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in geodezijo

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BIM AS MULTISCALE FACILITATOR FOR BUILT ENVIRONMENT ANALYSIS

BIM KOT POSPOŠEVALEC ANALIZ GRAJENEGA OKOLJA NA VEČ MERILIH

BIM A+ European Master in Building Information Modelling

Master thesis No.:

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Izvleček:

Ta raziskava obravnava uporabo informacijskega modeliranja zgradb (BIM) kot pospeševalnika za analize grajenega okolja na več merilih in raziskuje uporabo digitalnih podatkov za lažje razumevanje odnosa med zgradbami in mesti.

Običajno se geografsko, urbano, arhitekturno, inženirsko ter gradbeno področje (AEC) štejejo za različne domene. Vendar, v zadnjem času se njihove strokovne meje brišejo zaradi prekrivanja ciljev in uporabe orodij. Danes je izmenjava informacij med strokami, ki delujejo na različnih prostorskih merilih, še vedno glavni problem sodelovanja in izmenjave znanja. Potrebne so novi načini sodelovanja, interoperabilnost in integracija podatkov.

Cilj te raziskave je oceniti zmogljivosti BIM za lažjo izmenjave podatkov med deležniki, ki obravnavajo projekte na različnih merilih. Poudarek je na prenosu informacij z uporabo odprtih standardov v okviru analize grajenega okolja. Naloga nudi pregled trenutnih orodij, metodologij in delotokov, ki podpirajo večrazsežno okoljsko presojo, hkrati pa izpostavlja ovire na tej poti. Glavni cilj študije je predlagati delotoke, ki podpirajo integracijo podatkov in analiz na različnih merilih, da bi premagali oviro interopreabilnosti podatkov med različnimi strokami in orodji. Ta raziskava je razdeljena na štiri dele: povzetek trajnostnih politik v Evropi, pregled večrazsežne analize porabe energije, ki ji sledi odsek o delotokih in interoperabilnosti podatkov. Študija se zaključi s prikazom študije primera, pridobljenimi izkušnjami in predlogi za razvoj v prihodnosti.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

This research explores the use of Building Information Modelling (BIM) as multiscale facilitator for built environment assessment, exploring the use of digital data to facilitate an understanding of the relation between buildings and cities.

Conventionally, the geographical, urban and Architectural, Engineering and Construction (AEC) fields are considered different domains. However, their disciplinary boundaries are recently being blurred by overlapping objectives and tools. Nowadays, the exchange of information among disciplines working at different spatial scales is still a major problem to collaboration and knowledge sharing. There is a need for shared collaborative practices, interoperability and data integration.

The goal of this research is to assess BIM capabilities to facilitate data sharing among stakeholders dealing with different scales. Emphasis is placed on the transmission of information using open standards in the context of built environment analysis. It provides an overview of current tools, methodologies and workflows that support multiscale environmental assessment, while highlighting obstacles along the path. The study aims to propose workflows that support data integration among different scales, to overcome the barrier of data interoperability between different discipline domains. The work is organized into four main chapter: a summary of sustainable policies in Europe, an overview of multiscale analysis for energy consumption, followed by a section on workflows and data interoperability. The study concludes with the demonstration of a case study, lesson learned and suggestions for future works.

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1 INTRODUCTION

This research explores the use of Building Information Modelling (BIM) as multiscale facilitator for built environment analysis, in the context of the Energy Performance in Buildings Directive (EU EPBD). The study explores the exploitation of digital data to facilitate an understanding of the relation between buildings and cities, opening several possibilities of analysis at different spatial scales. The work aims to explore BIM potential to facilitate different stages of the design process, highlighting the opportunities offered to develop an integrated process.

1.1 The problem

Nowadays, the geographical, urban and Architectural, Engineering and Construction (AEC) fields are considered different domains. However, the boundaries of these disciplines are being blurred by overlapping interests, purposes and tools, for which are needed collaborative practices and improved software interoperability.

When talking about the digital built environment, Semantic Modelling allows the representation of objects with their properties, structures and relationships along with their 3D visualisation. This semantic information can be useful only if distinct stakeholders share the same understanding of it. International organizations and standardization bodies dealing with the built environment are working on this matter, trying to harmonize content and structure for an integrated digital built environment.

Nevertheless, at present the exchange of information between disciplines working at different spatial scales is still a matter of intense research. As a matter of fact, even though there are several open standards with certain similarities, there are still many obstacles to data integration for seamless multiscale information sharing.

1.2 Goals and objective

The main research goal is to assess BIM capabilities to facilitate data sharing among stakeholders, that are dealing with different spatial scales. Emphasis is placed on the transmission of information using open standards, which are not tied to specific software vendors or applications, in the context of built environment analysis. Another purpose of the work is to provide an overview of current tools, methodologies and workflows that support multiscale environmental assessment. In this perspective, the modelling of a semantically rich city model provides the means to test the assumption. A further objective of the work is to highlight criticalities and obstacles along the path, emphasizing areas that need attention and therefore setting the ground for further research that would contribute to this area of study. Finally, the study aims to propose workflows that support data integration among different scales, to overcome the barrier of data interoperability between different discipline domains.

1.3 Methodology and structure

The methodology adopted to address the topic of research includes both a literature review and a practical application on a case study, referring to examples and similar works, cited from time to time. The literature review comprises books, scientific publications, conference proceedings, industry reports and standards. The case study is identified in collaboration with the Slovenian architecture firm Enota, with which the author collaborated during the drafting of this document.

The work is composed of four main sections, each investigating a relevant subject for the understanding of BIM as multiscale facilitator for the analysis of the built environment. These are:

1. *Summary of sustainable policies in Europe*, which illustrates European sustainable strategies, as the “Clean Energy for All Europeans Package” [1], the “Energy Performance of Building Directive” [2] and the “Energy Efficiency Directive”[3].
2. *Overview of multiscale analysis for energy consumption*, that outlines methodologies and applications to assess built environment performances at different scales. It explores various approaches to Green Building and Neighbourhoods, looking into certification processes and analysis tools.
3. *Workflows and data interoperability*, focusing on procedures and data schemas to share information for multiscale analysis, with emphasis on energy performances. BIM data are analysed and discussed, along with City Information Modelling (CIM) and Geographic Information System (GIS) data structures and format.
4. *Presentation of a case study*, with a practical use. The case study examines the renovation and extension of an historical hotel in Ljubljana, proposing a top-down and a bottom-up approaches to multiscale data integration between BIM and semantically rich 3D city models.

2 SUSTAINABLE POLICIES IN EUROPE

2.1 The Clean Energy for all Europeans Package [1]

In 2019, the European Union published a thorough update of its energy policy agenda[1] to accelerate the shift toward cleaner energy. The deal on this energy program named the "Clean Energy for all Europeans Package" was a key achievement in the direction of the union's energy strategy announced in 2015. After the political endorsement by the Council and the European Parliament, following the commencement of the EU regulations, the EU member states have between one and two years to rearrange the new instructions as national law.

The new rules will bring significant benefits from a consumer, environmental and economic perspective. By managing these changes at EU level, the legislation emphasizes EU leadership in the fight against global warming and contribute to the EU's long-term strategy to achieve carbon neutrality by 2050.

2.2 EPBD: Energy Performance of Buildings Directive EU 2018/844 [2]

The building stock is accountable for 36% of CO_2 emissions and 40% of total energy consumption[2], the major energy consumer in Europe. The EU could achieve its energy objectives if succeed to improve its buildings' energy performance. The Energy Performance of Buildings Directive, also known as EPBD, defines measures for the building sector to meet the challenges. The European Union has created a legal agenda consisting of the EPBD and the Energy Efficiency Directive (2012/27/EU). Both were modified in 2019 by the "Clean Energy for all Europeans Package". The EPBD delivers a powerful signal about the EU's dedication to renovate the building sector and improve building renovation initiatives.

The EPBD covers a broad variety of strategies to assist governments in enhancing energy efficiency of buildings. EU countries need renovation strategies to decarbonise the buildings by 2050, to promote the success of national energy and climate plans. All newly constructed buildings have to be Nearly Zero-Energy (NZEB) by 31 December 2020 [2]. Intelligent technologies will be promoted, and the well-being of users will be addressed. In addition, EU countries must carry out energy-efficient retrofit on 3% of the area of governmental buildings.

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1 "Clean energy for all Europeans package". https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en. Accessed 28 Apr. 2020.

2 "Energy performance of buildings directive". https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en. Accessed 28 Apr. 2020.

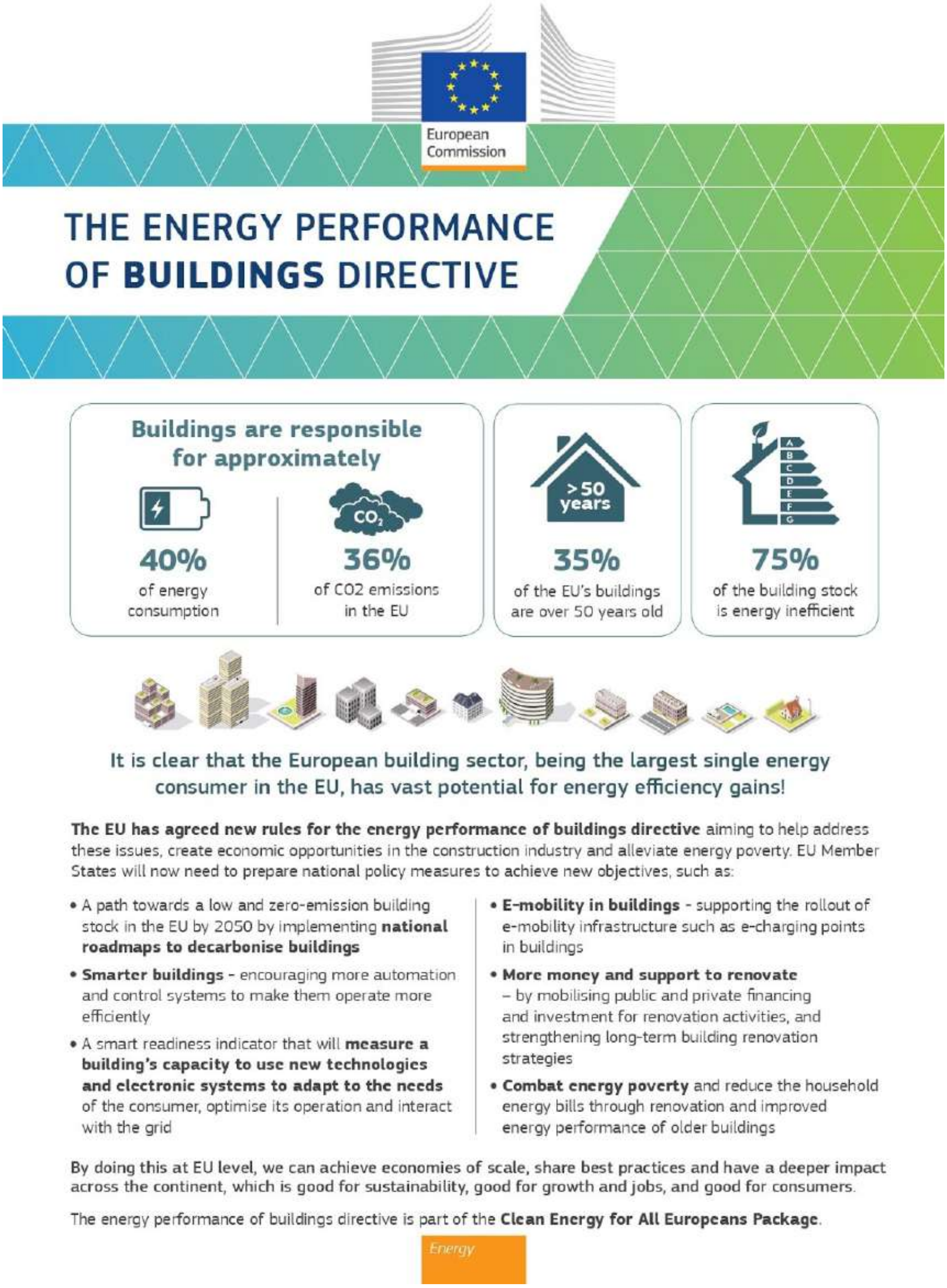


Figure 1: Factsheet. Energy Performance in Buildings Directive[3]

[3] "FactSheet. EPBD". https://ec.europa.eu/energy/sites/ener/files/documents/buildings_performance_factsheet.pdf. Accessed 28 Apr. 2020

2.3 Energy Efficiency Directive 2018/2002/EU [3]

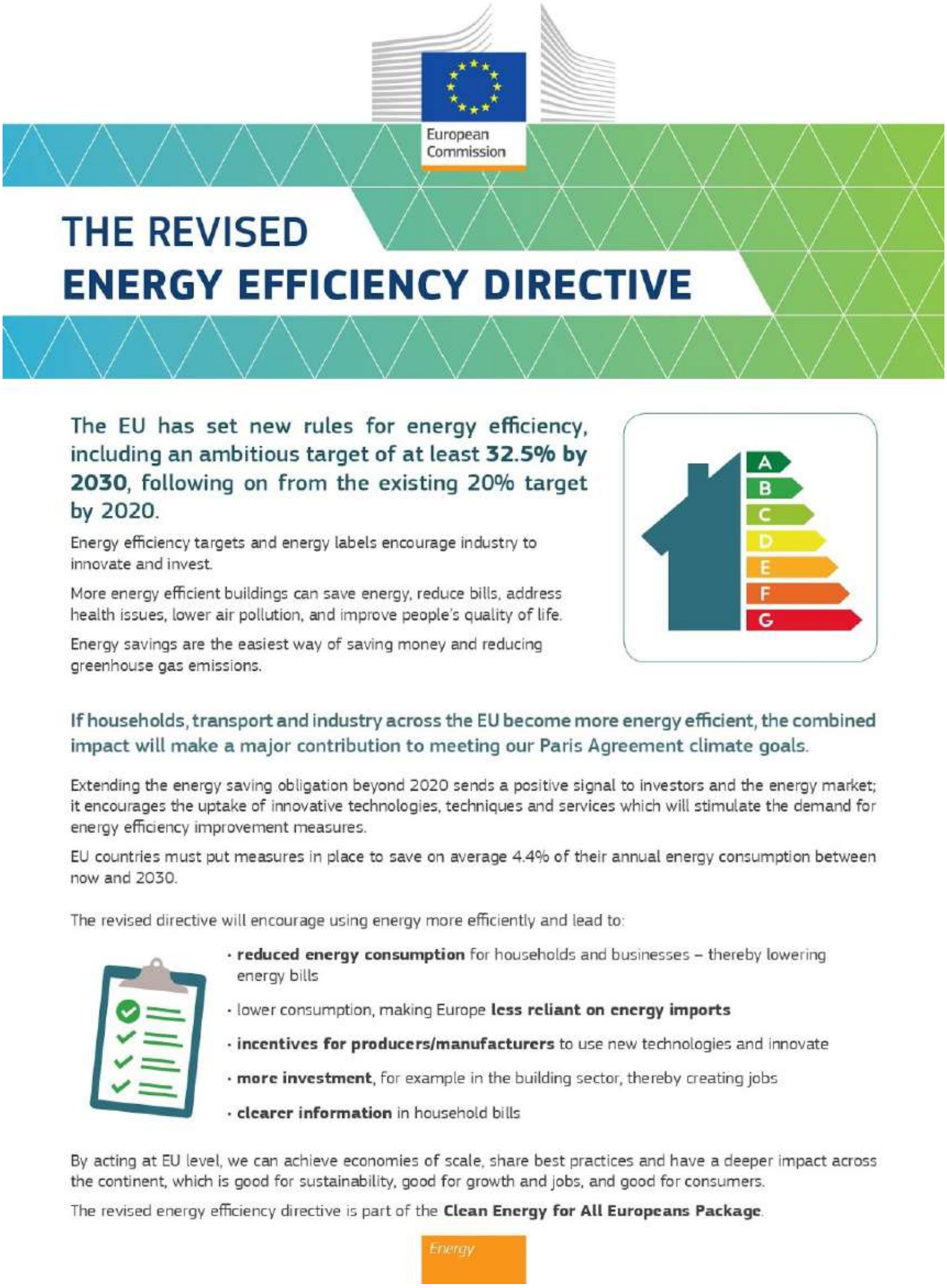
The Energy Efficiency Directive (2012/27/EU) sets out a series of mandatory measures to meet 20% energy efficiency goal by 2020[4]. It requires all member states to improve efficiency in their use of energy, accounting for all stages of its chain.

Several important measures have been adopted all across Europe to improve energy efficiency, accounting for technological innovations and particular requirements of each national market. These include a 1.5% annual cut in energy sales; long-term renovation strategies; and compulsory energy performance certificates for buildings. In addition, national energy efficiency action plans need to be discussed each three years and minimum energy efficiency standards and labelling of products need to be set. Moreover, consumers shall have free access to their data on energy consumption. The Commission has also issued best practices on efficient energy use.

The central aspect of the directive is a 32.5% energy efficiency target by 2030 [3], that was set relative to model estimates for 2030. The Directive allows for a possible revision of the goal in 2023 if economic or technological developments lead to significant cost reductions. It also includes requirements to save energy for the end-users, already established in 2012. EU countries are required to reach 0.8% final energy savings each year between 2021 and 2030.

The Directive is active from December 2018 and all member states shall update national law accordingly by 25 June 2020, and are expected to establish national energy policies with a ten-year duration, setting out how methodologies to achieve energy efficiency for 2030.

[4] "Energy Efficiency Directive". https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/energy-efficiency-directive_en. Accessed 28 Apr. 2020



European Commission

THE REVISED
ENERGY EFFICIENCY DIRECTIVE

The EU has set new rules for energy efficiency, including an ambitious target of at least 32.5% by 2030, following on from the existing 20% target by 2020.

Energy efficiency targets and energy labels encourage industry to innovate and invest.

More energy efficient buildings can save energy, reduce bills, address health issues, lower air pollution, and improve people's quality of life.

Energy savings are the easiest way of saving money and reducing greenhouse gas emissions.

A B C D E F G

If households, transport and industry across the EU become more energy efficient, the combined impact will make a major contribution to meeting our Paris Agreement climate goals.

Extending the energy saving obligation beyond 2020 sends a positive signal to investors and the energy market; it encourages the uptake of innovative technologies, techniques and services which will stimulate the demand for energy efficiency improvement measures.

