented as external shading surfaces (shown in Figure 7). As mentioned above, the spatial discretization should follow the level of modelling detail.

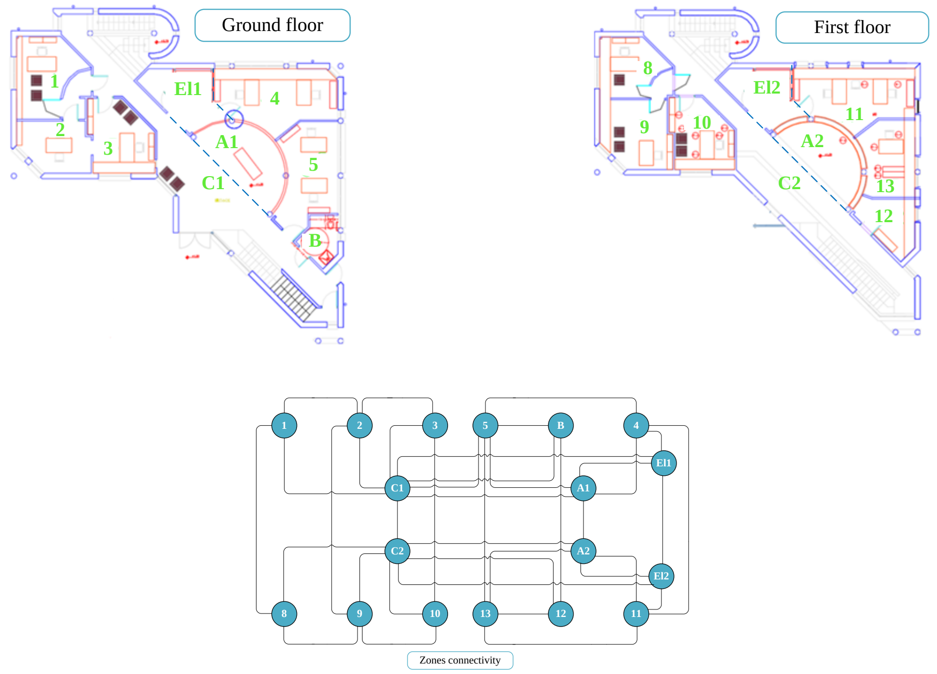

Figure 8: Zoning of the TUC building (above); connectivity graph for the thermal interactions (below).

As an example consider below the spatial discretization of the TUC test-bed. Shown in Figure 8 (top) is the floor plan of the building and the spatial separation into offices which are also considered as thermal zones. The building has a triangular shape with two sets of offices connected by a long corridor that crosses the building. For this (rather ad hoc but “natural”) selection of zones, shown in Figure 8 (bottom) is a connectivity graph demonstrating the various thermal interactions. Each node in that graph represents one of the thermal zones and links between to nodes, imply an adjacency (either via a wall or an air boundary) through which an energy exchange is happening. Obviously creating this graph requires detailed understanding of the geometry and the surfaces through which thermal exchanges occur (we discuss more on this later). Any of the zonal-approximation tools, in the process of setting up the conservation equations to be solved, creates (implicitly) this adjacency graph and forms a number of ordinary differential equations (ODEs) the number of which is proportional to the nodes (i.e. zones) selected. Integration of the resulting equations yields the temperature (humidity, carbon dioxide, or other contaminant) evolution in time. As mentioned above,

[7] Certain simplifications are still made, especially with regard to radiative exchange in non-convex spaces, but this is beyond of the scope of the present document.

the selection of the way the zoning happens is the single most important parameter in defining the spatial resolution accuracy. Moreover, the effect of zoning on the accuracy can depend on the type of DPI which is computed. This discussion, hints at a requirement for the simulation model input generator module: it is important that as part of the process an appropriate zoning should be selected and this depends on the DPI or DPIs that have to be calculated. The possibility of automatically (by use of an algorithm) selecting the proper zoning is an important consideration that should be included in the design of module.

The zoning defined in Figure 8, although reasonable, can be problematic when comfort DPIs have to be computed. The presence of the solar atrium above zones A2 and C2, along with the radiation model used, gives an uneven heat distribution between the simulation and reality. For this reason, splitting the corridor into more zones, so that the solar gain and radiant exchange effects can be correctly captured is necessary. In Figure 9, a different zoning is introduced by splitting zones C1 and C2 in the original case to smaller zones. In the latter case, comparing simulation results can be shown to be in good agreement with sensor measurements obtained from a sensor placed on the curved wall of A1 [18], [19]. Compared to the quasi-static methodologies a more granular zoning is required here. Advantages of the additional modelling detail is that, at this level of detail, temperature and other variations can be correctly captured but at the expense of a more detailed and lengthy definition of boundary conditions, along with higher computational complexity.

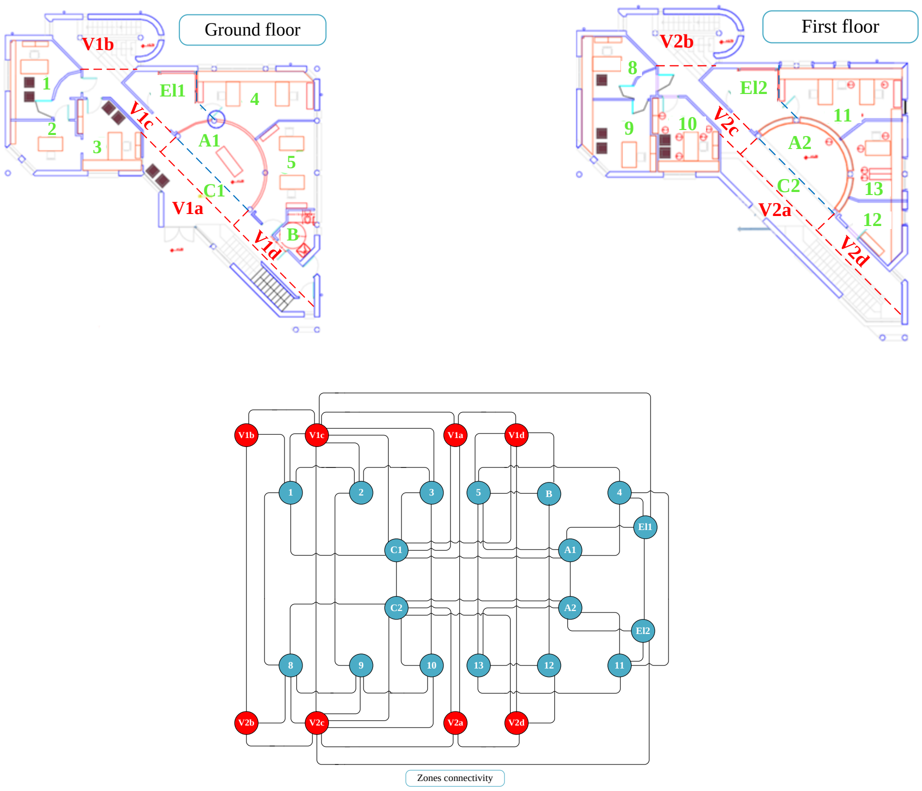

Figure 9: Zoning of the TUC building to account correctly for solar gains through the atrium (top); connectivity graph for inter-zone thermal interactions (bottom).

The zoning shown in Figure 9 is one of the many ways that the discretization can be defined. Many other choices for defining the zones exist, each of them yielding different model-level representations of the same building. As can be expected, assuming these different approaches are done in a way that all effects can be captured similar results should be expected: temperature histories calculated will be different, but such deviations will be “small.” This undefined degree of smallness, combined with the difficulty of having a uniquely defined zoning procedure, introduces an uncertainty that is hard to quantify. In most cases this does not pose a serious problem: the errors introduced due to “discretization” errors are of comparable or smaller magnitude, compared to the errors due to the zoning modelling assumption and uncertainties of other inputs. But still, a methodology for unambiguously defining the zoning approximation is desired.

We mention another calculation methodology, of potential interest to OptEEmAL: System of Resistances and Capacitances (SRC) [21].

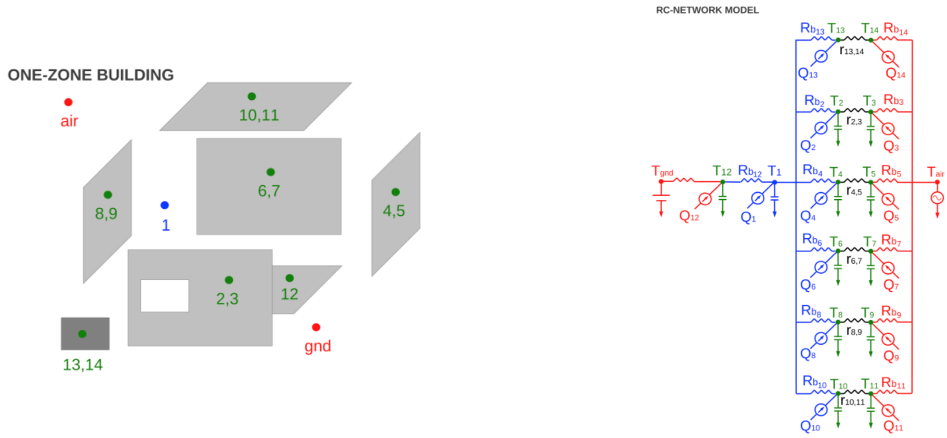

Figure 10: System of Resistances and Capacitances (SRC)

SRC also follows the zonal paradigm: the building is split into surfaces each of which comprises a number of surfaces. Information for setting up the spatial discretization is obtained from an IFC or gbXML data file. In a pre-processing step, the zones (nodes) and surfaces (links) define the connectivity graph. Each opaque surface element is modelled using a 1R2C representation (one thermal resistance, two thermal capacitances or using the Conduction Transfer Function methodology); representation of other opaque and transparent elements is similar. The SRC uses the connectivity graph to assemble the overall thermal network representing the building.

In Figure 10, an example is given for a single zone: on the left a decomposition of the building to surfaces is shown; on the right, the generated thermal circuit is depicted. Heat sources are used to represent thermal interactions, e.g. due to solar gains. Within SRC, a detailed 3-D modelling is used to calculate radiative exchanges between internal and external surfaces; in that sense the level of modelling detail for SRC is similar to the one utilized by EnergyPlus and TRNSYS. Using the elemental assembly, a system of ODEs is formulated and then a numerical discretization scheme (e.g. Euler's method) is used to numerically solve the resulting conservation equations.

One desirable design aspect of SRC is the use of the standardized IFC or gbXML data models, for data input. In that sense, a more direct link exists between CAD/BIM software (used to design the building) and the input to conduct the thermal simulation. This represents a first step in the direction of methodologies to be explored within OptEEmAL; for the simulation model input generator module, data from the District Data Model (DDM) will be utilized to collect pertinent geometric parameters and to create the connectivity graph; this information will in turn form the basis, together with the zoning algorithm for generation of the required inputs, using a dictionary that is appropriate to the tool being selected.

In the previous calculation methodologies only sensible heat calculations were described. It is also possible to include latent heat into the calculation methodology: this is particularly desirable in the presence of humidification and dehumidification systems. In these cases, the air of building spaces is considered a mixture of dry air and water in the vapour state [22]. The amount of water vapour present building spaces' air affects the temporal thermal heat storing capability of the air and the heat transfer rate between the air and neighbour building elements [23]. Therefore, to specify the percentage of water vapour in building spaces' air, vapour transfers between the outside air or adjacent air volumes and the air volume of the space under consideration have to be accounted at every simulation time instant, by augmenting the system of energy conservation equations with mass conservation equations for the moisture content in the air.

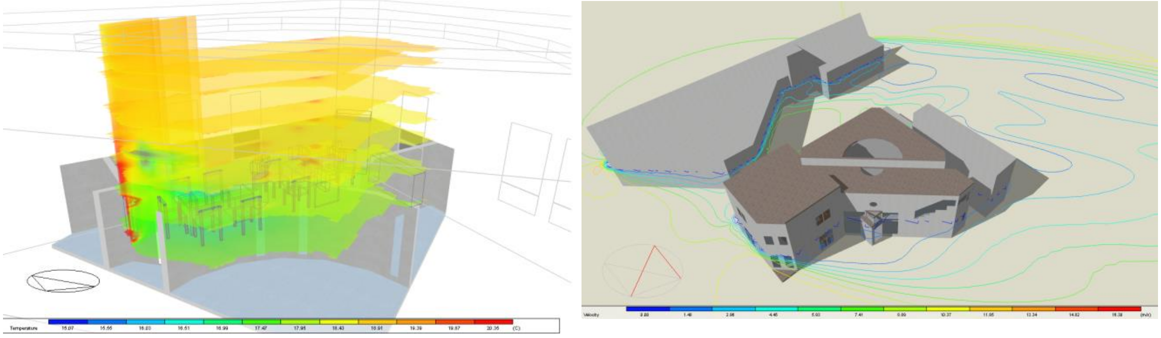

Figure 11: CFD calculate ions for the TUC test-bed: temperature distribution in a zone during heating (left); external CFD calculation to determine the pressure and velocity fields [15].

The zonal approximation is acceptable for many envisaged and practical use scenarios, as it manages to strike a balance between accuracy and the errors introduced by uncertainties (values for thermal properties, occupancy and operation schedules, user actions, etc.). Still in some cases, looking at finer-than-zone scales can be justified. Such cases include: thermal comfort studies where the temperature distribution and its variations within a room or a zone must be known; or in ventilation studies, where the age of air can be an important parameter; or even for the determination of the placement of temperature sensors so that a good reading, representative of the average temperature in the zone, can be ensured. In all these cases, the granularity offered by considering zonally averaged parameters is just not enough. It is exactly for these cases, that the use of Computational Fluid Dynamics (CFD) calculation methodologies can come handy. Shown in Figure 11, are two examples, of the implementation of such methodologies for the TUC test-bed. Shown on the left, is the temperature distribution on one of the rooms during winter heating mode, to estimate the homogeneity of the temperature fields due to heating from the radiators. A second example is shown on Figure 11 (right), here an external CFD calculation was performed to find pressure and velocity fields, developed in the building due to the presence of winds and the interactions with nearby structures. The information shown, velocity field on a plane parallel to the ground, is especially useful for estimating the pressure coefficient on windows, so that better modelling of infiltration can be achieved.

The topic of CFD is very mature and has been developed, applied, and extensively validated in many fields where the dynamic behaviour of fluids (e.g. air) needs to be computed. In these methodologies, first the solution space is defined and appropriate initial and boundary conditions are defined. Then a space-filling partition is introduced using pyramidal or hexahedral elements. The size of these elements should be smaller than a characteristic length scale related to the size of the flow structures that have to be resolved. This partition is often defined in a conforming manner, where the computational grid is defined in a conformant to the boundaries fashion. Then the conservation laws are stated: typically, the Navier-Stokes equations for mass and momentum conservation and the energy conservation equation. A discretization methodology, like the finite-volume or finite-element method is then used to discretize the partial differential equations, on volumes or elements defined in the partitioned space. As a result of the discretization a large system of equations, is solved numerically to yield approximations to the temperature, pressure and velocity fields.

The biggest problem for CFD implementation as whole building calculation methodologies is the need for boundary conditions, to be prescribed on all boundaries of the computation domain. An approach which is often used is to first use a zonal-type approximation, which is seen as a cruder first step, to create the boundary conditions, and then use these boundary conditions to pose and solve the CFD problem. This can be problematic for complex geometries, as a data transformation process has to occur between different domains. As can be readily inferred the pollution due to uncertainties in the results of the zonal approximation, is propagated in the CFD calculations. Unless great care is taken in performing the transfer of information between the two approaches, the validity of the obtained results is always subject to scrutiny. In that sense, CFD for whole-building simulation can be helpful as a quasi-qualitative tool for understanding fundamental flow structures, but with little hope of matching real operation situations in great detail.

2.2.4 State-space calculation methodologies

Beyond the physics-based approaches discussed in the previous Sections, models developed specifically for a particular purpose (e.g. control design) are often developed and utilized in their respective contexts. In this case, no "one-size-fits all" solution exists. The purpose of using these models is markedly different from the ones mentioned above: it is not for performance estimation, or foretelling the variation of relevant parameters, but rather their characteristics stem from their role in the context where they will be used. In the example of the model-based control design, typically state-space models adhering to certain mathematical constraints (e.g. linearity or quasi-linearity) are required. The accuracy of such models may not be of essence but rather their ability to correctly capture dynamics and sensitivities of the system that is being modelled, as this is the critical quality needed for control design. The accurate zonal models described above, are computationally expensive and in a form that is not amenable to control design. For computational efficiency, the number of states should be "small," as repeated evaluations might be required within the control design context where they will be applied.

In the building application domain, the development of such models remains an open problem – although see [24] for a discussion and some preliminary suggestions. Towards defining such models many approaches are possible. In the case where historical data from building sensors are available, structured identification can be performed. These data can be used as an input to a number of identification methods [25], [26], [27], so that data-driven model inference can be achieved. This situation is especially limiting as the data might not already exist, thus an online experiment to the real building has to be conducted. On the other hand, such an experiment can be quite expensive and the system might not be excited enough to capture all relevant dynamics [24].

What seems more plausible is the use of a "detailed" (in the sense of the previous section) model, acting as a surrogate of the real building. Using structured identification, a simpler purpose-built model can thus be constructed. What is particularly attractive in this approach is that excitation necessary for the identification happens at the simulation level, so it is possible to excite the system in many ways that would be impractical, or even unrealistic, if they were to be applied in the real building. The importance of proper excitation for the creation of such simplified models, is also relevant for OptEEmAL; one set of the Energy Conservation Measures (ECMs) considered, belong to the building energy management and control category. As such many of the ideas discussed in the references above, could also be relevant for our case. For different ECMs where systems of passive design characteristics are altered the "excitation" can refer to sufficient exploration of the ECM catalogue space. The situation there is more complicated but the development and use of meta-models can provide a viable option. All such options are particularly relevant in the OptEEmAL optimization context – see D4.1 for more details – where the repeated evaluation for different design alternatives in the context of a global optimization algorithm, can incur unmanageable computation effort.

When computational effort constraints are present, model-reduction can be yet another approach towards a purpose-built simulation model. Here model-reduction [29] techniques are used to simplify (=reduce the dimensionality) of a given model, while retaining certain characteristics. Overall, model-reduction of non-linear models (as they appear in the context of building physics), can be a challenging task because one has to account for bifurcations in approximating the solution manifold and the models obtained using such approaches, can only be valid locally in the solution space, with little guarantees with regard to more global approximation capabilities. Such approaches might be less relevant within OptEEmAL as they fail to capture influences associated to differing ECMs.

Nevertheless, such approaches can be both relevant and useful for the DPI evaluation tasks. Providing support for such models, is a consideration, which can be relatively easy accommodated as they have fewer dependencies and simpler requirements compared to the transient calculation methodologies defined above. What is perhaps more interesting is how these models are developed and this largely depends on the usage – this will form considerations for the development of work in relation to WP4 activities in OptEEmAL.

2.2.5 Calculation Methodologies to be supported in OptEEmAL

In the OptEEmAL platform, and within the simulation model input generator module, the desire is to support one or more of these tools as needed for the calculation of the pertinent DPIs. As mentioned above quasi-static and CFD calculation methodologies are primarily useful either for compliance modelling (the former) or for detailed predictions regarding specifics that do not relate directly to the set of DPIs selected – as such, both of these calculation methodologies are of lesser importance within OptEEmAL. The use of time-steps in the range of a minute to one hour allows to account for the dynamics of active climate control systems, but also to incorporate control strategies that use state measurements as inputs to compute actuation commands. The desire to use simulation for benchmarking and decision-support purposes, also suggests that a “small” time step might be warranted. In view of the comments above, in Figure 12, the type of calculation methodologies of interest to OptEEmAL can be identified.

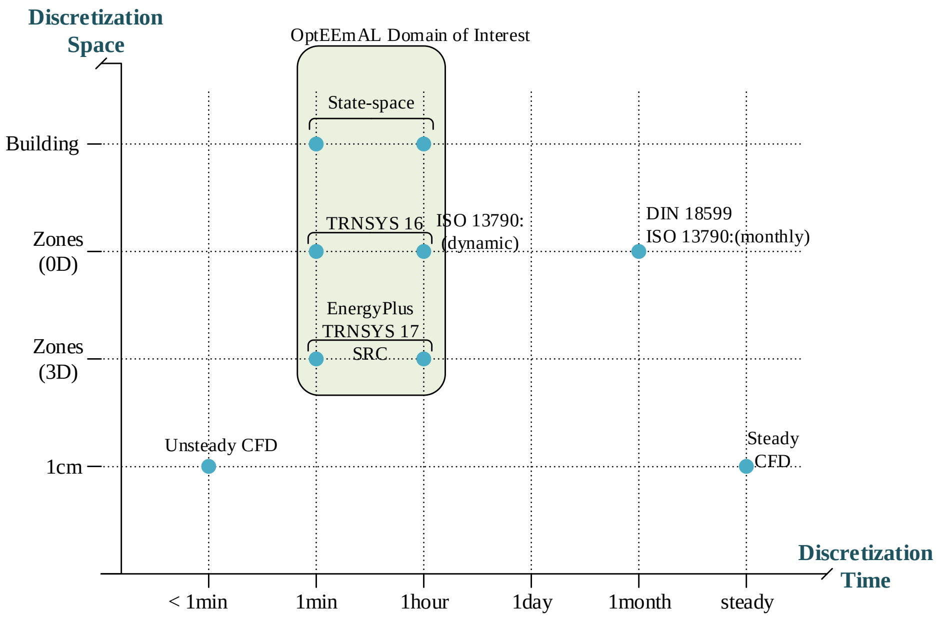

Figure 12: Amalgamation of discussion in this section

Shown in Figure 12 are the calculation methodologies discussed is the previous Sections, on a diagram with the spatial and temporal discretization on its two axes. The classification based on the spatial discretization is important as it determines the level of modelling detail and the amount of information that has to be prescribed as input, when defining the geometry and other related information. The temporal discretization dimension is also important as it determines the integration time step, and consequently the granularity in which dynamically changing data (occupancy, weather, etc.) should be defined.

Concerning the 3D zonal-type transient methodologies, currently numerous BEP simulation tools exist. The most popular between them are: BLAST (Building Loads Analysis and System Thermodynamics); BSim (Danish Building Research Institute); DeST (Designer's Simulation Toolkits; DOE-2.1E (Department of Energy); ECOTECT; Ener-Win; Energy Express; Energy-10; EnergyPlus; eQUEST; ESP-r; HAP (Hourly Analysis Program); HEED; IDA ICE (Indoor Climate and Energy); IES<VE> (<Vrtual Environment>); PowerDomus; SUNREL; Tas; TRACE (Trane Air Conditioning Economics); TRNSYS(Transient Systems Simulation); and Modelica. The accuracy of the simulation results strongly depends on the calculation engine used. A relevant standard for calculation engine validation is the ANSI/ASHRAE Standard 140-2007 Standard Method of Test for the Evaluation of

Building Energy Analysis Computer Programs [43]; here, a set of synthetic benchmarks is defined (Cases) ordered in order of modelling complexity. The goal of this standard is to provide a standardized methodology for testing and debugging building energy analysis methodologies. As part of the standard, a well-defined testing procedure is established: if a calculation methodology fails a case, a number of diagnostic subcases are defined to help identify the root cause of the failure. Also, unlike other standards, there are no accuracy limits to determine that a calculation methodology has "passed" a case, rather a comparative approach is recommended, in which the results of the calculation methodology are compared against other state-of-the-art tools. This comparative methodology serves two purposes: first, to help diagnose modelling and coding errors; and second, to compare against other state-of-the-art approaches so that output variability due to different modelling approaches can be better understood. In many cases empirical validation studies, have been conducted against calculation engines, strengthening the confidence in the capabilities to correctly mirror reality. It should be emphasized that once a calculation methodology has passed all tests of a validation procedure, and is deemed "validated", this in no cases does it imply that the calculation methodology represents the truth. It does show that a set of algorithms have shown, through a repeatable procedure, to perform according to the state-of-the-art. Different studies for different BEP simulation related tasks contrast the capabilities of existing BEP simulation engines. Crawley et al. [16], pioneers of such studies, have detailed the functionality and differences of twenty major building simulation tools. In [44] an energy performance comparison methodology to identify performance problems from a comparison of measured and simulated energy performance data is presented, and eight different simulation engines are evaluated for their capability to be used for that task. The simulation engines selection is based in their ability to contain more than the average number of HVAC components and system types. Eventually, EnergyPlus is reported as the most suitable simulation engine, since none of the other tools incorporates two of our requirements: the ability to create partial geometry models from IFC-based BIM geometry and/or the ability to directly link to optimization tools.

In [46] the review focuses on tools that can be used at multiple stages of the life-cycle and that provide functionalities to exchange data with other tools in open standard building information models, the IFC and gbXML. Concerning the optimization in BEP simulation, in [45], the intensity of utilization of twenty widely used building simulation programs [16] is investigated, concluding to the results presented in Figure 2.4. The investigation is based on a search performed on Scopus (abstract and citation database) for the period 2000 – 2013, using the following keywords: name of a simulation tool; optimization; and building. There, EnergyPlus and TRNSYS seem to be the most frequently used tools, however EnergyPlus will be selected, due to its text-based format of inputs and outputs that facilitates the coupling with optimization algorithms and, their strong capabilities as well.

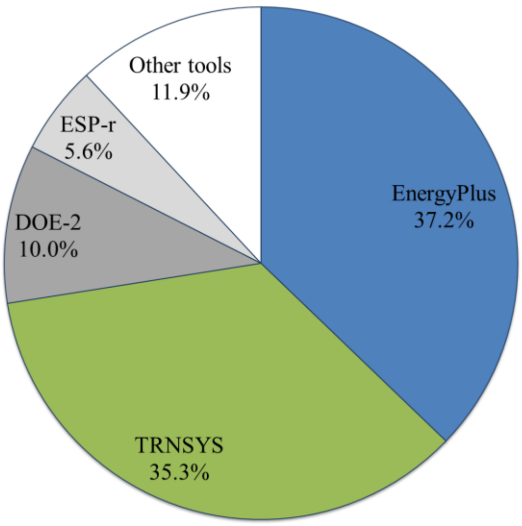

Figure 13: Utilization share of major simulation programs in building optimization [45]

2.3 District-level Calculation Methodologies

2.3.1 Energy and Comfort DPIs

District level energy calculation methodologies are commonly categorized to ‘‘top-down’’ and ‘‘bottom-up’’ [42]. “Top-down” methodologies assume that the building sector is an energy sink and do not distinguish energy consumption due to individual end-uses. “Top-down” methodologies mainly rely on statistical data. Macroeconomic indicators --- such as gross domestic product, employment rates, and price indices --- climatic conditions and number of units are frequently used variables in “top-down” methodologies.

The strengths of top-down methodologies are the need for only aggregate data which are widely available, simplicity, and reliance on historic district energy values which provide ‘‘inertia’’ to the model. At the same time, the reliance on only historical data is their main drawback, as top-down methodologies have no inherent capability to model discontinuous advances in technology. Furthermore, the lack of detail regarding the energy consumption of individual end-uses eliminates the capability of identifying key areas for improvements for the reduction of energy consumption. For that reason, “top-down” methodologies are not investigated within OptEEmAL.

“Bottom-up” methodologies are based on a theoretical analysis of the building sector including specific characteristics that may not be fully captured by top-down methods. This theoretical analysis is derived from a simulation model, which acts as a surrogate of the real building sector. Therefore, the success of these methodologies relies on the accuracy of the models used; if the model is accurate, the bottom-up methodologies can be used to identify improvement opportunities in energy efficiency.

Common input data to bottom-up models include geometry, envelope materials, equipment and appliances, climate conditions, indoor temperatures, occupancy schedules and equipment use. Bottom-up models have the capability of determining the energy consumption of each end-use and as such can identify areas of improvement. As energy consumption is calculated, the bottom-up approach has the capability of determining the total energy consumption of the district-scale energy systems without relying on historical data. The primary drawback caused by this level of detail is that the input data requirement is greater than that of top-down models and the calculation or simulation techniques of the bottom-up models can be complex.

Compared to the building-scale energy simulation, the simulation of district-scale energy systems and their interactions represents a challenge that is addressed only in parts by the calculation methodologies discussed in Section 2.2. EnergyPlus and other detailed building simulation tools are very capable at the calculation of building-level performance indicators, but have limited capabilities when interacting energy systems at the district scale exist [30]. In [31], an extensive review for urban energy system modelling approaches is performed. One of the conclusions of the review is that while many tools exist, there are significant gaps and district-level simulation is much less mature than building-level tools.

If the interactions between buildings in a district are weak, then it is possible to use multiple EnergyPlus simulations. Weak interactions should be understood in that there are no interacting energy systems (i.e. district energy systems like, for example, district heating) or effects from long-wave radiation from neighbouring buildings. In the literature there are reports of approaches for inclusion of such interactions: namely the use of co-simulation approaches or for inclusion of long-wave radiation effects the use of shading surfaces. But while the implementation of specific examples is possible, it is very hard to develop a generic tool that can be included in the OptEEmAL platform.

It is for this reason that integrated district-level simulation tools – although only relatively few exist – should be used in cases where coupling exist. In [31], an attempt is made to collect such tools that support a number of use cases at the district-level. These tools range from simplified modelling tools, to purpose built tools for specific use cases (e.g. design of district heating) to very detailed tools for microclimate or lighting simulation. The result of the analysis is shown in Figure 14, with most of the tools available characterised in terms of the supported offered for modelling district-level systems.

	External air flow	SW radiation	LW radiation	Building thermal	User behaviour	Building system	Thermal network	Electrical network	Gas network	District plant	Thermal storage	Wind power	Photovoltaics	Ground source	Spatial	Transportation	Embodied energy	
CitySim	X[1]	D[2]	D	S	D	S	S	X	X	X	S[3]	S[4]	S	S[4]	D	X	X	City energy simulation for groups of buildings / city quarters.
EnergyPlus	S	D	S[4]	D	D	D	S	X	X	S	S	S	S	D	S[5]	X	X	Detailed building simulation, limited interactions.
ESP-r	S	D	S	D	D	D	S	D[6]	X	S	D[7]	S	S	S	S	X	X	Detailed building simulation, thermal and elec networks possible.
IDA ICE	S	D	S	D	D	D	D[8]	X	X	S	S	X	S	D	S	X	X	Detailed building simulation, thermal networks possible.
Polysun	X[9]	D	S	S[10]	D	D	D	S	X	S	D	X	D	D	X	X	X	Detailed solar thermal and hydraulic systems.
TRNSYS	L	D	D	D	D	D	D	S	X	D	D	D	D	D	X	X	X	Detailed simulation tool for systems and single buildings.
Envi-met	S	S	S	S	X	X	X	X	X	X	X	X	X	X	S	X	X	Microclimate model.
KULeuven IDEAS lib	S	D	D	D	D[11]	D	S	D	X	S	S	X	D[12]	D[13]	X	X	X	District-level Modelica library.
LBNL District lib	S	D	D	D	S	D	S	D	X	S	S	S	D	D[14]	X	X	X	District (and building) Modelica libraries.
energyPRO	X	X	X	L	X	D	D	D	X	D	D	D	D	S	S[15]	X	X	Techno-economic simulation of energy systems.
RETScreen	X	X	X	S	X	S	S	X	X	S	S	S	S	S	X	X	X	Energy, life cycle cost, emissions, finance and risk analysis.
HOMER	X	X	X	L[16]	X	X	X	X[17]	X	S	X	D	D	X	X	X	X	Microgrid design optimisation.
Termis	X	X	X	L	X	X	D	X	X	S	S	X	X	X	L	X	X	Operate, simulate & optimise district heating networks.
Neplan	X	X	X	L	X	X	D	D	D	S	X	D	S	X	L[18]	X	X	Simulate & optimise electrical, water, gas and heating networks.
NetSim	X	X	X	L	X	X	D	X	X	D	X	X	X	X	L[19]	X	X	District heating, cooling and steam simulation environment.
EnerGis	X	X	X	S	X	S	S[20]	X	X	S	X	X	S	S	D	X	X	GIS-based urban energy and district heat network design tool.
SynCity	X	X	X	S	D	S[21]	S	S	S	S	D	S	S	S	D[22]	D	X	Integrated tool for holistic urban energy systems modelling [23].
EPIC-HUB	X	X	X	L	X	S	S	S	S	S	X	L	L	X	S	X	X	Middleware platform for multi-carrier infrastructure systems.
MEU	X	L	L	L[24]	S	S	S	S	X	S	X	X	S	X	D	X	X	Energy management tool for cities and multi-energy utilities.
UMI	X	L[25]	L	L	X	X	X	X	X	X	X	X	L	X	D[26]	D[27]	S	Rhino-based link to Radiance and EnergyPlus.
Radiance	X	D	D	X	X	X	X	X	X	X	X	X	D	X	D	X	X	Powerful ray-tracing program.
Solene	L	D[28]	D	S	S	X	X	X	X	X	X	X	X	X	D	X	X	Energy simulation for city quarters.
Fluent	D	D	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	CFD software.
OpenFOAM	D	X	D[29]	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Extensible CFD software.