EU countries must put measures in place to save on average 4.4% of their annual energy consumption between now and 2030.

The revised directive will encourage using energy more efficiently and lead to:

- **reduced energy consumption** for households and businesses – thereby lowering energy bills
- lower consumption, making Europe **less reliant on energy imports**
- **incentives for producers/manufacturers** to use new technologies and innovate
- **more investment**, for example in the building sector, thereby creating jobs
- **clearer information** in household bills

By acting at EU level, we can achieve economies of scale, share best practices and have a deeper impact across the continent, which is good for sustainability, good for growth and jobs, and good for consumers.

The revised energy efficiency directive is part of the **Clean Energy for All Europeans Package**.

Energy

Figure 2: Factsheet. Energy Efficiency Directive[5]

[5] "FactSheet. Energy Efficiency Directive". https://ec.europa.eu/energy/sites/ener/files/documents/energy_efficiency_factsheet.pdf. Accessed 28 Apr. 2020

3 MULTISCALE ANALYSIS OF ENERGY CONSUMPTION IN BUILT ENVIRONMENT

3.1 Building Performance analysis

3.1.1 LEED core concepts

The U.S. Green Building Council[6], also known as USGBC, is a non-profit organisation promoting a sustainable attitude to the built environment, through cost efficiency and energy-saving buildings. Its mission is the market transformation through its LEED Green Building Rating System™, educational offering, the Greenbuild international conference and support to public policy that enables green buildings and communities.

LEED is the acronym for Leadership in Energy and Environmental Design[7] and is a voluntary evaluation system which assesses and certifies projects based on their performance. Created by USGBC in the 1990s, LEED is developed through a consensus process, and it is continuously improved through the ad clarification of credit language. It is currently at version 4 (also LEED v4), in an ongoing process that will continue to evolve to respond to current and future market conditions. LEED is a measurement system conceived to evaluate existing and new buildings. It is based on recognized energy and environmental principles with a balance between established practices and rising concepts, that provides an assessment of environmental performance considering the entire building and its entire life cycle. LEED addresses all building types including retail, schools, university, campuses, health care, hospitality, tenant spaces, warehouses, development of building core and envelope, homes, neighbourhoods, data centres, industrial and manufacturing facilities, and the operation and maintenance of existing buildings.

The LEED rating system is composed by *prerequisites* and *credits*. Prerequisites must be considered in any LEED-certified project. Instead, credits are optional strategies that the project team can include for achieving points and increase the building performances accounted for the LEED certification. In other words, the design proposal has to fulfil all the prerequisites and gain a minimum of credits to achieve LEED certification. Credits and prerequisites are listed in the following classes: location and transportation; sustainable sites; water efficiency; energy and atmosphere; material and resources; indoor environmental quality; integrative process; innovation; regional priority [4].

A project must pass three minimum requirements to be suitable for LEED certification:

[6] https://www.usgbc.org/ Accessed 28 Apr. 2020
[7] "LEED rating system" https://www.usgbc.org/leed. Accessed 28 Apr. 2020

- It shall be in a stable location and located on pre-existing soil, to avoid displacement and disrupting existing ecosystems.
- It must use reasonable LEED boundaries, such as parking, sidewalks and landscaping. They are associated with the project and support its typical operation.
- It must not exceed project size requirements. The minimum size requirements depend on the project but vary from 250 sqft for commercial interiors to 1000 sqft for existing buildings

LEED rating system has 110 total points, 100 base points obtainable from the main credit categories, six points related to innovation strategies, plus four points if the design addresses urgent regional issues. The level of LEED certification is decided according to a progressive scale:

- Projects earning 40-49 points are LEED Certified;
- Projects earning 50-59 points are LEED Silver;
- Projects earning 60-79 points are LEED Gold;
- Projects earning 80 or more points are LEED Platinum

Figure 3: The four LEED certification

LEED is centered on the assessment of a set of environmental impacts that creates the LEED system goals. By assigning the highest point values to credits that will have the most significant impact on a goal, LEED encourages project teams to apply the strategies that will result in higher-performing buildings.

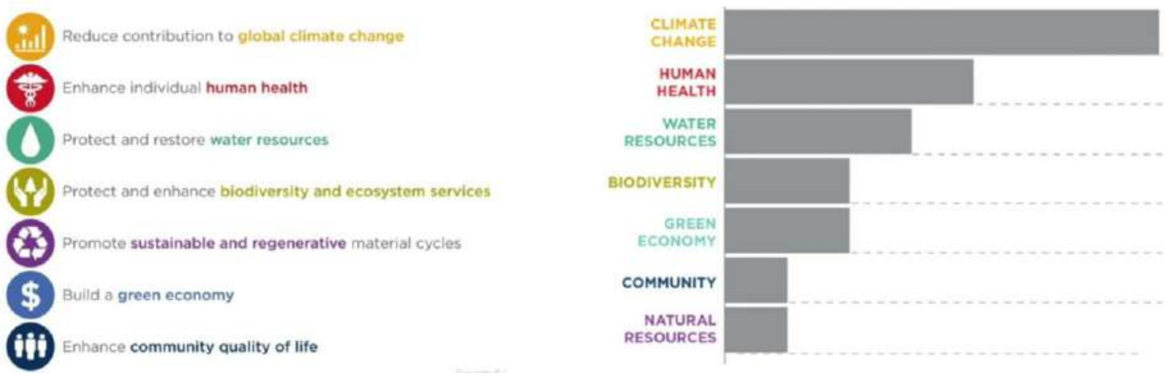


Figure 4: The LEED environmental impacts and system goals [5]

The credit point value expresses the potential to reduce the building's environmental impact and its ability to produce a positive impact on its users and the environment. The *LEED project checklist*, also known as *scorecard*, is a list of all possible credits divided by credit category, prerequisites and credits. The checklist helps project teams to plan the target certification level they wish to achieve. It can also be utilised as a task responsibility matrix to address the credits throughout the project.

LEED certification provides an impartial verification from third-party that the project satisfies the performance requirements needed to achieve the green building peculiarities. It follows these steps[8]:

1. The application form is presented to GBCI. Afterwards, the team receives information to guide the process. All the procedures are pursued in LEED online[9] (project activities, including registration and credit documentation), a storage web-portal that the team can use to upload project information. A template is provided to be filled in with credit details.
2. LEED credits and prerequisites have to be properly documented. The team chooses the credits to develop, subsequently uploads the documentation required to the portal online. Afterwards, the administrator uploads the appropriate fee and the documents.
3. GBCI checks the documents uploaded.
4. The release of the certificate is the last procedure. When the document checking is performed, the team can acknowledge or not accept the verdict. Those project that pass the selection obtain the certificate.

The LEED evaluation systems are voluntary. They are applied to enhance the sustainability of buildings and promote environmental transformation. During the certification process the project team can receive guidance from USGBC and GBCI to comply with the rating system requirements. *Project Credit Interpretation Rulings* [6], or CIR are managed by the GBCI, and guarantee to the design groups to receive expert advice on how to meet the LEED obligations. However, they do not ensure the award of credits and the team shall nonetheless detail the results achieved during the certification process. The decision stays private and applies to a single project only. LEED Interpretations, however, can establish a precedent. The design groups are obliged to listen to all interpretations that are made public in the Addenda online database before the registration date.

3.1.2 Net Zero Energy Buildings

The EPBD define NZEB all the buildings with nearly zero energy consumption, as facilities that are extremely efficient in terms of energy performance, where the little energy required is supplied by

[8] "Guide to LEED Certification: Commercial" https://www.usgbc.org/tools/leed-certification/commercial. Accessed 28 Apr. 2020
[9] "LEED Online". https://www.leedonline.com/ Accessed 28 Apr. 2020

renewable resources [7]. Furthermore, the updated document imposed that all new publicly owned buildings must be NZEB by 2018, and that all newly built facilities must be NZEB by the end of 2020.

EU countries have to conform with the Directive and draw up national programs, outlining how the number of NZEBs is planned to be increased in their respective country. Follows the definition of NZEB in each partner country this master, to show a summary of requirements for building's energy performances and the differences between them.

Table 1: Edited from "National applications of the NZEB definition – The complete overview" [8]

Main aspect of national NZEB definition			**Country**		
			Italy	**Portugal**	**Slovenia**
Detailed definition	Included in legal document	Governmental decree/law			
		Technical regulation			
		National NZEB plan			
	Not yet included in a legal document				
High energy performance	Tighter requirements compared to current values	Heating energy demand			
		Primary energy			
Nearly zero / low amount of energy required. Limits:	Component U-values				
	Mean U-value of building envelope				
	Heat transfer coefficient/heat loss of building envelope				
	System efficiencies				
	Heating energy demand				
	Cooling energy demand				
	Primary energy				
	Summer overheating				
Significant extent of renewable energy	Minimum share in %				
	(Choice of) exemplary RES measures				
Primary energy indicator in kWh/m² year	Included				

In the first section of the definition, the determining feature that distinguish a 'NZEB' is its as energy performance, which must be very high and must comply with the Directive guidelines. The following section explains the guidelines to comply with energy performances. The EPBD does not provide a differentiation between new and existing buildings, and to recognise the different climatic peculiarities it does not impose any target value. Indeed, the document demands the countries to outline guidelines for high energy building performances and the suggestions for the usage of renewable resources [7], according to their national context and environmental condition.

A 2017 research [9] highlighted how the local weather is long for being the driving factor influencing selection and adoption of the building technologies to lower building's energy loads. In fact, the adaptability to climatic context was not relevant for the choice of a specific technology, while this was the case for the investment costs. However, the availability of natural sources as solar irradiation affected the use of renewable technologies. The researchers stated that the crucial issue is the diverse calculation methodology for the performance indicators across EU states, which are estimated with different boundary conditions and conversion factors. Jointly with the lack of a consistent approaches for measuring buildings' performance, this leads to very different national strategies.

3.2 Urban-scale energy analysis

Each year, an increasing number of people populate urban areas, following the growing economic and social trends which open opportunities for business, education and lifestyle. To sustain the day-today life, work and activities, a significant amount of resources and energy are consumed in cities, due to their inhabitants' demand. Urban energy analysis is a broad area of research which attempt to model, evaluate and classify urban energy systems, adopting a variety of different approaches. These mainly differ in their spatial scale and temporal dimension, but have also relevant differences in the techniques adopted to perform the analyses and the target users and application domains these cover [10].

Generally speaking, the modelling techniques consider both the supply and the demand sides to describe an energy system. These can be specified by the user as input or calculated by the software as an output. Considering urban environments, in the AEC sector much attention is placed in the simulation of the demand side of the chain, where energy loads required to heat, cooling and ventilate interior spaces are subjected to a preliminary assessment prior to construction. These analysis are mainly driven by policies aiming to diminish energy consumption in buildings and urban areas.

3.3 Methodology and simulation types

Many research groups are looking into the impact of energy efficiency measures in urban environments, developing Urban-Scale Energy Modelling (USEM) tools and methodologies which can be applied at the neighbourhood or metropolitan level. These platforms are being used to evaluate urban energy systems under different scenarios, aiming to propose optimal solutions. Researchers suggest that due to the variety of analysis area, USEM programs consist of a collection of different smaller platforms [11]. These can be grouped into five main categories, listed in the following image. For this research, the focus is on the platforms for urban meteorology and building energy demand.

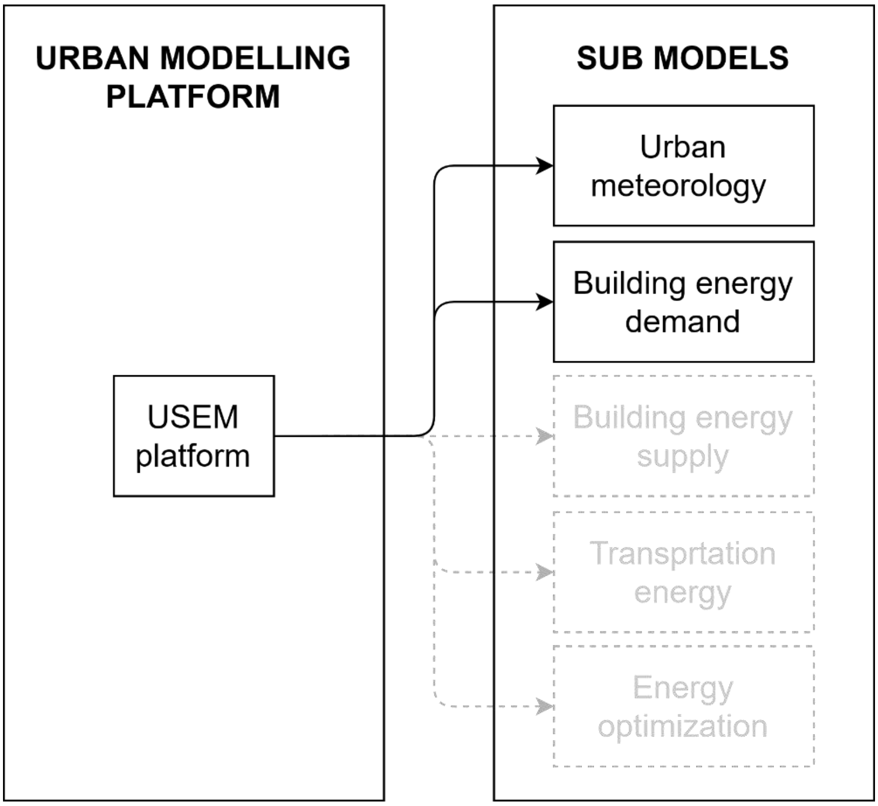


Figure 5: Aggregate analysis that can constitute a urban platform, modified from [11].

3.3.1 Tools for Urban Meteorology Analysis

Meteorological data is a central piece of information for building simulation. It can be obtained from two main sources: measured data, or synthetic data from aggregates averages per month. While it is recognized that buildings' energy loads are linked to climatic changes, usual data on local climate hardly reflect the fact. To overcome this shortcoming are available tools that morph weather data, such as CCWorldWeatherGen [12] and WeatherShift™ [13]. These software can generate forecasted weather conditions adjusting for changing climate.

At the urban scale, the local temperature and air circulation are affected by the buildings shape and their heat emissions, causing the Urban Heat Island effect (UHI), characterized by higher mean air temperature. For this reason, the climatic data may not be reliable enough to model the energetic behaviour in an urban context. Thus, the modelling of urban climate becomes crucial to understand the urban heat load. The software ENVI-met [14] is used to estimate the urban microclimate considering a variety of specific local characteristics. Other urban microclimate models are the RayMan model [15], and SkyHelios [16].

The software Radiance [17] can be used to analyse solar and daylighting. This tool measures the incidence of solar energy on buildings and reproduces both electric light and daylight, considering the urban obstacles. Radiance is implemented in the USEM platform Umi [18]. The Urban Weather

Generator tool (UWG) [19] calculates the temperature of air in urban canyons by modelling the heat island effect, considering energetic estimations at neighbourhood scale.

A common methodology considers the progressive use of modelling tools: in CitySim three climate models at different scale are used to forecast atmospheric condition in the city based on the urban context. The CitySim simulation engine is designed for urban-scale simulation, focusing on the flows of energy of several facilities [20]. The platform includes the ability to model different energetic characteristics of buildings, with simplifying approximations. This allows to have a relatively fast simulation according to the number of buildings. As a consequence, the ability to evaluate the influence of buildings in the alteration of urban microclimate enables the development of optimised planning solutions for new development [21].

3.3.2 Tools for Building Energy Demand Modelling

Speaking of metropolitan scale, an evaluation of buildings' energy loads consists of the description of the buildings and the simulation of their energy demand. The characterization of the facilities consists in the identification of the construction type and its geometric definition. The identification of the building typology requires to define attributes as usage, date and form for every facility. Because of the variety of these building attributes, the typology is characterized by an aggregation of common characteristics. Then, the buildings' morphology draws information from cadastral databases, statistical evaluations and remote sensing.

Most urban platforms emphasise the metropolitan energy demand and can be categorized as Urban Building Energy Modelling (UBEM) platforms [11], which simulate the energy loads under different conditions. The tools analysed by A. Sola et al. to assess buildings energy loads over an urban area combine detailed building energy models and an aggregation of facilities stock over a broader portion of city. A representative subset is proposed here from the selection of the referenced study.

- **DOE-2** [22] is used to simulate building cooling, heating, lighting and ventilation. It is applied for modelling a variety of energy generation systems like photovoltaics (PV), heat pumps, Thermal Energy Storage, boilers and chillers.
- **EnergyPlus** [23] (partially built on DOE-2) can be coupled with GIS and is used to simulate building cooling, heating, hot water demand and lighting. It can be used to model a variety of energy generation systems such as PV and Building Integrated Photovoltaics (BIPV), cogeneration, boilers and chillers.
- **TRNSYS** [24] can be used with GIS and is employed to simulate the building ventilation, heating and cooling demand. Modelling capabilities for energy generation systems include PV, solar thermal, Ground-Source Heat Pump (GSHP) TES, boilers and chillers. It can be integrated within the district thermal network.

- **Modelica** [25] is an object-oriented simulation language used to simulate models building heating, cooling, appliance and lighting. It can model PV, GSHP, boilers and chillers, and it can be integrated within the district thermal network and electricity network.

These simulation tools can be used sequentially. Thus, the output of one is used as input for the other. One approach for co-simulating entire buildings is the cross-platform OpenStudio, that collect several applications and reads the input and output files of EnergyPlus. This platform can also perform simulations with sophisticated daylight assessment using Radiance [26].

4 INTEROPERABILITY AND WORKFLOWS

4.1 BIM, CIM and GIS

The geospatial and Architectural, Engineering and Construction (AEC) fields are usually considered different domains. Geographic Information System (GIS) practitioners are concerned with large scale data describing the existing environment, whereas the finer scale corresponding to the designs of buildings is managed by Building Information Modelling (BIM) specialists. Between these two domains, at the urban scale the activities partially overlap. However, most of the GIS are poor in terms of attributes concerning semantic information, hence the concept of City Information Modelling (CIM) arises from the combination between GIS and BIM, where CityGML is an example of established semantic model in the digital city, quickly adopted as an international standard [27]. This boundary domain is recently being blurred by the overlap of intention and tools, as in the case of GIS applications at urban-scale, scan-to-BIM methodologies, and the use of BIM for infrastructure projects. That said, it is clear the need for collaborative practices that can be met through improved software interoperability and data integration [28].