Figure 14: Capabilities of district-level tools (from [30]).
Legend: (D) Detailed Support; (S) Simplified Support; (L) Link to external tool; (X) No support.

From the list of tools on the Figure, few can be used to perform multi-disciplinary analyses, and when the details associated with each of the packages – this is out of the scope of this text, but see in [30] for a thorough analysis – CitySim and EnergyPlus are two options that have reasonable support for modelling the building but also supports modelling resource flows in district configurations.

2.3.2 Environmental and Social DPIs

The analysis of environmental impacts of the built environment is addressed through a wide range of methodologies at both the individual building scale and the city scale [51]. At the individual building scale, among various methodologies (e.g. statistical models, simulation) life cycle assessment (LCA) is the clearly accepted scientific methodology for quantitative assessment of building over their entire lifespan accounting for upstream impacts [52]. A lot of LCA studies and associated reviews have been done at the building scale [53] [54] [55] and have highlighted the dominance of the use phase (especially due to energy consumption for heating and cooling), the increase of the share and absolute value of embodied energy for low-energy buildings and the fact that these analysis mainly consist of life cycle energy assessments, forgetting one of the key features of the LCA methodology, the multi-criteria approach [51].

At the urban level, [52] indicates that the LCA methodology is again a dominant method and is complementary with other methodologies used at the city/territory scale such as consumption-based approaches (CBA), metabolism-based approaches (MBA) and complex systems approaches [56] [57].

In addition, there is currently a growing interest for the district scale in the field of urban sustainability assessment and the sustainability concerns that nowadays focus mainly on buildings will probably soon be transferred to the district [58].

As an answer to this growing interest, a new trend stems in the application of LCA at the district scale and several papers related to the application of LCA at the district scale have already been published [51]. But they mainly consist of specific case studies with a heterogeneous application of the LCA methodology preventing common conclusions to be drawn. These first applications of the LCA methodology at the district scale in the recent past years have also led to the development of the first LCA tools at the district scale. For the time being, a very little number of tools are commercially available for such analysis. novaEQUER [59], SOLEN [60] and NEST [61] appear as the most advanced LCA tools at the district level. When adding the possibility to have a 3D visualisation of the district under study, the list is even shortest with only novaEQUER and NEST providing such a feature. Finally, most existing LCA tools are focused on new district/urban development projects. As far as we know, only one of the commercially existing tools allows the assessment of retrofitting projects (in combination with all the features mentioned earlier) and this tool is NEST. This is the main reason why NEST has been selected to be part of the OptEEmAL platform.

The LCA calculation methodology implemented in NEST is in line with international standards for LCA in general such as ISO 14040 [62] and 14044 [63] and construction specific standards such as EN 15978 [64]. Data used are taken from the ecoinvent LCA database [65] as well as national and international statistical database.

With respect to social aspects, the quantitative assessment of social aspects for district retrofitting projects is in its early stage of development and not a single existing tools can be considered as relevant for this type of assessment. Although some social aspects are quantitatively assessed in the NEST tool (presence of schools, of shops, transportation networks, etc.), they are not in line with the social DPI to be investigated in OptEEmAL. As such, no existing tool can be used in the OptEEmAL platform for the assessment of social aspects and a specific algorithm will be developed in the project.

3 Simulation Tools to be supported in OptEEmAL

In Section 2, our analysis was focused on the calculation methodologies – and respective tools embedding those methodologies -- available for the DPIs calculation, focusing on the Energy and Comfort, the most challenging DPIs to be computed. Various methodologies – and respective tools embedding those methodologies -- were analysed, concluding to the simulation tools that are selected to be used within OptEEmAL. This Section briefly presents these simulation tools and their input/output format (dictionary) files, required to properly describe information requested and generated from each tool.

3.1 Energy and Comfort DPIs

3.1.1 EnergyPlus

As mentioned earlier, EnergyPlus can be used either for building or for district level energy performance simulation. EnergyPlus [09] is a software released by the U.S. Department of Energy. EnergyPlus follows the zonal thermal models paradigm, where the building is divided into spaces (thermal zones), each with a constant temperature, humidity etc. The energy conservation differential equation and the mass conservation differential equation on each zone are used to evaluate the evolution in time of the zonal thermal parameters.

In EnergyPlus structure the whole building (district) is divided into three main parts: Zone, System and Plant. The entire system consists of many interacting modules which are integrated and controlled by the Integrated Solution Manager. The schematic subroutine calling tree shows the overall structure of the program.

- ProcessInput (InputProcessor)
- ManageSimulation (SimulationManager)
  - ManageWeather (WeatherManager)
  - ManageHeatBalance (HeatBalanceManager)
- ManageSurfaceHeatBalance(HeatBalanceSurfaceManager)
- ManageAirHeatBalance (HeatBalanceAirManager)
- CalcHeatBalanceAir (HeatBalanceAirManager)

EnergyPlus 8.2.0 is the first version written in C++, while earlier versions of EnergyPlus were all written in the FORTRAN programming language. EnergyPlus 8.2.0 is at least 20% faster than EnergyPlus 8.1.0 for a wide range of models.

3.1.1.1 Input format file

The main input file is the input data file (IDF), an ASCII file which contains information about the building and the HVAC system to be simulated. The EnergyPlus input data are structured into classes. For each class, fields are defined, which describe the characteristics of the class objects. Objects are the instances of a class. All the available classes are listed into the Input Data Dictionary file (IDD).

3.1.1.2 Weather format file

The EnergyPlus Weather file (EPW) is an ASCII, csv format file containing the hourly or sub-hourly weather data needed by the simulation program.

3.1.1.3 Output format file

Beyond a wide variety of EnergyPlus output variables, particular variables can be reported depending on the actual simulation problem described in the IDF. The Report Data Dictionary (RDD) is a text file listing those variables available for reporting during the simulation of a certain IDF. For instance, Fanger's predicted mean vote could not be reported, if People class objects for all zones have not been defined. Selecting an output variable from that list, an object of the Output:Variable class is defined and imported in the initial IDF.

After an initial IDF -- enriched with the selected Output:Variable objects -- simulation run, the resulted data-sets of the selected variables are printed in a comma separated text by a semi column, where each column corresponds to a unique variable time-series with reporting frequency defined by the modeller, commonly equal to the simulation timestep.

3.1.2 CitySim

CitySim [32], [33] is a district energy performance simulation tool that comprises a Solver and a Designer (graphical user interface). It focuses on the energy flows of multiple simplified building models and their interdependent relationship with their urban climate. It consists of a simple resistor-capacitor thermal model for simulating the behaviour of the building stock and a radiation model for shortwave radiation to identify solar gains on facades and roofs. CitySim includes building thermal, urban radiation, occupant behaviour, and plant/equipment models integrated as a single simulation engine. To achieve a good compromise between modelling accuracy, computational overheads and data availability, CitySim simulates multiple buildings up to city scale using simplified models. System simulation capabilities of CitySim include: Boilers, Cogeneration, Heat Pump, Tanks and Photovoltaic. CitySim implements simpler (but also more efficient) models for simulation of groups of buildings but takes into account radiative exchange and microclimate effects.

3.1.2.1 Input format file

Input is provided in a set of XML files that include information for buildings and systems in building and district level.

3.1.2.2 Weather format file

CitySim requires the weather data to be provided according to the Climate (CLI) format file, starting with a header that contains the city, and its geographical position, followed by the hourly meteorological data for a year, organized by day, month and hour.

3.1.2.3 Output format file

In contrast with EnergyPlus, where a plethora of output variables can be listed and reported, CitySim can report certain yearly output variables. These reported data-sets are printed in numerous text output files (.out).

3.1.3 HVAC Systems and Control

In this section, we describe how the simulation of HVAC systems and related control ECMs fits within the whole system simulation strategy and the functional blocks needed to integrate the control ECMs within the OptEEMaL platform. A detailed schematic is given in Figure 15. The simulation of passive ECMs to determine relevant DPIs related to building energy consumption profiles can be performed with different set of input parameters, for instance different zone temperature set-points corresponding to different levels of comfort. The HVAC component generator selects the active measures corresponding to the highest energy demand (full comfort). The role of the component generator block is to determine the sets of active measures that best fit the electrical and thermal load. A proper set of active measures can also be determined by the top-level optimizer which simultaneously optimizes passive, active and controls. After that active measures have been determined, based on all the information about building energy demand and associated levels of comfort, the control strategies generator selects and simulates the control ECMs applicable and computes the remaining DPIs (energy, economic and comfort) to fully characterize the considered refurbishment scenario. Note that although simulation tools such as EnergyPlus or CitySim have capabilities to model and simulate HVACs, we propose to simulate selected active ECMs along with their corresponding control ECMs using customised MATLAB scripts. The reason for that, is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls.

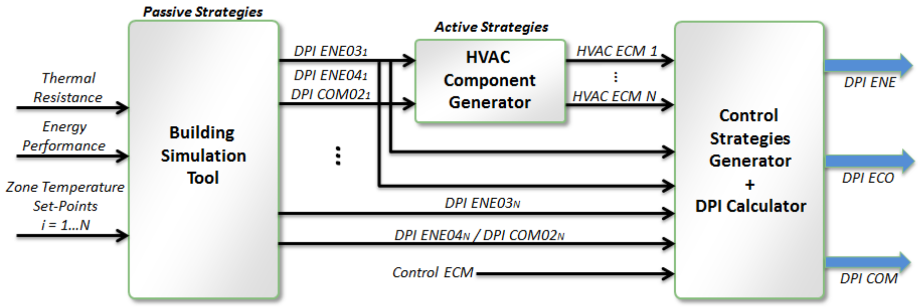

Figure 15: Scenario Generation Module

A Control ECM is included in the Control strategies simulation block through two separate modules as depicted in Figure 16. The first module performs the control ECM simulation receiving one or more profiles of electrical (L_{el}) and thermal (L_{th}) loads and returning electrical/thermal powers supplied by each active ECM ($P_1, \ldots, P_N$). In addition, the first module returns all the information about the active ECMs which are needed to evaluate the DPIs, for example the efficiencies ($\eta_1, \ \cdots \ \eta_N$). Note that the relevant information about the active ECMs are known once that they are selected out of the component generator block. Based on the computed power supplies and efficiencies, the second module computes desired set of DPIs by means of their analytic equations.

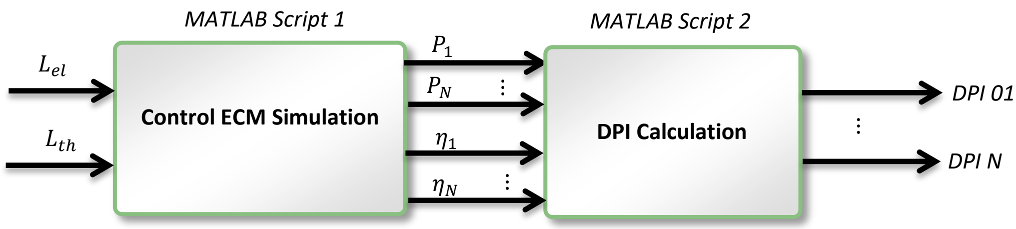

Figure 16: Implementation of Control ECMs as MATLAB Scripts

The DPI calculation module is part of the DPI calculation block illustrated in Figure 3 above. It includes the calculation of DPIs which are relevant with the output of the control ECM simulation block, including economic, energy and comfort DPIs. The optimiser uses the results obtained from DPI evaluation to modify the parametrised variables and to launch a new scenario generation based on the application of the probabilistic operators on the current population of ECMs.

3.1.3.1 Input format file

In the previous section we have introduced two MATLAB scripts for the simulation of active and control ECMs. The inputs of the first script for the control simulation are text files including the electrical and thermal load profiles. The profiles have minimum length of 24 hours whereas the time step is one hour. The second script takes as inputs the list of powers delivered by each active ECM selected by the tool and the corresponding equipment efficiencies, which are used to determine actual fuel consumption (e.g. consumption of natural gas).

3.1.3.2 Output format file

The outputs of the first script are the inputs required from the second script; they are text files containing the powers and the efficiencies associated with each active ECM. The outputs of the second script are text files including energy, economic and comfort DPIs.

3.2 Environmental DPIs

3.2.1 NEST

NEST is a software for the environmental and socio-economic assessment of urban development projects. NEST v1 is the result of a PhD thesis performed in Nobatek and GRECAU laboratory [61]. NEST offers an original combination of features such as the use of the LCA methodology as the core methodology, its 3D interface and its adaptation to retrofitting projects for instance. The main advantages of the LCA methodology are its multicriteria (Global Warming Potential, Primary Energy Consumption, etc) and multisteps (full life cycle) approaches. In NEST, different components of the district such as buildings (both from the operational and embedded environmental impacts perspective), roads, green areas, transportation systems, etc.

In its commercial version, NEST requires the user to input information about the district under study and to draw the 3D representation of the district. One of the important feature of NEST is to provide default data if the user does not have the requested information. This allows to perform the assessment in the early stages of urban development projects. This default data is based on national legislation, European statistical databases, etc.

NEST is nowadays further developed through Nobatek internal projects as well as national and international R&D projects. After a second version in 2013, a third version of NEST (NEST 3.0) has been released in April 2016.

3.2.1.1 Input format file

The NEST input will be an xml file containing the information about the buildings of the district and outputs from energy simulations needed as inputs for the NEST calculations.

3.2.1.2 Output format file

The NEST output file will be an xml file containing the results of the environmental calculations performed in NEST.

3.3 Urban, Social and Global DPIs

The DPIs grouped under the categories of urban, social and global DPIs are to be calculated through simplified calculations performed by the OptEEmAL tool. They will require as input data previously calculated DPIs and other data that will be listed below. The algorithms needed to perform these calculations will be implemented using MATLAB within the private cluster computing component of the simulation module.

These DPIs tackle, namely:

Urban category: all four DPIs (Percentage of buildings with an A rating in the Energy Performance Certificate, Percentage of buildings compliant with PassivHaus Standards, Percentage of buildings compliant with EnerPHit Standards and Percentage of buildings compliant with nZEB standards) will compare the results obtained on certain values to some fixed reference values and if the results comply with all the imposed conditions then the considered building will be contemplated as compliant. From the addition of all the building surfaces that comply with these conditions and the total building surface (obtained from either the CItyGML file or the IFCs introduced) the percentage of compliant buildings will be obtained.

Social category: this DPI measures the percentage of inhabitants that use more than 10% of their incomes to pay energy bills. Again, a simple formula will be used, where firstly the cost of the energy consumption per inhabitant will be calculated and then this value compared to the incomes of inhabitants. The incomes of inhabitants which are lower than the 10% of the price used to pay energy bills will be considered energetically deprived inhabitants. Energy poverty will then be obtained dividing the number of these energetically deprived inhabitants by the total number of inhabitants to obtain the percentage.

Global category: these two DPIs bring into relation two previously calculated DPIs (ENV04 and ENV03, respectively) with ECO02, which represents the investments. Therefore, a simple division is required to calculate them.

3.3.1.1 Input format file

As previously stated the main input format file will be numeric values obtained by the OptEEmAL platform in the calculation of other DPIs. Thus, the main input file will be an XML containing the required input data to perform the calculations.

3.3.1.2 Output format file

As for the input format file, the outputs will be provided in an XML file containing the results of the DPIs calculation through the algorithms and equations defined in D2.2: Report on District Sustainability Indicators to formulate and optimise scenarios.

4 Input Data

The development of the simulation model input-generator module strongly depends upon the availability and quality of input data. Following the discussion and selection of tools in Section 2, we delve deeper in this Section to topic of the input data requirements. This Section looks at these requirements from the perspective of their use in generation of the model inputs; as such it complements the analysis of input data requirements from the perspective of the user, which is presented in D1.2. Together these tasks provided input for the definition of the district data model which is presented in D2.1.

4.1 Computation tasks in OptEEmAL

Simulations and their respective calculation methodologies will be used with OptEEmAL to accomplish a variety of different tasks:

- Baseline DPI calculation.

  In this task the pre-refurbishment performance of the building is estimated. This might include the calculation of Energy, Comfort, Environmental and other DPIs. The use of monitored and contextual data can help ensure real-world relevance of the computed DPIs.

- Scenario DPI Evaluation.

  Following the definition by the platform users, of the retrofitting goals, and generation using the ECM catalogue of the various scenarios, each of these scenarios has to be evaluated. For energy- and comfort-related parameters depending on the interdependency of the systems, multiple building-level simulations might be issued, or if there is stronger coupling, then “pure” district-level tools will be utilized (CitySim). The same applies for the other types of DPIs.

- Model calibration.

  Although models are designed to predict the real behaviour of buildings and their systems as accurately as possible, their predictions may differ from measured values, because of a different number of reasons including: sensor measurement errors, modelling insufficiencies, or incorrect model parameter value’s estimations. Model calibration tasks rely on past sensor measurements in order to change the model parameter values and bridge the above gap; this functionality is important to ensure that the baseline DPI calculation reflects the true state of the neighbourhood.

4.2 Data Sources

For the OptEEmAL platform to support the tasks above, the need for supporting of calculation methodologies identified in the previous section becomes apparent. What also becomes clear is the type of integration needed with other components so that static and dynamic data can be obtained from the data repository and provided to the simulations. Therefore, there are two distinct requirements to support such simulations:

<u>Access to static data</u>

Static data is needed for setting up the simulation (building geometry, materials, etc.). These data are available on the BIM and CityGML models and are accessed through the DDM.

<u>Access to dynamic data</u>

Dynamic Data Schedules can be classified into three broad categories:

1. Monitored data (Source: Measurements)

Include factual data obtained from in building sensors, or other historical data obtained during actual building operation, gathered from the present time instant and backwards.

2. Georeferenced data (Source: External Services, Geo-referencing module)

   Forecast data, refer to predicted data obtained from external services or computed from forecasting modules. These data include weather predictions (obtained from a weather prediction service), occupancy forecasts (obtained from a room scheduling system), etc.

3. Reference data (Source: Contextual information, Standards)

   Reference data refer to synthetic data that are used in the absence of real measured data. These can be reasonable default (reference) values to be used in the simulation when no other information is available. These might be obtained using statistical aggregations of past data (e.g. Meteonorm weather data), or using standards' recommendations based on the building typology or other reasonable assumptions (e.g. occupancy schedules follow the working schedules). Obviously these synthetic data represent "average" Schedules, to be used in place of real data when these are not available. An example, could be when occupancy sensors are not installed in the building (or occupancy information cannot be indirectly inferred from other sources), reference occupancy data can then form reasonable substitutions. In the design-phase utilization of calculation methodologies, all dynamic data used are reference data.

4.3 Classification of Input Data

In this Section, we take a deeper look into input data, in an effort of classification based on the type of information which is required into two static and dynamic data categories. The discussion in this Section, helps make the types of data needed more concrete and will be useful for the analysis of the following Sections.

4.3.1 Static Data

The static data can be classified further into district and building level data as described in the following sections.

4.3.1.1 District level

The district level data category can be classified into the following subcategories:

A. Geometry.

The District Geometry data subcategory contains a geometric definition of all the buildings in a large sector of a geographical district, which is provided in a CityGML data file format. These buildings include: the buildings of interest of OptEEmAL platform together with surrounding buildings affecting the energy balance of the buildings of interest indirectly by blocking sunlight. Although CityGML geometric data may be provided in one of the four possible levels of detail (LoDx, x=1,2,3,4), as Figure 17 displays, only the external non-glazing envelope surfaces are extracted and used.

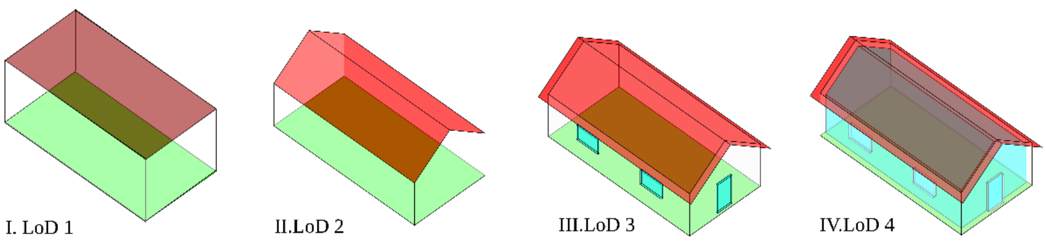

Figure 17: Illustration of Levels of Detail (LoDx ,x=1,2,3,4) in the geometric representations of CityGML

Opening elements (described in LoDx, x=3,4) are not taken into account and only the external walls and roof surfaces of the building envelopes are considered. Details regarding the building interiors (described in LoD4) are omitted as well and the buildings are approximated by simple polyhedral solids. Such simplifications are adopted since the main purpose of these data is twofold: either to provide information for calculating inter-building shading effects (opening information is not required in this case) and to be used as input to district scale simulation programs such as CitySim where only the glazing proportion of the envelope total area is required.

B. Energy Systems and Components

District energy systems and components refer to a set of devices enabling energy generation, conversion and/or distribution throughout the district. District shared energy generation and conversion systems are listed in table 3. More information can be found in D3.2. Distribution systems are the piping systems enabling the distribution of heat and/or cool and water circulation pumps. They can be modelled using a variety of models including losses and/or heat transfer between relevant subsystems.

Table 3: HVAC Systems and Components applicable at District Level

District Energy generation and distribution system	Energy generation	High efficient boiler Condensation boiler Cogeneration High efficient chiller (electricity) High efficient heat Pump
	Renewable generation	Biomass boiler
		Solar thermal collectors
		Photovoltaic collectors
		Geothermal
		ECM – Wind Turbine
	Energy Storage	Hot / Cold water tank Phase change materials units
	Distribution	Pipes, Water Circulation Pumps

4.3.1.2 Building level

The static building level data can be subdivided into several subcategories, which play different roles in building simulations as analysed in the following sections.

A. Geometry

The Building Geometry data subcategory contains a detailed geometrical definition of only the buildings of interest in OptEEmAL which is provided in an IFC data format. The geometrical description of each building of interest contains polyhedral representations of all the necessary elements to support a detailed building energy performance simulation performed by thermal simulation programs such as EnergyPlus.

These elements can be classified into the following three categories depending on their role in the simulation: *building constructions* which are layered entities which impede thermal flow among building spaces, *building openings* which can be considered layered entities which impede thermal flow under certain conditions (closed) and *building internal space volumes* the temperature of which is to be considered for energy calculations.

During the building design phase, these building geometry elements can be provided by the architectural view which is developed using a BIM software. From the simulation viewpoint however, the amount of information provided is too detailed for thermal simulation purposes. While the building construction and opening elements such as interior/exterior walls, floors, roofs and openings assume to be monolithic in the architectural view, their subdivision into thermal boundary surfaces is a prerequisite for energy simulation purposes. Hence, reduction, simplification and transformation of the data provided by the architectural view are the thermal simulation geometrical requirements [1]. With respect to this transformation, a subdivision process of architecturally defined surfaces into *thermal boundary surfaces*, which are defined as *space boundary surfaces,* is required [2] and is performed using the Common Boundary Intersection Projection (CBIP) algorithm described in Section 6.1. Finally, if these space boundary surfaces are available then, according to [3], then the IFC data model can be augmented to include the space boundary surfaces required for thermal simulation purposes.

The space boundary geometric representation of a building has two levels, useful for architectural and thermal simulation model generation purposes:

1st-level space boundaries: the building's spaces are defined by space boundaries according to the architectural view (example is displayed in Figure 18 part A).

2nd-level space boundaries: the building's spaces are defined by space boundaries according to the thermal simulation model generation requirements.

These boundaries can be distinguished further into two types: Type 2a which are the space boundary surfaces through which thermal energy flows either between two adjacent building spaces or between a building space and the outside environment and Type 2b which are the remaining surfaces if from the first level space boundaries the second level type 2a defined earlier, are removed. Examples of 2nd level space boundaries of type 2a and 2b are displayed in Figure 18 part B.

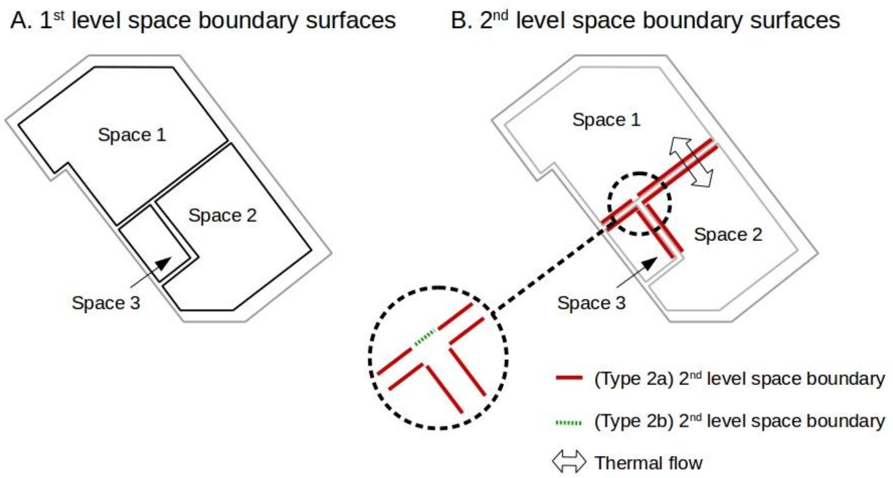

Figure 18: Examples of 1st and 2nd level space boundaries

B. Materials

DPI calculations require certain properties of materials of building constructions. All these properties are classified as material data for the DPI. These properties, include thermal, visual and cost properties.

As far as thermal properties are concerned, every building construction ranging from opaque constructions installed at building walls slabs and roofs and doors to transparent constructions installed at window opening volumes, is associated with a material layer stratification where different building material layers are “sandwiched” together following a specific order. Different handling is adopted for opaque and transparent constructions.

- For opaque constructions layer stratification is present in reality, the required thermal material properties referring to opaque constructions can be approximated using properties referring to a single construction. These properties include the thermal resistance and the thermal capacitance of an equivalent single material layer construction. If the single-layer approximation is not selected for an opaque construction for every layer present in the construction the values of four thermal properties are required for DPI evaluations which include: thermal conductivity, density, specific heat and thermal absorptance.

- For transparent constructions two thermal properties are required: The U-factor and the solar heat gain coefficient (SHGC).

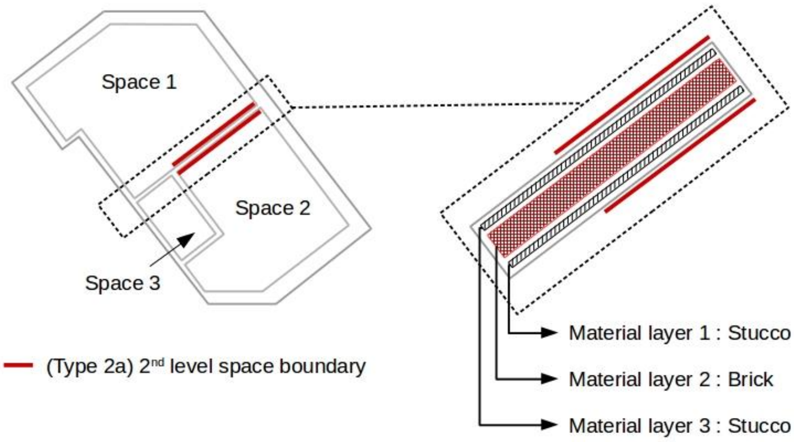

Figure 19: Building construction (internal wall)– 2nd level space boundary surfaces of type 2a and material layer stratification example

Regarding visual properties opaque constructions are handled as light obstacles and transparent constructions are considered entities which partially allow light to pass through. Therefore, for the outer surfaces of the construction the visual absorptance and reflectance property values are required and are contained in the material data class. Finally, for the cost related DPIs the monetary value of each construction and its respective material layer stratification must be provided.

Finally, every building element (wall, slab, door, window) and as a result the related 2nd-level spaces boundaries of type 2a described in the previous section, are related to a material layer stratification, as the example of Figure 19 displays.

In order to perform energy, thermal and visual simulations of a building, the thermal and visual properties of the material layer beddings of all type 2a space boundary surface pairs of the building, must be defined.

C. Energy Systems and Components

Building systems refer to a variety of devices ranging from active systems (fans, HVACs, heaters) to passive such as mechanical blinds. When interconnected energy systems exist at the district level, then it should be possible to represent this interconnectivity. Regarding modelling such systems within the simulation environment there are different possibilities each with their own input requirements. The simplest modelling approach is to use ideal systems: there not all energy system components are modelled and it is assumed that they system supplies heating or cooling to a zone without interdependence with other zones. A more detailed modelling is possible using the template functionality of EnergyPlus; these are objects that are intended to allow for several "usual" HVAC types to be expanded into EnergyPlus HVAC inputs with minimal user entries.

Table 4: HVAC Template objects supported in EnergyPlus

1. HVACTemplate:Thermostat
2. HVACTemplate:Zone:IdealLoadsAirSystem
3. HVACTemplate:Zone:BaseboardHeat
4. HVACTemplate:Zone:FanCoil
5. HVACTemplate:Zone:PTAC
6. HVACTemplate:Zone:PTHP
7. HVACTemplate:Zone:WaterToAirHeatPum

17. HVACTemplate:System:UnitaryHeatPump:AirToAir
18. HVACTemplate:System:UnitarySystem
19. HVACTemplate:System:VAV
20. HVACTemplate:System:PackagedVAV
21. HVACTemplate:System:ConstantVolume
22. HVACTemplate:System:DualDuct
23. HVACTemplate:System:DedicatedOutdoorAir

p
8. HVACTemplate:Zone:VRF
9. HVACTemplate:Zone:Unitary
10. HVACTemplate:Zone:VAV
11. HVACTemplate:Zone:VAV:FanPowered
12. HVACTemplate:Zone:VAV:HeatAndCool
13. HVACTemplate:Zone:ConstantVolume
14. HVACTemplate:Zone:DualDuct
15. HVACTemplate:System:VRF
16. HVACTemplate:System:Unitary
24. HVACTemplate:Plant:ChilledWaterLoop
25. HVACTemplate:Plant:Chiller
26. HVACTemplate:Plant:Chiller:ObjectReference
27. HVACTemplate:Plant:Tower
28. HVACTemplate:Plant:Tower:ObjectReference
29. HVACTemplate:Plant:HotWaterLoop
30. HVACTemplate:Plant:Boiler
31. HVACTemplate:Plant:Boiler:ObjectReference
32. HVACTemplate:Plant:MixedWaterLoop

These are sufficient to cover all commonly encountered cases and will be supported within the OptEEmAL input generation module. More advanced (and detailed) modelling of components might have to be supported on as needed basis. An even more detail modelling of HVAC systems and related controls can be implemented in MATLAB scripts as described in Section 3.1.3. Output of simulation script is used to compute DPIs relevant with active ECMs and controls.

At the district level, energy generation systems (e.g. CHP, renewables) and distribution systems (e.g. district heating) should be supported. The DDM should provide information to setup the CitySim calculations. A problem that has to be addressed within OptEEmAL is that much of the information needed for the description of renewables might not be obtainable from existing data models – e.g. the support of IFC for renewables is rather basic. Simplified calculation methodologies might be employed in that case. The definition of energy systems belongs to the static category, although data related to their operation, and interaction with other building elements is defined as dynamic and appears in the Section below.

4.3.2 Dynamic Data

Simulation programs require timing signals referring to the operation of devices including energy consuming, climate control equipment (such as HVACs, heaters, coolers) and passive devices (such as openings and blinds). These timing signals are in a broad sense, time dependent continuous functions which determine the operation state (on/off) as well as the operation mode characteristics of these devices. These functions belong to the general category of schedules (SCH). To define the values of the schedules used by the simulation programs, the time functions they refer to, have to be sampled at the simulation time instances.

A. Occupancy

Building spaces often remain unoccupied during specific time periods. By turning off energy consuming devices, during these unoccupied periods, substantial energy can be saved without violating comfort conditions. These time periods are defined by an occupancy parameter for each of the zones.

B. Internal gains

Operating building equipment (computers and electrical equipment) as well as the presence of people act as internal thermal sources (air and surrounding internal surfaces). Since this total amount of thermal energy, is a general non-negative number varying with time, it can be represented by a schedule (a time varying non-negative continuous function). This schedule is called internal gains schedule and is assigned to every building space. Usually the internal gains are estimated based on the number of people being inside a building space and the operational schedules for equipment in the same space. The operation schedule of controllable devices plays important role in the calculations performed during simulation. The schedules of controllable devices are determined by either model-based or rule-based control decisions.

The IFC schema includes classes for representing operation schedules (IfcTimeSeries). Objects of these classes can be attached to individual space instances. However, concerning the existing BIM-authoring tools, the operating schedules can be selected from predefined variants. Moreover, objects of these classes are usually related to another external information layer. Data exchange with external programs is not supported and as such sensed building data cannot be used. To overcome such a drawback, sensed data can be forwarded to BEP simulation model through a co-simulation setup.

C. Devices operation

During the building operation the schedules of certain devices are determined only by the user of these spaces. The above devices can be grouped together as uncontrollable devices. Their operations are determined by respective schedules. The schedules of these devices have to be included in the DDM. These include time function describing how the operation mode and related characteristics of these devices change with time. For example, if an HVAC belongs to the group of uncontrollable devices, the operation mode characteristics may refer to heating and cooling set-points, fan speed and other parameters defining its operation.

D. User Behavior

The second significant uncertainty with respect to forecasting and simulation is the modelling of the actions of users in the building. There are two important aspects to be explicated within this context: the definition of occupancy patterns, so that the system can have an estimate on when occupants will be present and when there will be cooling and/or heating needs that have to be satisfied; and the effect of user actions with respect to building services (e.g. opening and closing windows). Information on user-behaviour can be obtained utilizing a number of information sources:

- Reference Schedules as defined for particular building typologies in standards, or as user-input for the model (e.g. in office buildings, occupancy schedules are typically the working-hour schedules)
- Measured or inferred occupancy patters: utilizing, if available, sensor measurements.
- Data available from scheduling systems.

For the needs of OptEEmAL the detailed inclusion of occupancy patterns is not desired or possible. The desire is to have reasonably accurate occupancy data.

E. Weather data

As the calculation performed using physical models require the knowledge of boundary conditions, in buildings the simulation calculations require weather data values in order to be executed. Most of these data are provided by weather files which contain measurements obtained by weather stations. These are called weather file data. However, there are weather parameter values which are not provided by a weather file and have to be estimated [22]. These belong to the estimated weather data category. As the formats of weather files may differ some weather files may not contain the values of certain weather parameters. Similarly, to the values of the material some of the weather data values can be classified as fundamental if their values cannot be obtained using other weather parameter values and derived otherwise. In conclusion, weather data values are essentially sampled values according to the simulation inter-sample time intervals and are obtained either by using historical measured values or directly from a georeferenced weather service. If measured data are used, then special care should be taken when creating the direct and diffuse solar radiation components.

4.3.3 Simulation Parameters

Apart from dynamic and static data simulations require data which define the way calculations are being carried and are collected together under the simulation parameters category. Data from this category refer to parameter values required for the initiation of a simulation operation, defined as initial parameters, which include values such as: the total simulation time, the simulation time step the warming-up time and convergence tolerance criteria. Also the preferred outputs (for example: temperature, humidity, energy demands), can also be included in the initial parameters.

Surface convection and heat balance algorithm options, equipment and system sizing options, daylighting options, dynamic fenestration controls airflow analysis models, etc. also fall into this category. Values of these features can be initially set to default values. However, the modeller must have in mind that these features require domain expertise for input specification and output assessment and care should be taken in an automated transformation processes.

4.4 Data types and their Data Sources

Table 5 collects information on the different data types and identifies sources where these data can be obtained. Within OptEEmAL these data will be used to populate the DDM and then will be used by the simulation input generator module.

Table 5 Simulation Data Requirements and their Data Sources

Static Data Requirements	Data Sources		
Geometric	IFC, CityGML LoD1-LoD4		
Material	IFC		
Energy Systems and Components	IFC		
Simulation Parameters	User Defined		
Dynamic Data Requirements	Data Sources		
	Monitored	*Georeferenced*	*Reference*
Occupancy	X		X
Internal Gains	X		X
Devices Operation	X		X
User Behaviour	X		X
Weather	X	X	

Legend: (X): Potential Source of data; See D1.2 and D1.3 for data sources to be used in OptEEmAL.

Geometry Data

For geometric data two distinct sources are available: CityGML and IFC. In the CityGML specification, geometric information can be represented in various Levels of Detail (LoDs). These representations are essentially closed shell geometries, with levels of detail ranging from LoD1 to LoD4. In LoD1, LoD2 and LoD3 each building's envelope is defined as a closed shell geometry; in LoD4, in addition to the outer shell, the interior building room volumes are defined as well. The simplest geometric representation is LoD1, where buildings are modelled as rectangular boxes (see Figure 20 (I)); in LoD2 tilted roof surfaces in the building shell can also be included (see Figure 20 (II)). Both LoD1 and LoD2 descriptions, do not make provisions for the inclusion of openings and external roof overhangs. These are contained in LoD3 and LoD4 representations (cf. cases I, II against III and IV in Figure 20). Finally, LoD4 contains geometric representations of internal rooms as closed shell objects (Figure 20 (IV)).

On the other hand, the IFC geometric concepts include solid descriptions of building entities (walls, slabs, roofs, etc.) as opposed to surface descriptions contained in CityGML representations. Such solid descriptions are more detailed than CityGML LoD4 representations and include additional surfaces describing the thicknesses of the building elements such as surfaces at the frames of window and door entities (see Figure 20 (V)).

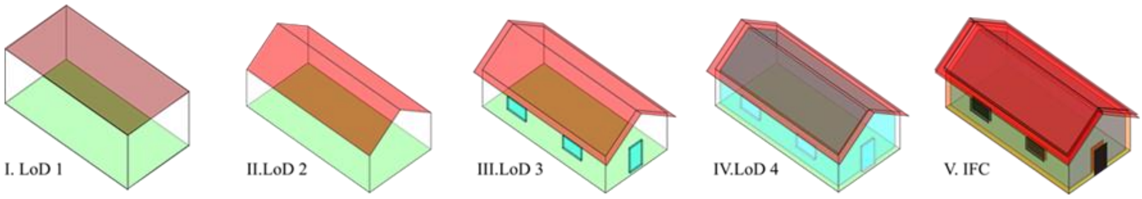

Figure 20: Representation of the same building using CityGML LoD (1-4) and IFC.

Material Data

The material data properties required for the DPI calculations, described in section 4.3.1.2, can be provided by the IFC schema but not from the official CityGML schema.

System data

The term system refers to any device installed in buildings which either: consumes energy (active), does not consume energy (passive) or generates energy from renewable sources (renewable source). Certain operation and cost characteristics of these devices must be provided for certain DPI calculations. Some of these characteristics can be provided from the IFC schema. Neither of these characteristics can be provided from the official CityGML schema. In the operation characteristics the scheduling operation of a system (the time instances when the system is on and off) is included.

Weather data

The simulation related operations of some DPI calculations, require certain weather parameter values of the district to be provided. For example, these parameter values include temperature, humidity and solar radiation, referring to the external district conditions for a specific period of time. Georeferenced information sources might provide valuable information.

4.5 Uncertainties and Validation

For all cases above, a calculation methodology can be seen as a well-defined deterministic calculation procedure, which encompasses models for the building and/or its constituents, along with means for establishing links, interactions and information exchange between the models. In all cases the modelling determines the type of inputs that have to be specified. The outputs are also determined from the nature of the calculation methodology.

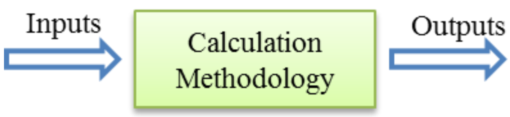

Figure 21: Calculation Methodologies – Input-Output Relationship

The inputs are given as a set of objects, each forming part of a larger data model. A dictionary can be used to define the object names and the data model. A parser, using the dictionary, reads the input and processes them for syntactic correctness and completeness in the definitions. Irrespective of the data model used, defining the input comprises two parts:

1. Modelling definitions (e.g. selection of zoning, representation of the HVAC system), and;
2. Factual data and boundary conditions specification (e.g. occupancy profiles, material properties, weather data, etc.).

As can be expected, the accuracy of the predicted outputs strongly depends on the calculation methodology used, but also on the quality of the inputs. As discussed in the previous Sections the selection of zoning can have a profound effect on the quality of the modelling: too crude a zoning and it may not be able to correctly capture relevant physical phenomena; too fine a zoning and excessive effort might be required for setting up the problem, in addition to longer computation times. What is maybe comforting being that if (any) one of the many "valid" zoning approaches is selected, the value of the outputs will not strongly depend on the selection – although small variations in the output values should be expected. Missing or uncertain data for specification of the boundary conditions can be more problematic: erroneous inputs are propagated via the calculation methodology to affect the outputs. In defining validation procedures for transient Calculation Methodologies all the issues above should be addressed.

The approach taken in [38], [39], [40] addresses Point 1 above by defining reference buildings that have only one zone. A specific set of boundary conditions and material and other parameters is prescribed regarding Point 2. As part of the standard a set of test cases are defined, that must be passed by a calculation methodology to test compliance with the standard. This way any tool that is capable of accommodating the boundary conditions described in the standard can be tested for compliance. Also a relevant standard for calculation methodology validation is the BESTEST methodology [41]. Here a set of synthetic benchmarks is defined (Cases) ordered in order of modelling complexity. The goal of this standard is to provide a standardized methodology for testing and debugging building energy analysis methodologies. As part of the standard, a well-defined testing procedure is established: if a calculation methodology fails a case, a number of diagnostic subcases are defined to help identify the root cause of the failure. Also, unlike the other standards, there are no fixed accuracy limits to determine that a calculation methodology has “passed” a case, rather a comparative approach is recommended, in which the results of the calculation methodology are compared against other state-of-the-art tools. This comparative methodology serves two purposes: first, to help diagnose modelling and coding errors; and second, to compare against other state-of-the-art approaches so that output variability due to different Modelling approaches can be better understood.

In many cases empirical validation studies, have been conducted against calculation methodologies, strengthening the confidence in the capabilities to correctly mirror reality. It should be emphasized that once a calculation methodology has passed all tests of a validation procedure, and is deemed “validated,” this does not imply that the calculation methodology represents the truth. It does show that a set of algorithms have shown, through a repeatable procedure, to perform according to the state-of-the-art. Unfortunately, a simulation and its’ predictive capabilities are as good as the multitude of assumptions (regarding occupancy, plug loads, occupant behaviour, BEMS actions, use of “typical year” weather data etc.) that have to be performed for the input data. In the design and retrofitting phases, where these tools are typically used, reasonable assumptions regarding all aspects of building operation and equipment are made and consequently used in the simulation process. It is very often the case, that such assumptions prove to be wrong and, for this reason, real-world (measured) energy performance can vary significantly from the one estimated upon invocation of the energy simulation models.

5 Tables and analysis

Following the description of the simulation tools to be supported within OptEEmAL in Section 3 and the different levels of detail of the input data presented in Section 4, it is obvious clear that simulation models of increasing quality could be constructed. A fundamental question that this Section tries to address is, what is the level of detail in the information so that the relevant DPIs can be computed with an accuracy which is sufficient for the decision-making process that the OptEEmAL tool is meant to support.

To answer this question and determine the level of information that should be sufficient, different scenarios for each possible DPI are analysed and ranked, concluding to the amount of information in describing the district to ensure that simulation models of sufficient accuracy can be constructed. From now on, each different scenario concerning the level of information's detail, will be named calculation methodology and it must not be confused with the calculation methodologies described in Section 2.

For the description of the DPIs characteristics and their calculation process diagrams the nomenclature displayed in the following table is adopted.

Symbol	Description
EP	Energy Plus tool
NS	NEST tool
CS	CitySim tool
HVAC	HVAC systems and control tool
OT	OptEEmAL tool

Moreover, certain functions are used during the sequential DPI calculation process – denoted with Fi, where i = 1, 2, ..., 8 – that will be performed by the OptEEmAL tool. These functions receive as inputs other DPIs or queried data from DDM, perform a single computation and return a single DPI value. These functions and their respective descriptions are presented next.

5.1 Energy DPIs

The data required for the evaluation of the energy related DPIs can be classified into nine categories displays in the following table:

Table 6: Categories of data requirements for Energy DPIs

Categories of Data Requirements for Energy DPIs				
Type of Information	Available Information / Datasets	Required Accuracy	Required Information	Calculation Tools
Simulation Parameters	Initial Parameters, Selected Algorithms	High	All datasets	EP, CS
Building Geometry	CityGML Lod1,	Variable (low to high)	One of the available	EP, CS

	CityGML Lod2, CityGML Lod3, CityGML Lod4, IFC		datasets	
Building Materials	Equivalent Single-Layer Opaque, Multi-Layer Opaque, Multi-Layer Transparent	Variable (low to high)	One or more than one, of the available datasets	EP, CS
Weather Data	Measurements	High	All datasets	EP, CS
Schedules	Reference Data, Measurements	Variable (low, high)	One of the available datasets	EP, CS
Internal Gains	Reference Data, Measurements	Variable (low, high)	One of the available datasets	EP, CS
Energy Systems	Ideal Load System, Systems' Templates, Detailed Description	Medium	One of the available datasets	EP, CS, HVAC
Exterior Equipment	Exterior Lights, Exterior Fuel Equipment, Exterior Water Equipment	Medium	None, one or more than one, of the available datasets	EP, CS
Renewable Energy Systems	Photovoltaic, Wind Turbine, Geothermal Heat Pump	Medium	None, one or more than one, of the available datasets	EP, CS, F5, F6, F7

For every energy-related DPI, the calculation flow diagrams followed by the tables of their characteristics are displayed below.

ENE01

ENE01 refers to the district's Energy Demand, the total energy required in order to maintain predefined conditions to all of the conditioned building spaces in the district. The boundaries of conditioned building spaces extend beyond the physical building room boundaries including multiple rooms or room parts. In order to maintain the predefined conditions (temperature, humidity...), ideal energy systems of infinite capacity and 100 % efficiency are considered in every conditioned building space in the district.

The following figure depicts the flow diagram for the ENE01 calculation, where two possible pathways to calculate the ENE01 are presented. In the first pathway, proper requested datasets are retrieved from the DDM to generate different IDF files for each building of interest that will be used as input to EnergyPlus. Each IDF file is simulated invoking EnergyPlus, where the output is the energy demand of the respective district's building. Then, function F1, performed by the OptEEmAL tool, is invoked that sums the individual building demand to evaluate the total energy demand of the district. According to Annex I, following this pathway, twenty different calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6 or the EP18 (see Annex I: Detailed Data Requirements (ENE01)) calculation methodology will be used.

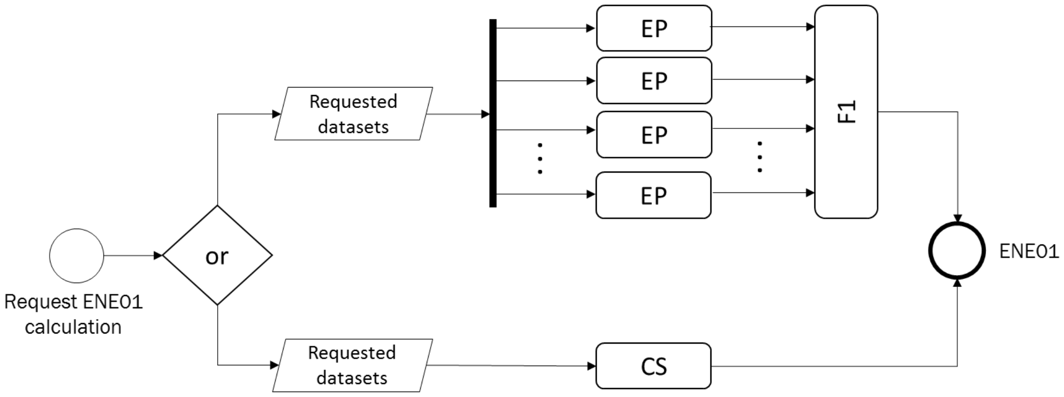

Figure 22: Flow diagram for the ENE01 calculation

In the second pathway, proper requested datasets are retrieved from the DDM to generate an xml file referring to the whole district to be used as input to CitySim. Here, four different calculation methodologies are available. However, within OptEEmAL the district scale-geometry's information will be available in LoD2 level of detail, while reference data will be used for the schedules. Hence, the CS3 (see Annex I: Detailed Data Requirements (ENE01)) calculation methodology will be used.

Table 7: DPI ENE01 characteristics

ENE01	
Number of possible calculation methodologies	24
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE01)
Calculation Tools	EP, CS, OT, F1
Unit	kWh/m²
Scale	District
Phase	Diagnosis, Evaluation

ENE02/ENE06/ENE12

ENE02 refers to the Final Energy Consumption DPI, evaluated by adding all the individual energy consumptions of the real systems installed in the building spaces of the district taking into account their efficiencies and all the associated energy losses. The specifications of the installed building systems are derived either from system templates or are based on the manufacturer's detailed description.

ENE06 refers to the Net Fossil Energy Consumed, the energy consumed by the district which comes directly from fossil fuel. Fossil fuels are materials which contain high concentration of carbon such as coal, petroleum and natural gas.

ENE12 refers to the Energy Consumption of public buildings per year, the part of the total energy consumption (DPI ENE02) which refers to public buildings in the district, for a single year period.

The aforementioned DPIs have common input data and simulation tools invocation requirements for their calculation. The following figure depicts the flow diagram for their calculation, where three possible pathways to calculate them are presented.

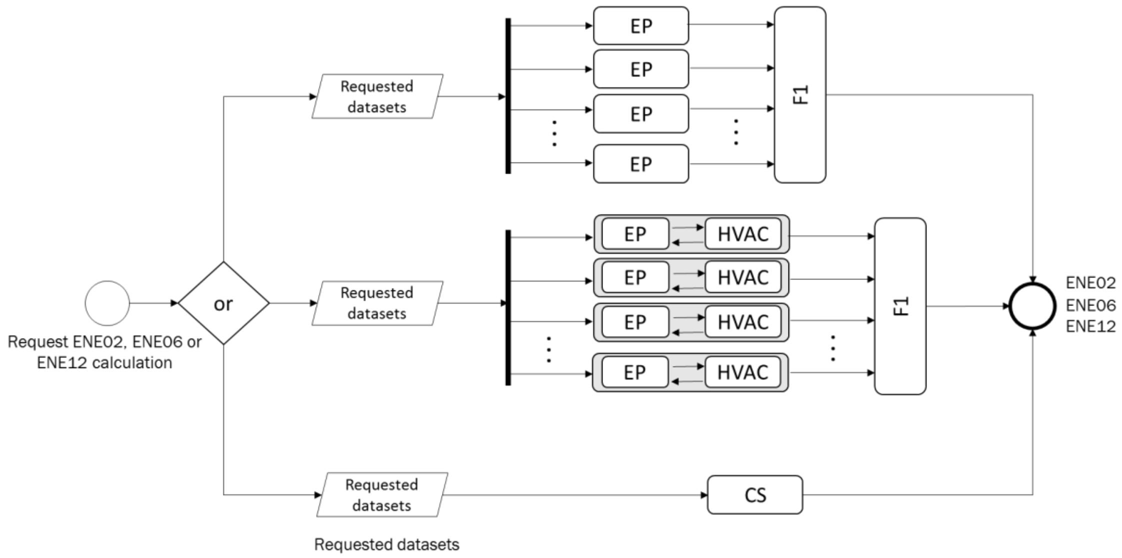

Figure 23: Flow diagram for the ENE02/ENE06/ENE12 calculation

In the first pathway, proper requested datasets are retrieved from the DDM to generate different IDF files for every building of interest that will be used as input to EnergyPlus. Each IDF file is simulated invoking EnergyPlus, where for each simulation, the output is the energy consumption of the respective district's building. Then, function F1, performed by the OptEEmAL tool, is invoked that sums the individual building's ENE02, ENE06 or ENE12 to evaluate the total ENE02, ENE06 or ENE12 of the district. The only difference between the first and the second pathway is how the HVAC systems are simulated. In the first pathway, the HVAC systems are simulated internally by EnergyPlus, while in the second pathway, they are simulated by the HVAC Systems and Control tool. According to Annex I, following either the first or the second pathway, twenty different calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6, the EP18, the EP26 or the EP38 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

Moreover, as mentioned in Section 3, although EnergyPlus has capabilities to model and simulate HVACs, within OptEEmAL the HVAC Systems and Control tool will be used. The reason for that is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls. Hence, the EP26 or the EP38 calculation methodology will be used.

In the third pathway, proper requested datasets are retrieved from the DDM to generate an xml file referring to the whole district to be used as input to CitySim. Here, four different calculation methodologies are available. However, within OptEEmAL the district scale-geometry's information will be available in LoD2 level of detail, while reference data will be used for the schedules. Hence, the CS3 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

Table 8: DPI ENE02/ENE06/ENE12 characteristics

ENE02/ENE06/ENE12	
Number of possible calculation methodologies	44
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools	EP, CS, HVAC, OT, F1
Unit	kWh/m²
Scale	District, Building
Phase	Diagnosis, Evaluation

ENE03/ENE04

ENE03 refers to the Peak load and Profile of Electricity Demand, containing peak electricity power load in Watts for every building space in the district as well as, the electricity power profile of the overall district for a considered period of time. The peak electricity load of the overall district is the maximum of the peak electricity power loads of all the conditioned building spaces in the district.

ENE04 refers to the Peak load and Profile of Thermal Demand, containing peak thermal power load in Watts for every building space in the district as well as, the thermal power profile of the overall district for a considered period of time. The peak thermal load of the overall district is the maximum of the peak thermal power loads of all the conditioned building spaces in the district.

The aforementioned DPIs have common input data and simulation tools invocation requirements for their calculation. The following figure depicts the flow diagram for their calculation, where two possible pathways to calculate them are presented.

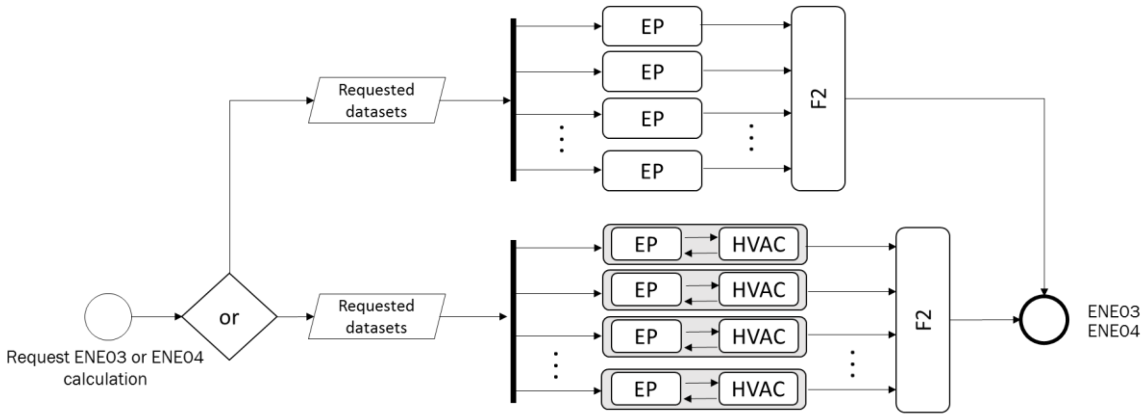

Figure 24: Flow diagram for the ENE03/ENE04 calculation

In the first pathway, proper requested datasets are retrieved from the DDM to generate different IDF files for every building of interest that will be used as input to EnergyPlus. Each IDF file is simulated invoking EnergyPlus, where for each simulation, the output is the electric or thermal demand profile of the respective district's building. Then, the function F2, performed by the OptEEmAL tool, is invoked that sums the individual building electric or thermal demand at each time step to evaluate the district's electrical or thermal profile and the corresponding peak value. The only difference between the first and the second pathway is how the HVAC systems are simulated. In the first pathway, the HVAC systems are simulated internally by EnergyPlus, while in the second pathway, they are simulated by the HVAC Systems and Control tool. According to Annex I, following the first or the second pathway, twenty different calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6, the EP18, the EP26 or the EP38 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

Moreover, as mentioned in Section 3, although EnergyPlus has capabilities to model and simulate HVACs, within OptEEmAL the HVAC Systems and Control tool will be used. The reason for that is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls. Hence, the EP26 or the EP38 calculation methodology will be used.

Table 9: DPI ENE03/ENE04 characteristics

ENE03/ENE04	
Number of possible calculation methodologies	40
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools	EP, CS, HVAC, OT, F2
Unit	kW
Scale	District Building
Phase	Diagnosis, Evaluation

ENE05

ENE05, the degree of energetic self-supply, is defined as ratio of locally produced energy and the local consumption over a period of time. If the district relies on its own energy production, then is considered energy independent and achieves the highest degree of energetic self-supply. On the contrary if the district relies on only external energy sources is totally energy dependent and has the lowest degree of energetic self-supply.

The following figure depicts the flow diagram for the ENE05 calculation, where two possible pathways to calculate the ENE05 are presented.

Initially, both pathways request for the ENE02 calculation to estimate the total energy consumption. Then, in the first pathway, proper requested datasets are retrieved from the DDM to generate an IDF file that includes all the energy production systems. The IDF file is simulated invoking EnergyPlus resulting to district's energy production. In the second pathway, proper requested datasets are retrieved from the DDM to generate an xml file referring to the whole district to be used as input to CitySim. Following either the first or the second pathway, after the district's energy production estimation, the function F3, performed by the OptEEmAL tool, is invoked to evaluate the ratio of two input quantities.

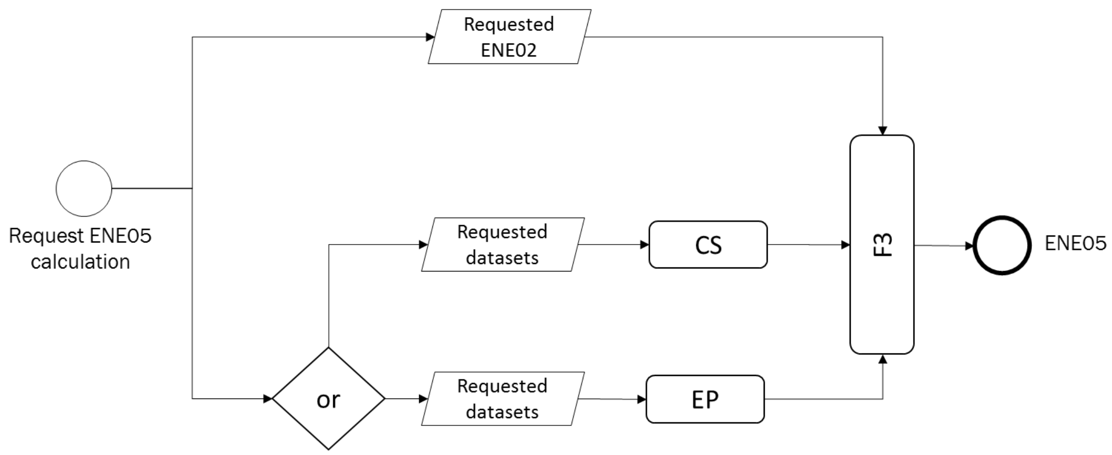

Figure 25: Flow diagram for the ENE05 calculation

According to Annex I, following the first pathway, forty different calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6, the EP18, the EP26 or the EP38 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

Moreover, as mentioned in Section 3, although EnergyPlus has capabilities to model and simulate HVACs, within OptEEmAL the HVAC Systems and Control tool will be used. The reason for that is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls. Hence, the EP26 or the EP38 calculation methodology will be used.

In the second pathway, four different calculation methodologies are available. However, within OptEEmAL the district scale-geometry's information will be available in LoD2 level of detail, while reference data will be used for the schedules. Hence, the CS3 (see Annex I: Detailed Data Requirements (ENE01)) calculation methodology will be used.

Table 10: DPIs ENE05 characteristics

ENE05	
Number of possible calculation methodologies	44
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools	EP, CS, OT, F3
Unit	kWh/kWh
Scale	District
Phase	Diagnosis, Evaluation

ENE07/ENE08/ENE10/ENE11

ENE07, the Energy use per capita, refers to the use of primary energy before transformation to other end-use fuels. This amount equals to indigenous production from renewable energy sources, plus energy imports, minus energy exports and the energy storage. This amount is divided by the number of inhabitants in the district.

ENE08, the total residential electrical energy use per capita, is the part of the total energy use, which refers to electric energy which is used for residential buildings in the district. This amount is divided by the total number of residents of the district.

ENE10, the total residential natural gas energy use per capita, is the part of the total energy use, which refers to energy originating from natural gas use and is used for the residential part of the district. This amount is divided by the total number of residents of the district.

ENE11, the total residential butane gas energy use per capita, is the part of the total energy use, which refers to energy originating from butane gas use and is used for the residential part of the district. This amount is divided by the total number of residents of the district.

The aforementioned DPIs have common input data and simulation tools invocation requirements to be calculated. The following figure depicts the flow diagram for their calculation, where three possible pathways to calculate them are presented.

In the first pathway, proper requested datasets are retrieved from the DDM to generate different IDF files for every building of interest that will be used as input to EnergyPlus. Each IDF file is simulated invoking EnergyPlus, where for each simulation, the output is the ENE07/ENE08/ENE10/ENE11 of the respective district's building. Then, the function F4, performed by the OptEEmAL tool, is invoked, which calculates the sum of all its input quantities divided by the number of inhabitants of the district. The only difference between the first and the second pathway is how the HVAC systems are simulated. In the first pathway, the HVAC systems are simulated internally by EnergyPlus, while in the second pathway, they are simulated by the HVAC Systems and Control tool. According to Annex I, following the first or the second pathway, twenty different calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6, the EP18, the EP26 or the EP38 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

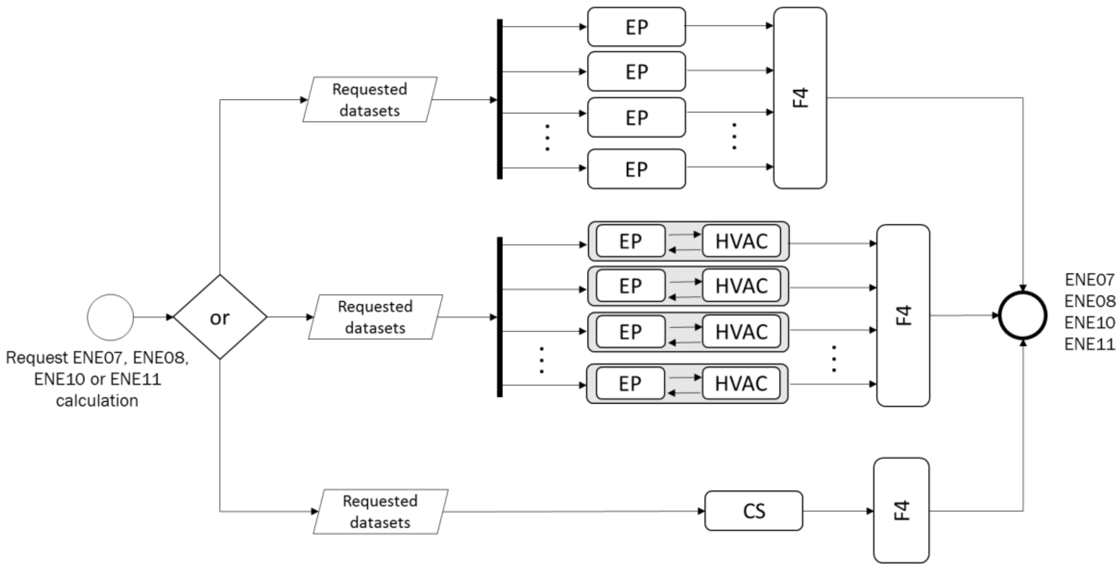

Figure 26: Flow diagram for the ENE07/ENE08/ENE10/ENE11 calculation

Moreover, as mentioned in Section 3, although EnergyPlus has capabilities to model and simulate HVACs, within OptEEmAL the HVAC Systems and Control tool will be used. The reason for that is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls. Hence, the EP26 or the EP38 calculation methodology will be used.