When talking about the digital built environment, a key aspect is Semantic Modelling. The 3D visualisation of real objects with geometries and appearances are only a partial aspect of the entities. Every object in a virtual urban model (building, water body) can carry much more information, such as knowledge about the object and its functionality. When speaking about Semantic Modelling in the context of a digital built environment, there has been a paradigm shift from geometric model to the representation of objects with their structured properties. However, this semantic information is only useful if distinct stakeholders share the same understanding of it. Therefore, it is useful the creation of a common ontology. In that case, applications can rely on a specific data quality that is agreed between data providers and users, concerning thematic, spatial structure and properties of the objects. On the other hand, data providers as municipalities create 3D models with a well-defined information, which will be needed for a several purposes. This allows companies to create applications that benefit from semantic information. The semantic model that is based on a common ontology represents a consensus over different application domains. Therefore, it can be beneficial to exchange information among these disciplines, using the model as an information carrier, while understanding the city ontology as a schema for the configuration of domain information.

Many applications constitute valid use case scenarios for an integrated digital built environment. Users need to create, modify and evaluate entities, their attributes and their relations during planning, design and operation. Once the model is created, the operators might want to interrogate its spatial and semantic content to perform multi-dimensional analyses. A multiscale approach to modelling, simulation and analysis is still nowadays not free of practical problems, both before and after construction operations.

As a matter of fact, both processes and technology are progressing toward the ability to integrate spatial information seamlessly. At the moment however, operations to map different data schemas, match geographic and local coordinates, and align geometric levels of development at different scales are still required. Data integration must consider the underlying understandings of spaces and their relationships.

With the aim to overcome the above-mentioned difficulties, the Integrated Digital Built Environment (IDBE) working group [28] identified three complementary – and sometimes conflicting – standards covering the scales and principles to model the built environment:

- Industry Foundation Classes (IFC) is adopted to transfer of detailed facility information;
- City Geography Markup Language (CityGML) is implemented for managing metropolitan data;
- Land and Infrastructure Conceptual Model (LandInfra) is used to model civil infrastructures.

The IDBE working group described the affinities and discrepancies of the three standards, explaining challenges to integration, and future actions. In fact, there are still obstacles to data integration. Follows a summary of the characteristics highlighted by the group that are relevant for the scope of this research.

Culture, practices, purpose and roles: IFC was created to transfer detailed building data, while CityGML was developed as working standard for urban simulations, and LandInfra addresses land and infrastructures facilities. CityGML is meant to describe the urban environment as it appears, whereas IFC and LandInfra are used to depict future possible scnarios.

Thematic scope: IFC supports fine-scale building and infrastructure components. CityGML and LandInfra support objects at coarser spatial resolution. In fact, CityGML covers utility networks, energy, hydrology and buildings, while LandInfra focuses on civil engineering activities as transportation infrastructures, and land government purposes as cadastre and surveying.

Figure 6: Thematic coverage of the three data standards [28].

Structure, sub-setting and extensibility: each standard has a core and additional components named *domain-specific data schemas* (IFC), *modules* (CityGML) or *parts* (LandInfra). IFC is enriched through an official procedure, whereas CityGML and LandInfra can be arbitrarily expanded through an Application Domain Extension (ADE). IFC files are application-specific extraction called Model View Definitions (MVDs), whereas in CityGML and LandInfra schemas subsets may be chosen by specifying a profile. The standards vary but intersect in some core elements, finding their common ground in the concept of building.

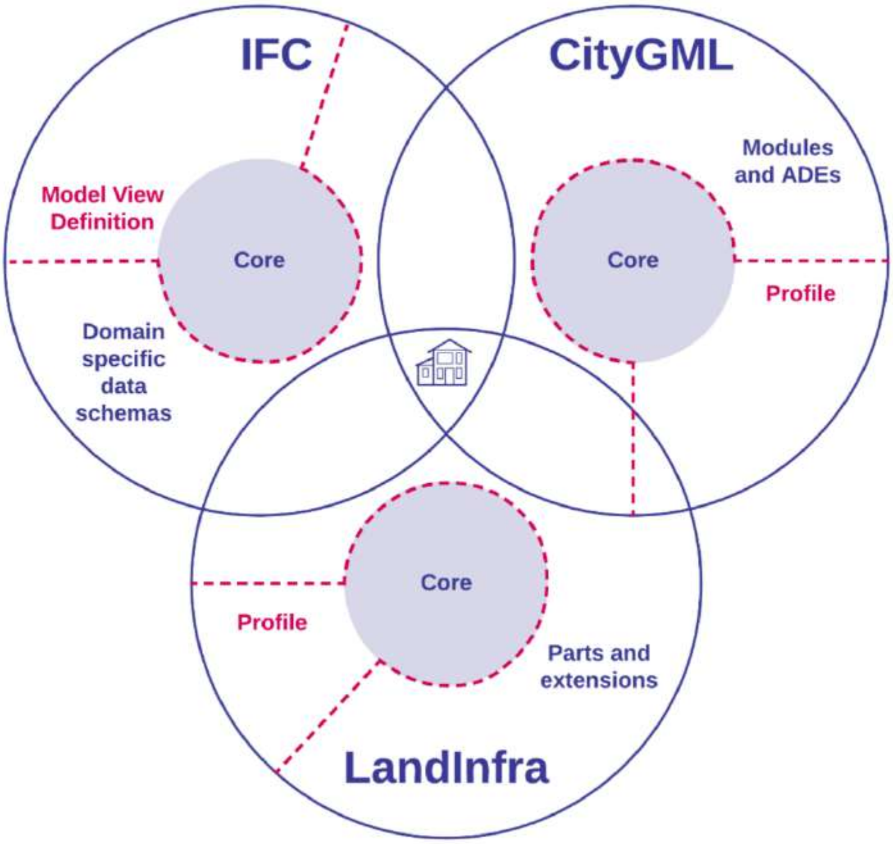


Figure 7: The standards differ but overlap; the concept of building is common [28].

Conceptualisation and semantics: IFC represents buildings as an aggregation of parts, CityGML characterizes the interiors of buildings as rooms, while LandInfra characterizes only the outer shape of buildings, being features of a facility. While IFC uses EXPRESS and EXPRESS-G to formalise concepts, CityGML and LandInfra adopt the Universal Modelling Language (UML) for the same purpose. However, IFC 5 will also be represented using UML. Even though the three standards can represent a building, their detailed structure is dissimilar.

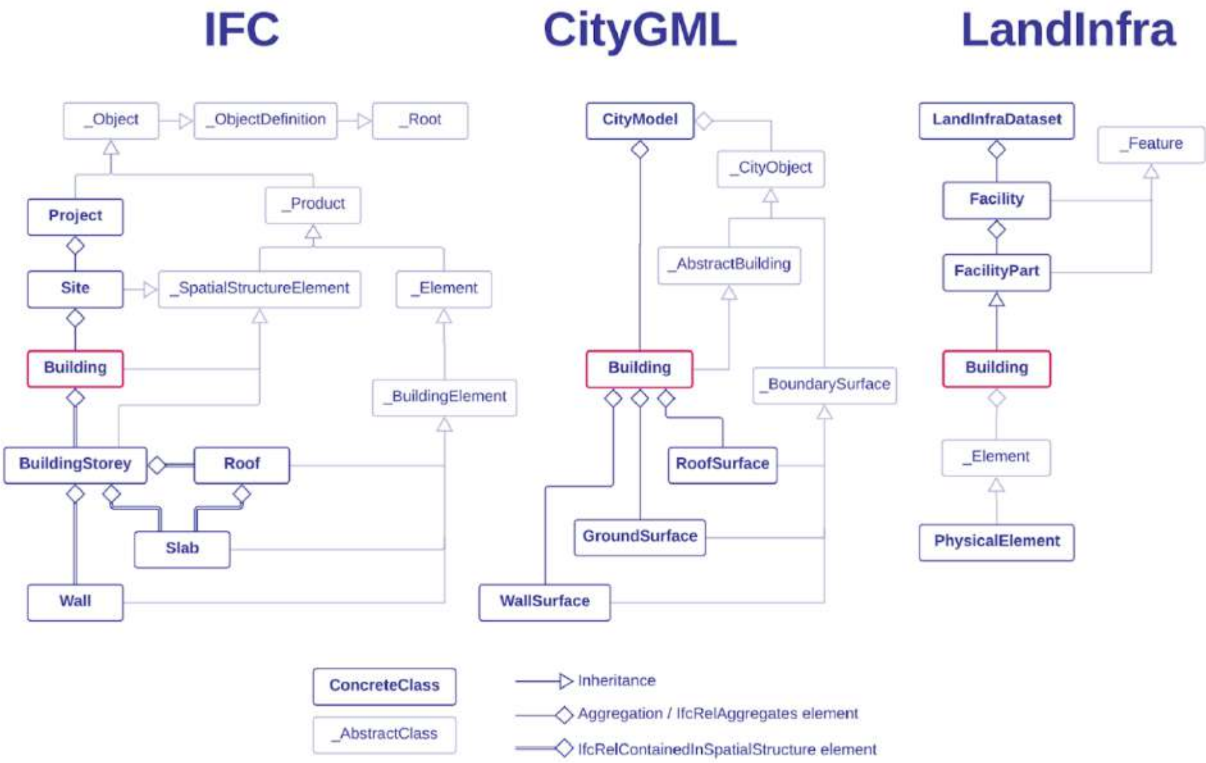


Figure 8: All three standards represent the concept of a building, but the detailed structure is dissimilar [28].

Coordinate Reference Systems (CRS): different scale calls for the use of two CRS. IFC works over small areas, and these are treated as flat using local cartesian CRSs. On the other hand, CityGML and LandInfra deal with larger features that are affected by the Earth's curvature, and therefore they adopt a geodetic CRS.

Geometries: different processes of data acquisition require different methodologies for geometric representation. In CityGML, data is generated by automated processes as photogrammetry or laser scanning, whereas in IFC and LandInfra data is manually generated. Therefore, LandInfra and CityGML implement B-Rep, while IFC also supports CSG and Swept Solid.

Spatial and network topologies: In IFC topologies like containment and spatial adjacency are objectified relationships like *RelContainedInSpatialStructure*. In CityGML these are implicitly represented in the boundary representations. For network topologies, IFC implement *IfcRelConnects* elements; on the other hand, CityGML makes use of *InterFeatureLink* elements.

Progressively detailed representations: The Levels Of Development (LOD) in IFC connects the model development to a progressive construction procedure. Instead, CityGML uses the LOD to progressively detail semantic-geometric representations. To transfer information from IFC to CityGML, a complex mapping method is required. LandInfra has not implemented LODs.

Encoding languages: IFC was conceived in the EXPRESS modelling language, instantiating STEP Physical Files and it supports an XML encoding (ifcXML) and JSON encodings, that can be derived from the conceptual UML. CityGML uses GML version 3, based on XML. The InfraGML encoding accompanies LandInfra.

Globally unique identification of real-world objects: IFC implements globally unique identifiers for all object instances. Instead, CityGML requires that an identifier be unique only within the instance document but not globally. LandInfra allows global unique identification of objects also outside the dataset.

These discrepancies between the standards cause some problem in software interoperability and data integration. On one hand, these are simplified by overlapping goals; challenges occur when schemas differ in the conceptualisation of objects, how it is formalised and how objects are represented.

4.2 BIM to BEM

Building Energy Modelling (BEM) predicts buildings' energy use based on simulations of energy and mass flows [23] and its corresponding energy savings, as compared to a standard baseline. These analyses take into account complex equations and thermodynamic principles, and are based on input parameters like the building geometry and the information related to HVAC technologies, weather, operation conditions, among others [29]. Accordingly, the estimate is only as accurate as the assumptions, which should be detailed and identified by the project team, the client, the building operator, and the end users

BEM facilitates decision making using predefined criteria describing building configuration and use. In current practice however, there are several technical and semantical gaps moving between BIM and BEM. Speaking about the model content, architectural and engineering BIM models are mainly constituted by building elements such as walls, floors, beams, roofs, windows etc. whereas BEM models are concerned about spaces (area, volume, utilization) and surfaces (type, adjacency and geometry). BEM does not demand a high level of model details. Thus, exact geometries are not relevant, as the final energy assessment will be not affected by a small deviation in a wall positioning [30].

In traditional practice, most BEM tools were only available as standalone applications with limited BIM interoperability. The workflow involved importing the BIM model as a reference to build the energy model, causing duplication efforts. Nowadays, most BIM authoring tools offer the ability to export information using data formats such as gbXML, which provide the opportunity to include BEM parameters, thus data can be exchanged without repeating the modelling process. Some BIM authoring tools also offer integrated simulation capabilities, avoiding the export/import process that might cause errors or data loss.

That said, BIM and BEM interoperability is still not fully developed, resulting with some information being lost during the process. The root cause might be in the fundamental interpretations of spaces: BIM authoring tools deals with construction elements, BEM tools need spaces or zones. The transfer of building geometry is still inadequate and not automatic, as most BIM models need to be simplified before they can be used for simulation in BEM software. Consequently, the analytical models' views of a building in BEM tools are not updated automatically with changes in the BIM model. If the simulation is done using different tool than the BIM authoring software, such as specialised application to asses building's heating and cooling loads, the workflow among project participants is still characterized by frequent design changes, which requires repetitive export and import procedures. As better explained in section 4.4, at the moment, there is no open standard that fully support a complete information exchange process for which geometry, and more importantly semantic information, is integrally transferred between the two platforms. Furthermore, at present day, there is a lack of uniform BEM standard in BIM when defining properties. However, pre-defined BIM templates can be utilized between different projects and professionals. In most BIM authoring software there are some predetermined assumptions based on codes such ASHRAE, which can be used as a baseline to start a project, but these need to be checked to ensure that they are updated to the latest version of energy codes. In future research, it is auspicial a more thorough exploration about the root causes of this weak interoperability through a detailed examination of the roles, responsibilities and processes of data.

4.2.1 BEM and Level of Information Need

The release of ISO 19650[10] introduced the Level of Information Need, which should replace the concept of Level of Definition (LOD) defined as per United States National BIM Standard as the extent to which an element's geometry and properties has been modelled and its reliability [31]. This LOD definition make explicit reference to the LOD guide developed by BIMforum[11].

The ISO 19650 introduces the Level of Information Need. In this definition one of the goals is to prevent the delivery of irrelevant information, specifying that the demand for information exceeding the minimum necessary is identified as wasteful. The standard emphasizes the close relationship between the Level of Information Need and the related objective, requiring to define the Level of Information Need for every information deliverable, and therefore implying that it can vary for every deliverable. Moreover, the standard reiterates that the reference standard for the assignment of the Level of Information Need must be defined at the beginning of each project, and introduces other metrics to define the *status* of the information or the *level of accuracy*.

[10] "ISO 19650-1:2018." https://www.iso.org/standard/68078.html. Accessed 3 Sep. 2020.
[11] "LOD - BIMForum." https://bimforum.org/lod/. Accessed 3 Sep. 2020.

That said, the ISO 19650 is not to tailored to any specific discipline, but rather to the AEC industry. Therefore, given the already mentioned lack of BEM standards, it is only possible to make some assumptions regarding the implementation of the Level of Information Need in BEM. This is done here following the UKBIM Alliance "*Information Management according to BS EN ISO 19650 - Guidance Part 1: Concepts*" [32], by pairing LOD definition with general LOI (Level of Information) regarding energy modelling.

Table 2: assumptions to adopt a Level of Information Need in BEM.

LOD	Geometry	Information	Analysis
100	Volumes and masses	Location and orientation	Climate
			Solar radiation
			EUI projection
			Sustainability goals
200	Generic description of construction elements	Overall system selection General thermal properties Occupancy schedules	PV capacity
			Massing orientation
			Spatial configuration
			Window/wall ratio
			Façade thermal performance
			Light power density
			HVAC types
300	Defined construction assemblies	Material properties Construction technology Occupancy schedules	Optimize PV systems
			Optimize massing orientation
			Optimize fenestration
			Optimize shading devices
			Photometric study
			Daylight occupancy sensors
			HVAC options optimization
			Sequence of operations
			Façade performances
400	Detailed construction elements, ready for documentation	Detailed description of systems properties and functions Detailed thermal properties of construction element	Glazing configuration
			Shading configuration
			Façade assemblies
			Walls, floors, roof assemblies
			Lighting fixtures configuration
			HVAC system configuration

4.3 BIM to CIM

Planning of the built environment is done at city or neighbourhood level and building level. As explained above in 4.1, urban designers manage the city and neighbourhood-scale using GIS tools, while architects and engineers develop building-scale models with BIM tools. Both applications are based upon distinct data schemas: where GIS use CityGML format, BIM uses IFC schema. Another important aspect concerns the purpose of these models. Architects and engineers tend to produce models for design intents, with great level of detail in terms of geometry and semantic content. Urban designers and municipality employees are mostly concerned with models representing the reality as it exists. This section of the research highlights the current processes and workflow for information exchange between the two domains, with emphasis on the framework and methodology which facilitate the management of information related to different analyses, among which building energy performance.

Researchers have advanced the hypothesis of a framework called City Information Modelling (CIM) [27], that integrate both models from GIS and BIM matching the features of their open standard data models. Looking at the main functions of an urban environment, the study proposes a cohesive classification of objects and entities that combines CityGML and IFC. The methodology adopted to model relevant information extracts facilities interiors data from BIM models, and geographical and spatial data from GIS models. This is depicted in the image below, modified from the mentioned research paper.