In the third pathway, proper requested datasets are retrieved from the DDM to generate an xml file referring to the whole district to be used as input to CitySim. The xml file is simulated invoking CitySim. Then, the function F4, performed by the OptEEmAL tool, is invoked, which calculates the sum of all its input quantities divided by the number of inhabitants of the district. Here, four different calculation methodologies are available. However, within OptEEmAL the district scale-geometry's information will be available in LoD2 level of detail, while reference data will be used for the schedules. Hence, the CS3 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

Table 11: DPI ENE07/ENE08/ENE10/ENE11 characteristics

ENE07/ENE08/ENE10/ENE11	
Number of possible calculation methodologies	40
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools and Functions	EP, CS, HVAC, OT, F4
Unit	kWh/hab
Scale	District
Phase	Diagnosis, Evaluation

ENE13/ENE17/ENE18/ENE19

ENE13, the energy use from district heating, is the amount of total district energy use which is originated from District Heating.

ENE17, the energy use from hydraulic, is the amount of total district energy use which is originated from hydraulic generators.

ENE18, the energy use from mini eolica, is the amount of total district energy use which is originated from wind turbine generators.

ENE19, the energy use from geothermal, is the amount of total district energy use which is originated from geothermal installations.

The aforementioned DPIs have identical input data and simulation tools invocation requirements with the ENE05. The following figure, depicts the flow diagram for their calculation, identical to the flow diagram of ENE05. For information concerning the calculation methodologies that will be supported within OpEEmAL, refer to the description of ENE05.

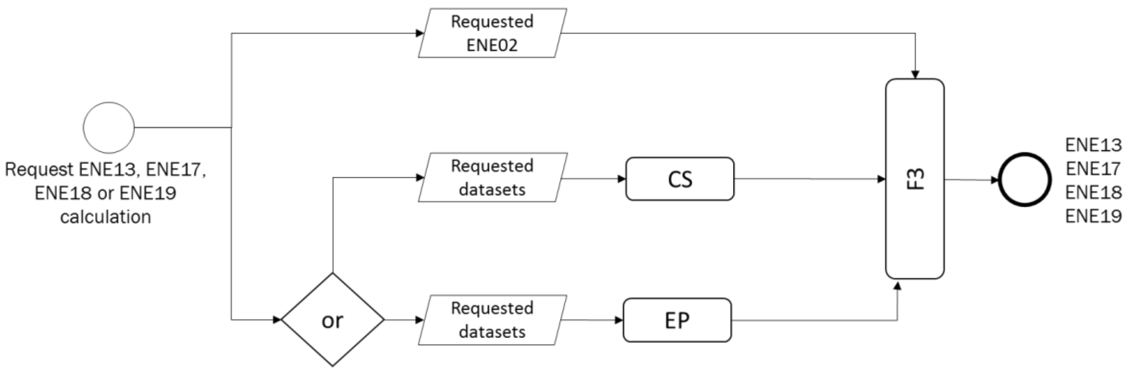

Figure 27: Flow diagram for the ENE13/ENE17/ENE18/ENE19 calculation

Table 12: DPIs ENE13/ENE17/ENE18/ENE19 characteristics

ENE13/ENE17/ENE18/ENE19	
Number of possible calculation methodologies	44
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools and Functions	EP, CS, F3
Unit	kWh/m²
Scale	District
Phase	Diagnosis, Evaluation

ENE14

ENE14 refers to the part of the total district energy use, where the energy is obtained directly from biomass materials.

The following figure depicts the flow diagram for the ENE14 calculation, where three possible pathways to calculate the ENE14 are presented. Initially, each pathway requests for the ENE02 calculation to estimate the total energy consumption. Then, in the first pathway, proper requested datasets are retrieved from the DDM to generate an IDF file that includes all the energy production from biomass materials. The IDF file is simulated invoking EnergyPlus resulting to district's energy production from biomass materials. In the second pathway, proper requested datasets are retrieved from the DDM to generate an xml file referring to the whole district to be used as input to CitySim. In the third pathway, the function F5, performed by the OptEEmAL tool, is invoked to evaluate the the district's energy production estimation from biomass materials. Following either the first, the second or the third pathway, after the district's energy production estimation from biomass materials, the function F3, performed by the OptEEmAL tool, is invoked to evaluate the ratio of two input quantities.

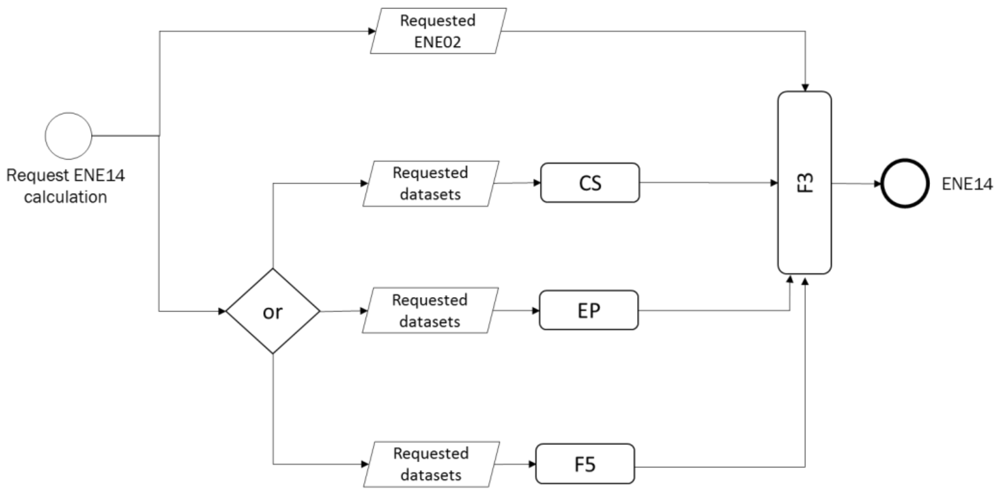

Figure 28: Flow diagram for the ENE14 calculation

According to Annex I, following the first pathway, forty different calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6, the EP18, the EP26 or the EP38 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

Moreover, as mentioned in Section 3, although EnergyPlus has capabilities to model and simulate HVACs, within OptEEmAL the HVAC Sytems and Control tool will be used. The reason for that is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls. Hence, the EP26 or the EP38 calculation methodology will be used.

In the second pathway, four different calculation methodologies are available. However, within OptEEmAL the district scale-geometry's information will be available in LoD2 level of detail, while reference data will be used for the schedules. Hence, the CS3 (see Annex I: Detailed Data Requirements (ENE01)) calculation methodology will be used.

In the third pathway, only one calculation methodology exists.

Table 13: DPIs ENE14 characteristics

ENE14	
Number of possible calculation methodologies	44
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools and Functions	EP, CS, OT, F3, F5
Unit	kWh/m²
Scale	District
Phase	Diagnosis, Evaluation

ENE15

ENE15 refers to the part of the total district energy use, where the energy is obtained directly from solar photovoltaic panels, installed in the buildings.

The following figure depicts the flow diagram for the ENE15 calculation, where three possible pathways to calculate the ENE15 are presented. Initially, each pathway requests for the ENE02 calculation to estimate the total energy consumption. Then, in the first pathway, proper requested datasets are retrieved from the DDM to generate an IDF file that includes all the energy production from solar photovoltaic panels, installed in the buildings. The IDF file is simulated invoking EnergyPlus resulting to district's energy production from solar photovoltaic panels. In the second pathway, proper requested datasets are retrieved from the DDM to generate an xml file referring to the whole district to be used as input to CitySim. In the third pathway, the function F6, performed by the OptEEmAL tool, is invoked to evaluate the the district's energy production estimation from solar photovoltaic panels, installed in the buildings. Following either the first, the second or the third pathway, after the district's energy production estimation from solar photovoltaic panels, installed in the buildings, the function F3, performed by the OptEEmAL tool, is invoked to evaluate the ratio of two input quantities.

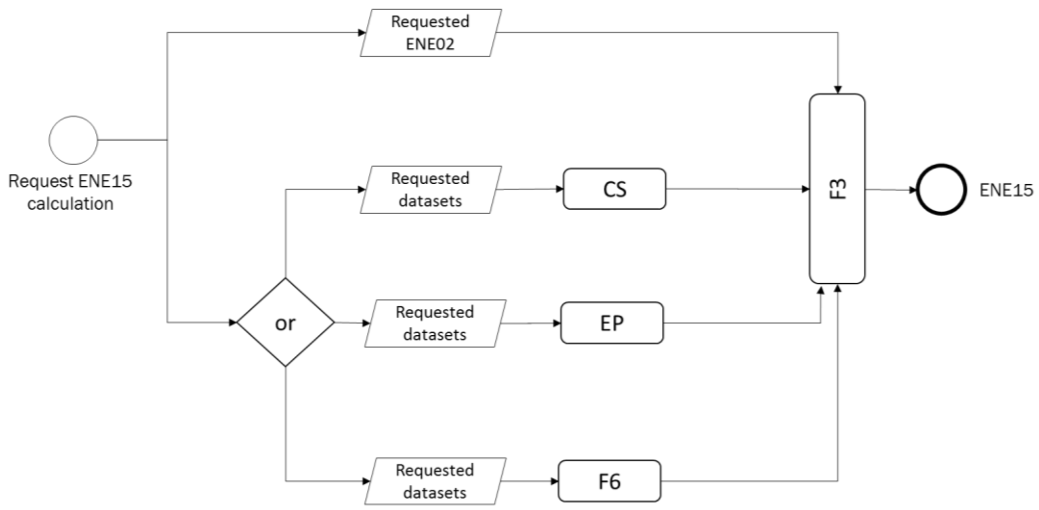

Figure 29: Flow diagram for the ENE15 calculation

According to Annex I, following the first pathway, forty different calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6, the EP18, the EP26 or the EP38 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

Moreover, as mentioned in Section 3, although EnergyPlus has capabilities to model and simulate HVACs, within OptEEmAL the HVAC Sytems and Control tool will be used. The reason for that is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls. Hence, the EP26 or the EP38 calculation methodology will be used.

In the second pathway, four different calculation methodologies are available. However, within OptEEmAL the district scale-geometry's information will be available in LoD2 level of detail, while reference data will be used for the schedules. Hence, the CS3 (see Annex I: Detailed Data Requirements (ENE01)) calculation methodology will be used.

In the third pathway, only one calculation methodology exists.

Table 14 DPIs ENE15 characteristics

ENE15	
Number of possible calculation methodologies	44
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools and Functions	EP, CS, OT, F3, F6
Unit	kWh/m²
Scale	District
Phase	Diagnosis, Evaluation

ENE16

ENE16 refers to the part of the total district energy use, where the energy is obtained directly from solar thermal panels, installed in the buildings.

The following figure depicts the flow diagram for the ENE16 calculation, where three possible pathways to calculate the ENE16 are presented. Initially, each pathway requests for the ENE02 calculation to estimate the total energy consumption. Then, in the first pathway, proper requested datasets are retrieved from the DDM to generate an IDF file that includes all the energy production from solar thermal panels, installed in the buildings. The IDF file is simulated invoking EnergyPlus resulting to district's energy production from solar thermal panels. In the second pathway, proper requested datasets are retrieved from the DDM to generate an xml file referring to the whole district to be used as input to CitySim. In the third pathway, the function F6, performed by the OptEEmAL tool, is invoked to evaluate the the district's energy production estimation from solar photovoltaic panels, installed in the buildings. Following either the first, the second or the third pathway, after the district's energy production estimation from solar thermal panels, installed in the buildings, the function F3, performed by the OptEEmAL tool, is invoked to evaluate the ratio of two input quantities.

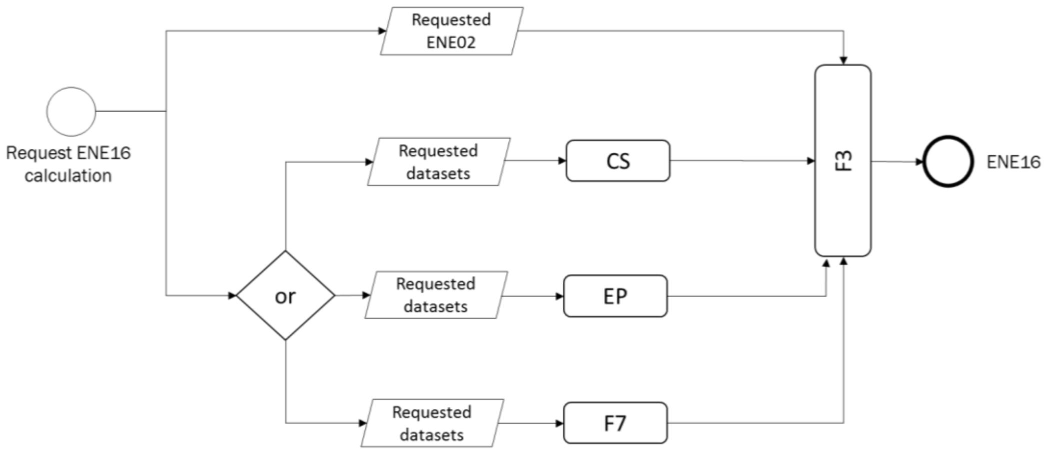

Figure 30 Flow diagram for the ENE16 calculation

According to Annex I, following the first pathway, forty different calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6, the EP18, the EP26 or the EP38 (see Annex I: Detailed Data Requirements (ENE02-ENE19)) calculation methodology will be used.

Moreover, as mentioned in Section 3, although EnergyPlus has capabilities to model and simulate HVACs, within OptEEmAL the HVAC Sytems and Control tool will be used. The reason for that is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls. Hence, the EP26 or the EP38 calculation methodology will be used.

In the second pathway, four different calculation methodologies are available. However, within OptEEmAL the district scale-geometry's information will be available in LoD2 level of detail, while reference data will be used for the schedules. Hence, the CS3 (see Annex I: Detailed Data Requirements (ENE01)) calculation methodology will be used.

In the third pathway, only one calculation methodology exists.

Table 15: DPIs ENE16 characteristics

ENE16	
Number of possible calculation methodologies	44

Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools	EP, CS, OT, F3, F7
Unit	kWh/m²
Scale	District
Phase	Diagnosis, Evaluation

ENE09

This DPI refers to the part of the total energy demand of the district which is covered by renewable sources of energy such as solar, wind and geothermal sources of energy.

ENE09 can be derived by the ENE13-ENE19 values. The following figure, depicts the flow diagram for their calculation. The renewable function F9, performed by the OptEEmAL tool, evaluates the percentage of the total energy demand that is covered by renewable sources. Essentially, it subtracts from the total energy demand ENE01 the sum up all the renewable energy use quantities (ENE13-ENE19) and divides the result with the total energy demand ENE01. The renewable function is used in order to evaluate the energetic self-supply of the district.

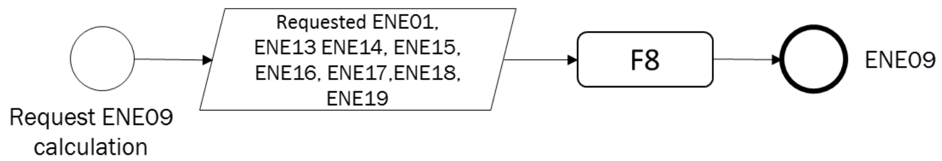

Figure 31: Flow diagram for the ENE09 calculation

Table 16: DPIs ENE09 characteristics

ENE09	
Number of possible calculation methodologies	44
Detailed Data Requirements	See Annex I: Detailed Data Requirements (ENE02-ENE19)
Calculation Tools	EP, CS, OT, F8
Unit	%
Scale	District
Phase	Diagnosis, Evaluation

For more information concerning the calculation methodologies that will be supported within OptEEmAL, refer to the description of ENE13-ENE19.

5.2 Comfort DPIs

The data required for the evaluation of the comfort related DPIs can be classified into twelve categories displays in the following table:

Table 17: Categories of data requirements for Comfort DPIs

Categories of Data Requirements for Comfort DPIs				
Type of Information	**Available Information / Datasets**	**Required Accuracy**	**Required Information**	**Calculation Tools**
Simulation Parameters	Initial Parameters, Selected Algorithms	High	All datasets	EP
Building Geometry	CityGML Lod1, CityGML Lod2, CityGML Lod3, CityGML Lod4, IFC	Variable (low to high)	One of the available datasets	EP
Building Materials	Equivalent Single-Layer Opaque, Multi-Layer Opaque, Multi-Layer Transparent	Variable (low to high)	None, one or more than one, of the available datasets	EP
Weather Data	Measurements	High	All datasets	EP
Schedules	Reference Data, Measurements	Variable (low, high)	One of the available datasets	EP
Internal Gains	Reference Data, Measurements	Variable (low, high)	None, one or more than one, of the available datasets	EP
Energy Systems	Ideal Load System, Systems' Templates, Detailed Description	Medium	None, one or more than one, of the available datasets	EP
Building Management Systems	Measurements	High	All datasets	HVAC
Clothing Value	Seasonal Dynamic	Medium	One of the available datasets	EP

Metabolic Rate	Constant Schedule	Medium	One of the available datasets	EP
Air Velocity	Reference Data, Measurements	Medium	One of the available datasets	EP
Acceptable Range	Constant	High	All datasets	EP

For every comfort related DPI, the calculation flow diagrams followed by the tables of their characteristics are displayed below.

COM01/COM02/COM04/COM05

COM01 refers to the local thermal comfort._Thermal comfort is difficult to measure because it is highly subjective. It depends on the air temperature, humidity, radiant temperature, air velocity, metabolic rates, and clothing levels, and each individual experiences these sensations differently because of his or her physiology and state. According to the ANSI/ASHRAE Standard 55-2010, thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. A method for describing thermal comfort is referred to as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). Using this DPI, the thermal comfort level of occupants can be evaluated using PMV and PPD. This thermal comfort level is estimated from air temperature, air velocity, metabolic rate, clothing and humidity.

COM02 refers to the Local Temperature Deviation from Set-Point. As mentioned in COM01, thermal comfort is difficult to evaluate because it is a subjective indicator. One of the parameters influencing thermal comfort is air temperature. With this DPI we consider more specifically the deviation of building and zone temperatures from desired values in terms of percentage of time outside a predefined comfort band. This DPI is needed for the assessment of control ECMs which aim at supplying the building thermal consumption such that the building/zone temperatures are maintained as close as possible to the corresponding set-points.

COM04 refers to the Indoor Air Quality. This DPI is evaluated by estimating the clearness of the air inside all the conditioned building spaces. This air clearness is affected by the presence of various air pollutants, such as CO_2, the concentration of which is estimated and added in order to evaluate the total air quality.

COM05 refers to the Visual Comfort. Using this DPI, the visual comfort level of the users of the conditioned building spaces of the district can be evaluated. This comfort level can be estimated based on the amount of light measured in lumens entering the building space which is originated from natural sources such as the sun or artificial sources such as building lights.

The following figure depicts the flow diagram for the COM01/COM02/COM04/COM05 calculation. Each of these comfort DPIs are specific outputs of the EnergyPlus simulation. Hence, proper requested datasets are retrieved from the DDM to generate different IDF files for every building of interest that will be used as input to EnergyPlus. Each IDF file is simulated invoking EnergyPlus, where for each simulation, the output is the Comfort DPI of the respective district’s building.

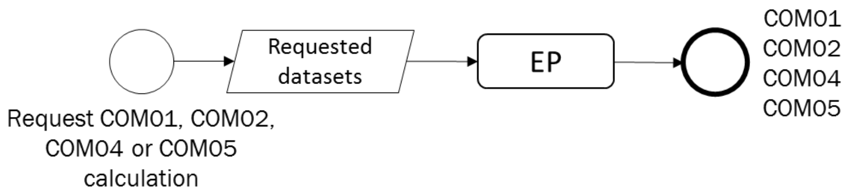

Figure 32: Flow diagram for the COM01/COM02/COM04/COM05 calculation

According to Annex I, one hundred five different calculation methodologies are available for the COM01 calculation. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules and the internal gains. Moreover, dynamic values of the clothing value, time variant, reference, values for the metabolic rate and reference data for the air velocity will be used. Hence, the EP66 or the EP74 (see Annex I: Detailed Data Requirements (COM01)) calculation methodology will be used.

Concerning the COM02 calculation, twenty-one calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules and the internal gains, and as such the EP6 or the EP18 (see Annex I: Detailed Data Requirements (COM01)) calculation methodology will be used.

For the COM04 calculation, forty calculation methodologies are available. However, within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules. Hence, the EP6, the EP18, the EP26 or the EP38 (see Annex I: Detailed Data Requirements (COM04)) calculation methodology could be used. Moreover, as mentioned in Section 3, although EnergyPlus has capabilities to model and simulate HVACs, within OptEEmAL the HVAC Sytems and Control tool will be used. The reason for that is the possibility of including OptEEmAL control ECMs instead of generic and simplified controls. Hence, the EP26 or the EP38 calculation methodology will be used.

For the COM05 calculation, thirteen calculation methodologies are available. Within OptEEmAL the building scale-geometry's information will be available in IFC or LoD2 level of detail, while reference data will be used for the schedules; however, LoD2 is not able to describe openings (windows/doors) and their visual properties. Moreover, reference data will be assumed for the artificial lighting devices. Hence, the EP9 (see Annex I: Detailed Data Requirements (COM05)) will be used.

Table 18: DPI COM01/COM02/COM04/COM05 characteristics

COM01/COM02/COM04/COM05	
Number of possible calculation methodologies	105 (COM01) 21 (COM02) 40 (COM04) 13 (COM05)
Detailed Data Requirements	See Annex I: Detailed Data Requirements (COM01, COM02, COM04 and COM05)
Calculation Tools	EP
Unit	Level (COM01) ^{o}C (COM02)

	n/a (COM04) Lux (COM05)
Scale	Building, District (COM01) Building, District (COM02) Building (COM04) Building (COM05)
Phase	Diagnosis, Evaluation

COM03

COM03 refers to the percentage of time outside the comfort zone. Standard comfort zones are established and comfort DPIs such as COM01 will be used to calculate COM02, utilizing function F9, performed by the OptEEmAL tool. The percentage of time outside the comfort zone needs to be normalized by the magnitude of the deviation to obtain meaningful values for COM02.

The following figure depicts the flow diagram for the COM03 calculation. Each of these comfort DPIs are specific outputs of the EnergyPlus simulation. Hence, proper requested datasets are retrieved from the DDM to generate different IDF files for every building of interest that will be used as input to EnergyPlus. Each IDF file is simulated invoking EnergyPlus, where for each simulation, the output is the Comfort DPI of the respective district's building.

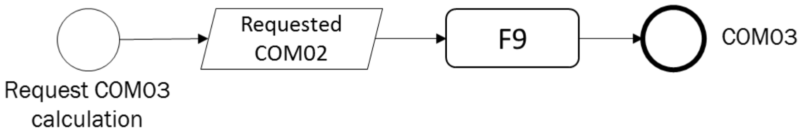

Figure 33: Flow diagram for the COM03 calculation

Table 19: DPIs COM03 characteristics

COM02	
Number of possible calculation methodologies	1
Detailed Data Requirements	-
Calculation Tools and Functions	OT, F9
Unit	%
Scale	Building, District
Phase	Diagnosis, Evaluation

5.3 Environmental DPIs

The data required for the evaluation of the environmental related DPIs can be classified into thirteen categories displays in the following table:

Table 20: Categories of data requirements for Environmental DPIs

Categories of Data Requirements for Environmental DPIs				
Type of Information	Available Information / Datasets	Required Accuracy	Required Information	Calculation Tools
Simulation Parameters	Initial Parameters, Selected Algorithms	High	All datasets	EP, CS
Building Geometry	CityGML Lod1, CityGML Lod2, CityGML Lod3, CityGML Lod4, IFC	Variable (low to high)	One of the available datasets	EP, CS
Building Materials	Equivalent Single-Layer Opaque, Multi-Layer Opaque, Multi-Layer Transparent	Variable (low to high)	One or more than one, of the available datasets	EP, CS
Weather Data	Measurements	High	All datasets	EP, CS
Schedules	Reference Data, Measurements	Variable (low, high)	One of the available datasets	EP, CS, NS
Internal Gains	Reference Data, Measurements	Variable (low, high)	One of the available datasets	EP, CS
Energy Systems	Ideal Load System, Systems' Templates, Detailed Description	Medium	One of the available datasets	EP, CS, HVAC
Exterior Equipment	Exterior Lights, Exterior Fuel Equipment, Exterior Water Equipment	Medium	None, one or more than one, of the available datasets	EP, CS
Renewable Energy Systems	Photovoltaic, Wind Turbine,	Medium	None, one or more than one, of the available	EP, CS

	Geothermal Heat Pump		datasets	
Source Energy Factors	Factors	High	One of the available datasets	EP, CS
Conversion Factors	GWP/type of fuel	High	One of the available datasets	EP, CS
Other DPIs	ENE01 ENE02	High	One of the available datasets	EP, CS, OT
ECMs Catalogue	GWP/FU	High	One of the available datasets	NS

For every environmental related DPI, the calculation flow diagrams followed by the tables of their characteristics are displayed below.

ENV01/ENV02/ENV03/ENV05/ENV06

ENV01 refers to the Global Warming Potential (GWP). This DPI is used to estimate the total CO_2 equivalent emissions (in kg CO_2 eq) due to the energy consumption and the use of construction materials in the district. For energy consumption, the final energy consumption values of different energy types are multiplied by appropriate conversion factors to estimate the CO_2 equivalent emissions. For construction materials, Greenhouse Gas emissions are accounted all along their lifecycle and then multiplied by the relevant conversion factors. Greenhouse Gases are all gases which have an influence on Global Warming namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide ($N_2 0$), etc. Conversion factors are called Global Warming Potentials. In OptEEmAL, the GWP indicator will be expressed in kg CO_2 equivalent per square meter of building and per year (kg CO_2 eq/m^2/year). It will be calculated for the diagnosis step as well as for all retrofitting scenarios.

ENV02 refers to the Global Warming Potential Investment. The GWP Investment is the GWP related to the retrofitting materials of a given scenario. It only accounts for building materials (ECMs in the case of OptEEmAL) used in a given retrofitting scenario. In OptEEmAL, this indicator will be expressed in kg CO_2 equivalent per square meter of building (kg CO_2 eq/m^2). It will be calculated only for retrofitting scenarios as it is equal to zero in the diagnosis step (no retrofitting materials used).

ENV03 refers to the Global Warming Potential Reduction. The GWP Reduction is the difference between the GWP of the baseline and the GWP of a given retrofitting scenarios. It accounts both for energy consumption and construction materials. In OptEEmAL, this indicator will be expressed in kg CO_2 equivalent per year (kg CO_2 eq/year). It will be calculated only for retrofitting scenarios.

ENV05 refers to the Embodied energy of refurbishment scenarios. The Embodied Energy is the energy requirement to construct and maintain the building. For instance, for a brick wall, it is the energy required to make the bricks, transport them to site, lay them, plaster them and if necessary paint and re-plaster over the wall's life cycle. The Embodied Energy of refurbishment scenarios is the equivalent of ENV02 (related to C02 emissions) but for energy. In OptEEmAL, this indicator will be expressed in MJ of primary energy per square meter of building (MJ/m^2). It will be calculated only for retrofitting scenarios as it is equal to zero in the diagnosis step (no retrofitting materials used).

ENV06 refers to the Energy payback time, the time needed to save the amount of primary energy "invested" in the life cycle of retrofitting materials (production, transport, end-of-life, etc.) with the energy consumption reduction due to the retrofitting process. The Energy Payback Time is the ratio of the energy “invested” over the energy “saved”. In OptEEmAL, this indicator will be expressed in years. It will be calculated only for retrofitting scenarios.

The following figure depicts the flow diagram for the ENV01/ENV02/ENV03/ENV05/ENV06 calculation. Each of these comfort DPIs are specific outputs of the NEST simulation. Hence, proper requested datasets, along with a request for the ENE02 calculation, are retrieved from the DDM to generate a proper xml file that will be used as input to NEST. Invoking NEST, the simulation runs and returns the requested environmental DPI value.

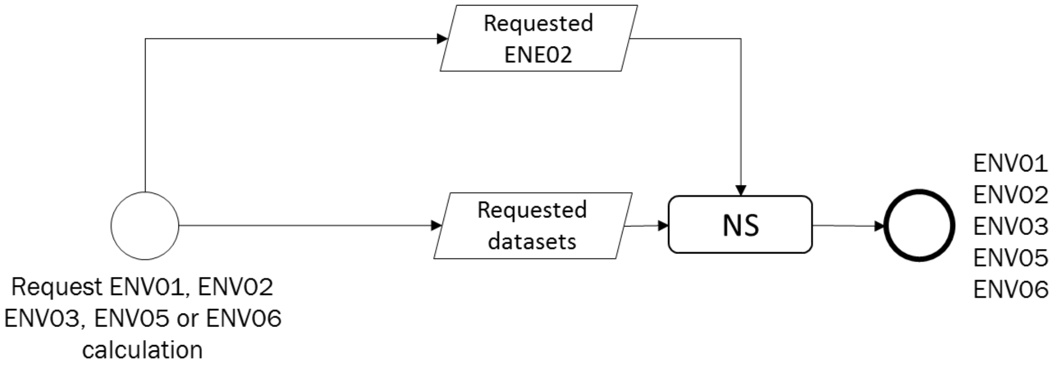

Figure 34: Flow diagram for the ENV01/ENV02/ENV03/ENV05/ENV06 calculation

Table 21: DPI ENV01/ENV02/ENV03/ENV05/ENV06 characteristics

ENV01/ENV02/ENV03/ENV05/ENV06	
Number of possible calculation methodologies	1
Detailed Data Requirements	--
Calculation Tools	NS
Unit	$kgCO2/m^2$ (ENV01/ENV02/ENV03) MJ/m^2 (ENV05) Years (ENV06)
Scale	District
Phase	Diagnosis, Evaluation

ENV04

ENV04 refers to the Primary energy consumption. Life cycle energy consumption is usually expressed in Primary Energy rather than delivered energy (or final energy) units. The primary energy is defined as the intrinsic energy in a primary product or resource. The primary energy contained in a block of coal used to fire a power station will be many times greater than the delivered electrical energy at a premise due to heat losses at the power plant and transmission losses in the electricity grid. In OptEEmAL, this indicator will be expressed in MJ of primary energy per square meter of building and per year (MJ/m^2/year). It will be calculated for the diagnosis step as well as for all retrofitting scenarios.

The aforementioned DPI has identical input data and simulation tools invocation requirements with the ENE02/ENE06/ENE12. The following figure, depicts the flow diagram for its calculation, identical to the flow diagram of ENE02/ENE06/ENE12. For more information concerning the calculation methodologies that will be supported within OptEEmAL, refer to the description of ENE02/ENE06/ENE12.