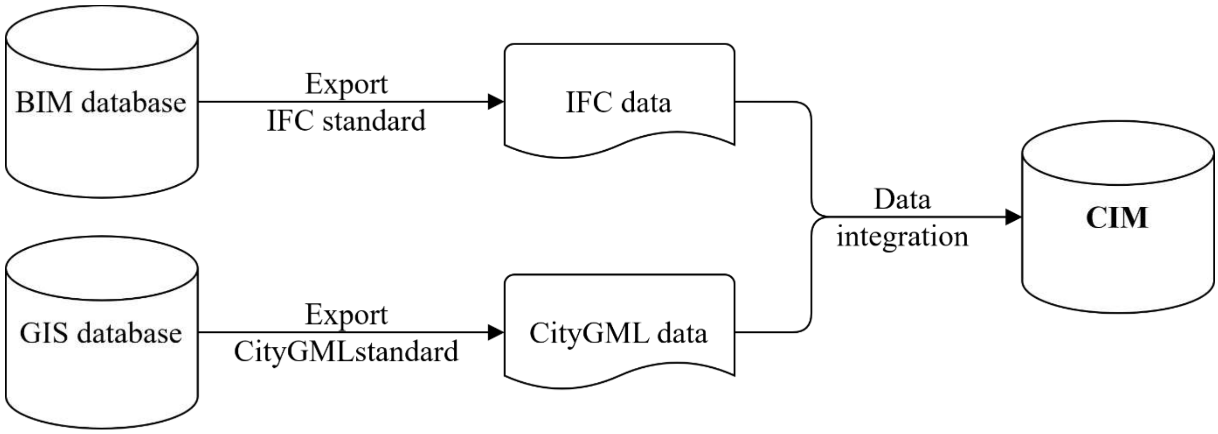


Figure 9: City Information Modelling general framework, modified from [27]

The different representation of semantic and geometric properties of objects between the two data schemas, appears to be the main obstacle to seamless integration. However, the integration between building and city scale modelling is critical for research and practice at both spatial scales. Indeed, at the urban scale a semantically rich model can offer insights about environmental and contextual constraints and opportunities, which can affect the building design. On the other hand, aggregates building models can deliver a semantically rich urban model. A specific study on the matter [33] has individuated fifteen classes which carry similar semantic representation between IFC and CityGML. These are listed in the figure below. However, the vast amount of IFC classes that cannot be matched with CityGML classes have severely compromised interoperability between the data models.

Table 3: CityGML and IFC classes semantics similarities. Modified from [33]

cityGML type	IFC class
Address	BuildingAddress
Annotation	IfcAnnotation
Beam	IfcBeam
Building	IfcBuilding
BuildingFumiture	IfcFumishing Element
Column	IfcColumn
Door	IfcDoor
FloorSurface	IfcSlab
FlowTerrninal	IfcFlowTerrninal
Railing	IfcRailing
RoofSurface	IfcRoof
Room	IfcSpace
Stair	IfcStair
WallSurface	IfcWall
Window	IfcWindow

Several researches have analysed strategies of information transfer to communicate between CityGML and IFC, ultimately resulting in two approaches for data integration. One uses ADE, the mechanism which allows to extend cityGML schema for domain specific applications (see summary in section 4.4.2). Some issues resulting from this approach were the complex data model, the excessive files size, and geometric discrepancies. The other approach applies unidirectional transformation of IFC into CityGML [34] [33]. The issues found in this approach were again related to file size and geometric errors.

Recent research [35] looks into different approaches to CityGML and IFC integration, and it appears that the key for integration is data conversion. The process of extracting, transform and load information from a data schema to a different one is called ETL (Extract, Transform and Load). This workflow has returned adequate results in terms of file size, processing time, semantic and geometric correctness, at different CityGML LOD. Moreover, it could be generalized to offer personalized data mapping.

4.3.1 Data integration tool: FME

The ETL workflows could be developed with a variety of software, among which it was chosen to illustrate Feature Manipulation Engine (FME), from the software house Safe[12]. The choice has been made based on the availability of free and public resources, and the possibility to test the platform using academic license. FME offer a data conversion technology that includes built-in support for both IFC and CityGML schemas, giving control over which portions of a dataset are converted and how. Its

[12] "FME" https://www.safe.com/. Accessed 3 Jun. 2020.

conversion instruments can extract and reorganize the source data to fit the constraints of the target model. Therefore, FME allows to reorganize the IFC data and match its content to CityGML.

Figure 10: FME by Safe Software is a tool for data integration

Beyond these functionalities FME supports different file formats and databases. However, its strength resides in the variety of 3D, GIS and spatial database data schema support.

A generalized workflow to integrate IFC building data and CityGML urban data is represented in Figure 11. The BIM model is prepared according to the required model uses through a BIM authoring software. From there, it is possible to export data in IFC format, while other domain specific object attributes can be exported in another format such as xlsx excel file. These data are then read using FME “readers” which allows to import different file format and define their input data model or data schema. Once into FME, these data are subjected to various transformations that aim to reorganize the data in such a way that it can be written according to the CityGML standard. The output files resulting from such ETL workflow are then integrated in the database where the urban data is managed and stored, and can be utilized for different use cases.

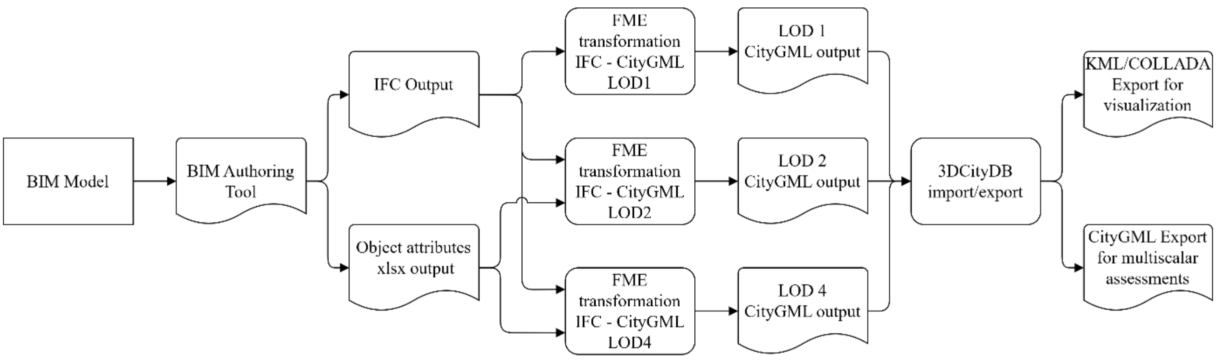


Figure 11: Generalized workflow to integrate IFC and CityGML data. Modified from [35]

4.4 Data structures and format

4.4.1 Building scale: IFC, gbXML

In BIM exist two data model to transfer design information between stakeholders: IFC[13] and gbXML[14]. Before analysing the two data structures however, it is necessary to clarify the concept of openBIM®[15] and understand the interoperability process requirements. OpenBIM goal is to enhance the management and accessibility of digital data. It is a vendor-neutral collaborative process which facilitates efficient collaboration among all members. OpenBIM simplifies interoperability by removing the constrains of proprietary data formats, discipline, and phase of a project. It enhances project delivery and performance by enabling participants to develop collaborative practice, breaking down data silos. Firms adopting openBIM have better communication and information exchange, due to the implementation of recognised standards and practices, with the goal of establishing a shared language.

The openBIM approach recognises that in the AEC industry interoperability is essential to achieve the digital transformation. To achieve better interoperability, however, are required open standards which allows consistent data transmission providing third-party quality checks. Importantly, cooperation cannot be constrained by exclusive practice or data format. Ultimately, what creates value to all participants involved in a collaborative effort is the flexibility to choose the technology they prefer. That said, buildingSMART® supports a shared agreement between participants to accelerate standard implementation, which deal with methodologies and information typical to the AEC sector, including:

- IFC as a data model tailored for the specific requirements of the sector
- Information Delivery Manual (IDM) as an approach to describe processes and requirements
- Model View Definitions (MVD) as specifications for the transmission of data model
- BIM Collaboration Format (BCF) as a transmission procedure based on models
- buildingSMART Data Dictionary (bSDD) as a source of definitions for objects and properties

IFC: Industry Foundation Classes

The IFC is a data model based on object, developed by the former International Alliance for Interoperability (IAI) in 1995, and promoted by buildingSMART to simplify interoperability in the AEC industry[16]. IFC can handle information across various disciplines contributing to a building, from ideation to demolition. The IFC is an open international standard (ISO 16739-1:2018), meaning that it is vendor-neutral and usable across different devices and platforms, for several use cases.

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[13] "ISO 16739-1:2018" https://www.iso.org/standard/70303.html. Accessed 2 Sep. 2020.
[14] "gbXML" http://www.gbxml.org/Schema_Current_GreenBuildingXML_gbXML. Accessed 2 Sep. 2020.
[15] "openBIM Definition" https://www.buildingsmart.org/about/openbim/openbim-definition/. Accessed 15 May. 2020.
[16] "Industry Foundation Classes (IFC)." https://technical.buildingsmart.org/standards/ifc/. Accessed 1 May. 2020.

The IFC's architecture distinguishes four layers. At its base, The Resource layer describe geometry, costs, material, quantity, etc. The Core layer comprises the extensions, including common entity definitions such as process, group, product and actor. Here the Product Extension identifies abstract components like space, site and building, while the remaining two extensions define process and control concepts like, procedure, tasks and performance. The Interoperability layer encompasses entity definitions tailored to a common product or process applied throughout multiple specialties; these are usually used for exchange among different disciplines. The domain layer covers specialized descriptions that characterize a discipline; these are used for sharing information within a single domain.

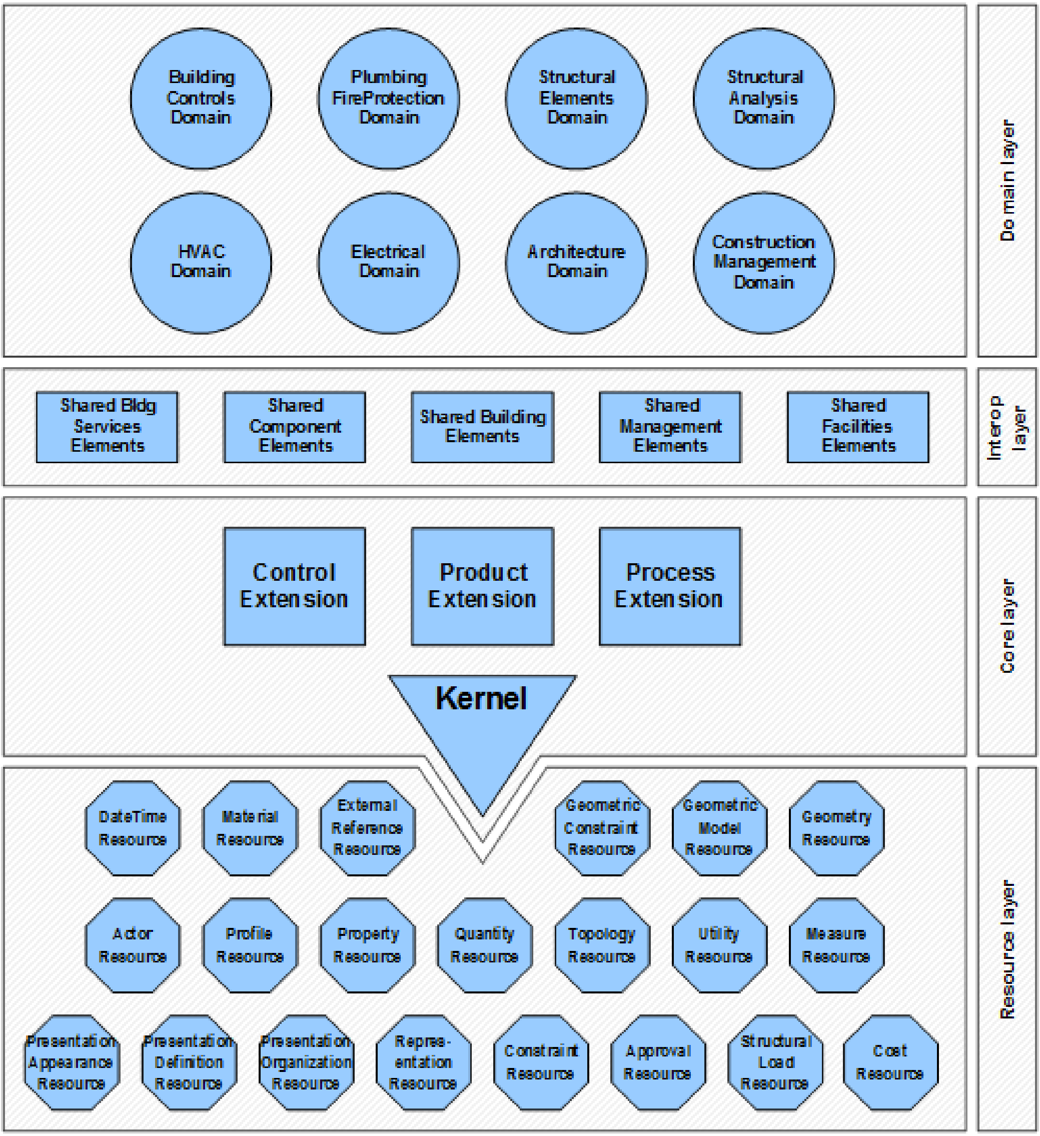

Figure 12: IFC Data schema architecture with conceptual layers[17]

[17] "Introduction - buildingSMART International Standards Server." https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/link/introduction.htm. Accessed 3 Sep. 2020.

However, the IFC building representation has not been fully endorsed by the developers of BEM tools, as certain requirements of energy models are not fully accommodated by IFC. This data model treats buildings as an aggregation of components such as walls, ceilings, roofs and floors. Such a representation can accommodate construction-related inquiries but does not fully meet the requirements for performance inquiries [36]. As an example, the IFC4 Design Transfer View of Revit™ is still not complete: even if it can store material properties, internal gains and 2nd-level space boundaries [37], other important information is lost during the export of IFC4.

IFC has the capability to identify spaces, but lacks the clear topological relationships between spaces. Space in IFC is a secondary notion, a product of the intersections of different building components, rather than the fundamental unit constituting a building. IFC spaces are defined by space boundaries. These space boundaries are aligned to the reference line, which the corresponding architectural element has been modelled in the BIM authoring software. As such, the space boundary may be positioned on the inside or outside facet of the element, or half-way between the two facets. This assignment results in gaps and overlaps among boundaries of different spaces. To arrive at an acceptable geometric representation of spaces, these gaps and overlaps must be accounted for. This requires complex geometry analysis and transformation algorithms to identify different problematic of space boundaries and adjust accordingly. These transformations are the subject of ongoing efforts towards the implementation of IFC models in performance assessment tasks [36].

IDM: Information Delivery Manual for Building Energy Modelling

The AEC industry brings together in a project specific organisation many different companies and authorities. It is necessary for all stakeholders to be aware about what information must be transmitted. The issue becomes more relevant with digital tools because most platforms have reduced capacity to interpret data. BuildingSMART proposed the ISO 29481-1:2016, that suggests an approach to identify processes and information movement during the lifecycle of a building. The method appears to be useful for detailing processes and information exchange among parties. An IDM must be supported by software: its main goal is to allow communication of relevant data in such a way that it can be understood by the receiving application. For this reason, it is tricky to formulate IDMs where there are no structured and documented processes: it is essential to agree on procedures, activities and exchange requirements. The author of an IDM must have a clear strategy on how to get the document implemented in software.

The ongoing development of an IDM for Building Energy Modelling was publicly presented on the 14th May by buildingSMART, and it is currently at the end of its *Phase 1*, of a process divided in two phases. In this phase the technical team completed a literature review of existing IDM development in the area of energy simulation. The output is a document containing an overview of requirements to develop the Model View Definition (MVD) for Building Energy Modelling, simulation and analysis, which has to be reviewed by an expert panel. In the *Phase 2* the team will be involved with the development of multiple MVDs in parallel, engaging with Green Building Certifications. The goal of the effort is to produce a standardized life-cycle process map that has achieved international consensus, which designers can follow to understand the full process and the information required by a semantically rich model that fulfils the purpose.

MVD: Model View Definition

A Model View Definition (MVD)[18] is a subgroup used to extract only the required information stored in the IFC schema, for a domain-specific data transfer procedure. Given the broad variety of data that can be stored in the IFC schema, and known that not every stakeholder is interested nor need the totality of this information, an MVD will filter the data extracted from the BIM model according to the domain-specific demands of the receiving party. In this view, the definition of a MVD follows the receiving party needs in terms of data exchange and worklow.

During a project's lifecycle different actors such as architect, engineer, builder, owner etc. have each its own responsibility, when it comes to generate and manage data relevant to the project. For collaboration purposes, the sharing of such data among team-members and external collaborators is imperative. Hence, it is important to specify what portion of all the data have to be exchanged for a certain task. This can be accomplished by analysing the IFC data model and divide it into smaller "views" that match the receiving user's information requirements.

Generally speaking, most software tools that allow IFC export also support MVDs. However, the number and type of MVD supported by a specific application is related to the specific tasks that program has to accomplish, such as architectural design, structural analysis, energy assessment and so on. If projects' participants along with software houses and other interested party support and develop the use of MVD, it is likely to achieve a good level of standardization in the information transmission process. This would also expedite the communication and facilitate a frequent dialogue among the parties.

[18] "Model View Definition". https://technical.buildingsmart.org/standards/ifc/mvd/. Accessed 3 Sep. 2020.

GBXML: Green Building XML

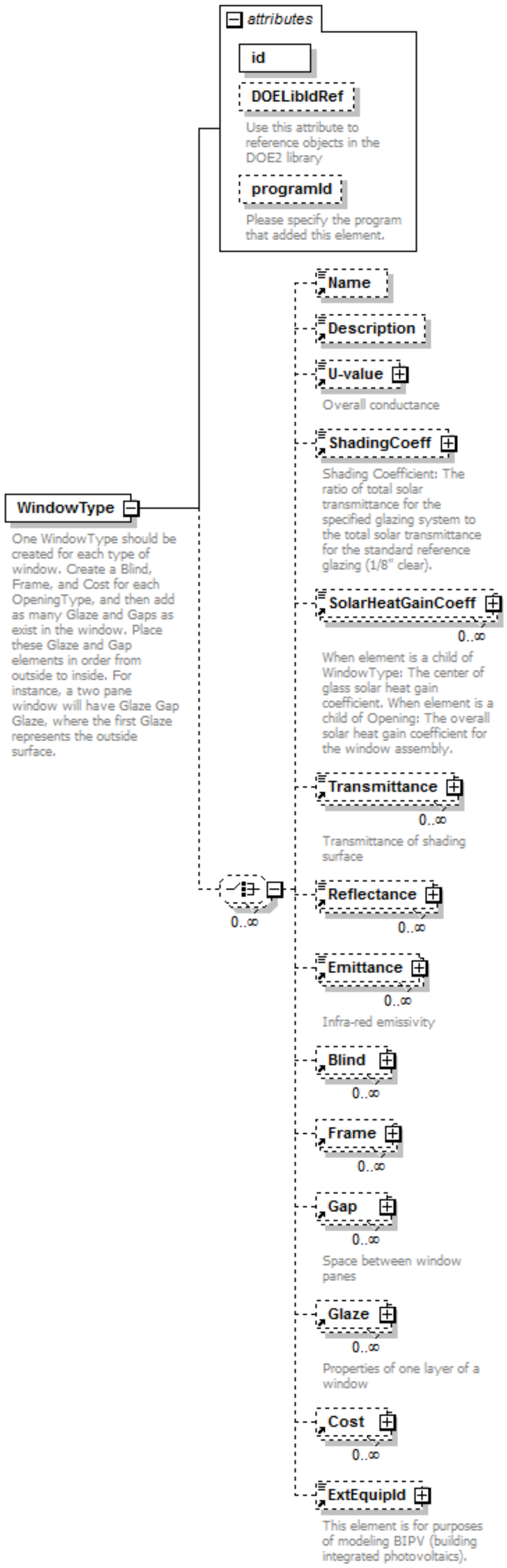

Figure 13: part of gbXML schema

The gbXML[19] schema is intended to simplify the transmission of building data from authoring tools to analysis applications. gbXML is optimized for the transfer of building properties to reduce interoperability issues. This facilitate the design of sustainable and energy efficient buildings, by enabling designers to collaborate and take advantage of the potential benefits of BIM gbXML is written according to the instructions detailed in the Schema Definition (XSD), that is a document specifying all the XML entities which can be included in a file to define a facility.