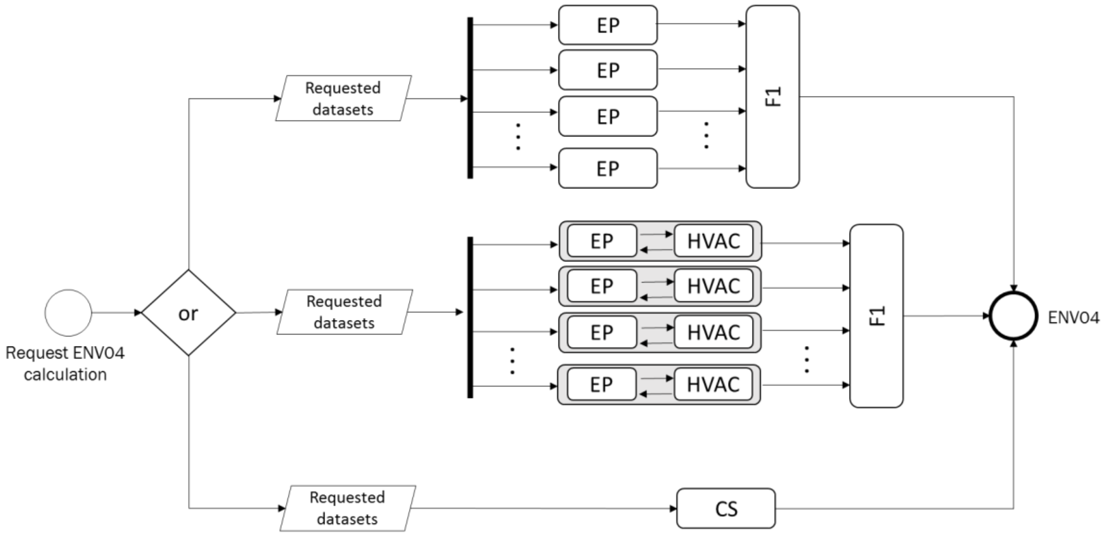

Figure 35: Flow diagram for the ENV04 calculation

Table 22: DPI ENV04 characteristics

ENV04	
Number of possible calculation methodologies	44
Detailed Data Requirements	--
Calculation Tools and Functions	NS, CS, HVAC, OT, F1
Unit	MJ/m²
Scale	District
Phase	Diagnosis, Evaluation

5.4 Economical DPIs

The data required for the evaluation of the economical related DPIs can be classified into two categories displays in the following table:

Table 23: Categories of data requirements for Economical DPIs

Categories of Data Requirements for Economical DPIs				
Type of Information	Available Information / Datasets	Required Accuracy	Required Information	Calculation Tools

Energy cost per fuel	Constant	High	All datasets	OT
Other DPIs	ENE02	High	One of the available datasets	EP, CS, HVAC, NS, OT

For every economical related DPI, the calculation flow diagrams followed by the tables of their characteristics are displayed below:

ECO01

ECO01, the Operational energy cost, is the number of monetary units required during the operation of a particular district refurbishment solution. It is calculated as the energy consumption per type of fuel multiplied to the energy cost per type of fuel.

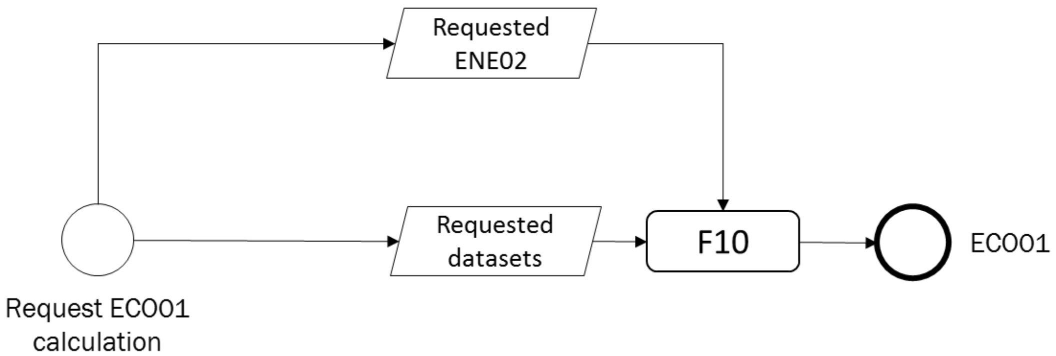

Figure 36: Flow diagram for the ECO01 calculation

The previous figure depicts the flow diagram for its calculation. For its calculation, initially the ENE02 and specific datasets are requested. Then, function F10, performed by the OptEEmAL tool, is invoked to estimate the ECO01 value.

Table 24: DPI ECO01 characteristics

ECO01	
Number of possible calculation methodologies	1
Detailed Data Requirements	--
Calculation Tools and Functions	OT, F10
Unit	€/year
Scale	District
Phase	Diagnosis, Evaluation

ECO02

ECO02, Investments, are the total monetary assets related to each refurbishment scenario. This DPI is an evaluation DPI and it will be calculated multiplying COST/FU of ECM and quantity of this ECM within the refurbishment scenario. Alternatively, this value will be expressed in relation to the total square meters' refurbishment surface.

The following figure depicts the flow diagram for its calculation. For its calculation, initially the specific datasets are requested. Then, function F11, performed by the OptEEmAL tool, is invoked to estimate the ECO02 value.

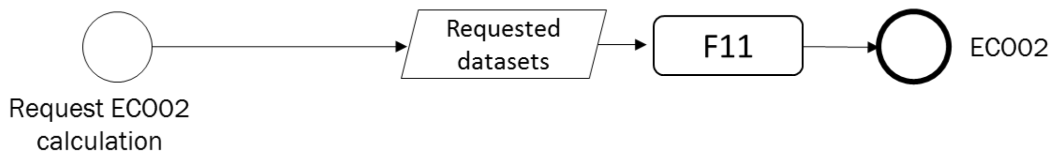

Figure 37: Flow diagram for the ECO02 calculation

Table 25: DPI ECO02 characteristics

ECO02	
Number of possible calculation methodologies	1
Detailed Data Requirements	--
Calculation Tools and Functions	OT, F11
Unit	€ or €/ m² of refurbished surface
Scale	District
Phase	Diagnosis, Evaluation

ECO03

ECO03, the life cycle cost, is the number of monetary units required for the initial installation, operational energy cost and maintenance of a particular refurbishment scenario.

The following figure depicts the flow diagram for its calculation. For its calculation, initially the ECO02 and specific datasets are requested. Then, function F12, performed by the OptEEmAL tool, is invoked to estimate the ECO03 value.

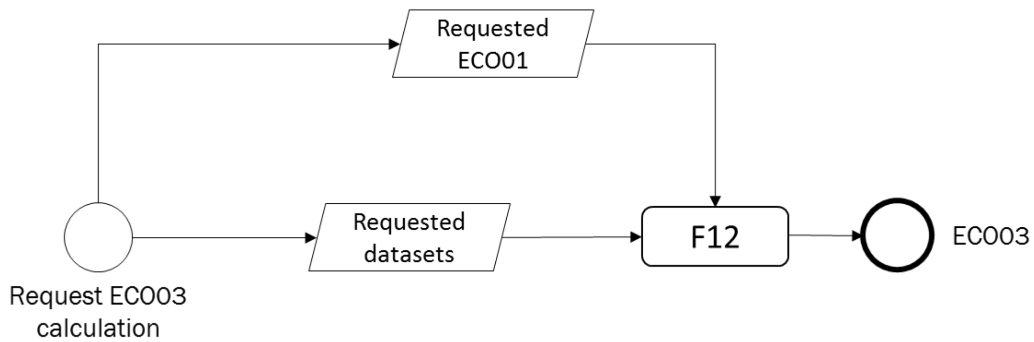

Figure 38: Flow diagram for the ECO03 calculation

Table 26: DPI ECO03 characteristics

ECO03	
Number of possible calculation methodologies	1
Detailed Data Requirements	--
Calculation Tools and Functions	OT, F12
Unit	€ or €/ m² of refurbished surface
Scale	District
Phase	Diagnosis, Evaluation

ECO04

ECO04, the return on investment, is the clear gain in monetary units associated with a particular refurbishment scenario (gain minus the total cost), relative to the total cost of this refurbishment scenario. In OptEEmAL the return on investment is the ratio of the difference of the gain minus the life cycle cost divided by the total life cycle cost of the refurbishment scenario.

The following figure depicts the flow diagram for its calculation. For its calculation, initially the ECO02, the ECO03 and specific datasets are requested. Then, function F13, performed by the OptEEmAL tool, is invoked to estimate the ECO01 value.

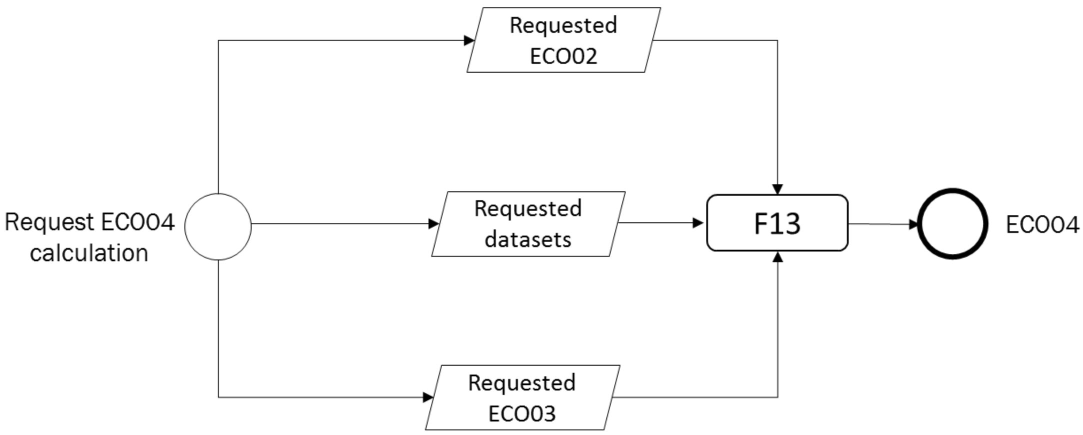

Figure 39: Flow diagram for the ECO04 calculation

Table 27: DPI ECO04 characteristics

ECO04	
Number of possible calculation methodologies	1
Detailed Data Requirements	--

Calculation Tools and Functions	OT, F13
Unit	%
Scale	District
Phase	Diagnosis, Evaluation

ECO05

ECO05, the payback period, is the time it takes to cover the investment costs. It can be calculated from the number of years elapsed between the initial investment, its subsequent operating costs and the point in time when cumulative savings offset the investment.

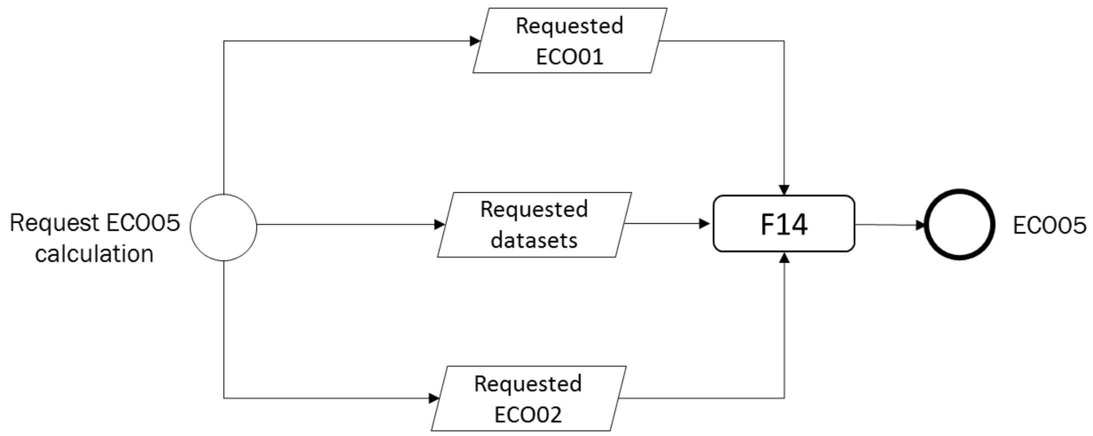

Figure 40: Flow diagram for the ECO05 calculation

The previous figure depicts the flow diagram for its calculation. For its calculation, initially the ECO01, the ECO02 and specific datasets are requested. Then, function F14, performed by the OptEEmAL tool, is invoked to estimate the ECO01 value.

Table 28: DPI ECO04 characteristics

ECO05	
Number of possible calculation methodologies	1
Detailed Data Requirements	--
Calculation Tools and Functions	OT, F14
Unit	years
Scale	District
Phase	Diagnosis, Evaluation

5.5 Social DPIs

The data required for the evaluation of the social related DPIs can be classified into two categories displays in the following table:

Table 29: Categories of data requirements for Social DPIs

Categories of Data Requirements for Social DPIs				
Type of Information	Available Information / Datasets	Required Accuracy	Required Information	Calculation Tools
Average Incomes	External Sources Real Data	High	One, or more than one, of the available datasets	OT
Other DPIs	ECO01 ENE02	High	One, or more than one, of the available datasets	OT

For the social DPI, the calculation flow diagrams following by the tables of their characteristics are displayed below.

SOC01

SOC01, the Energy poverty measured as % of inhabitants that use more than 10% of their incomes to pay energy bills, is used to estimate the ability of the district inhabitants to pay energy bills. It is expressed as the percentage of people that are in energy poverty using the definition of energy poverty as "Situation in which a household has to spend more than one tenth of its income to pay bills to heat its dwelling to an acceptable standard based on levels recommended by the World Health Organization.

The following figure depicts the flow diagram for its calculation. For its calculation, initially the ECO01, the ENE07 and specific datasets are requested. Then, function F15, performed by the OptEEmAL tool, is invoked to estimate the ECO01 value.

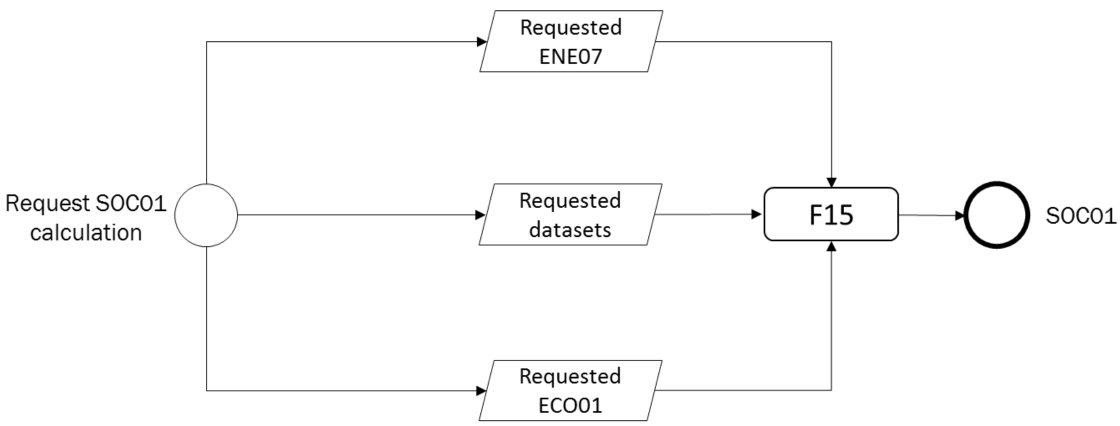

Figure 41: Flow diagram for the SOC01 calculation

Table 30: DPI SOC01 characteristics

SOC01	
Total Number of Evaluation Scenarios	1
Detailed Data Requirements	--
Calculation Tools and Functions	OT, F15
Unit	%
Scale	District
Phase	Diagnosis, Evaluation

5.6 Urban DPIs

The data required for the evaluation of the urban related DPIs can be classified into nine categories displays in the following table:

Table 31: Categories of data requirements for Urban DPIs

Categories of Data Requirements for Urban DPIs				
Type of Information	Available Information / Datasets	Required Accuracy	Required Information	Calculation Tools
Energy Performance Certificates	Impact of Heating / Cooling Systems Information on Primary Energy Consumption Information on Carbon Dioxide Emissions	High	One, or more than one, of the available datasets	OT
Other DPIs	ENE01 ENE02 ENV01 ENE03 ENE04 ENE09 COM03 ENV04	High	One, or more than one, of the available datasets	EP, CS, HVAC, NS, OT

For the urban related DPI, the calculation flow diagrams following by the tables of their characteristics are displayed below.

URB01

URB01, the Percentage of buildings with an ‘A’ rating in the Energy Performance Certificate (EPC), is devoted to the calculation of the percentage of buildings that can reach an A rating in the Energy

Performance Certificate (EPC). Nowadays, and since the implementation of the obligation to certify the performance of dwellings and premises at European level, each country has established certain reference values some dependent on the demand, C02 emissions or consumption to be accomplished in order to rate a dwelling or premise in a scale normally from A to G (most to least efficient, respectively). To obtain these values in real life, it is necessary to deploy a specifically validated tool to be able to certify a determined rating. In OptEEmAL, since these reference values are to be calculated by more precise tools than the ones proposed by the different countries in Europe, the value obtained from the indicator ENE01 "Energy demand" will be deployed for comparison purposes, since this parameter is the most widely used in the different countries' ratings. Another issue to be dealt with in the platform is the comparison value upon which to contrast the results. To this regard and after having analysed the different values established by the countries a figure has been fixed in the platform of 25kWh/m^{2}y demand. It is a restrictive value, but it ensures to comply with the conditions of the strictest countries.

The following figure depicts the flow diagram for its calculation. For its calculation, initially the ENE01 and specific datasets are requested. Then, function F16, performed by the OptEEmAL tool, is invoked to estimate the URB01 indicator.

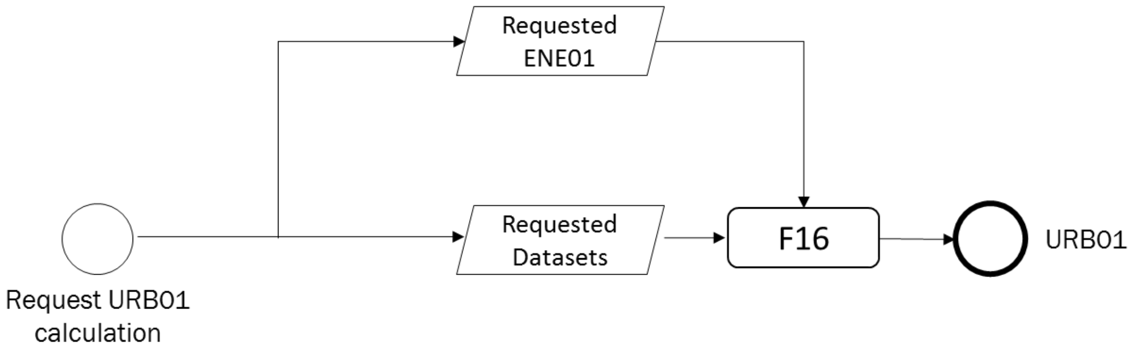

Figure 42: Flow diagram for the URB01 calculation

Table 32: DPI URB01 characteristics

URB01	
Total Number of Evaluation Scenarios	1
Detailed Data Requirements	--
Calculation Tools	OT
Unit	%
Scale	District
Phase	Evaluation

URB02/URB03

URB02, the Percentage of buildings compliant with PassivHaus standards, will calculate the percentage of buildings compliant with adapted PassivHaus standards. It will be based on the comparison of other indicators calculated within OptEEmAL (listed below) to satisfy the requirements established by the PassivHaus Institute for a determined dwelling or premise to be certified as PassivHaus.

The following figure depicts the flow diagram for the URB02 or the URB03 calculation. For their calculation, initially the ENE01, the ENE03, the ENE04 and the COM03 are requested. Then, function F17, performed by the OptEEmAL tool, is invoked to estimate the URB02 or the URB03 indicator.

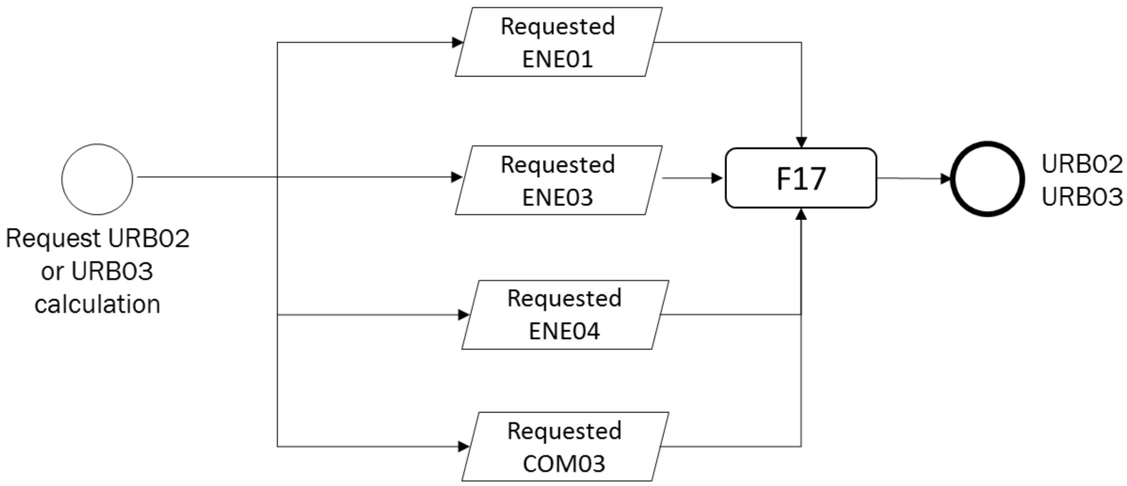

Figure 43: Flow diagram for the URB02/URB03 calculation

Table 33: DPI URB02/URB03 characteristics

URB02/URB03	
Total Number of Evaluation Scenarios	1
Detailed Data Requirements	--
Calculation Tools	OT, F17
Unit	%
Scale	District
Phase	Evaluation

URB04

URB04, the Percentage of buildings compliant with nZEB standards, will calculate the percentage of the district buildings that are compliant with nearly Zero Energy Building's standards.

The following figure depicts the flow diagram for the URB02 or the URB03 calculation. For their calculation, initially the ENE09, the ENV04 and the URB01 are requested. Then, function F18, performed by the OptEEmAL tool, is invoked to estimate the URB04 indicator.

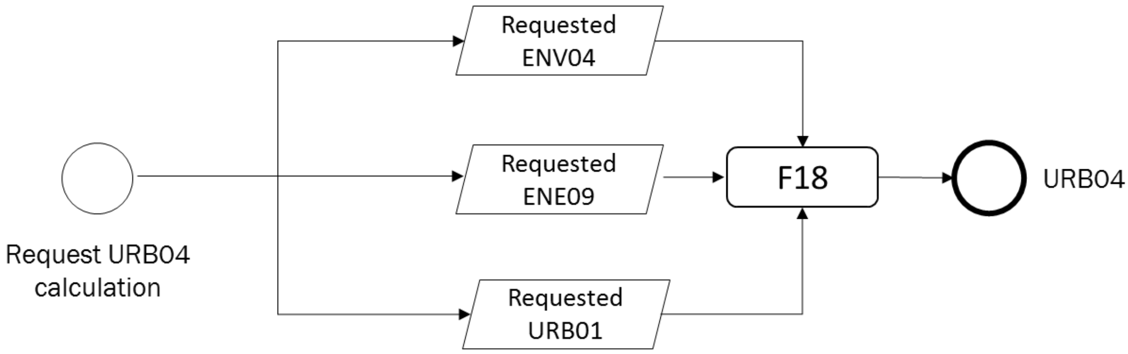

Figure 44: Flow diagram for the URB04 calculation

Table 34: DPI URB04 characteristics

URB04	
Total Number of Evaluation Scenarios	1
Detailed Data Requirements	--
Calculation Tools	OT, F18
Unit	%
Scale	District
Phase	Diagnosis, Evaluation

5.7 Global DPIs

The data required for the evaluation of the global related DPIs can be classified into one category displays in the following table:

Table 35: Categories of data requirements for Global DPIs

Categories of Data Requirements for Global DPIs				
Type of Information	Available Information / Datasets	Required Accuracy	Required Information	Calculation Tools
Other DPIs	ECO02 ENV03 ENV04	High	One of the available datasets	NS, OT

For the global DPI, the calculation flow diagrams following by the tables of their characteristics are displayed below.

GLO01

GLO01, the kWh energy saved / euro invested, measures the ratio of the estimated energy savings of a particular refurbishment scenario divided by the total monetary amount in euros invested to this scenario.

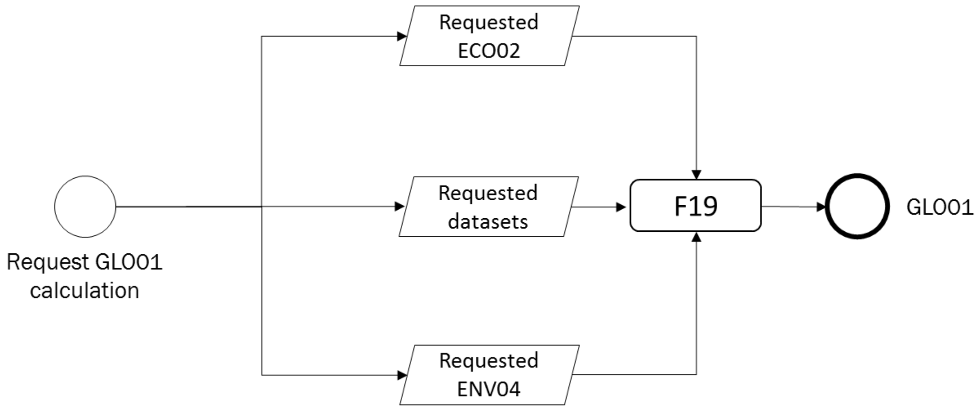

Figure 45: Flow diagram for the GLO01 calculation

It brings into relation two previously calculated DPIs, namely: ENE02 (evaluation and diagnosis) “Final energy consumption” and ECO02 “Investments”. This ratio is estimated by invoking function F19, performed by the OptEEmAL tool.

Table 36: DPI GLO01 characteristics

GLO01	
Total Number of Evaluation Scenarios	1
Detailed Data Requirements	--
Calculation Tools and Functions	OT, F19
Unit	kWh / €
Scale	District
Phase	Evaluation

GLO02

GLO02, the C02 saved / euro invested, measures the ratio of the estimated C02 savings of a particular refurbishment scenario divided by the total monetary amount in euros invested to this scenario.

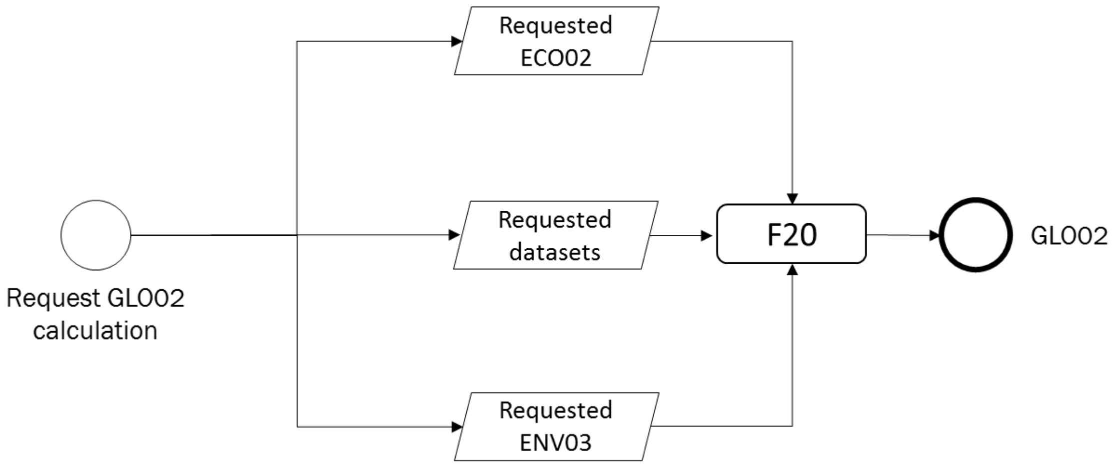

Figure 46: Flow diagram for the GLO02 calculation

It brings into relation two previously calculated DPIs, namely: ENV03 “GWP reduction” and ECO02 “Investments”. This ratio is estimated by invoking function F20, performed by the OptEEmAL tool.

Table 37: DPI GLO02 characteristics

GLO02	
Total Number of Evaluation Scenarios	1
Detailed Data Requirements	--
Calculation Tools and Functions	OT, F20
Unit	kg CO_2/a /€
Scale	District
Phase	Evaluation

6 Data Processing

The evaluation of the candidate retrofitting scenarios is based on the DPI calculation which also is an output of multiple simulation executions, which either refer to individual buildings or to the district as a whole. These district and building level simulations require as input several input files which will be generated automatically for every building and for the whole district based on the DDM and depending on the selected ECM measures of the candidate retrofitting scenarios. Such simulation input file generation process is illustrated in Figure 47.

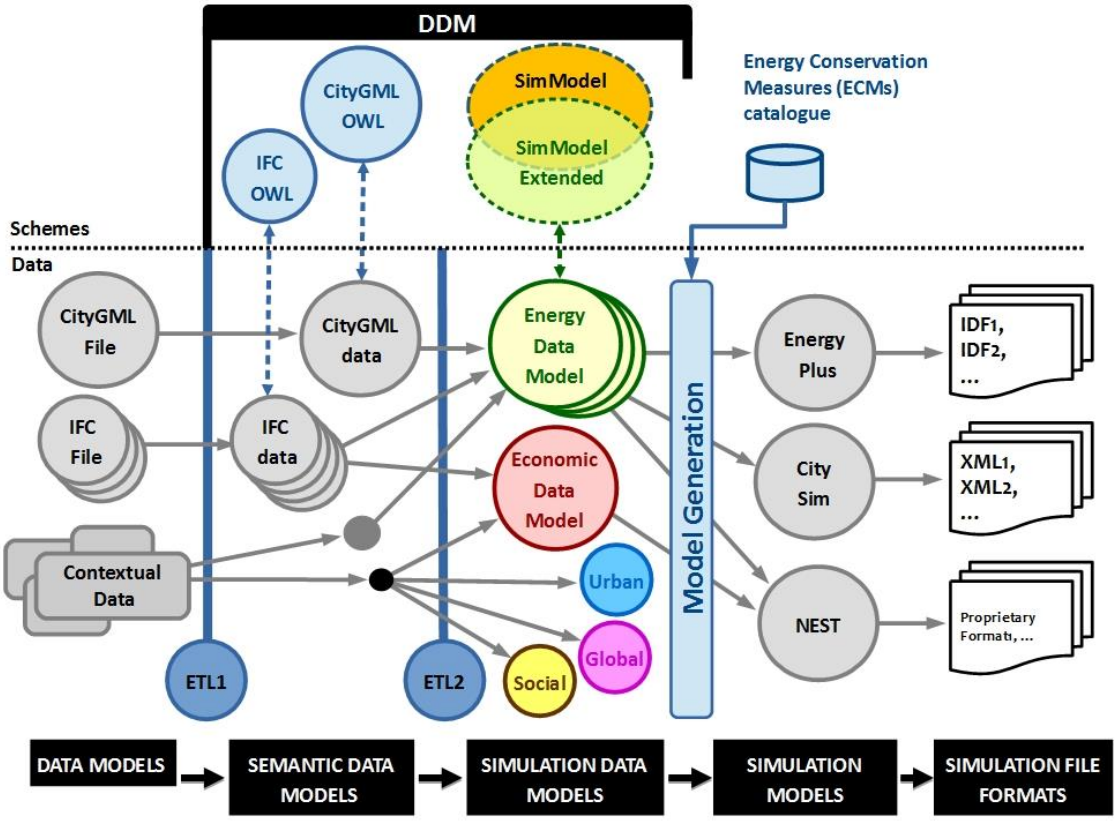

Figure 47: Overview of the simulation data integration process in the OptEEmAL platform

According to [04], for the baseline and every retrofitting scenario, different simulation input files are generated automatically for all the simulation programs: IDF files for every building of interest, to be used as input to Energy plus, an xml file referring to the whole district to be used as input to CitySim and multiple propriety format files to be used as NEST input.

This input file generation process is triggered by a Model generation process which uses as input Energy Data Models (referring to each building and to the whole district) and one Economic Data model (referring to the whole district) which are sub-models of the DDM, in combination with appropriate energy conservation measures queried from the ECM catalogue.

As illustrated in Figure 47: Overview of the simulation data integration process in the OptEEmAL platform, the DDM sub-models (Energy Data Models for every building of interest and the Economic Data Model for the district) are generated using a two-stage (Extraction and Transformation Layer) ETL process. In the first stage of this process (ETL1) intermediate semantic data models are generated from a single CityGML file, multiple IFC files (one for every building of interest) and contextual data. In the second stage (ETL2), the desired data sub-models (Energy and Economic) are generated using queries on the intermediate semantic models.

6.1 Data Quality

Although both district and building data may be available for simulation model generation, there is no guarantee that these data are suitable for this purpose, because the quality of the data is not at an acceptable level. There are three stages of data quality checking operations in order to ensure a quality level suitable for a simulation model generation. These operations include consistency, correctness and completeness checks and are explained analytically in the following sections.

6.1.1 Data consistency

The first checking operation ensures that an inserted detailed building model (IFC) is consistent with the underlying district model (CityGML). Although BIM geometric data obtained from an IFC file, might be visually correct, they may be inconsistent with the CityGML geometric data, which are described in world coordinates. Such inconsistencies occur when the geometric definition of a building in IFC model appear slightly rotated or translated with respect to the CityGML shell geometric definition of the same building. The inserted IFC model is considered CityGML-consistent if all IFC architectural elements are located inside a single CityGML shell. In any other case an inconsistency is declared and is communicated back to the user by the platform GUI for correction.

6.1.2 Data correctness

Both building and district data should be checked for correctness, before being used as inputs to the simulation model generation process. Incorrect data have many causes and the respective errors have different characteristics, as discussed next.

Error causes

There are three different sources of the errors appearing in building and district data files, which can be listed, depending on their causes, as follows:

- Scanning errors. Some of the district geometric data are generated from point clouds obtained from terrestrial or airborne scanning devices, which contain errors related to malefaction of these devices or incorrect geo-referencing of the obtained points.
- Design errors. Oftentimes building and district data files contain errors caused by incorrect design where the designer specifies incorrectly an architectural element, or material property or electromechanical system.
- Exporter errors. Finally, there are cases where either the IFC (building) or the CityGML (district) exporters generate errors by populating incorrectly the classes of the respective data files.

Error classification

Errors appearing in district and building data can be classified, with respect to their characteristics, into the following two categories:

- Missing data. There are cases where district or building data are not complete. For example, certain data might be omitted from the specification of the material layer properties of a construction. These errors are characterized as missing data errors.
- Incorrect data. Apart from the missing data errors, there are cases where district and building data are incorrect. For example, a solid geometric representation of an architectural element, might be misplaced with respect to other element representations.

A more detailed investigation of the geometric errors encountered in IFC files, and correction techniques, can be found in [4].

6.1.3 Data completeness

Finally, the inserted detailed building models are checked for completeness. More specifically, IFC data have to satisfy certain minimum data requirements expressed as a set of conditions in order to be suitable for simulation model generation, which are:

- Boundary conditions. The boundary surfaces, i.e. surfaces at which a building is attached to the outside air and ground, should be explicitly defined for every building of interest.
- Conditioned spaces. For every building of interest, at least one conditioned space volume, i.e. a building space which is going to be studied thermally, should be specified.
- Material properties and space boundaries. The second level space boundary surfaces of type 2a, for every building of interest, should be provided. If not, they should be calculated using the CBIP algorithm described below. Additionally, every second level space boundary surface pair of type 2a, should be linked semantically to a building construction, characterised by a set of thermal properties as illustrated in Figure 19.
- Shading group definitions. For every building of interest, a set of neighbour building shading the building of interest during a period of a whole year, should be specified as the shading group of the building of interest, as described below.

Provided that the above conditions are satisfied, the simulation model generation process can be performed, as described in the following section.

CBIP Algorithm

The Common Boundary Intersection Projection (CBIP) algorithm [5], [6], will be used within OptEEmAL platform as a building model data completeness tool. More specifically, CBIP will receive as input an incomplete (not containing, the required for simulation model generation, topology of the 2nd level space boundary surfaces of type 2a) architectural building model of a building of interest, calculate all the type 2a space boundary surfaces and update the initial incomplete building model.

Apart from calculating the type 2a space boundaries of a building of interest, CBIP also calculates the external shading surfaces, i.e. the building envelope surfaces of extended architectural elements which block external sunlight (balconies, extended roofs, etc.) which are also required for simulation model generation process.

Finally, an important prerequisite for the correct operation of CBIP is the architectural model of the building of interest to be free from any type of error described in section 6.1. The algorithmic details of CBIP are described in D4.5.

Shading Groups Definition

The simulation of a building in a district environment differ from the simulation of the same building alone, due to the implications of shading effects from nearby buildings cite [7] in the district. In order to include such phenomenon and increase the accuracy of the generated simulation model, a data district and building data completeness rule was added, named shading group definition as mentioned in section 6.1.3.

The shading group of a building of interest is defined as the set of neighbour buildings blocking direct sunlight to the building of interest for a specific period during a whole year. Given the district data as input, a specific algorithm has been developed which evaluates the building shading groups of all the buildings of interest. This algorithm is described in detail in Deliverable 4.5.

6.2 Simulation Input Files Generation

Different processes are followed for the generation of the simulation input files depending on the simulation tool as described in subsection 6.2.1. Additionally, certain simulation tools like EnergyPlus and CitySim require weather files for their operation which are also generated automatically as analysed in subsection 6.2.2.

6.2.1 Simulation Input Files

There are two possible pathways in which the data required for the simulation model generation can be generated:

1. In the first option, an XML file, following the SimModel XSD schema, will be generated for each building according to the respective IFC file, utilizing a IFC to SimModel transformation process. Moreover, retrofitting scenarios from the ECM catalogue, applicable to a certain building and derived from the scenarios generator module, will be listed to the corresponding SimModel file, as well. Finally, each SimModel file will be transformed to an RDF file applying an XSLT transformation process.

2. In the second option every IFC file per building and candidate retrofitting scenario from the ECM catalogue will be converted to an RDF file according to the ifcOWL specifications. The resulted RDFs will be converted to other RDFs according to the SimModel OWL specifications by an RDF2RDF conversion tool (see option 2 in figure).

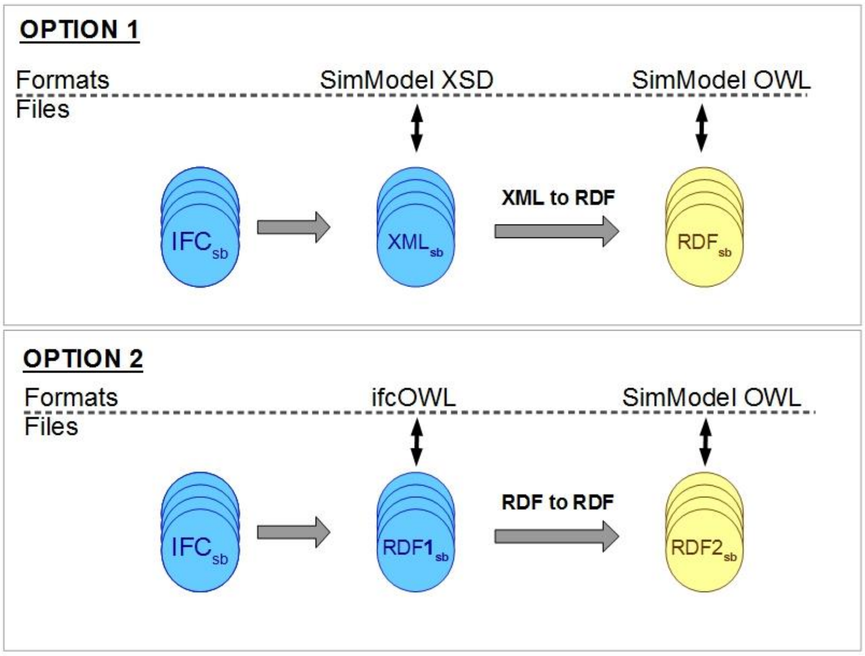

Figure 48: Possible pathways for the SimModel RDF generation

The final outputs of both options will be RDF files according to the SimModel OWL format which will be queried using SPARQL in order to provide the required data for the simulation input file generation.

In the final stage of the overall process, data retrieved from the appropriate SPARQL queries to the RDF file will comply with certain groups of transformation rules to generate the required simulation input files: IDF files for every building of interest, to be used as input to Energy plus, an xml file referring to the whole district to be used as input to CitySim and multiple propriety format files to be used as NEST input.

6.2.2 Weather Files

According to D1.3, in our attempt to store the data retrieved in a standard (unified) format, the weather data, retrieved utilizing the geoclustering module, will be converted to RDF format files, to be stored in the contextual repository through the corresponding connector of the communication logic layer.

This information will be retrieved by the simulation model input generator module which will be in charge of configuring the simulation files and launching the simulation tools. Concerning the weather data retrieved, the simulation files configuration refers to the respective weather files generation, where certain transformation rules (refer to D4.5) will be introduced to convert RDF format files to EPW, cli or other format files.

6.3 Simulation Runtime

As mentioned in D4.1, in the context of optimization, the repeated evaluation of various alternative scenarios is required. This can be a time-consuming process and therefore computational complexity considerations are important.

Within OptEEmAL, a methodology for automated generation of simulation input files is adopted, including: a query on the DDM requesting information; a processing of the geometry acquired data by a 2nd-level space boundary identification algorithm, the Common Boundary Intersection Projection (CBIP) algorithm; and a transformation process that converts the derived data to the EnergyPlus and the rest selected simulation tools input files. Concerning the EnergyPlus input file, commonly the geometry-related input data, derived by applying the aforementioned methodology, is of high detail due to numerous surfaces and thermal zones, increasing the simulation runtime, and as such not suitable for computationally demanding tasks, as the optimization process. Hence, within simulation model input generator module, support of simulation speed-up approaches is required.

6.3.1 Thermal Zones Reduction

Concerning the building scale simulation runtime, in common practice, a full-scale thermal simulation model treats each room of a building as an individual thermal zone. Such an assumption increases significantly the simulation runtime, since computational effort is more than proportional to the number of zones. Hence in many cases, building simulation modelers incorporate the HVAC zones definition, where each zone consists of one or more rooms and a thermostat assigned to that zone. At this level of detail, the thermal simulation model, where each HVAC zone is a thermal zone, can be still expensive for computationally demanding tasks. Concerning a further zoning reduction, building simulation experts are able to reduce the number of HVAC-thermal zones, but such a reduction is usually based on some similarity between the regions being combined (e.g. similar internal loads). Towards an automatic methodology to reduce the number of zones, utilizing simulation results of a full-scale, validated, thermal simulation model, in D4.5 [05], two approaches are presented. The first approach utilizes the Hierarchical Clustering theory [47], while the second approach adopts the Koopman modes theory [48]. The Koopman modes, as a systematic approach to zoning and model reduction, has recently been proposed in [49], where motivational results are presented for a real building.

6.3.2 Meta Models

During the optimization process, several factors affecting the building energy – such as construction materials, daylight and solar control measures, and activity-related parameters – are investigated, increasing the solution space of the optimization problem. Most optimization processes support workflows, which directly combine genetic algorithms with accurate building simulation software. The major disadvantage of such approaches is that energy simulations are computationally expensive. One way to address this is to adopt the thermal zoning reduction technique, discussed previously. Another approach is to replace the expensive simulations with fast surrogate models for estimating the energy consumption of each candidate solution, called “Meta-models”.

The Meta-model is pre-trained on simulated data, and is used to quickly evaluate candidate solutions without directly interfacing with the computationally expensive simulation tool during search. Gaussian Process theory can be used to develop such models, while simulated data in which the meta-model will be pre-trained can be provided using EnergyPlus in conjunction with Jeplus [50].

7 Computation

The implementation of the DPI calculation process is based on the actor model. This model is a conceptual model to deal with concurrent computation and provides the interface for the interaction between primitive software units, named actors. An actor is a process that executes a function and share the result with others by sending them messages. The representation of each DPI calculation is performed using the MoML schema (Modelling Markup Language). This schema contains all required information (ports, links and properties) for the representation of the actors with the necessary concurrency specifications. The Simulation module is responsible to parse the given representation and to initialize in the memory the calculation logic. Within the module, there are several predefined actors that can be used:

- GetDPI. Retrieves the stored DPIs from the Project repository through the CLL.
- StoreDPI. Stores the DPIs to the Project repository through the CLL.
- ClusterConnector. Handles the asynchronous communication between the module and the private cluster computing infrastructure.
- FormulaProcessor. Performs simplified calculations based on mathematical formulas.
- InputDataFileGen. Performs the transformation process of the populated simulation data models to the corresponding input data files.
- OutputFileProcessor. Performs post-processing on the output files of the simulation tools, coming through the cluster.

As shown in the following figure, the component initialises the instances of the actors, as well as the interconnections between them, in order to perform the calculation. When the module invokes the calculation process, all the software entities related with data acquisition will request data from the DDM using the interfaces provided by the web services. The returned serializable objects will be forwarded to the input of the ports of the connected software units. The diagram for each DPI computation process, is listed in the Annex II.

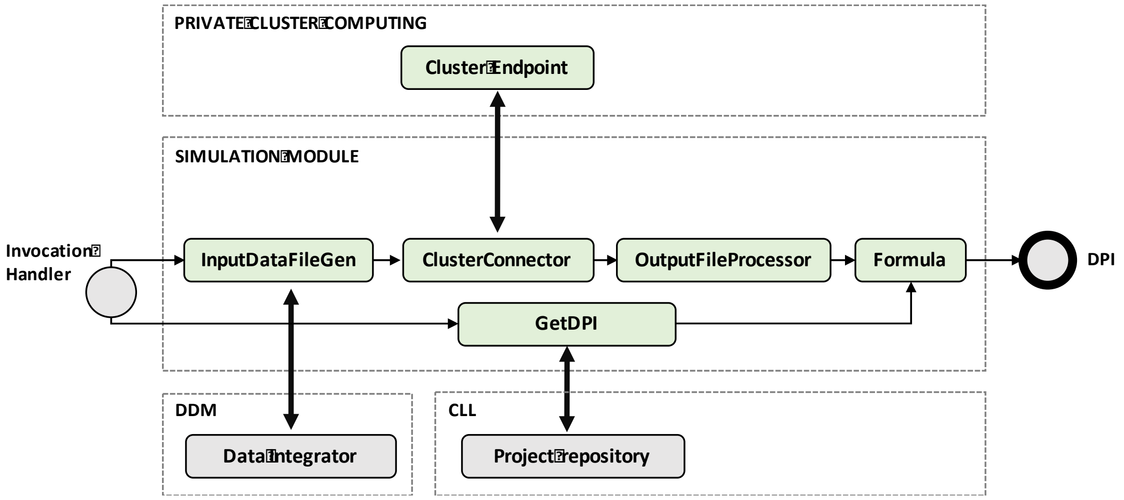

Figure 49: Interconnections between actors for a calculation process

The representation of the above example with the use of the MoML schema is listed below. Each entity includes specific types of ports and properties. The wiring of the primitive software units is achieved using relations and links between the ports.

```
<entity name="dpi">
        <entity name="dpi:invocation_handler" class="actors.sm.InvocationHandler">
                  <port name="out-1">
                         <property name="output"/>
                </port>
                  <port name="out-2">
                         <property name="output"/>
                </port>
```

```
        </entity>
        <entity name="dpi:get_dpi" class="actors.sm.GetDPI">
                <property name="name" value="DPIXX"/>
                  <port name="in">
                        <property name="input"/>
                </port>
                <port name="out">
                        <property name="output"/>
                </port>
         </entity>
         <entity name="dpi:input_data_file_gen" class="actors.sm.InputDataFileGeneration">
                  <port name="in">
                        <property name="input"/>
                </port>
                <port name="out">
                        <property name="output"/>
                </port>
         </entity>
         <entity name="dpi:cluster_connector" class="actors.sm.ClusterConnector">
                  <port name="in">
                        <property name="input"/>
                </port>
                <port name="out">
                        <property name="output"/>
                </port>
         </entity>
         <entity name="dpi:output_file_processor" class="actors.sm.OutputFileProcessor">
                  <port name="in">
                        <property name="input"/>
                </port>
                <port name="out">
                        <property name="output"/>
                </port>
         </entity>
         <entity name="dpi:mathematical_formula" class="actors.sm.FXX">
                  <port name="in">
                        <property name="input"/>
                </port>
                <port name="out">
                        <property name="output"/>
                </port>
         </entity>
         <entity name="dpi:store_dpi" class="actors.sm.StoreDPI">
                <property name="name" value="DPIXX"/>
                  <port name="in">
                        <property name="input"/>
                </port>
         </entity>
         <relation name="r0"/><relation name="r1"/><relation name="r2"/><relation name="r3"/>
         <relation name="r4"/><relation name="r5"/><relation name="r6"/><relation name="r7"/>
         <link port="dpi:invocation_handler.out-1" relation="r0"/>
         <link port="dpi:input_data_file_gen.in" relation="r0"/>
         <link port="dpi:invocation_handler.out-2" relation="r1"/>
         <link port="dpi:get_dpi.in" relation="r1"/>
         <link port="dpi:input_data_file_gen.out" relation="r3"/>
         <link port="dpi:cluster_connector.in" relation="r3"/>
         <link port="dpi:cluster_connector.out" relation="r4"/>
         <link port="dpi:output_file_processor.in" relation="r4"/>
         <link port="dpi:output_file_processor.out" relation="r5"/>
         <link port="dpi:mathematical_formula.in-1" relation="r5"/>
         <link port="dpi:get_dpi.out" relation="r6"/>
         <link port="dpi:mathematical_formula.in-2" relation="r6"/>
         <link port="dpi:mathematical_formula.out" relation="r7"/>
         <link port="dpi:store_dpi.in" relation="r7"/>
</entity>
```

7.1 Distributed Computation

Within the OptEEmAL platform, the evaluation of the retrofitting scenarios requires the execution of external tools under virtualized computing resources provided by cloud computing infrastructure. The distributed nature of this process requires orchestration techniques and an enterprise messaging framework that connects the services, ideally in a loosely coupled manner in order to maximize scalability. Asynchronous messaging is widely used, providing many benefits, but also brings challenges such as the delivery sequence of the messages and the concurrency of the services. The main functionality of the cluster infrastructure will be obtained using a secure and private containerized environment hosted on dedicated compute nodes. This containerized environment is a lightweight virtualization system that does not require to setup virtual machines on physical hardware (hypervisors). The available implementations like Docker, LXC and Rocket use the cgroups resource management functionality as its basis and adds the POSIX standard capabilities to implement process and network isolation. The containers make the workloads portable and distributed in a standardized manner and allow the developer to package the software components with all the dependences into a standardized unit. Currently three Docker images have been created and tested, one for each simulation tool. The deployment of these images to the cluster requires operating systems especially designed for providing robust infrastructure to clustered environments. Operating systems such as CoreOS and RancerOS were tested, because they provide only the minimal functionality required for deploying applications inside containers, together with built-in mechanisms for service discovery and configuration sharing. As shown in the following figure the containers of the simulation tools and the front-end services are the primary components of the cluster.

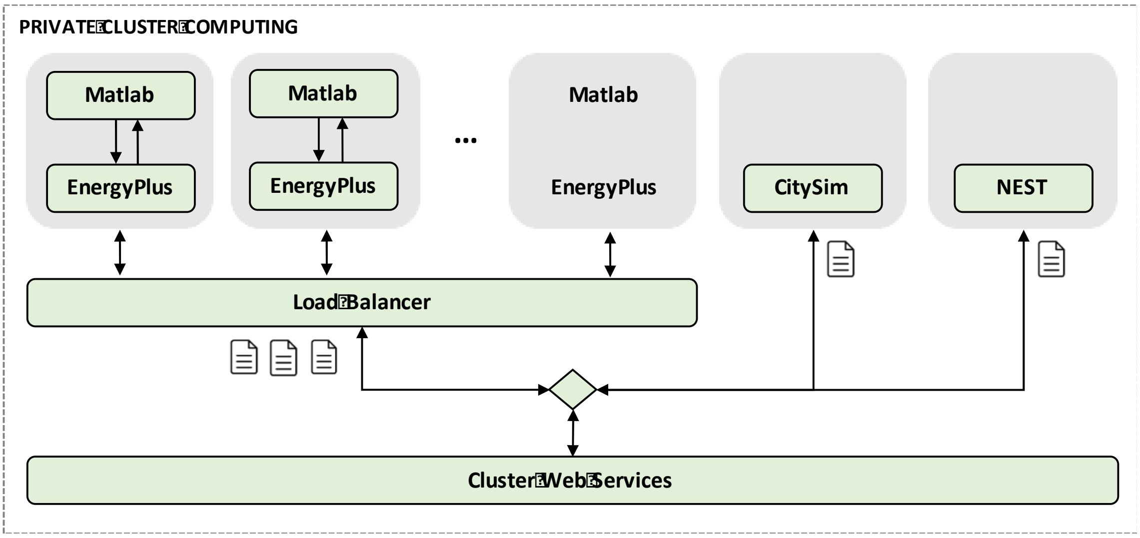

Figure 50: Private Cluster Computing Architecture

8 Conclusions

The focus of this Deliverable has been the requirement collection and the design of the simulation model input generator module; a module that retrieves information from the District Data Model, transforms these data to proper simulation files; launches appropriate tools to simulate the models, and aggregates simulation outputs to compute the final DPIs.

Initially, our analysis concentrated on documenting the calculation methodologies – and respective tools that implement those methodologies. Our focus was primarily on the Energy and Comfort DPIs, being the most challenging ones to be computed. Various tools were analysed and categorised with important modelling aspects, concluding to the simulation tools that has been selected to be used within OptEEmAL: 1) EnergyPlus, CitySim, HVAC and OptEEmAL tool for the Energy DPIs; 2) EnergyPlus HVAC and OptEEmAL tool for the Comfort DPIs; 3) NEST, EnergyPlus, CitySim, HVAC and OptEEmAL tool for the Environmental DPIs; and 4) OptEEmAL tool for the Economic, Social, Urban and Global DPIs. Furthermore, an analysis of data required for the generation of proper simulation inputs files for the selected simulation tools was performed. The analysis is directly linked to the work in D2.1, which aims at encoding these requirements in the definition of the District Data Model (DDM).

In Section 5 and Annex I, it was noticed that based on the level of detail of the available data it is possible to construct simulation models of increasing quality to be used for the Energy and Comfort DPIs calculation. Hence, different scenarios for each DPI were analysed and ranked, concluding to the amount of information in describing the district which is sufficient for the decision-making process that the OptEEmAL tool is meant to support. The analysis has led to a selection of the appropriate calculation methodology that provides sufficient accuracy for the calculations in OptEEmAL.

Having selected the level of detail in the information so that the relevant DPIs can be computed, certain processing stages were listed as prerequisites towards the simulation input files generation: the data quality stage, where certain data processing algorithms, to guarantee that both district and are suitable for our purpose, were presented; the simulation input files generation stage, where different processes for the generation of the simulation input and weather files depending on the simulation tool, were presented; and the simulation runtime reduction stage, where two different simulation speed-up approaches were proposed. These processing stages are going to be analysed in D4.5. Finally, in our attempt to describe the technical implementation of the DPI calculation process, a conceptual model to deal with concurrent computation and to provide the interface for the interaction between primitive software units, named actors, has been proposed.

More details on the algorithmic development of components as well as on the detailed software engineering will be provided in D4.5 – an intermediate version of which is available.

9 References

[01] OPTEEMAL CONSORTIUM: D1.2 Requirements and Specification of input data process to evaluate users' objectives and current conditions, Feb 2016.

[02] OPTEEMAL CONSORTIUM: D2.1 Requirements and Specification for the District Data model, Feb 2016.

[03] OPTEEMAL CONSORTIUM: D2.2 Report on District Sustainability Indicators to formulate and optimize scenarios, Aug 2016.

[04] OPTEEMAL CONSORTIUM: D2.3 Functional architecture of the data repository, Aug 2016.

[05] OPTEEMAL CONSORTIUM: D4.5 Simulation Input Model Generator Prototype, Aug 2016.

[06] OPTEEMAL CONSORTIUM: D5.2 Functional architecture specification, interfaces definition and overall platform design, Aug 2016.

[07] H. YEONSOOK, A. GODFRIED AND R. CHOUDHARY. Risk analysis of energy-efficiency projects based on Bayesian calibration models. In *Proceedings 2011 Building Simulation Conference,* pp. 2579-2586, 2011.

[08] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. ISO 13790: 2008: Thermal performance of Buildings-Calculation of energy use for space heating and cooling. Geneva, Switzerland, 2008.

[09] DB. CRAWLEY, LK LAWRIE, FC WINKELMANN, ET AL. EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, 2001: 319–331.

[10] SA. KLEIN, WA. BECKMAN, AND JA. DUFFIE. TRNSYS: A Transient Simulation Program. *ASHRAE Transactions* 82 (1976): 623-633.

[11] K. MOSS. Heat and mass transfer in buildings, Taylor & Francis, Jul 16, 2007.

[12] E. MALDONADO (ED.). Implementing the Energy Performance of Buildings Directive. Brussels, 2016. Available online (Link).

[13] GERMAN INSTITUTE FOR STANDARDIZATION. DIN 18599-1: Energetische Bewertung von Gebäuden, 2013.

[14] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. ISO 13790: 2008: Thermal performance of Buildings, Calculation of energy use for space heating and cooling. Geneva, Switzerland: International Organization for Standardization, 2008.

[15] A. DRÖSCHER, M. PICHLER, H. SCHRANZHOFER, A. CONSTANTIN, N. EXIZIDOU, G. GIANNAKIS, D. ROVAS. Validation Results of the Models. PEBBLE Project Deliverable D2.2, 2011.

[16] DB. CRAWLEY, JW. HAND, M. KUMMERT, BT. GRIFFITH. Contrasting the Capabilities of Building Energy Performance Simulation Programs. *Proceedings of Building Simulation 2005,* Montreal, Quebec, Canada, IBPSA, pp. 231-238.

[17] E. LOKEN. Use of multi-criteria decision analysis methods for energy planning problems. *Renewable and Sustainable Energy Reviews*,11 (2007), pp. 1584-1595.

[18] MF. PICHLER, A. DRÖSCHER, H. SCHRANZHOFER, A. CONTANTIN, M. HUBER, G. GIANNAKIS, N. EXIZIDOU, AND DV. ROVAS. Simulation Model Improvements. *PEBBLE Deliverable* 2.3, 2011.

[19] PEBBLE CONSORTIUM. "Positive Energy Buildings through Better controL dEcisions." FP7-ICT-2009.6.3, Contract #248537.

[20] BAAS CONSORTIUM. "Buildings as a service (Ecosystem)" FP7-ICT-2011.6.2, Contract #288409.

[21] G.N. Lilis, G.I. Giannakis, D.V. Rovas and E.B. Kosmatopoulos. Energy efficient building ventilation control using the finite element modelling of SRC. *IEEE European Modelling Symposium*, Malta 14-16 Nov. 2012.

[22] ASHRAE. Psychrometrics. ASHRAE Handbook - Fundamentals (SI), pp.1-16, 2009.

[23] ASHRAE. Ventilation and infiltration. ASHRAE Handbook, 16, pp.1-36, 2009.

[24] S. PRIVARA, Z. VANA, E. ZAVCEKOVA AND J. CIGLER. Building Modelling: Selection of the Most Appropriate Model for Predictive Control. *Energy and Buildings,* 55, pp. 341-350, 2012.

[25] M. YALCINTAS AND S. AKKURT. Artificial neural networks applications in building energy predictions and a case study for tropical climates. International journal of energy research, (29), pp. 891-901, 2005.

[26] S. PRIVARA, Z. VANA, D. GYALISTRAS, J. CIGLER, C. SAGERSCHNIG, M. MORARI AND L. FERKL. Modelling and identification of a large multi-zone office building. In *Proceedings IEEE International Conference on Control Applications (CCA)*, pp. 55-60, 2011.

[27] S. Privara, Z. Vana, J. Cigler. and L. Ferkl. Predictive control oriented subspace identification based on building energy simulation tools. In *Proceedings 20th Mediterranean Conference on Control & Automation (MED)*, pp. 1290–1295, 2012.

[28] S. Privara, J. Siroky, L. Ferkl, J. Cigler. Model predictive control of a building heating system: The first experience. *Energy and Buildings*, 43:2, pp. 564572, 2011.

[29] K. Deng, P. Barooah, PG. Mehta and SP. Meyn. Building thermal model reduction via aggregation of states. In *Proceedings of 2010 American Control Conference*, pp. 51185123, 2010.

[30] J. Allegrini, K. Orehounig, G. Mavromatidis, et. al. A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renewable and Sustainable Energy Reviews*, 52, pp. 1391-1404, 2015.

[31] J. Keirstead, M. Jennings, A. Sivakumar. A review of urban energy system models: approaches, challenges and opportunities. *Renewable and Sustainable Energy Reviews,* 16(6), pp. 3847-3866,2012.

[32] D. Robinson, F. Haldi, et al. CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning. In *Proceedings of BS2009*, 11th International Building Performance Simulation Association Conference, Glasgow, Scotland, pp. 1083-1090.

[33] D. Thomas, C. Miller, et al. Multiscale co-simulation of EnergyPlus and CitySIM models derived from a building information model. In *Proceedings Fifth German-Austrian Conference,* pp.469-476, BauSIM 2014, 2014.

[34] M. Wetter. Building Controls Virtual Test Bed. Lawrence Berkeley National Laboratory, 2016.

[35] V. Bazjanac, A. Kiviniemi. Reduction, Simplification, Translation and interpretation in the exchange of model data. In *Proceedings of CIB W78 Conference*, pp. 163-168, Slovenia, 2007.

[36] V. Bazjanac. Space boundary requirements for modelling of building geometry for energy and other performance simulation. In *Proceedings of CIB W78 Conference*, Sophia-Antipolis, France, 2010.

[37] M. Weise, T. Liebich, R. See, V. Bazjanac, T. Laine and B. Welle. Implementation guide: Space boundaries for energy analysis. *US General Services Administration (GSA) and Open Geospatial Consortium* (OGC), 2011.

[38] European Committee for Standardization. EN15251: Indoor environmental input parameters for design and assessment of energy performance of buildings - addressing indoor air quality, thermal environment, lighting and acoustics, CEN Standard EN15251, 2007.

[39] European Committee for Standardization. EN16798-1: Energy performance of buildings. Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. CEN Standard Draft EN16798-1, 2015.

[40] International Organization for Standardization. ISO 13791: Calculation of Internal Temperatures of a Room in Summer without Mechanical Cooling – General Criteria and Validation Procedures. *ISO Standard*, ISO 13791:2012, 2012.

[41] ANSI/ASHRAE. ASHRAE 140-2014: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. *ASHRAE Standard,* 2014.

[42] LG Swan, VI Ugursal. Modelling of end-use energy consumption in the residential sector: A review of modelling techniques. *Renewable and sustainable energy reviews*, 2009, 13.8: 1819-1835.

[43] ASHRAE. Standard method of test for the evaluation of building energy analysis computer programs. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.: Atlanta (2007).

[44] Maile, T. Comparing measured and simulated building energy performance data. PhD thesis, Stanford University, 2010.

[45] Nguyen, A.-T., Reiter, S., and Rigo, P. A review on simulation-based optimization methods applied to building performance analysis. Applied Energy 113 (2014), 1043-1058.

[46] Bahar, Y. N., Pere, C., Landrieu, J., and Nicolle, C. A thermal simulation tool for building and its interoperability through the building information modeling (bim) platform. Buildings 3, 2 (2013), 380-398.

[47] Maimon, O., and Rokach, L. Data mining and knowledge discovery handbook, vol. 2. Springer, 2005.

[48] Mezic, I. Spectral properties of dynamical systems, model reduction and decompositions. Nonlinear Dynamics 41, 1-3 (2005), 309-325.

[49] Georgescu, M., and Mezic, I. Building energy modeling: A systematic approach to zoning and model reduction using koopman mode analysis. Energy and Buildings 86 (2015), 794-802.

[50] Zhang Y. JEPlus e an EnergyPlus simulation manager for parametrics. De Montfort University; 2012.

[51] M. Lotteau, P. Loubet, M. Pousse, E. Dufrasnes et G. Sonnemann. Critical review of life cycle assessment (LCA) for the built environment at the neighbourhood scale. Building and Environment, vol. 93, pp. 165-178, 2015.