XML is a markup language describing rules to encode documents in a format that can be read by both humans and machines. The W3C[20] and other specifications [38] define XML. gbXML is an XML file type with more than 500 elements and attributes, that allows many building characteristics to be described for analysis. The figure shows a subset of these elements. gbXML can handle 1st and 2nd space boundaries, opaque construction and materials, thermal and emission properties, cost and LCA, HVAC equipment, glazing shades and their operation, energy, power, efficiencies, water consumption and physical characteristics; lighting and controls; schedules. The strength behind gbXML is the geometric elements that allow the tools to draw a schematic or analytical view of the building for import into analysis tools and also for display on web-based and desktop tools.

[19] "gbXML" http://www.gbxml.org/Schema_Current_GreenBuildingXML_gbXML. Accessed 28 Apr. 2020.
[20] "XML." https://www.w3.org/TR/xml. Accessed 28 Apr. 2020.

4.4.2 Urban scale: CityGML

CityGML is an application of the Geography Markup Language (GML)[21] to build and transfer 3D city models. GML is a standard for the transfer of spatial data published by the Open Geospatial Consortium (OGC)[22]. CityGML aims to propose shared definitions of objects, attributes and relationships at the core of 3D urban models. This is particularly important for the management of 3D city models, which allows to reutilize the information in several domains. GML is implemented to detail how to define data formats to transfer geographical information; therefore, it offers just an overall structure composed by abstract entities and types, along with geometry and topology. However, the final file-format to transfer data is the outcome of specific domain definitions, which require the extension or restriction of the abstract GML types and elements. As a result, different applications have varying application schemas, and CityGML is one of them.

From the real world, it is required to create an abstraction of reality which only contains those aspects of interest for the application (objects and classes). That abstraction leads to an application schema and the definition of feature types. This application schema, which is usually defined in the Unified Modelling Language (UML) or the XML schema, defines the contents and structures to be used in a geographic database. After the structure is detailed, it is possible to start gathering data. The data that is acquired follows the structure defined before.

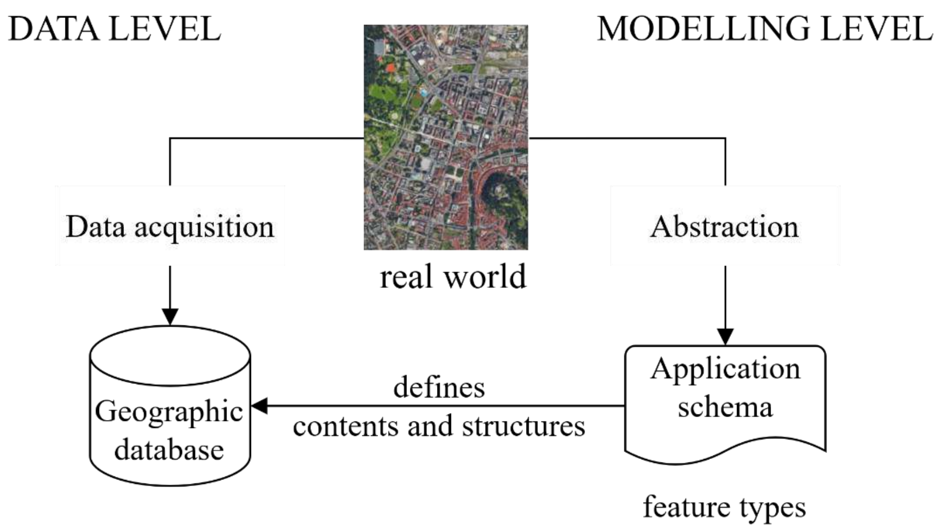

Figure 14: CityGML Application Schema, modified from Kolbe, T., 2008[23]

[21] "GML". https://www.ogc.org/standards/gml. Accessed 28 Apr. 2020
[22] "OGC". https://www.ogc.org/. Accessed 28 Apr. 2020
[23] Kolbe, Thomas H., 'Lectures on CityGML, Section II - GML Concepts and Application Modeling', 2008. Available online at https://www.3dcitydb.org/3dcitydb/CityGMLCourse/

CityGML includes many aspects of city model, including its geometry, topology, and semantics. It makes a distinction among vegetation, water, buildings and transportation. Geometry and semantic characteristics are divided into five LoD allowing to describe the same entity with distinct degree of detail [39].

The LoD0 is a 2D DTM with a map or an aerial image. LoD1 is a volumetric model and a LoD2 building has roof and textures. LoD3 reveal construction details on walls and roofs, balconies and loggias, detailed transportation entities and vegetation. LoD4 adds interior building spaces, doors, furnitures and stairs.

Figure 15: CityGML Level Of Detail

Objects' physical characteristics in CityGML are represented by a model integrating both geometries and topologies, according to the B-Rep [40], which can include also semantic properties like attributes, relations and hierarchies between entities. Regarding the spatial description, geometries are linked to semantic entities. Hence, the model is composed by two orders: the semantic and the geometric-topological, with relation between the two.

Frequently objects' attributes have values that can be discretized. For instance, the roof types that can be constructed are restricted to limited typologies like hip roof, flat roof, saddleback roof and so on. If properties like this one are filled manually as a string, spelling mistake or synonyms will obstacle interoperability. Therefore, in CityGML similar attributes can have values specified as Code Lists, which registers all values ensuring that the one name is only used for one concept.

The model of buildings is a central part of CityGML, allowing the description of its properties and geometries. The main class is an Abstract Building, which can be detailed as a Building or a Building Part. In LoD1 an Abstract Building is represented by a simple block using a *SolidGeometry*.

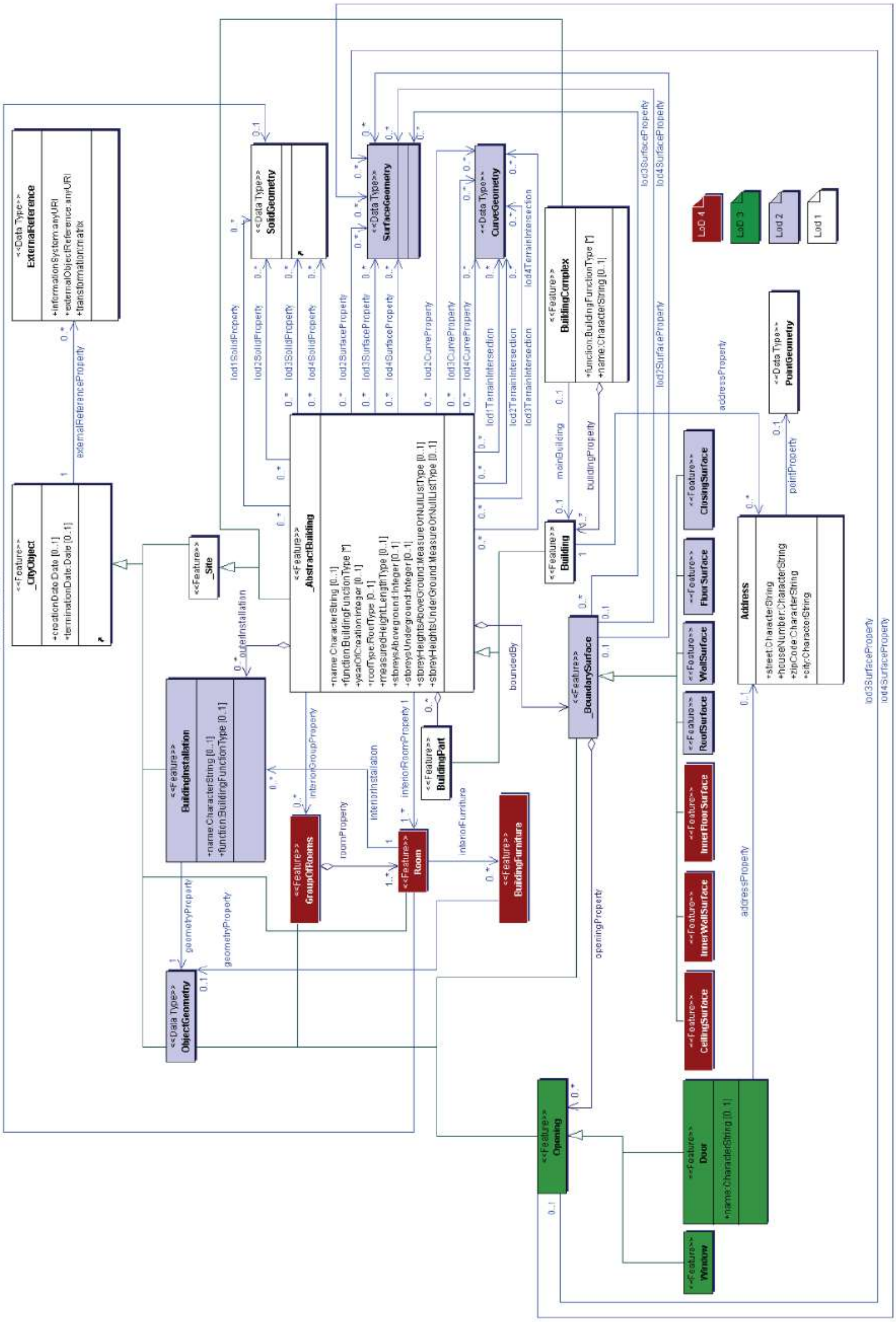

Figure 16: UML-Diagram of CityGML’s building model [41].

Using CityGML, urban models may be used in energy planning [42] and thermal simulations [43]. Clearly, to allow for such activities the model require domain-specific semantics, for example, the assessment of building energy demand needs information about function, materials, occupants and others [44]. CityGML provide the means for capturing such information, and thus allowing many specific applications, thanks to its data schema configuration,

On one side, CityGML was conceived as a generic format to store urban models, allowing to describe generic attributes. This means that, by itself, it does not store information required by specific applications. On the other hand, the model can be enriched with domain-specific data via the definition of an extension schema based on CityGML, called Application Domain Extensions (ADE). This methodology allows the definition of specific classes, relationships and attributes for domain-specific activities which need many specific features such as the Energy ADEs [45].

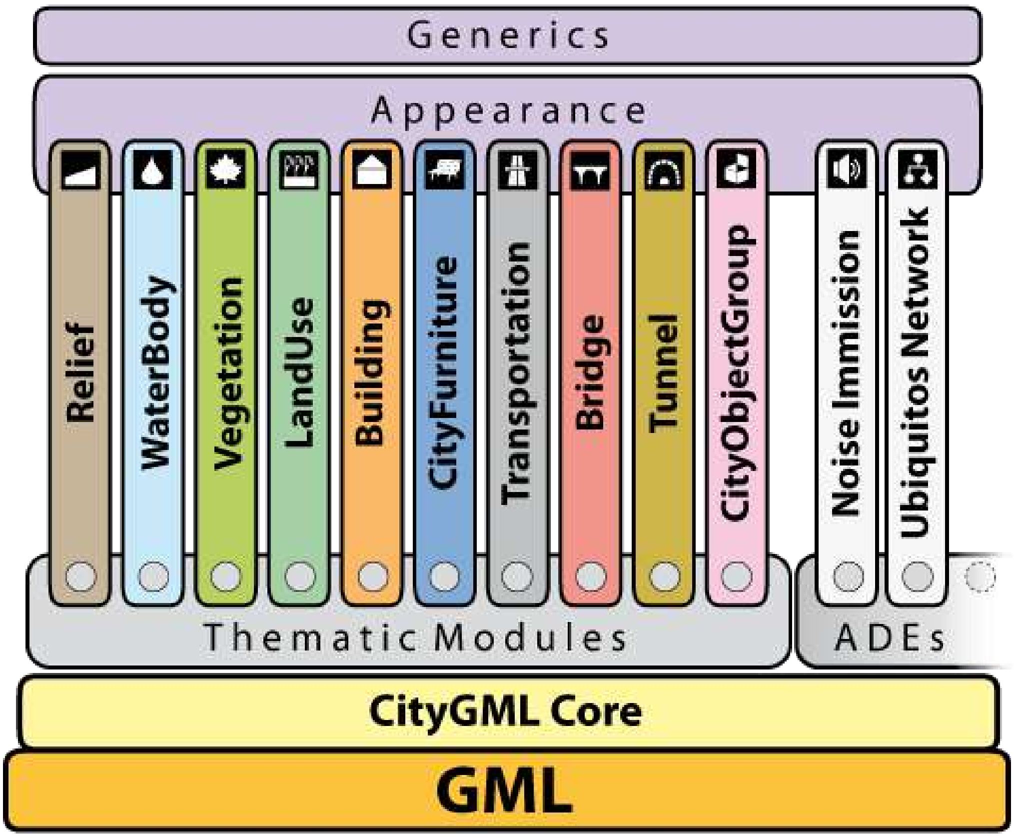

Figure 17: CityGML thematic modules and ADEs [24]

[24] From VirtualcitySISTEMS web page: https://www.virtualcitysystems.de/en/solutions

CityGML Energy ADE [46]

The ADE mechanism, used to extend CityGML functionality with domain specific needs, is capable to enhance interoperability for urban energy simulations. This, paired with the scale overlap among CityGML and open BIM standards, open an interesting possibility for multiscale energy assessment.

The CityGML Energy ADE was conceived through a common consensus-driven development process, involving international experts from several European countries. This collaboration process led to the publication of the Energy ADE 1.0 in January 2018. Interestingly enough, the Energy ADE allows for energy assessment both at the building and urban scale, focusing on building physical properties and its systems. The research group analysed existing data models for energy simulation with the goal of finding shared characteristics and modelling methodologies. This led to the identification of classes and attributes and their organisation in modules, shortly described below.

- The **Energy ADE Core** module define abstract base classes and data types. It extends the classes Abstract Building and City Object with new attributes.
- The module **Building Physics** supports attributes to define zones within energy assessment.
- The module on **Occupant Behaviours** allows to describe building’s occupants.
- The module on **Material and Construction** provides descriptive attributes of materials.
- The module for **Energy Systems** enables to detail building's devices for energy usage.
- Other **Supporting Classes** provide time series, schedules and weather data.

There is much interest in spatial RDBMS capability to make use of the Energy ADE, broadening the support for energy analyses. Unfortunately, the 3DcityDB [47][25], an open-source application of cityGML schema, is not mature enough to manage Energy ADE elements. Researchers are actively investigating strategies to enable the 3DCityDB to deal with any ADE [42].

Figure 18: Example of Energy ADE application for building heating loads, from Agugiaro et al. [48]

[25] “3DCityDB”. https://www.3dcitydb.org/3dcitydb/. Accessed 25 Jul. 2020

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5 CASE STUDY: RENOVATION AND EXTENSION OF HISTORICAL HOTEL IN LJUBLJANA

5.1 Hotel Bellevue

5.1.1 The context

The project involves the renovation and extension of the building at the address Pod Gozdom 12, in Ljubljana, to result in a new hotel. The existing structural core of the building is maintained, while everything else is removed and reconstructed.

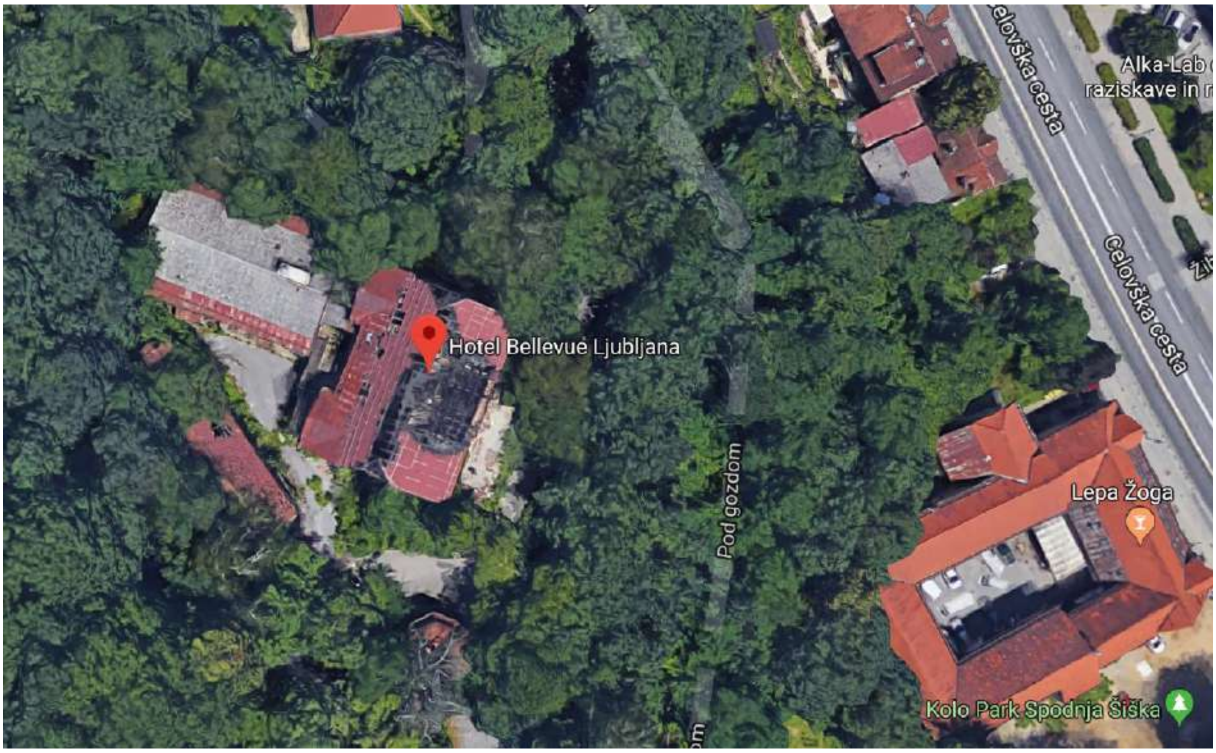


Figure 19: Aerial view from Google Maps

The property is in poor condition due to decades of neglect as well as several fires. In the last fire of 11 May 2014, the roof was destroyed.