[52] J. Anderson, G. Wulfhorst et W. Lang, Energy analysis of the built environment—A review and outlook. Renewable Sustainable Energy Review, vol. 44, pp. 149-158, 2015.

[53] M. Buyle, J. Braet et A. Audenaert. LCA in the construction industry: A review. International Journal of Energy and Environment, vol. 6, pp. 397-405, 2012.

[54] L. Cabeza, L. Rincon, V. Vilarino, G. Perez et A. Castell. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable Sustainable Energy Journal, vol. 29, pp. 394-416, 2014.

[55] O. Ortiz, F. Castells et G. Sonnemann. Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials, vol. 23, pp. 28-39, 2009.

[56] T. Baynes et T. Wiedmann. General approaches for assessing urban environmental sustainability. Current Opinion in Environmental Sustainability, vol. 4, pp. 458-464, 2012.

[57] E. Loiseau, G. Junqua, P. Roux et V. Bellon-Maurel. Environmental assessment of a territory: An overview of existing tools and methods. Journal of Environmental Management, vol. 112, pp. 213-225, 2012.

[58] J. Oliver-Sola, A. Josa, A. Arena, X. Gabarell et J. Rieradevall. The GWP-Chart: An environmental tool for guiding urban planning processes. Application to concrete sidewalks, Cities, vol. 28, pp. 245-250, 2011.

[59] M. Colombert, C. De Chastenet, Y. Diab, C. Gobin, G. Herfray, T. Jarrin, P. Peuportier, T. C. et T. Maxime. Analyse de cycle de vie à l'échelle du quartier: un outil d'aide à la décision? Le cas de la ZAC Claude Bernard à Paris (France). Environnement Urbain, vol. 5, pp. 1-21, 2011.

[60] LEMA. SOLEN Evaluation quartier, 2015. [En ligne]. Available: http://solen-energie.be/nos-tests/evaluation/quartier/1.

[61] G. Yepez-Salmon. Construction d'un outil d'évaluation environnementale des écoquartiers: vers une méthode systémique de mise en oeuvre de la ville durable, 2011.

[62] International Standardisation Organisation, Environmental management—Life cycle assessment—Principles and framework, 2006.

[63] Organisation, International Standardisation, ISO 14044 - Environmental Management - Life Cycle Assessment - Principles, frameworks and guidelines, 2006.

[64] International Standardisation Organisation, Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method, 2011.

[65] ecoinvent, 2013. [En ligne]. Available: http://www.ecoinvent.org/. [Accès le 2016].

Annex I: Energy and Comfort DPIs – Detailed Data Requirements

Table 38: Detailed Data Requirements of DPI ENE01

DPI ENE01: Energy demand																										
			DPI Evaluation Scenarios																							
Calculation Methodology			EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8	EP9	EP10	EP11	EP12	EP13	EP14	EP15	EP16	EP17	EP18	EP19	EP20	CS1	CS2	CS3	CS4
Data Type	**BEPS - Data Req.**																									
Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Building Geometry Description	CityGML LoD1		x	x	x	x																	x	x		
	CityGML LoD2						x	x	x	x															x	x
	CityGML LoD3										x	x	x	x											o	o
	CityGML LoD4														x	x	x	x							o	o
	IFC4 (Design Transfer View)																		x	x	x	x			o	o
Building Materials	Equivalent single layer/ Opaque	Total thermal resistance	x		x		x		x		x		x		x		x		x		x					
		Total thermal capacitance	x		x		x		x		x		x		x		x		x		x					
	Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x	x	x	x	x
		Density		x		x		x		x		x		x		x		x		x		x	x	x	x	x
		Specific Heat		x		x		x		x		x		x		x		x		x		x	x	x	x	x
		Thermal Absorptance		x		x		x		x		x		x		x		x		x		x	x	x	x	x
	Multi layer/Transparent	U-factor									x	x	x	x	x	x	x	x	x	x	x	x				
		SHGC									x	x	x	x	x	x	x	x	x	x	x	x				
	Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				
	Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				
Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x			x		x	
	Measurements				x	x			x	x			x	x			x	x			x	x		x		x
Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x			x		x	
	Measurements				x	x			x	x			x	x			x	x			x	x		x		x
Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Cooing Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Systems' Templates																									
	Detailed Description																									
Exterior Energy Use Equipment	Exterior Lights		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				
	Exterior Fuel Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Exterior Water Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Renewable Energy Systems	Photovoltaic Systems		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Wind Turbine		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Combined Heat and Power		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Geothermal Heat Pump		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				
Level of Accuracy			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**1**	**2**	**3**	**4**

Table 39: Detailed Data Requirements of DPI ENE02-ENE19 and ENV04 (1/2)

DPIs ENE02 - ENE19 (1/2)																						
			DPI Evaluation Scenarios																			
Calculation Methodology			EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8	EP9	EP10	EP11	EP12	EP13	EP14	EP15	EP16	EP17	EP18	EP19	EP20
Data Type	**BEPS - Data Req.**																					
Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Building Geometry Description	CityGML LoD1		x	x	x	x																
	CityGML LoD2						x	x	x	x												
	CityGML LoD3										x	x	x	x								
	CityGML LoD4														x	x	x	x				
	IFC4 (Design Transfer View)																		x	x	x	x
Building Materials	Equivalent single layer/ Opaque	Total thermal resistance	x		x		x		x		x		x		x		x		x		x	
		Total thermal capacitance	x		x		x		x		x		x		x		x		x		x	
	Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x
		Density		x		x		x		x		x		x		x		x		x		x
		Specific Heat		x		x		x		x		x		x		x		x		x		x
		Thermal Absorptance		x		x		x		x		x		x		x		x		x		x
	Multi layer/Transparent	U-factor									x	x	x	x	x	x	x	x	x	x	x	x
		SHGC									x	x	x	x	x	x	x	x	x	x	x	x
	Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x		
	Measurements				x	x			x	x			x	x			x	x			x	x
Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x		
	Measurements				x	x			x	x			x	x			x	x			x	x
Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature																				
		Cooing Setpoint Temperature																				
	Systems' Templates		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Detailed Description																					
Exterior Energy Use Equipment	Exterior Lights		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Exterior Fuel Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Exterior Water Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Renewable Energy Systems	Photovoltaic Systems		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Wind Turbine		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Combined Heat and Power		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Geothermal Heat Pump		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Level of Accuracy			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Table 40: Detailed Data Requirements of DPI ENE02-ENE19 and ENV04 (2/2)

DPIs ENE02 - ENE19 (2/2)																										
			DPI Evaluation Scenarios																							
Calculation Methodology			EP21	EP22	EP23	EP24	EP25	EP26	EP27	EP28	EP29	EP30	EP31	EP32	EP33	EP34	EP35	EP36	EP37	EP38	EP39	EP40	CS1	CS2	CS3	CS4
Data Type	**BEPS - Data Req.**																									
Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Building Geometry Description	CityGML LoD1		x	x	x	x																	x	x		
	CityGML LoD2						x	x	x	x															x	x
	CityGML LoD3										x	x	x	x											o	o
	CityGML LoD4														x	x	x	x							o	o
	IFC4 (Design Transfer View)																		x	x	x	x			o	o
Building Materials	Equivalent single layer/ Opaque	Total thermal resistance	x		x		x		x		x		x		x		x		x		x					
		Total thermal capacitance	x		x		x		x		x		x		x		x		x		x					
	Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x	x	x	x	x
		Density		x		x		x		x		x		x		x		x		x		x	x	x	x	x
		Specific Heat		x		x		x		x		x		x		x		x		x		x	x	x	x	x
		Thermal Absorptance		x		x		x		x		x		x		x		x		x		x	x	x	x	x
	Multi layer/Transparent	U-factor									x	x	x	x	x	x	x	x	x	x	x	x				
		SHGC									x	x	x	x	x	x	x	x	x	x	x	x				
	Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				
	Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				
Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x			x		x	
	Measurements				x	x			x	x			x	x			x	x			x	x		x		x
Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x			x		x	
	Measurements				x	x			x	x			x	x			x	x			x	x		x		x
Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature																								
		Cooing Setpoint Temperature																								
	Systems' Templates																						x	x	x	x
	Detailed Description		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
Exterior Energy Use Equipment	Exterior Lights		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				
	Exterior Fuel Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Exterior Water Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Renewable Energy Systems	Photovoltaic Systems		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Wind Turbine		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Combined Heat and Power		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Geothermal Heat Pump		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				
Level of Accuracy			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	1	2	3	4

Table 41: Detailed Data Requirements of DPI COM01 (1/5)

DPI COM01: Local Thermal Comfort (1/5)																									
					DPI Evaluation Scenarios																				
Calculation Methodology					EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8	EP9	EP10	EP11	EP12	EP13	EP14	EP15	EP16	EP17	EP18	EP19	EP20	OT1
Data Type	BEPS - Data Req.																								
Radiant Temperature	Estimation	Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Building Geometry Description	CityGML LoD1		x	x	x	x																	
			CityGML LoD2						x	x	x	x													
			CityGML LoD3										x	x	x	x									
			CityGML LoD4														x	x	x	x					
			IFC4 (Design Transfer View)																		x	x	x	x	
		Building Materials	Equivalent single layer/ Opaque Construction	Total thermal resistance	x		x		x		x		x		x		x		x		x		x		
				Total thermal capacitance	x		x		x		x		x		x		x		x		x		x		
			Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x	
				Density		x		x		x		x		x		x		x		x		x		x	
				Specific Heat		x		x		x		x		x		x		x		x		x		x	
				Thermal Absorptance		x		x		x		x		x		x		x		x		x		x	
			Multi layer/Transparent Constr.	U-factor									x	x	x	x	x	x	x	x	x	x	x	x	
				SHGC									x	x	x	x	x	x	x	x	x	x	x	x	
			Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
			Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
		Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
				Cooing Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Systems' Templates																						
			Detailed Description																						
	Measurements																								x
Clothing Value	Seasonal				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Dynamic																								
Metabolic Rate	Constant				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Schedule																								
Air Velocity	Reference Data				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Measurements																								
Level of Accuracy					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Table 42: Detailed Data Requirements of DPI COM01 (2/5)

DPI COM01: Local Thermal Comfort (2/5)																									
					DPI Evaluation Scenarios																				
Calculation Methodology					EP21	EP22	EP23	EP24	EP25	EP26	EP27	EP28	EP29	EP30	EP31	EP32	EP33	EP34	EP35	EP36	EP37	EP38	EP39	EP40	OT2
Data Type	BEPS - Data Req.																								
Radiant Temperature	Estimation	Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Building Geometry Description	CityGML LoD1		x	x	x	x																	
			CityGML LoD2						x	x	x	x													
			CityGML LoD3										x	x	x	x									
			CityGML LoD4														x	x	x	x					
			IFC4 (Design Transfer View)																		x	x	x	x	
		Building Materials	Equivalent single layer/ Opaque Construction	Total thermal resistance	x		x		x		x		x		x		x		x		x		x		
				Total thermal capacitance	x		x		x		x		x		x		x		x		x		x		
			Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x	
				Density		x		x		x		x		x		x		x		x		x		x	
				Specific Heat		x		x		x		x		x		x		x		x		x		x	
				Thermal Absorptance		x		x		x		x		x		x		x		x		x		x	
			Multi layer/Transparent Constr.	U-factor									x	x	x	x	x	x	x	x	x	x	x	x	
				SHGC									x	x	x	x	x	x	x	x	x	x	x	x	
			Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
			Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
		Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
				Cooing Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Systems' Templates																						
			Detailed Description																						
	Measurements																								x
Clothing Value	Seasonal																								
	Dynamic				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Metabolic Rate	Constant				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Schedule																								
Air Velocity	Reference Data				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Measurements																								
Level of Accuracy					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Table 43: Detailed Data Requirements of DPI COM01 (3/5)

DPI COM01: Local Thermal Comfort (3/5)																									
Calculation Methodology					EP41	EP42	EP43	EP44	EP45	EP46	EP47	EP48	EP49	EP50	EP51	EP52	EP53	EP54	EP55	EP56	EP57	EP58	EP59	EP60	OT3
Data Type	**BEPS - Data Req.**																								
Radiant Temperature	Estimation	Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Building Geometry Description	CityGML LoD1		x	x	x	x																	
			CityGML LoD2						x	x	x	x													
			CityGML LoD3										x	x	x	x									
			CityGML LoD4														x	x	x	x					
			IFC4 (Design Transfer View)																		x	x	x	x	
		Building Materials	Equivalent single layer/ Opaque Construction	Total thermal resistance	x		x		x		x		x		x		x		x		x		x		
				Total thermal capacitance	x		x		x		x		x		x		x		x		x		x		
			Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x	
				Density		x		x		x		x		x		x		x		x		x		x	
				Specific Heat		x		x		x		x		x		x		x		x		x		x	
				Thermal Absorptance		x		x		x		x		x		x		x		x		x		x	
			Multi layer/Transparent Constr.	U-factor									x	x	x	x	x	x	x	x	x	x	x	x	
				SHGC									x	x	x	x	x	x	x	x	x	x	x	x	
			Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
			Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
		Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
				Cooing Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Systems' Templates																						
			Detailed Description																						
	Measurements																								x
Clothing Value	Seasonal				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Dynamic																								
Metabolic Rate	Constant																								
	Schedule				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Air Velocity	Reference Data				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Measurements																								
Level of Accuracy					**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**

Table 44: Detailed Data Requirements of DPI COM01 (4/5)

DPI COM01: Local Thermal Comfort (4/5)																									
					DPI Evaluation Scenarios																				
Calculation Methodology					EP61	EP62	EP63	EP64	EP65	EP66	EP67	EP68	EP69	EP70	EP71	EP72	EP73	EP74	EP75	EP76	EP77	EP78	EP79	EP80	OT4
Data Type	BEPS - Data Req.																								
Radiant Temperature	Estimation	Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Building Geometry Description	CityGML LoD1		x	x	x	x																	
			CityGML LoD2						x	x	x	x													
			CityGML LoD3										x	x	x	x									
			CityGML LoD4														x	x	x	x					
			IFC4 (Design Transfer View)																		x	x	x	x	
		Building Materials	Equivalent single layer/ Opaque Construction	Total thermal resistance	x		x		x		x		x		x		x		x		x		x		
				Total thermal capacitance	x		x		x		x		x		x		x		x		x		x		
			Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x	
				Density		x		x		x		x		x		x		x		x		x		x	
				Specific Heat		x		x		x		x		x		x		x		x		x		x	
				Thermal Absorptance		x		x		x		x		x		x		x		x		x		x	
			Multi layer/Transparent Constr.	U-factor									x	x	x	x	x	x	x	x	x	x	x	x	
				SHGC									x	x	x	x	x	x	x	x	x	x	x	x	
			Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
			Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
		Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
				Cooing Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Systems' Templates																						
			Detailed Description																						
	Measurements																								x
Clothing Value	Seasonal																								
	Dynamic				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Metabolic Rate	Constant																								
	Schedule				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Air Velocity	Reference Data				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Measurements																								
Level of Accuracy					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Table 45: Detailed Data Requirements of DPI COM01 (5/5)

DPI COM01: Local Thermal Comfort (5/5)					DPI Evaluation Scenarios																				
Calculation Methodology					EP81	EP82	EP83	EP84	EP85	EP86	EP87	EP88	EP89	EP90	EP91	EP92	EP93	EP94	EP95	EP96	EP97	EP98	EP99	EP100	OT5
Data Type	BEPS - Data Req.																								
Radiant Temperature	Estimation	Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Building Geometry Description	CityGML LoD1		x	x	x	x																	
			CityGML LoD2						x	x	x	x													
			CityGML LoD3										x	x	x	x									
			CityGML LoD4														x	x	x	x					
			IFC4 (Design Transfer View)																		x	x	x	x	
		Building Materials	Equivalent single layer/ Opaque Construction	Total thermal resistance	x		x		x		x		x		x		x		x		x		x		
				Total thermal capacitance	x		x		x		x		x		x		x		x		x		x		
			Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x	
				Density		x		x		x		x		x		x		x		x		x		x	
				Specific Heat		x		x		x		x		x		x		x		x		x		x	
				Thermal Absorptance		x		x		x		x		x		x		x		x		x		x	
			Multi layer/Transparent Constr.	U-factor									x	x	x	x	x	x	x	x	x	x	x	x	
				SHGC									x	x	x	x	x	x	x	x	x	x	x	x	
			Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
			Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
		Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
				Cooing Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Systems' Templates																						
			Detailed Description																						
	Measurements																								x
Clothing Value	Seasonal																								
	Dynamic				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Metabolic Rate	Constant																								
	Schedule				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Air Velocity	Reference Data																								
	Measurements				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Level of Accuracy					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Table 46: Detailed Data Requirements of DPI COM02

DPI COM02: Percentage Outside Range																									
					DPI Evaluation Scenarios																				
Calculation Methodology					EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8	EP9	EP10	EP11	EP12	EP13	EP14	EP15	EP16	EP17	EP18	EP19	EP20	OT1
Data Type	**BEPS - Data Req.**																								
Operative Temperature	Estimation	Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Building Geometry Description	CityGML LoD1		x	x	x	x																	
			CityGML LoD2						x	x	x	x													
			CityGML LoD3										x	x	x	x									
			CityGML LoD4														x	x	x	x					
			IFC4 (Design Transfer View)																		x	x	x	x	
		Building Materials	Equivalent single layer/ Opaque Construction	Total thermal resistance	x		x		x		x		x		x		x		x		x		x		
				Total thermal capacitance	x		x		x		x		x		x		x		x		x		x		
			Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x	
				Density		x		x		x		x		x		x		x		x		x		x	
				Specific Heat		x		x		x		x		x		x		x		x		x		x	
				Thermal Absorptance		x		x		x		x		x		x		x		x		x		x	
			Multi layer/Transparent Constr.	U-factor									x	x	x	x	x	x	x	x	x	x	x	x	
				SHGC									x	x	x	x	x	x	x	x	x	x	x	x	
			Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
			Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
		Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x			x	x			x	x	
		Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
				Cooing Setpoint Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
			Systems' Templates																						
			Detailed Description																						
	Measurements																								x
Acceptable Range					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Level of Accuracy					**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**

Table 47: Detailed Data Requirements of DPI COM04 (1/2)

DPI COM03: Indoor Air Quality (1/2)																						
			DPI Evaluation Scenarios																			
Calculation Methodology			EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8	EP9	EP10	EP11	EP12	EP13	EP14	EP15	EP16	EP17	EP18	EP19	EP20
Data Type	**BEPS - Data Req.**																					
Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Building Geometry Description	CityGML LoD1		x	x	x	x																
	CityGML LoD2						x	x	x	x												
	CityGML LoD3										x	x	x	x								
	CityGML LoD4														x	x	x	x				
	IFC4 (Design Transfer View)																		x	x	x	x
Building Materials	Equivalent single layer/ Opaque	Total thermal resistance	x		x		x		x		x		x		x		x		x		x	
		Total thermal capacitance	x		x		x		x		x		x		x		x		x		x	
	Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x
		Density		x		x		x		x		x		x		x		x		x		x
		Specific Heat		x		x		x		x		x		x		x		x		x		x
		Thermal Absorptance		x		x		x		x		x		x		x		x		x		x
	Multilayer / Transparent Constr.	U-factor									x	x	x	x	x	x	x	x	x	x	x	x
		SHGC									x	x	x	x	x	x	x	x	x	x	x	x
	Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x		
	Measurements				x	x			x	x			x	x			x	x			x	x
Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x		
	Measurements				x	x			x	x			x	x			x	x			x	x
Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature																				
		Cooing Setpoint Temperature																				
	Systems' Templates		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Detailed Description																					
Exterior Energy Use Equipment	Exterior Lights		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Exterior Fuel Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Exterior Water Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Renewable Energy Systems	Photovoltaic Systems		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Wind Turbine		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Combined Heat and Power		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Geothermal Heat Pump		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Level of Accuracy			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

Table 48: Detailed Data Requirements of DPI COM04 (2/2)

DPI COM03: Indoor Air Quality (2/2)																						
			DPI Evaluation Scenarios																			
Calculation Methodology			EP21	EP22	EP23	EP24	EP25	EP26	EP27	EP28	EP29	EP30	EP31	EP32	EP33	EP34	EP35	EP36	EP37	EP38	EP39	EP40
Data Type	**BEPS - Data Req.**																					
Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Building Geometry Description	CityGML LoD1		x	x	x	x																
	CityGML LoD2						x	x	x	x												
	CityGML LoD3										x	x	x	x								
	CityGML LoD4														x	x	x	x				
	IFC4 (Design Transfer View)																		x	x	x	x
Building Materials	Equivalent single layer/ Opaque	Total thermal resistance	x		x		x		x		x		x		x		x		x		x	
		Total thermal capacitance	x		x		x		x		x		x		x		x		x		x	
	Multi layer/Opaque Construction	Thermal conductivity		x		x		x		x		x		x		x		x		x		x
		Density		x		x		x		x		x		x		x		x		x		x
		Specific Heat		x		x		x		x		x		x		x		x		x		x
		Thermal Absorptance		x		x		x		x		x		x		x		x		x		x
	Multi layer/ Transparent Constr.	U-factor									x	x	x	x	x	x	x	x	x	x	x	x
		SHGC									x	x	x	x	x	x	x	x	x	x	x	x
	Green Roof Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Phase Change Materials		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Schedules	Reference Data		x	x			x	x			x	x			x	x			x	x		
	Measurements				x	x			x	x			x	x			x	x			x	x
Internal Gains	Reference Data		x	x			x	x			x	x			x	x			x	x		
	Measurements				x	x			x	x			x	x			x	x			x	x
Energy Sytems	Ideal Load Sytem	Heating Setpoint Temperature																				
		Cooing Setpoint Temperature																				
	Systems' Templates																					
	Detailed Description		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Exterior Energy Use Equipment	Exterior Lights		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Exterior Fuel Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Exterior Water Equipment		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Renewable Energy Systems	Photovoltaic Systems		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Wind Turbine		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Combined Heat and Power		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Geothermal Heat Pump		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Level of Accuracy			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

Table 49: Detailed Data Requirements of DPI COM05

DPI COM04: Visual Comfort																	
					DPI Evaluation Scenarios												
Calculation Methodology					EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8	EP9	EP10	EP11	EP12	OT1
Data Type	**BEPS - Data Req.**																
Operative Temperature	Estimation	Simulation Parameters	Initial Parameters		x	x	x	x	x	x	x	x	x	x	x	x	
			Selected Algorithms		x	x	x	x	x	x	x	x	x	x	x	x	
		Building Geometry Description	CityGML LoD3		x	x	x	x									
			CityGML LoD4						x	x	x	x					
			IFC4 (Design Transfer View)										x	x	x	x	
		Building Constructions	Opaque Construction	Visible absorptance	x	x	x	x	x	x	x	x	x	x	x	x	
			Transparent Construction	Visible transmittance	x	x	x	x	x	x	x	x	x	x	x	x	
				Front side visible reflectance	x	x	x	x	x	x	x	x	x	x	x	x	
				Back side visible reflectance	x	x	x	x	x	x	x	x	x	x	x	x	
		Weather Data	Hourly		x	x	x	x	x	x	x	x	x	x	x	x	
		Schedules of lighting devices	Reference Data		x	x			x	x			x	x			
			Measurements				x	x			x	x			x	x	
	Measurements																x
Level of Accuracy					1	2	3	4	5	6	7	8	9	10	11	12	13