Hotel Bellevue was built in 1909 and it was sold several times in its history, until it was nationalised by the Yugoslav government in 1953. After the Slovenian independence (1991) the property seems to have lost its prestige, and it was sold in 2005 to a student agency. The hotel was declared a cultural heritage of local importance in 2007.The surrounding area consists mainly of trees and bushes, and front of the entrance is still present the wooden pavilion, as can be seen in the pictures below.

Figure 20: The actual condition of the property[26] and an historic postcard of the café Bellevue.[27]

5.1.2 The project

The plot intended for construction includes a total of 4893m^2, where the gross floor area of buildings, excluding parts of the basement intended for the service space, amount to a total of 11155 m^2. The historic building will be partly demolished and reconstructed as a replica, using modern building materials, in accordance with local regulation for the conservation of cultural heritage. A new addition is designed to be functionally related but highlighting its distinction from the pre-existing facility. This will preserve the character of the Bellevue Hotel and its relationship with the surrounding.

[26] https://lh5.googleusercontent.com/p/AF1QipNKRZDALWWlPF1yL3RsH_T7zQ9q_FcaB1IMkeB0=w1440-h1440-pd. Accessed 25 Jun. 2020.

[27] "Razglednica Zajčeve restavracije in kavarne Bellevue.jpg" https://commons.wikimedia.org/wiki/File:Razglednica_Zaj%C4%8Deve_restavracije_in_kavarne_Bellevue.jpg. Accessed 25 Jun. 2020.

Figure 21: Exterior render of the historic building and its new addition

Other facilities in the complex, as the two wooden pavilions and the small outbuilding are being reconstructed. In the latter, the so-called Villa Bellevue, will be arranged 3 accommodation units. The hotel will have capacity of 102 rooms and 3 apartments in the historic building, plus spaces dedicated to catering, wellness and congress. The project also deals with the arrangement of traffic and the external areas around the building.

Figure 22: South view of the complex with the pavilions and exterior area

The facility will adopt energy saving principles and heat conservation technologies, using as much renewable energy sources as possible in the operation of building systems, as to ensure energy efficiency. The building will be properly oriented and designed with a favourable ratio between the surface of the thermal envelope and its conditioned volume. The rooms will be optimally distributed for efficient heating, cooling and lighting. Materials and construction elements and the entire external surface of the facility will enable efficient management of energy flows. Passive building strategies as cross ventilation and night cooling will ensure that solar radiation and high outdoor temperatures will not overheat the interior spaces. Hot water will be centrally provided using renewable energy sources. Where this is not possible, it will be ensured the energetic efficiency of the system. Natural daylighting strategies will be adopted to lower the energy loads for interior lighting.

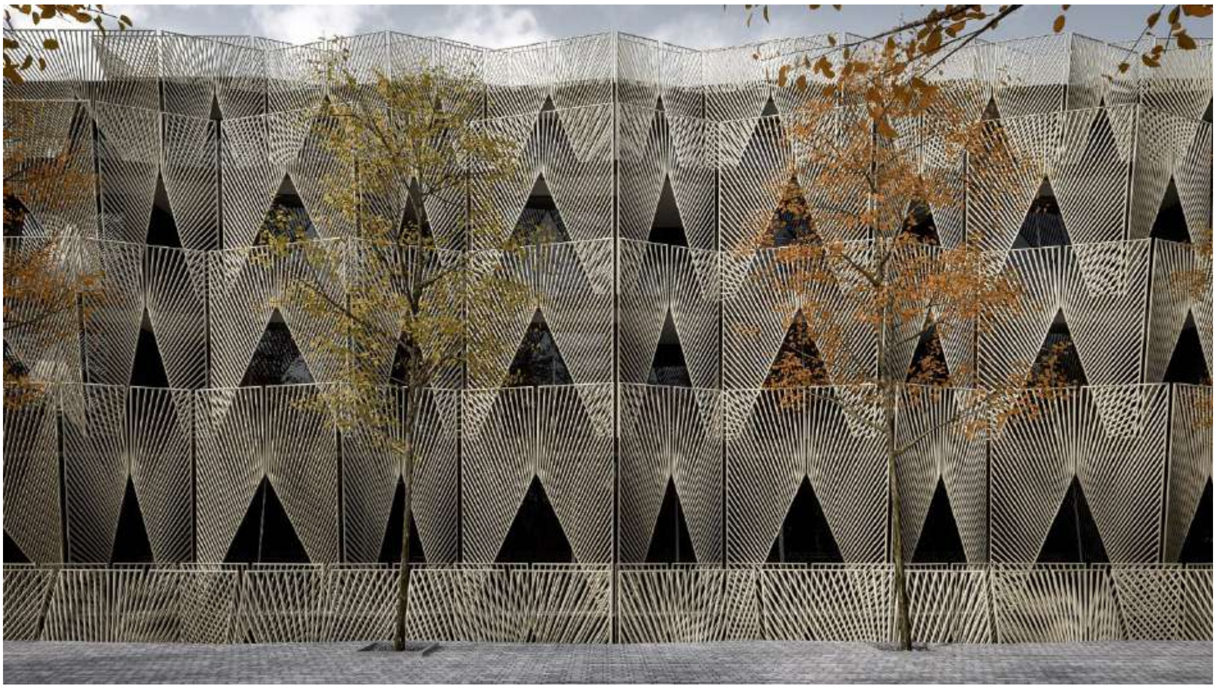


Figure 23: Detail of the facade for the extension of the hotel

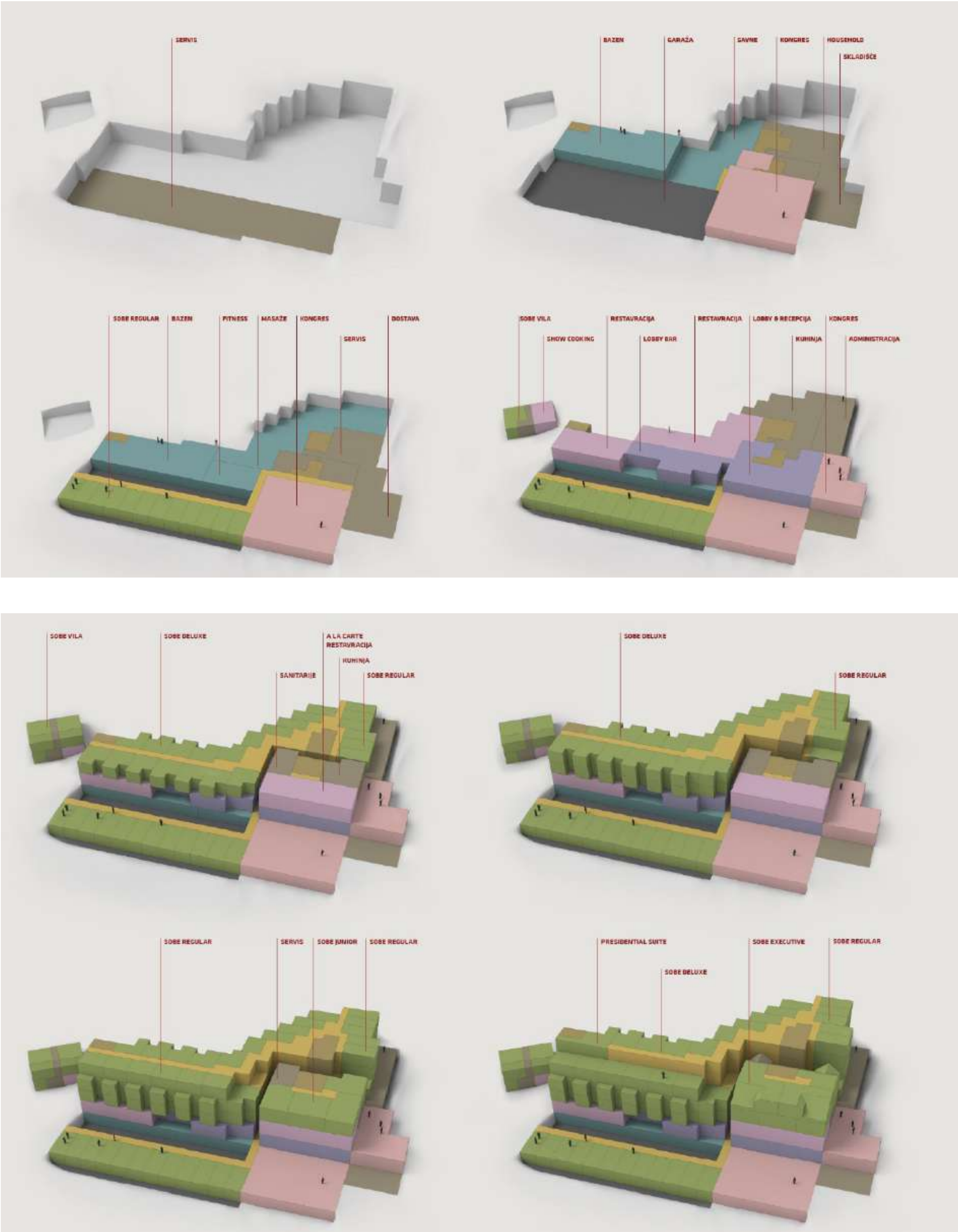


Figure 24: 3D volumetric diagrams with the functional distribution

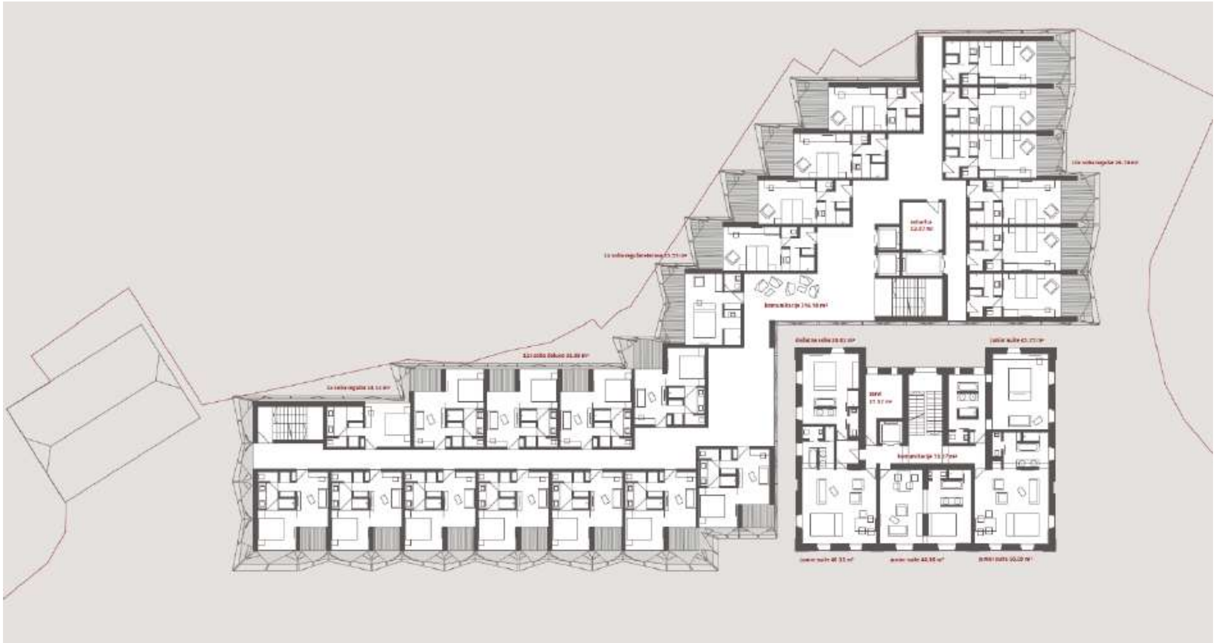


Figure 25:Typical floorplan of the hotel

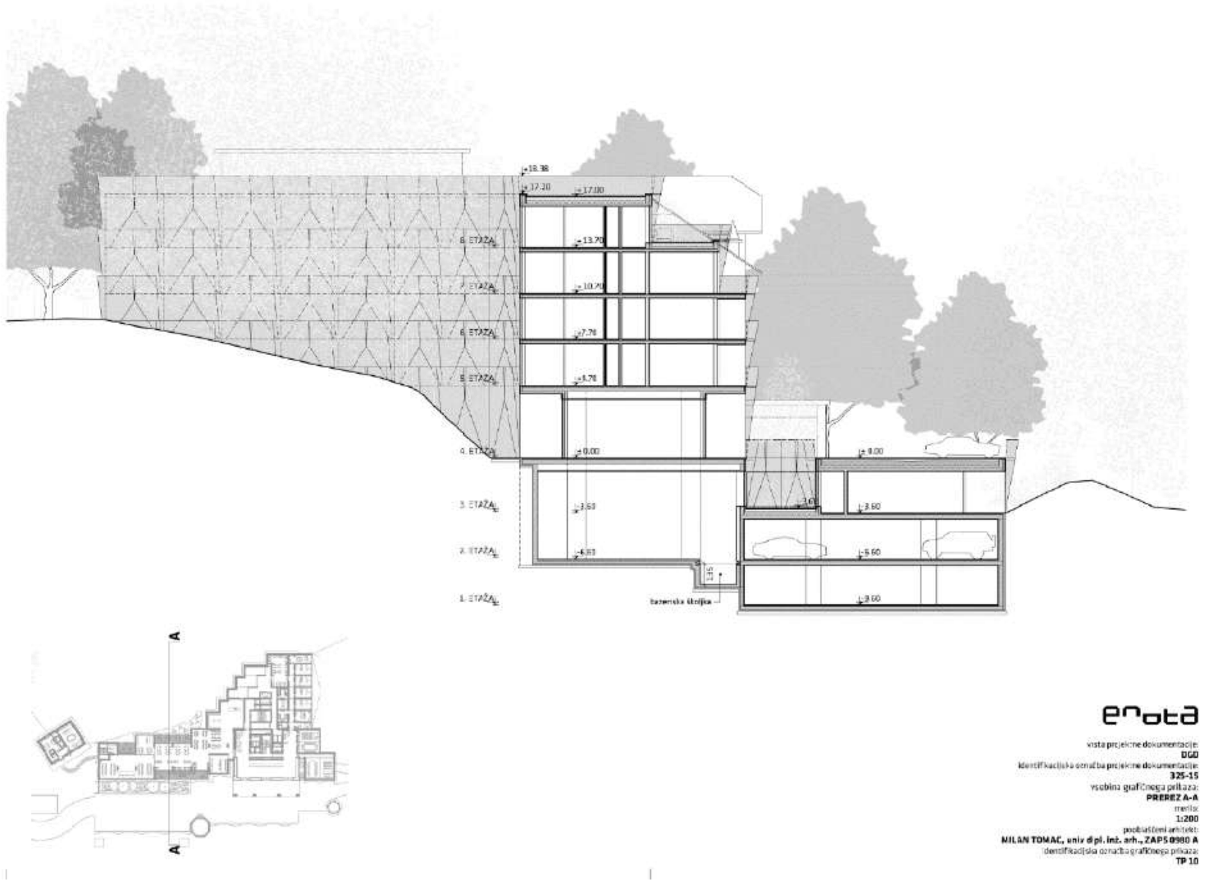


Figure 26: Transversal section of the new extension

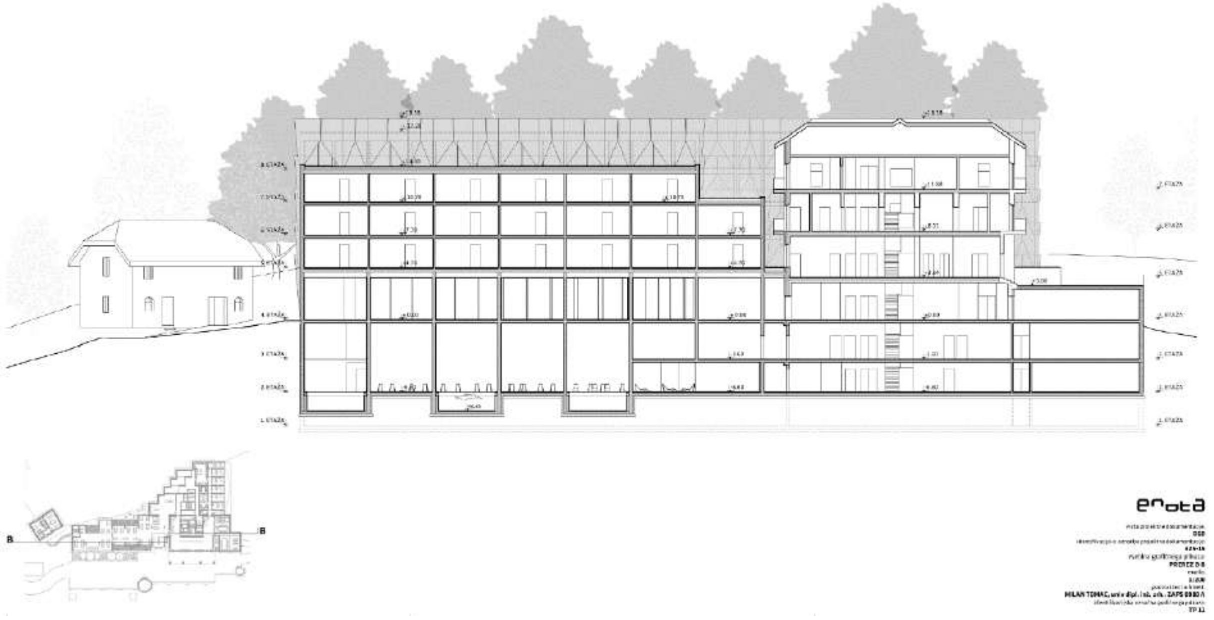


Figure 27: Longitudinal section of the building

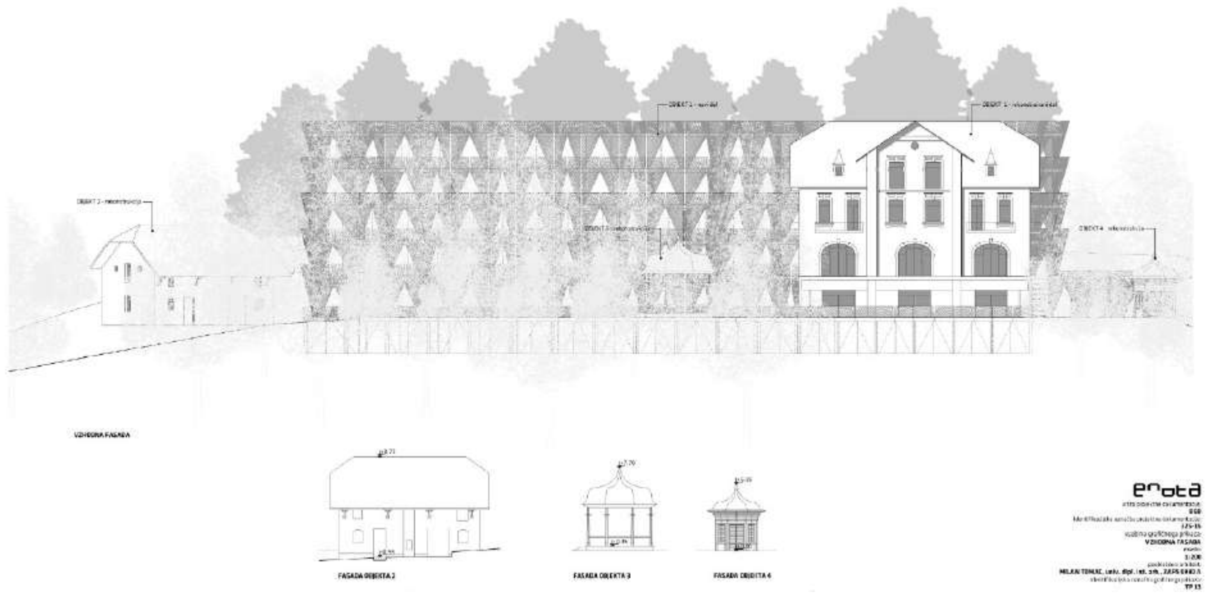


Figure 28: Main facade of the hotel

5.2 Methodology

5.2.1 Top-down approach

The methodology illustrated below proposes a top-down approach for multiscale analysis of the built environment. It involves the conception of a semantic 3D city model that can be used as a base for different urban scale assessments. The information derived from these analyses can then be used as guidelines to inform energy, transportation, and social policies.

An urban settlement is a complex aggregate of different elements such as entities, processes and actors. Nowadays, the modelling of the city is generally relegated to sector-specific applications, each one with its own professionals, standards and planning rules. However, individual sectors could achieve substantial improvements if coordinated with a common model, and CityGML is one of the data models that can enable this. This requires agreeing on common terminology and tools. Furthermore, in city modelling are involved multiple scales (e.g. city, district, block, building, apartment and room). With cityGML, the city is decomposed into objects with clear semantics, spatial and thematic properties. For this research, the main objects of interest are the buildings and their thematic data.

The semantic 3D city model of a portion of Ljubljana is derived from public data available online, in the webpage of the Ministry of the Environment and Spatial Planning, Geodetic Administration of the Republic of Slovenia[28]. Lidar data is acquired via the online Environmental Atlas, maintained by the Environmental Agency of the Republic of Slovenia (ARSO)[29]. At the same time, specific data regarding the Municipal Spatial Plan of the City of Ljubljana is available in the webpage of the Ministry of the Environment and Spatial Planning, Spatial Information System[30]. The process is subdivided in two steps: first the modelling of geometric features up to LoD1, then the enrichment of the urban model focusing on several building characteristics.

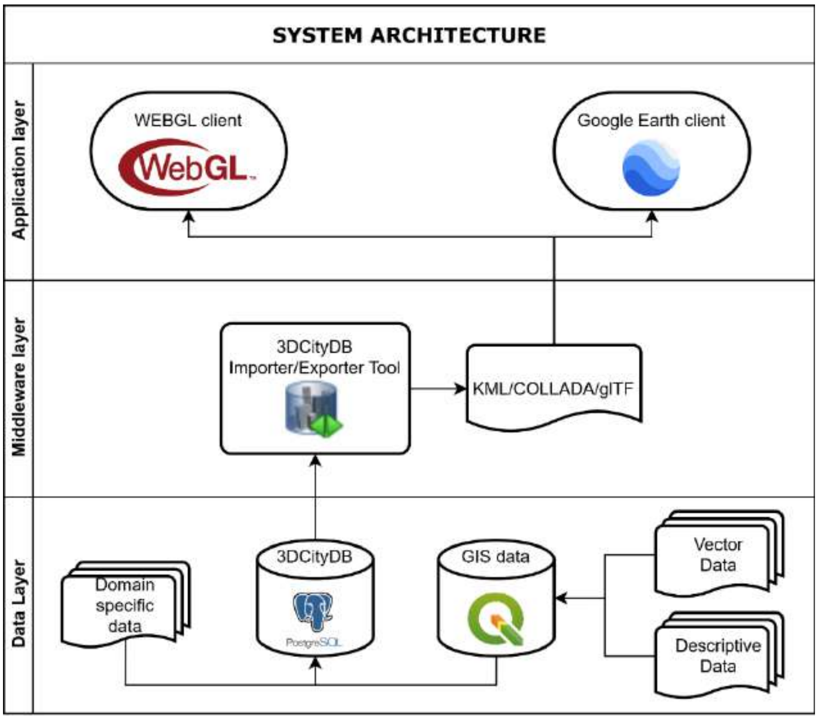


Figure 29: Generic description for a SOA. Modified from Giovannini et al.[49]

[28] "eGP - e-Geodetski podatki - Geodetska uprava." https://egp.gu.gov.si/egp/. Accessed 25 Jun. 2020.
[29] "Lidar GIS viewer." http://gis.arso.gov.si/evode/. Accessed 25 Jun. 2020.
[30] "Dostop do podatkov o prostorskih aktih" https://dokumenti-pis.mop.gov.si/javno/veljavni/O61I/index.html. Accessed 25 Jun. 2020.

The process of creation and usage of a semantic 3d city model can be described referring to a system architecture describing a Services Oriented Architecture (SOA) with three components.

The data layer stores information about the facilities. The fundamental component of this layer is the 3DCityDB [47], which is built integrating GIS data and other domain-specific data. The database holds the information about city objects, which is organised according to the cityGML schema, for different modelling procedures and assessments. The middleware layer manages the relation between the application component and the data component, allowing to access to the information stored in the database via the 3DCityDB Import - Export Tool[31]. The WebGL technology[32] along with Google Earth[33] client were employed in the application component.

Step 1: Ljubljana city model geometries in LoD1

Today the modelling of 3D city models at LoD2 is nearly automated, however it requires specialised software that are neither free nor open source. In the context of this research the model is created up to LoD1, using the open-source software “3dfier” developed at TU Delft[34]. 3dfier takes 2D GIS datasets and makes them three-dimensional with the support of point cloud files. Every polygon in the GIS files is extruded and connected to the ground, creating a single Digital Surface Model (DSM) is constructed. The output is an error-free surface which can be saved as cityGML, cityJSON, OBJ, IMGeo and CSV.

[31] "3DCityDB." https://www.3dcitydb.org/. Accessed 10 Jul. 2020
[32] "WebGL Specification - Khronos Group." https://www.khronos.org/registry/webgl/specs/1.0.0/. Accessed 2 Sep. 2020.
[33] "Explore Google Earth." https://earth.google.com/web. Accessed 2 Sep. 2020.
[34] "Open-source projects." https://3d.bk.tudelft.nl/code/. Accessed 25 Jun. 2020.

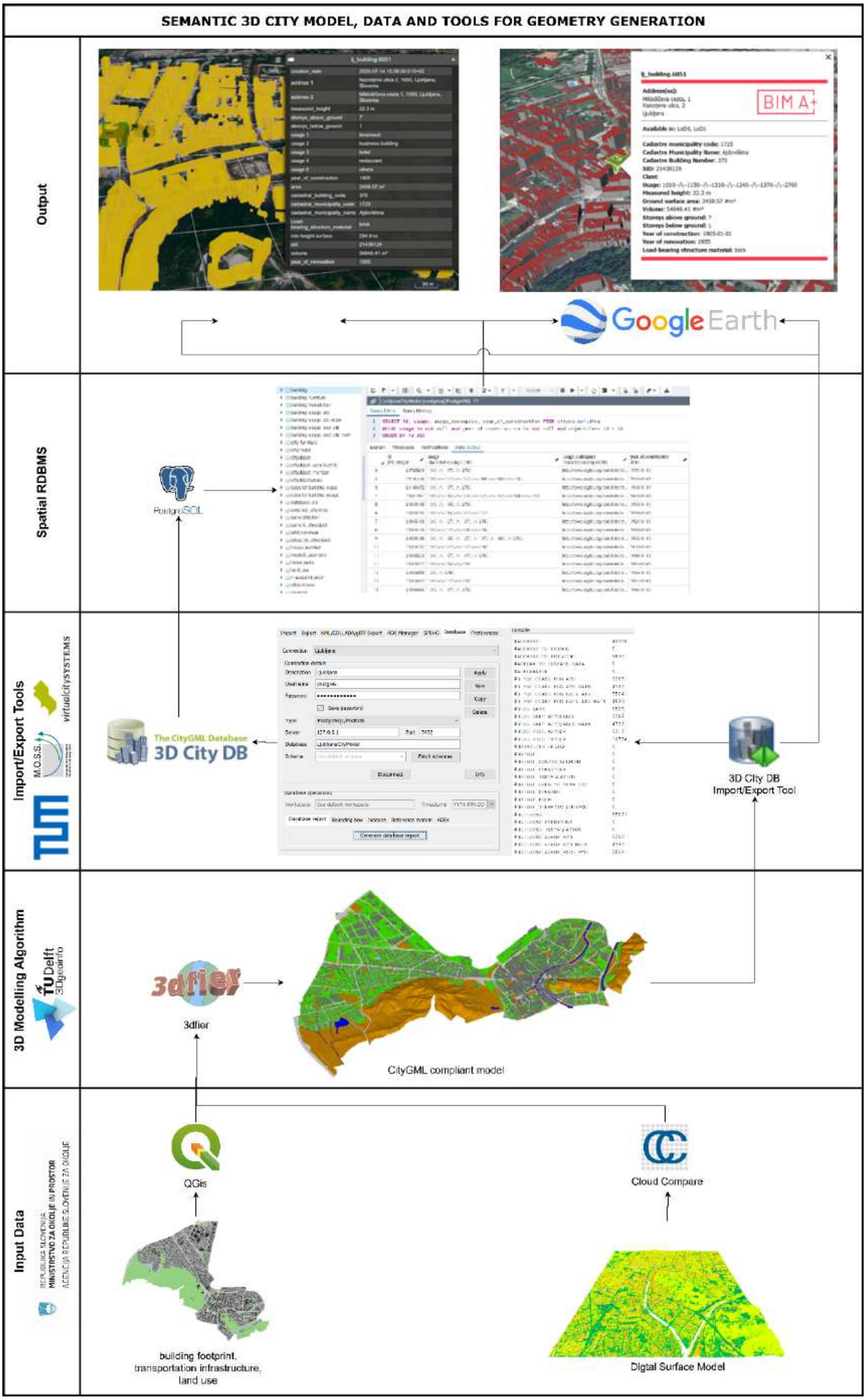


Figure 30: Dataset and applications used in creation of the urban model

The input of the algorithm consists of Digital Surface Model (DSM) files and a set of topologically connected polygons. The GIS dataset downloaded from the institutional webpages mentioned above consists of the municipal boundaries of Ljubljana, the city quarters and the orthophoto. These provide context and act as masking polygons for Boolean operation of subtraction.

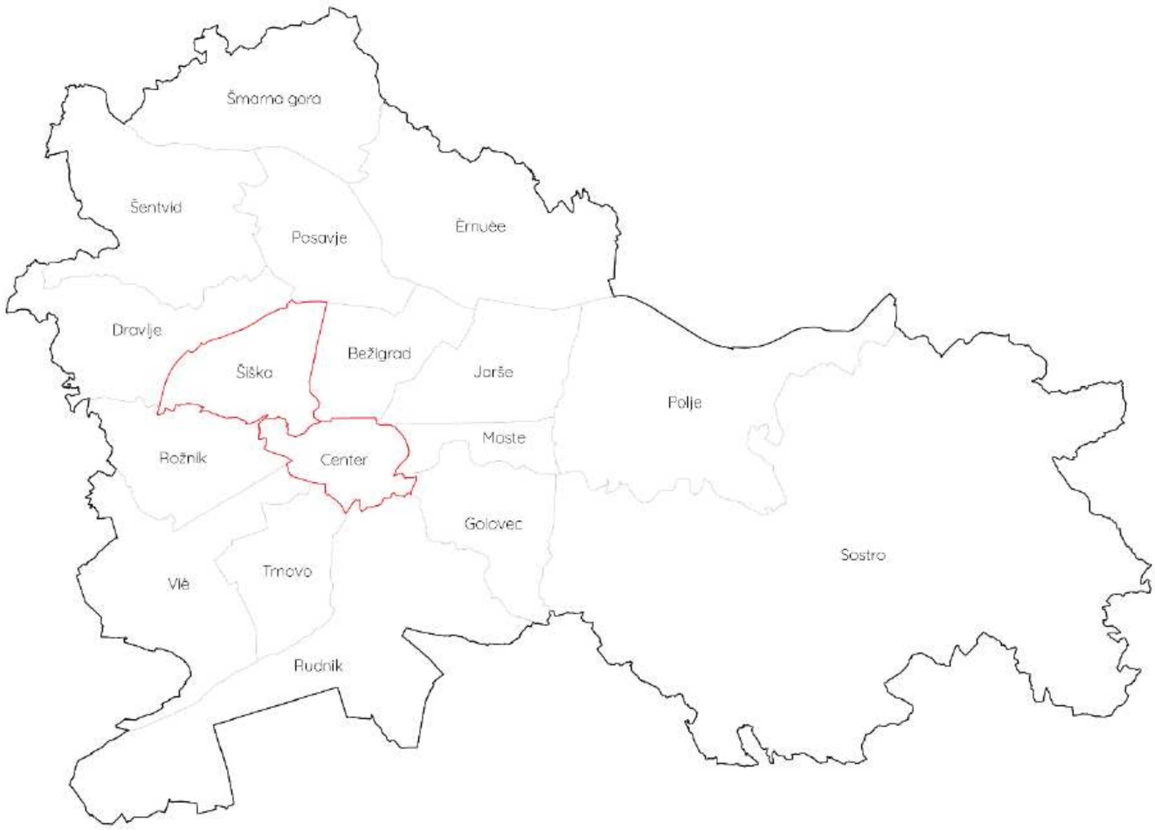
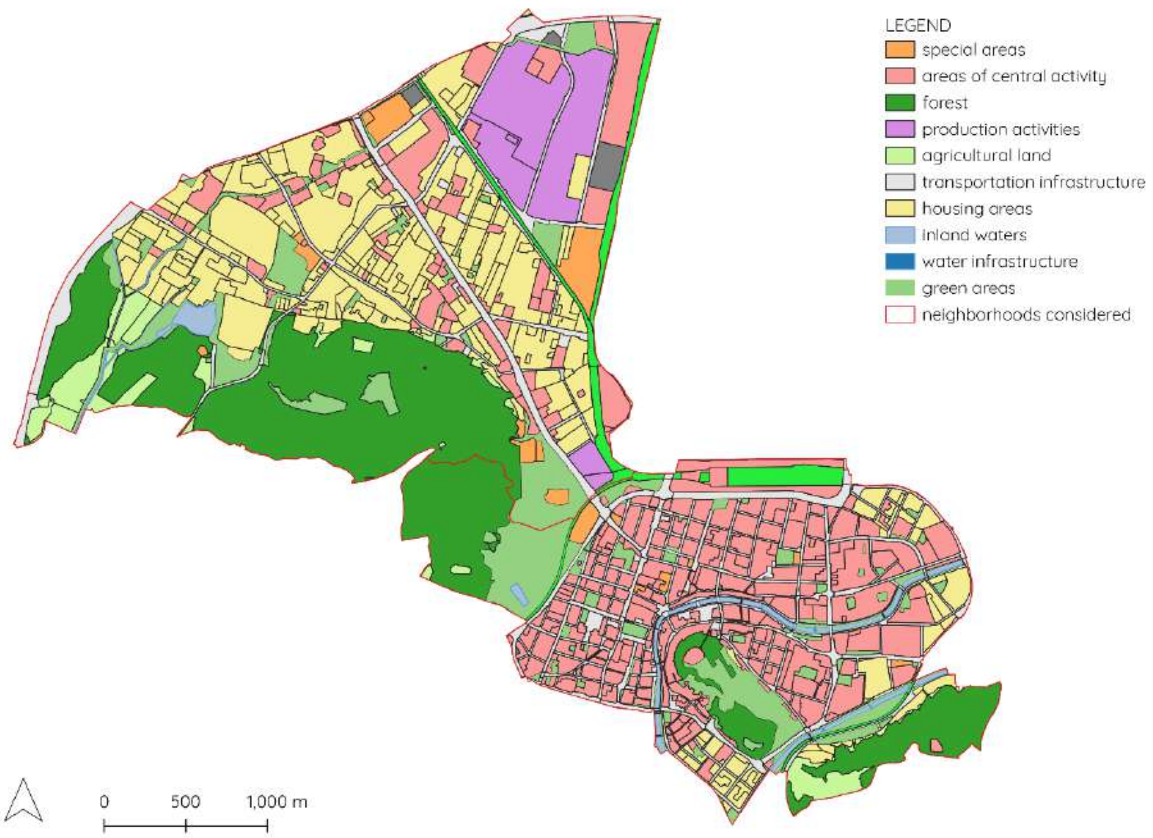


Figure 31: the municipal boundaries of Ljubljana and the neighbourhoods.