Annex II: Process Diagrams

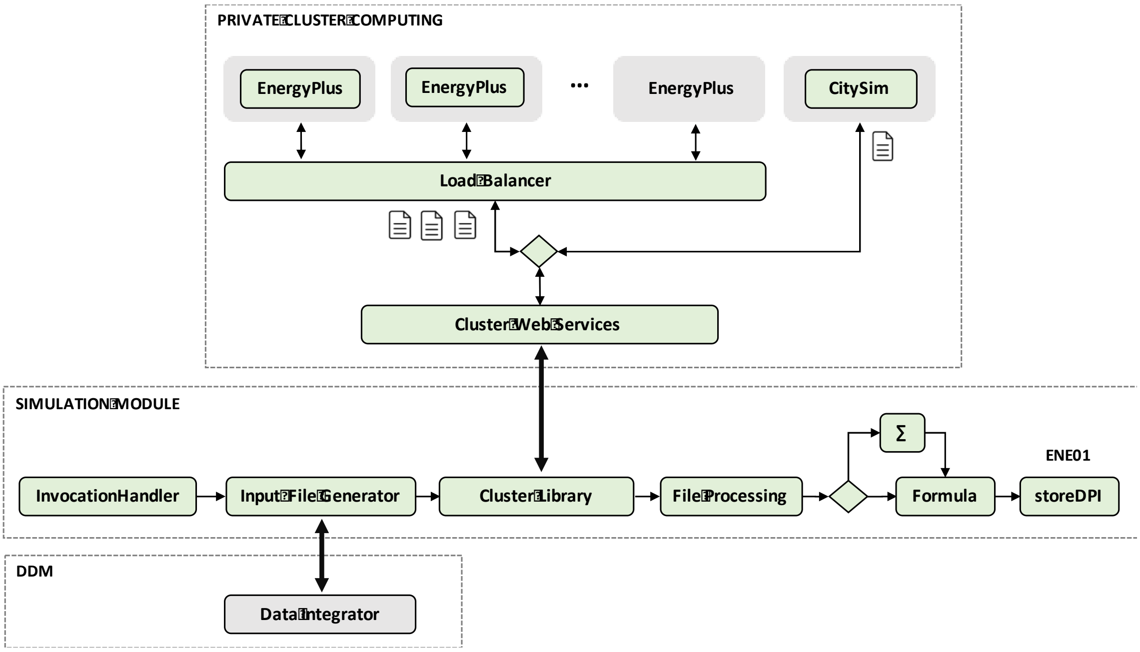

Figure 51: Process diagram of ENE01, ENE02

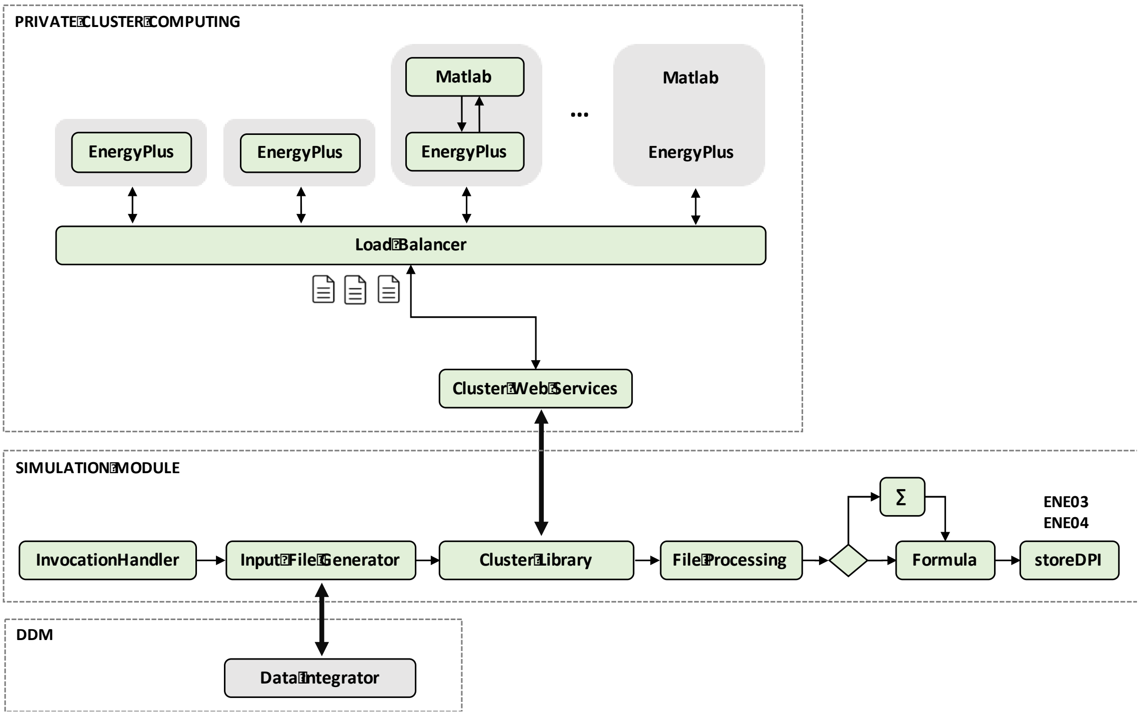

Figure 52: Process diagram of ENE03, ENE04

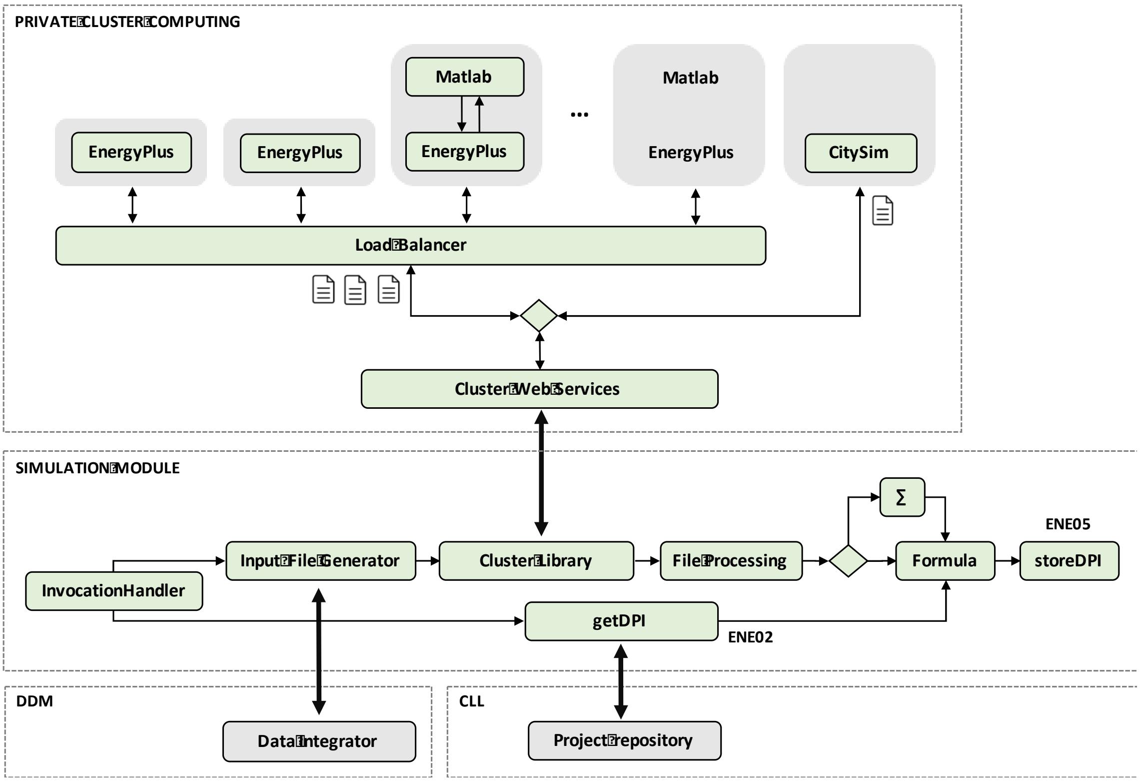

Figure 53: Process diagram of ENE05

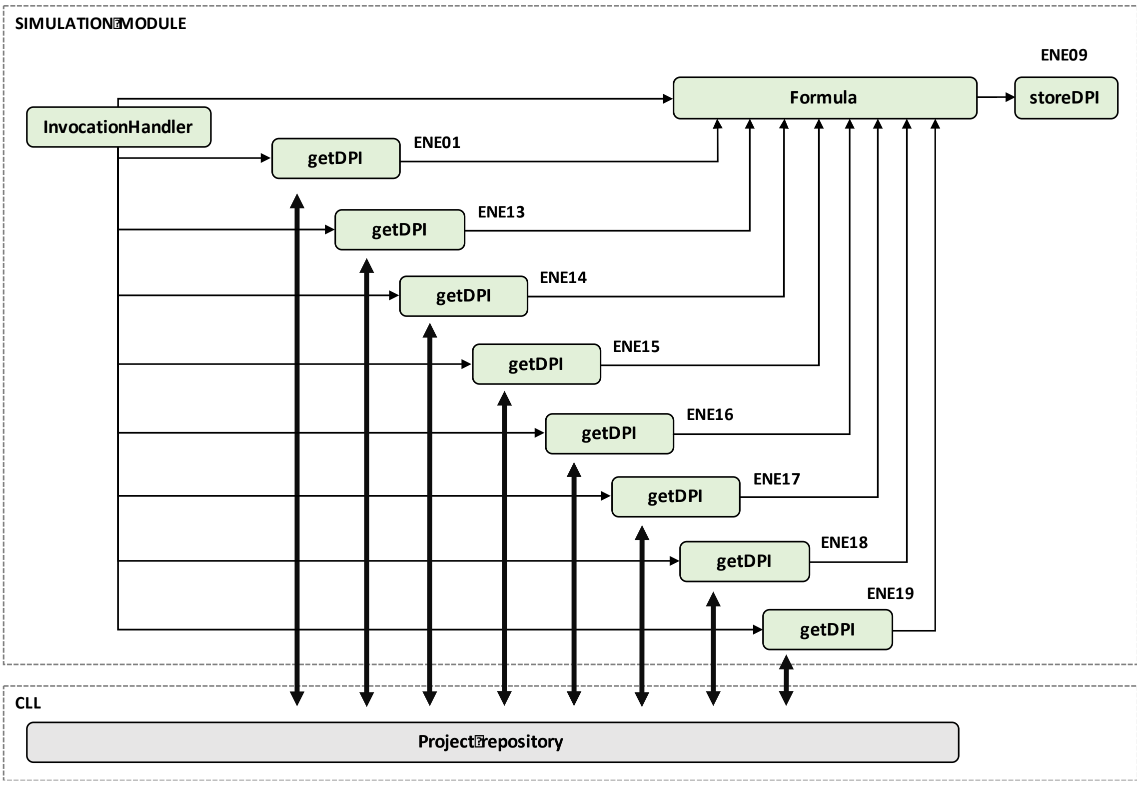

Figure 54: Process diagram of ENE09

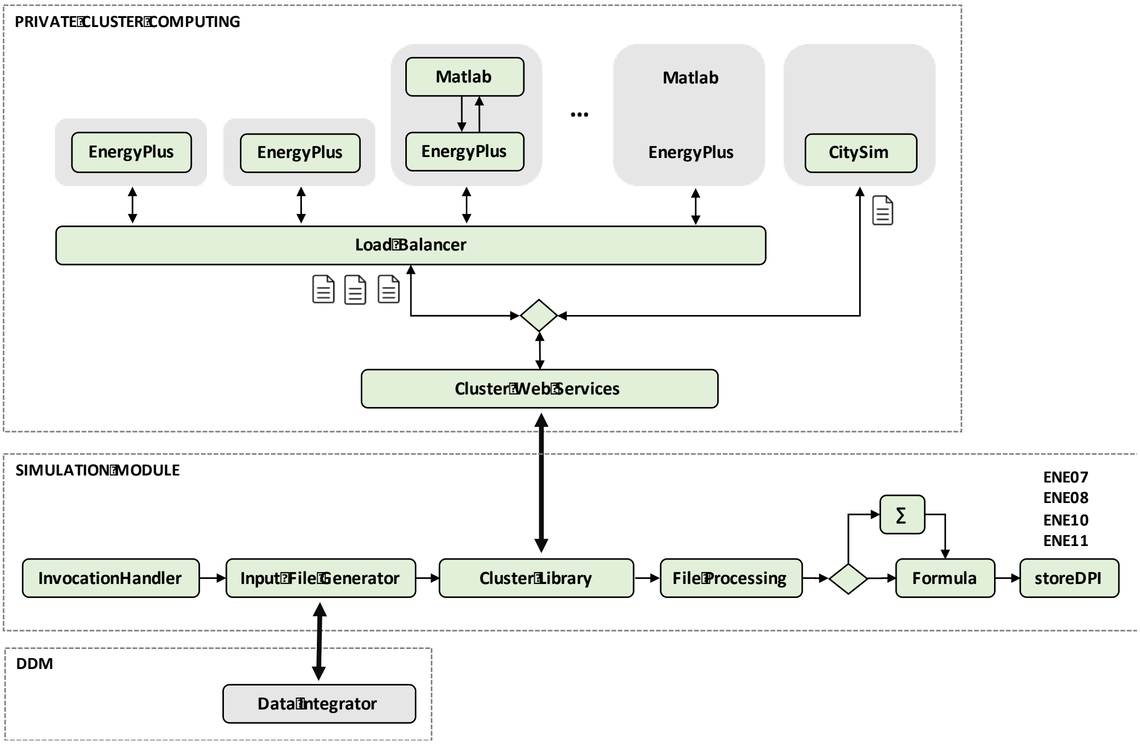

Figure 55: Process diagram of ENE07, ENE08, ENE10 and ENE11

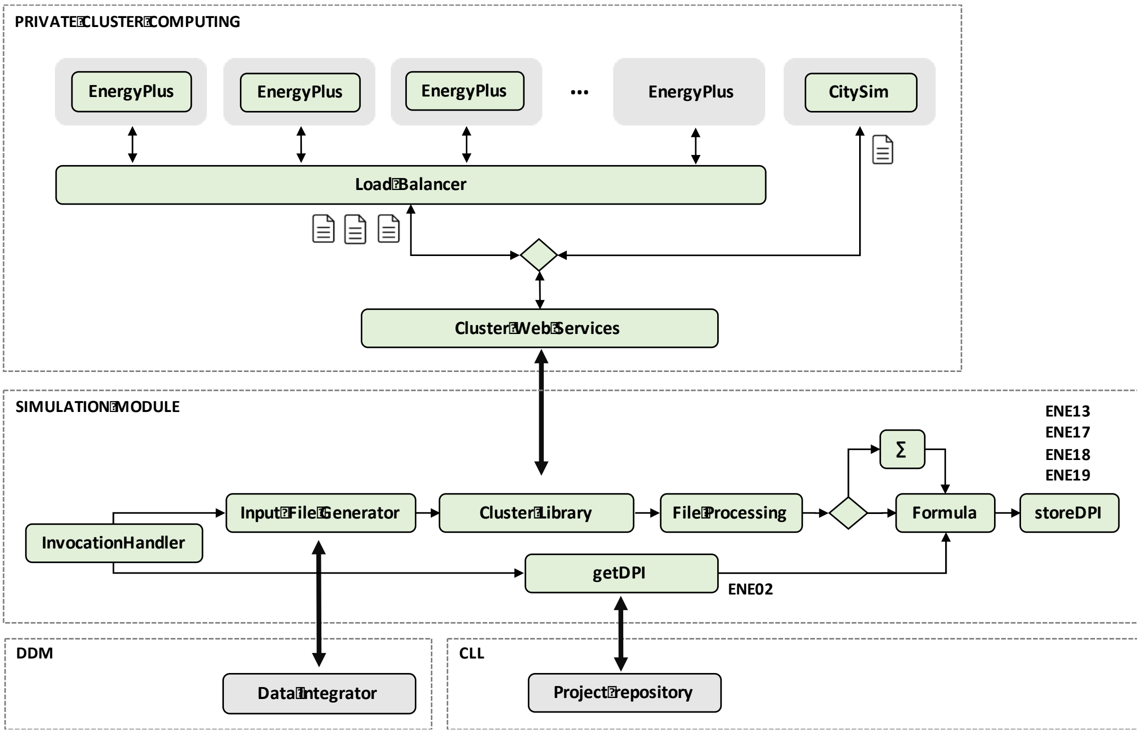

Figure 56: Process diagram of ENE13, ENE17, ENE18 and ENE19

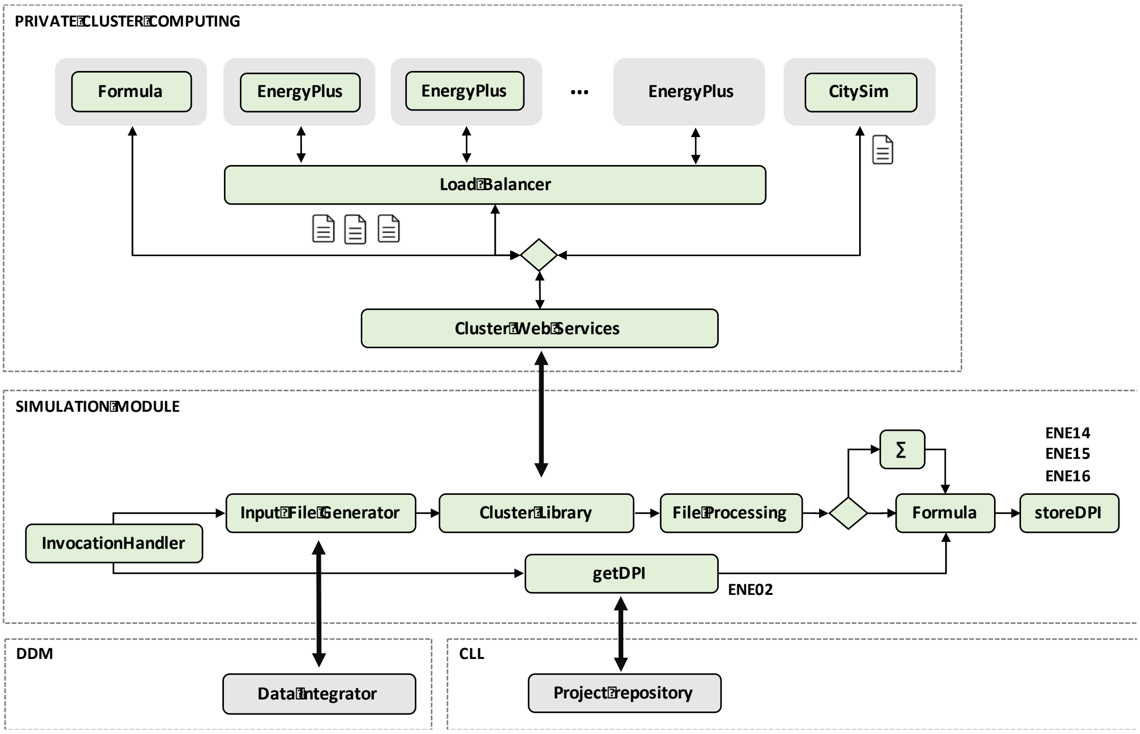

Figure 57: Process diagram of ENE14, ENE15 and ENE16

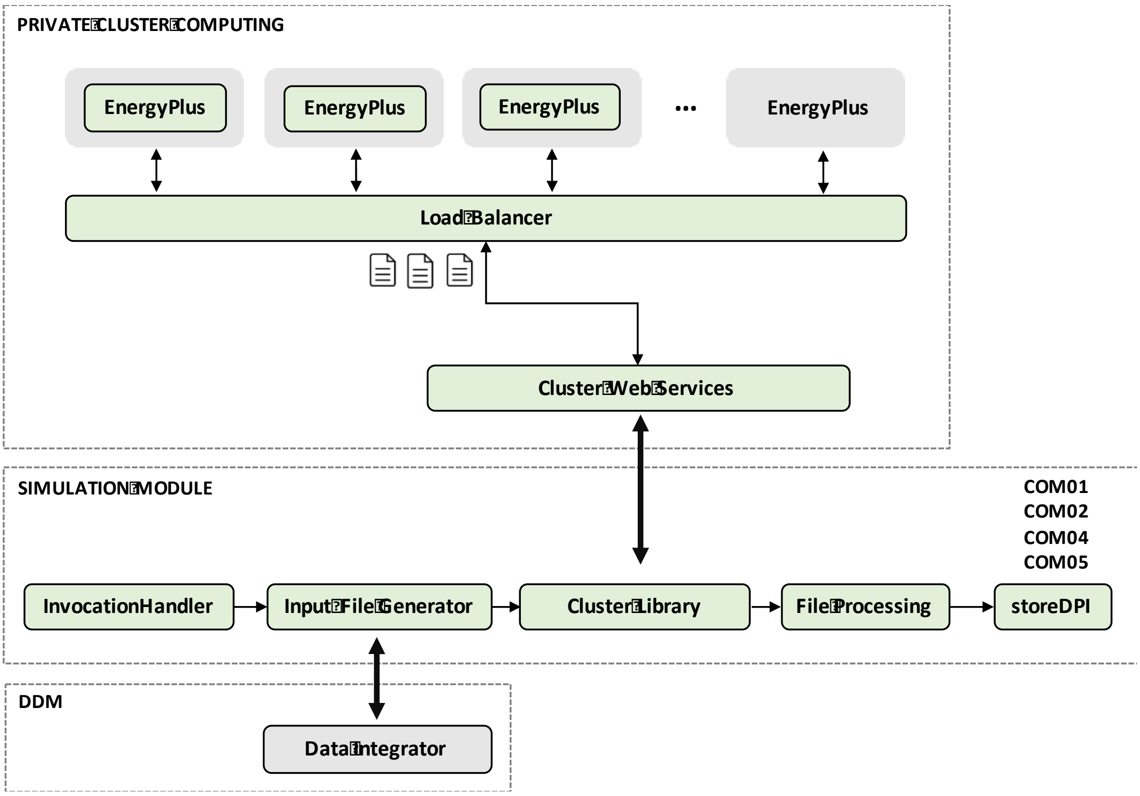

Figure 58: Process diagram of COM01, COM02, COM04 and COM05

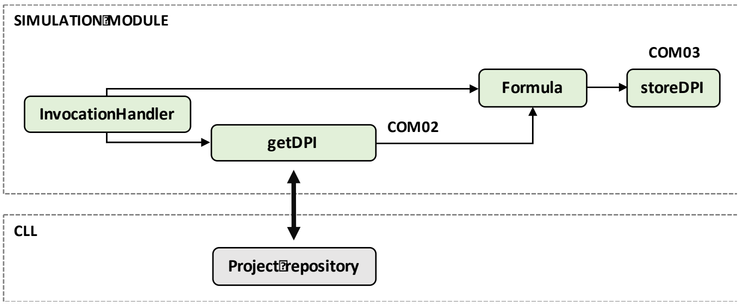

Figure 59: Process diagram of COM03

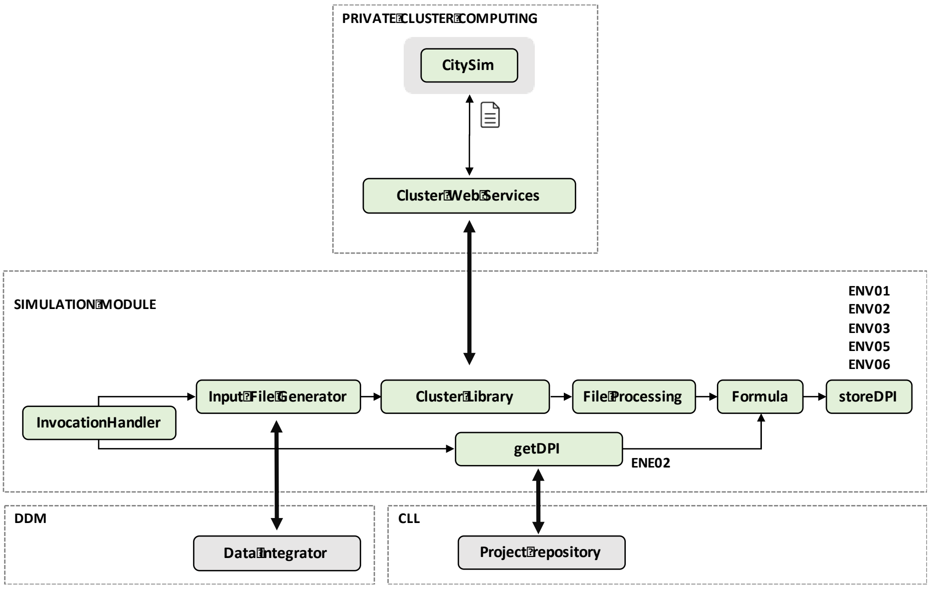

Figure 60: Process diagram of ENV01, ENV02, ENV03,ENV05 AND ENV06

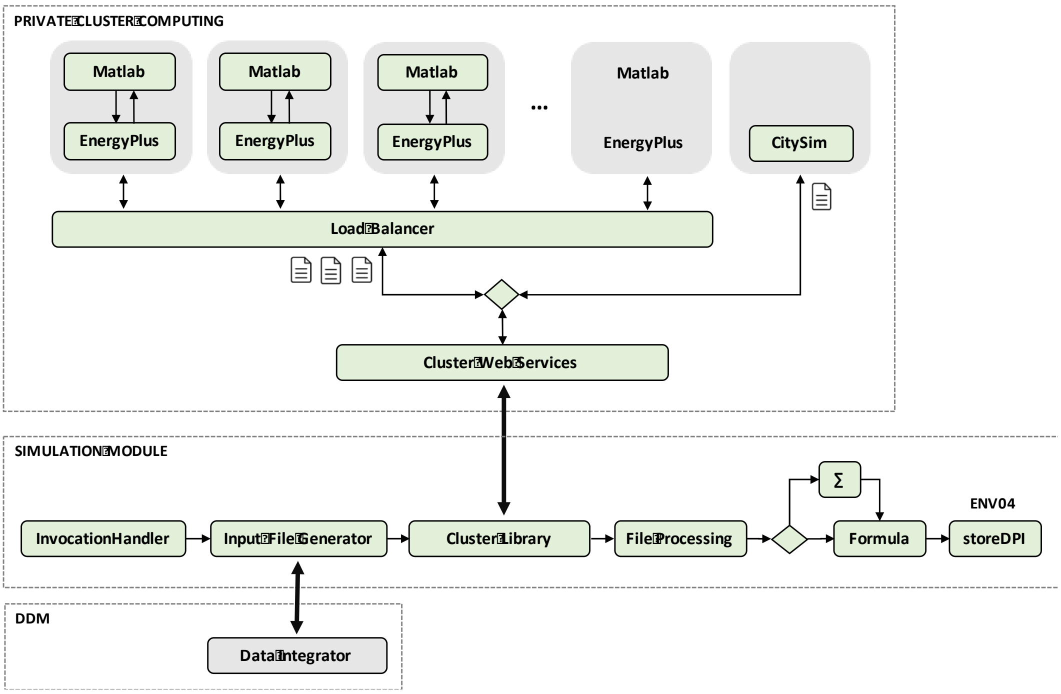

Figure 61: Process diagram of ENV04

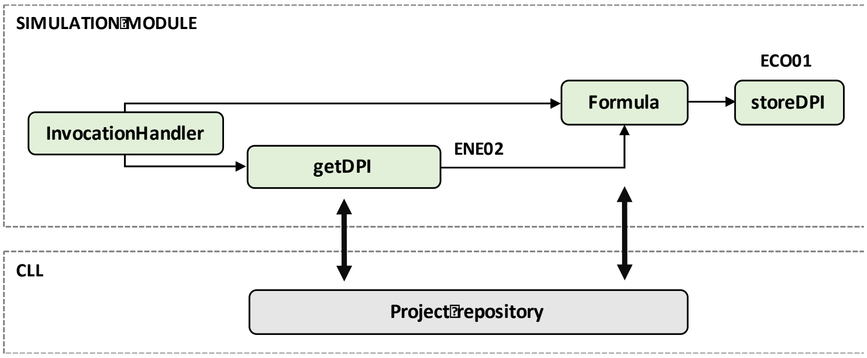

Figure 62: Process diagram of ECO01

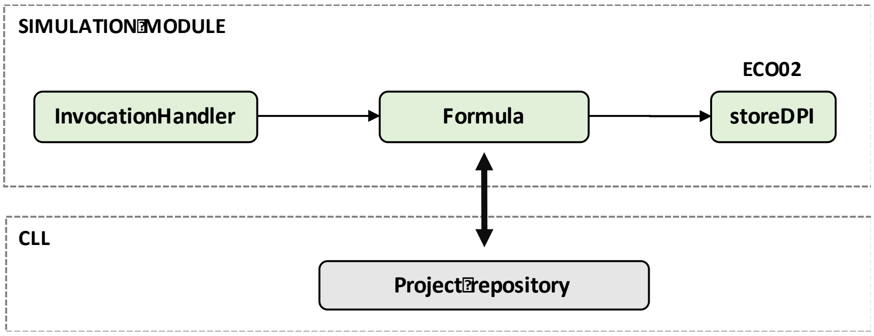

Figure 63: Process diagram of ECO02

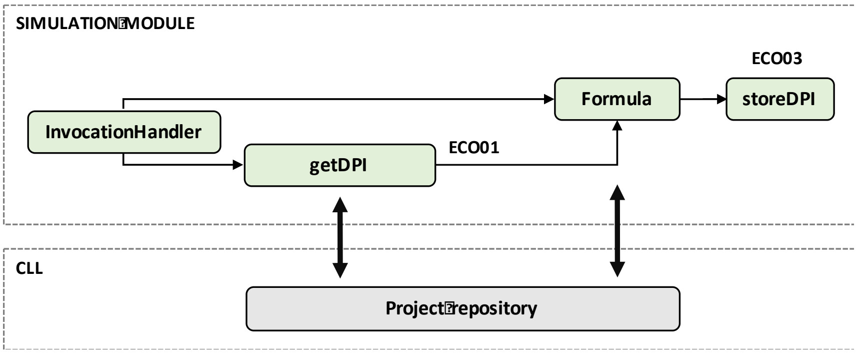

Figure 64: Process diagram of ECO03

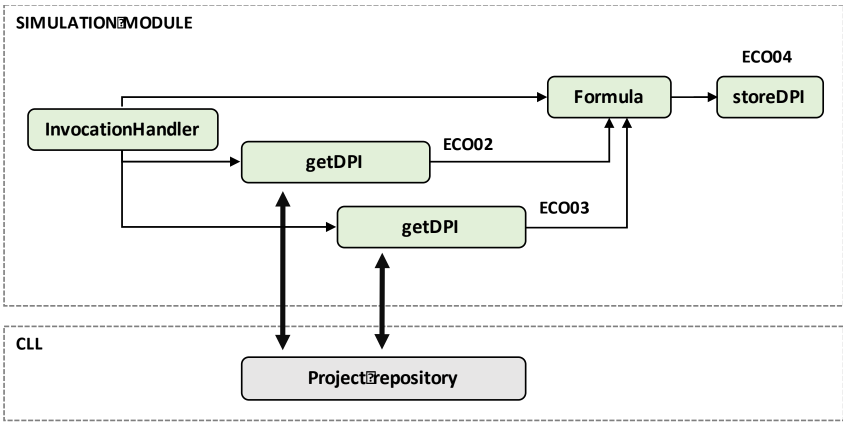

Figure 65: Process diagram of ECO04

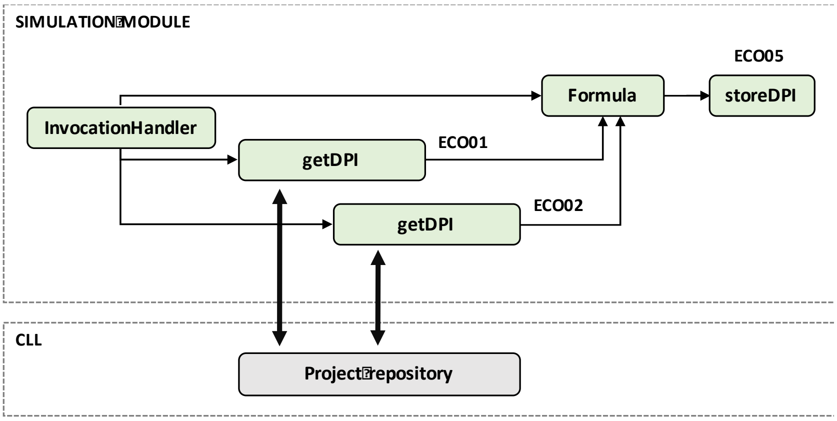

Figure 66: Process diagram of ECO05

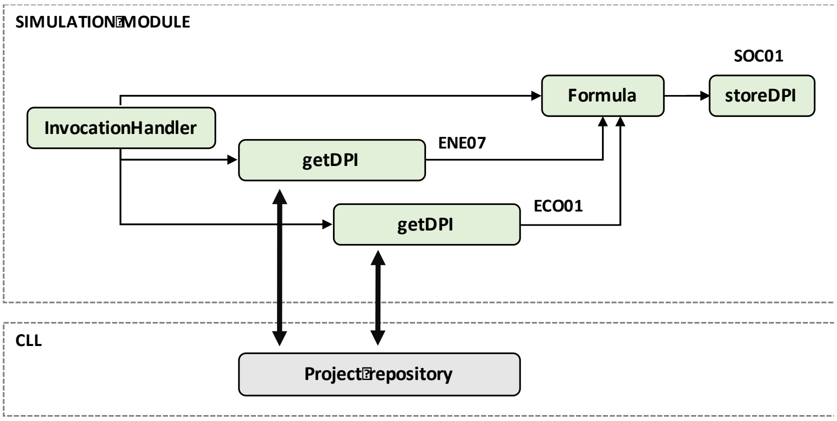

Figure 67: Process diagram of SOC01

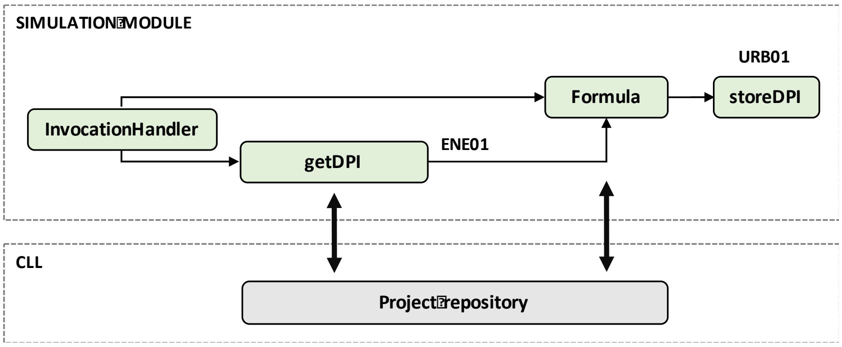

Figure 68: Process diagram of URB01

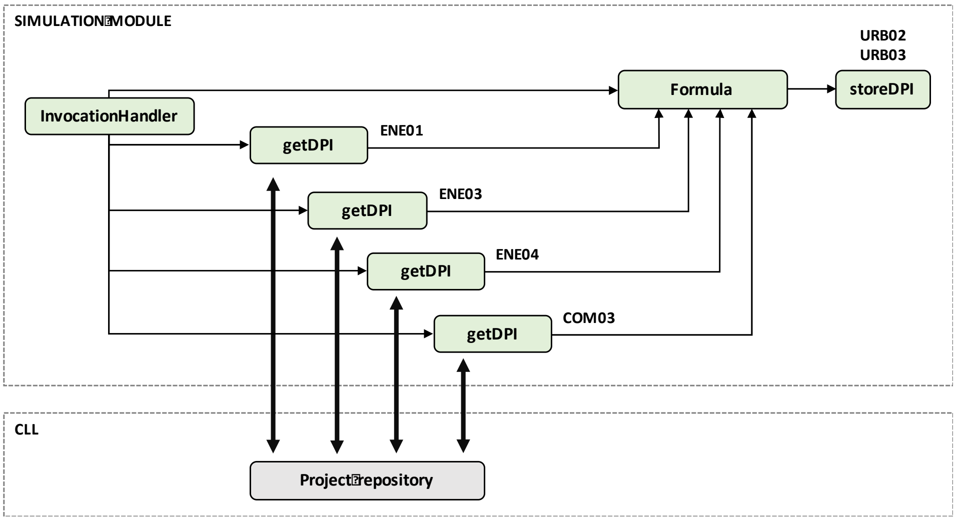

Figure 69: Process diagram of URB02 and URB03

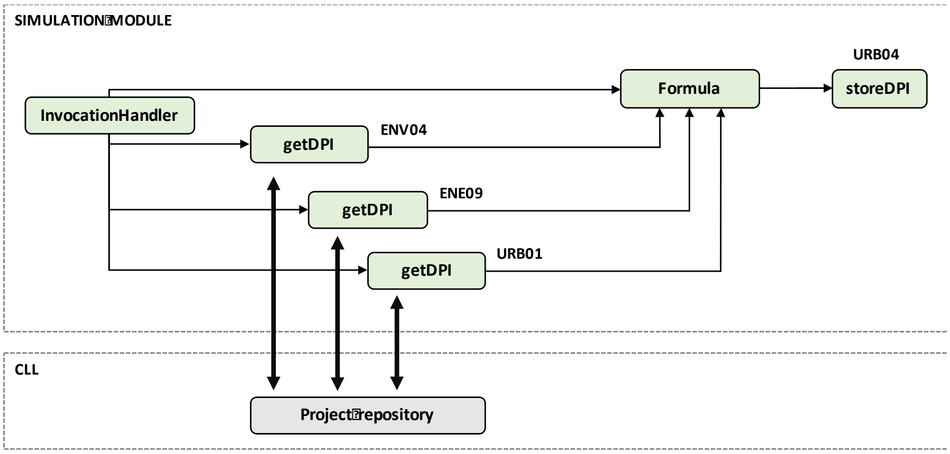

Figure 70: Process diagram of URB04

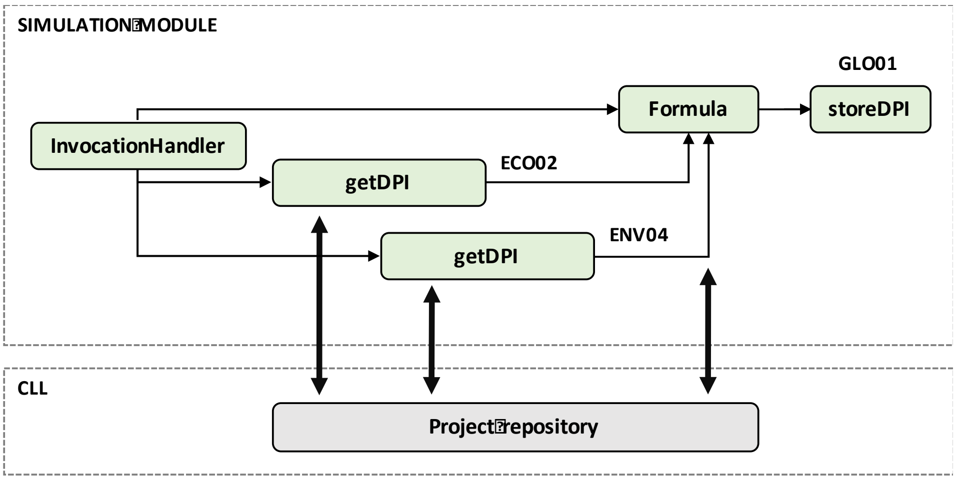

Figure 71: Process diagram of GLO01

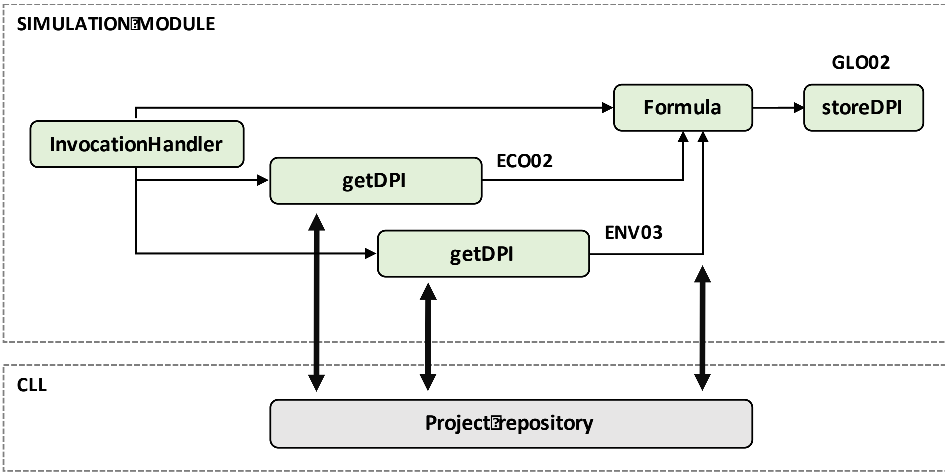

Figure 72: Process diagram of GLO02