Figure 32: The orthophoto and boundaries of the considered neighbourhoods

The dataset regarding the Municipal Spatial Plan of the City of Ljubljana was downloaded and edited using the open-source software QGis[35], to be used in 3dfier. This was useful to obtain the semantic and 2D geometrical information related to the city entities that can be elaborated by 3dfier software, namely: buildings, roads, bridges, terrain, vegetation and water bodies.

[35] " QGIS project" https://www.qgis.org/en/site/. Accessed 25 Jun. 2020.



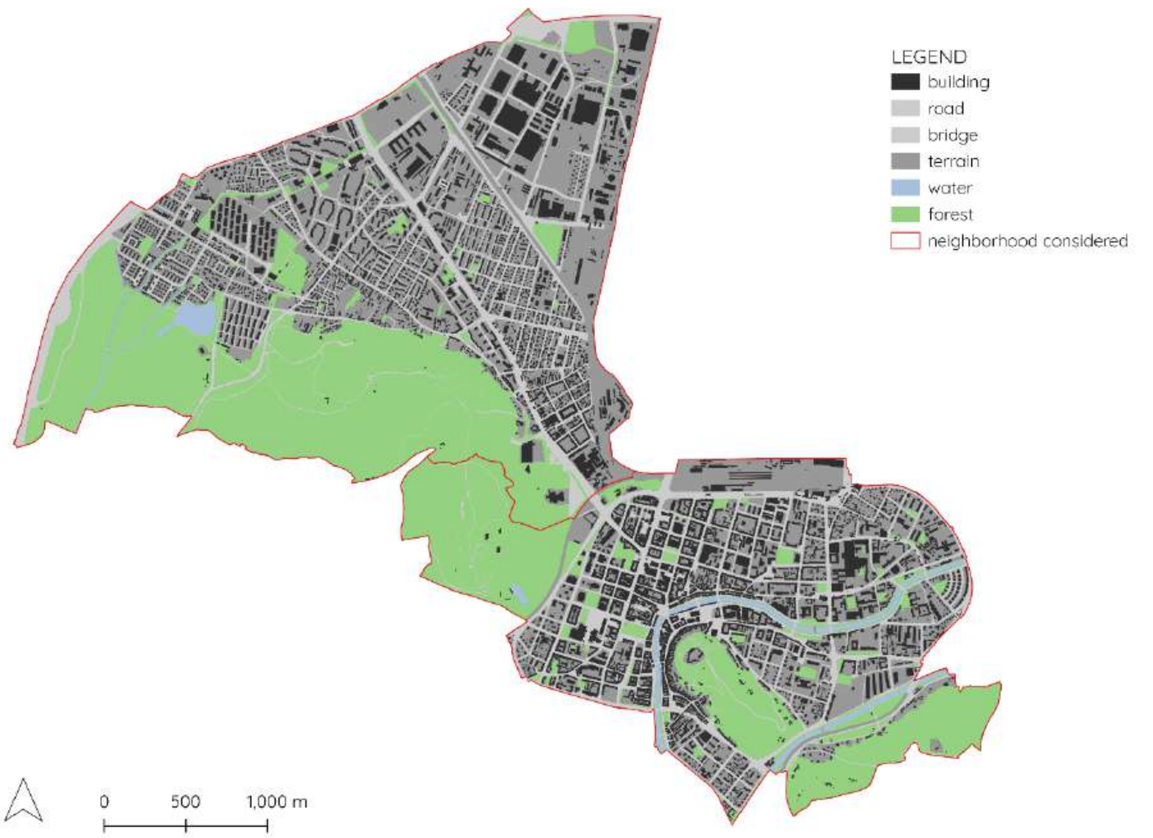


Figure 33: From the Municipal Spatial Plan to the Features managed by 3dfier

The data sources for building footprints are:

- Graphic data from the cadastre of buildings, which is geo-referenced and building footprints have unique IDs, however multiple buildings are often aggregated in a single footprint.
- National Topographic Model obtained from the latest cyclic aerial photography of Slovenia and laser scanning of Slovenia. This is more detailed, coincide well with the DSM and there is no important distortion. Unfortunately, it has incomplete classification of buildings' type, usage and year of construction. However, it provides links to the cadastral data.

Figure 34: Example of building aggregation in the cadastre of buildings (blue).

The cadastre of buildings has therefore cardinality issues. Sometimes it lacks clear identification of multiple building parts. To overcome this problem, it was decided to preserve the descriptive data of the cadastre of buildings, but use the topographic map as a source for building footprint. The unique building IDs, required to run the 3dfier algorithm and create 3d geometry, are automatically generated during the export of the building footprint in GML format. However, to make use of the descriptive data from the cadastre, the cadastral codes had to be transferred to the topographic map. The topographic map includes structures such as sheds and garages which are typically unheated. These were removed through integration with the database of addresses and both a spatial and table database join.

Figure 35: 3D reconstruction of considered neighborhoods, circa 9640 buildings in LoD1

Step 2: Ljubljana city model attributes enrichment

After the 3D reconstruction of all features contained in the neighbourhood considered, the building models were enriched with descriptive datasets. For attribute datasets a translation from Slovenia to English language was required, along with other procedures to solve semantic and structural incompatibilities. Each building was described with the following attributes:

Table 4: Data, sources and attributes describing building features.

Data	Source	CityGML Attribute
Unique Building identifier	REN/KS	id
Cadastral municipality code	REN/KS	cadastral_municipality_code
Cadastral municipality name	RPE	cadastral_municipality_name
Cadastral building code	REN/KS	cadastral_building_code
Building class	-	class
Building part usage	REN	usage
Number of underground floors	REN	storeys_below_ground
Number of floors above ground	REN	storeys_above_ground
Building height	-	measured_height
Construction year	REN	year_of_construction
Renovation year	REN	year_of_renovation
Material load-bearing structure	REN	load-bearing_structure_material
Building volume	-	volume
Building ground area	-	area
Building addresses	REN/RPE	address

REN = Slovenian Real-estate Registry; KS = Slovenian Building Cadastre; RPE = Slovenian Register of Spatial Units

Information not following the CityGML standard was integrated using *GenericAttribute*. This is highlighted in the table with a grey background.

Figure 36 Shows an Entity Relation diagram illustrating the attributes and the relations between the data, while Figure 37 exemplify another cardinality issue between the cadastral building footprint, in blue, and the addresses represented as green and red dots. Where the addresses are represented as red dots, these are referring to different building units that are represented with a single cadastral footprint.

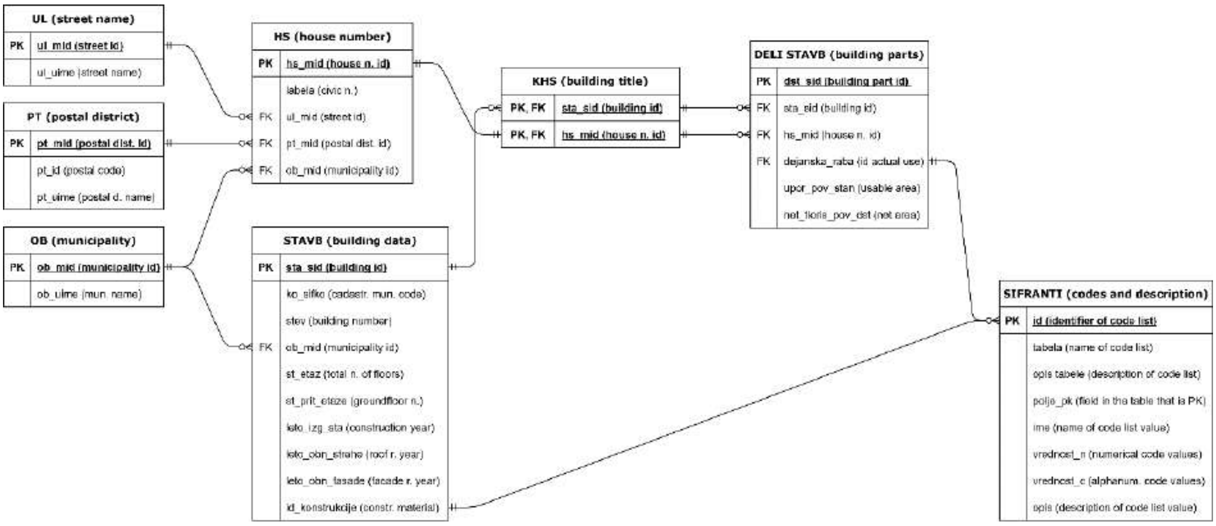


Figure 36: Entity Relation diagram, English translation in parenthesis

BUILDING_ID	ADDRESS_ID
33914791	12922566
33914791	12922574
33914791	12922604

BUILDING_ID	ADDRESS_ID
26799342	12922566
21427367	12922574
26799344	12922604

Figure 37: Addresses before and after spatial joint

Using the 3DcityDB applications, the city model was imported into a database, where descriptive information was organized as attributes. Figure 38 exemplify a view in Google Earth of the constructed model exported as a .kml, whereas Figure 39 shows the model in the 3DCityDB Webmap Client.

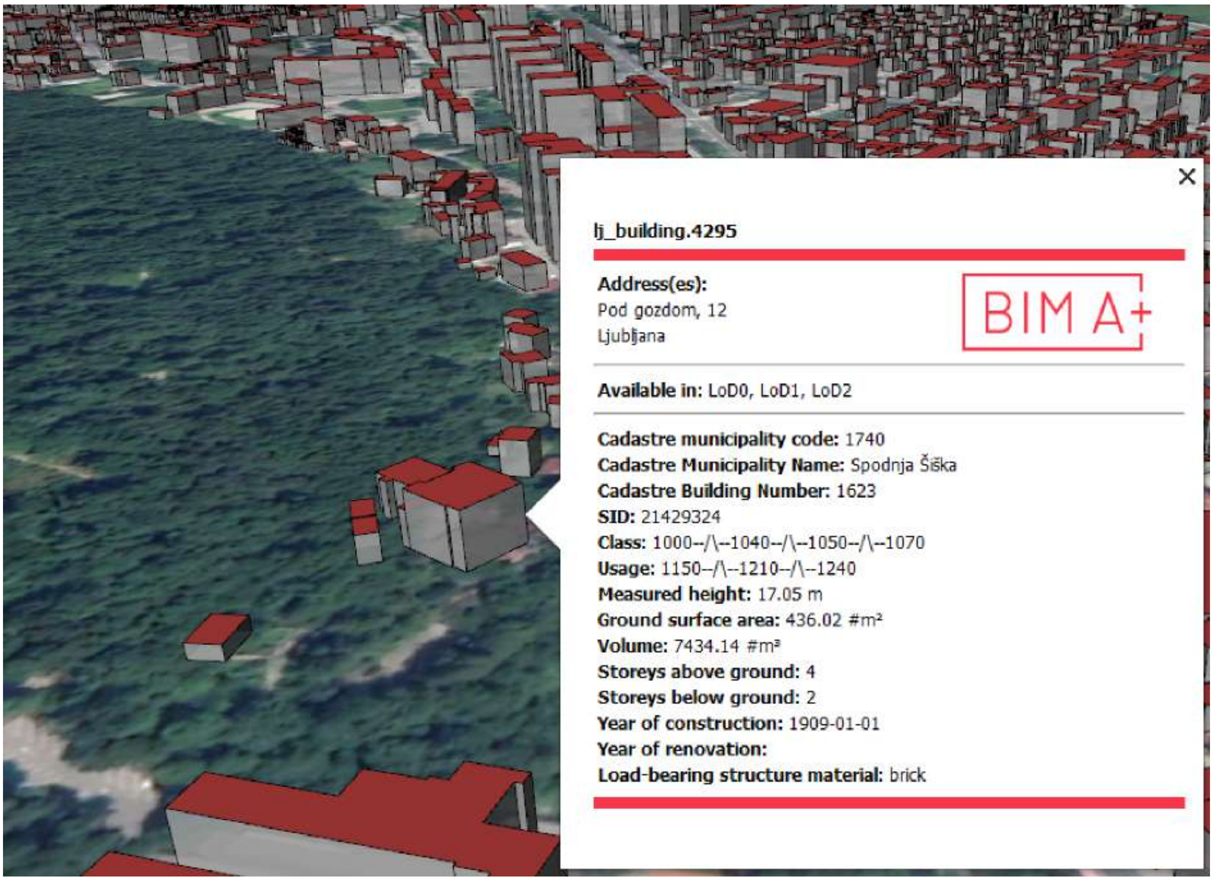


Figure 38: A view of the urban model in Google Earth.

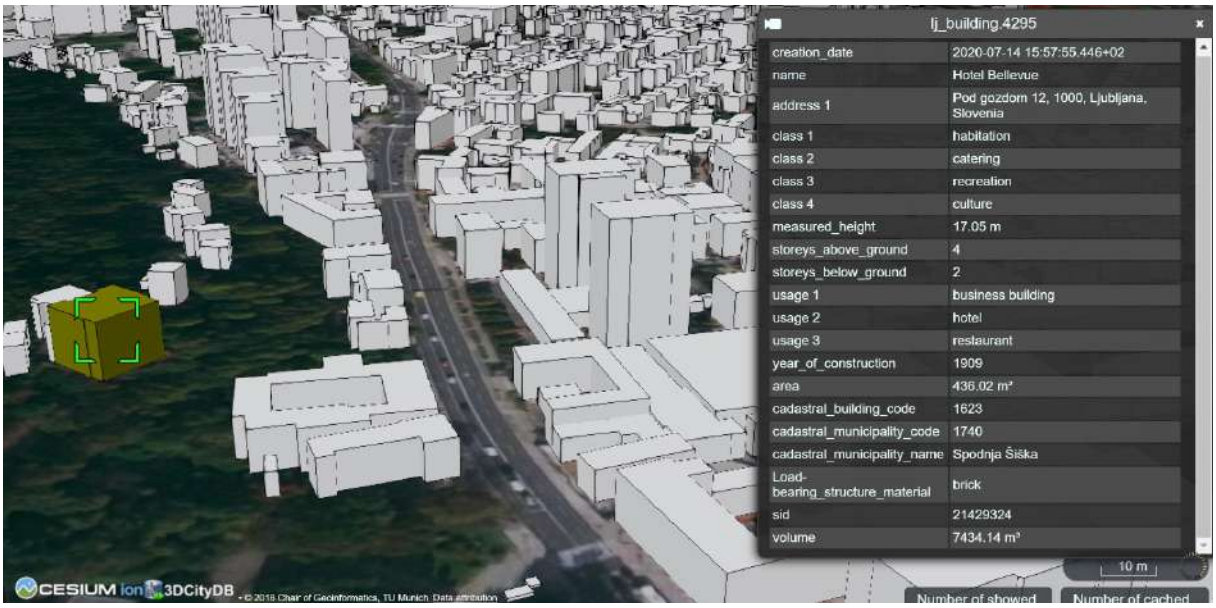


Figure 39: the model in the 3DCityDB Webmap Client

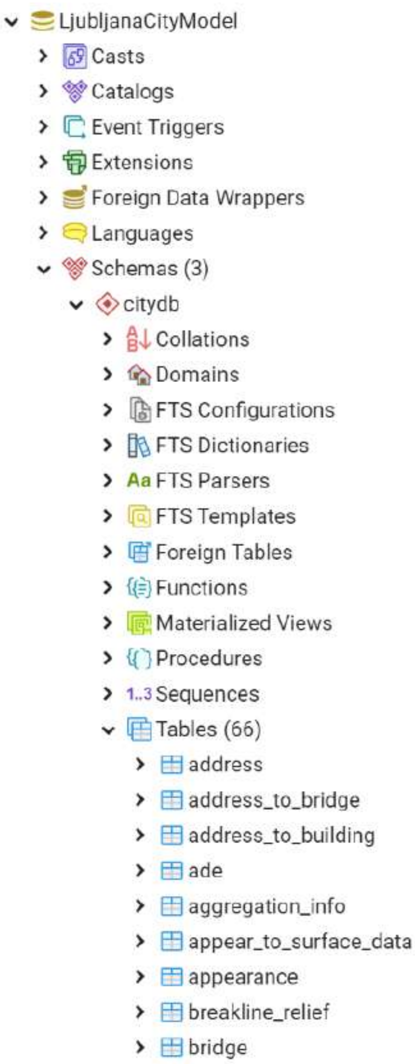


Figure 40: the structure of the 3D City Database

The Structured Query Language (SQL) is used to handle databases and PostgreSQL[36] is a open-source Relational Database Management System (RDBMS). PostGIS[37] extends the database with support for GIS entities and allowing to query the model using SQL. PgAdmin[38] provides the DB administration GUI. It is important to higlight the underlying structure that support the creation of a semantic 3D city model: A PostgreSQL *server* contains one or multiple *databases*, that are composed by one or multiple *schema.* A schema contains *tables*, *views*, and *function*, where tables consist of *columns* and contain *records.*

3DCityDB[39] is an open-source application of the cityGML schema that can be downloaded along with an import/export tool, to handle CityGML data from and to the database, and several SQL statements to create the schema. From the UML diagram it is then possible to define database tables, thus moving from Object-Oriented models to Entity-Relation models.

To define the different usages of the buildings, it was necessary to import into the 3d city database all relevant building parts from the cadastre of building, because here is where such information is stored. Figure 41 shows the SQL statement to perform such operation, using *gmlid_codespace* as temporary attribute fields to store the *building_parent_id*, which determines to which *Building* the *buildingPart* pertains to. Because the topographic map was used as a source for building footprint instead of the cadastre of building, the *address_to_building* table was used to join the building parts with the correct *building_parent_id* after spatial join.

[36] "PostgreSQL." https://www.postgresql.org/. Accessed 10 Jul. 2020.
[37] "PostGIS." https://postgis.net/. Accessed 10 Jul. 2020.
[38] "pgAdmin." https://www.pgadmin.org/. Accessed 10 Jul. 2020.
[39] "3DCityDB." https://www.3dcitydb.org/. Accessed 10 Jul. 2020

```sql
INSERT INTO cityobject (id, objectclass_id, gmlid, gmlid_codespace, name)
SELECT bldgpart_id, objctcls_id, gml, building_id, atb_bldg_id FROM
    (SELECT
        bp.dst_sid AS bldgpart_id,
        bp.sta_sid AS building_id,
        atb.building_id AS atb_bldg_id,
        atb.address_id AS adrs_id,
        25 AS objctcls_id,
        CONCAT('lj_buildingpart.', bp.dst_sid::varchar) AS gml
    FROM ren_bldgpart bp
    LEFT JOIN address_to_building atb ON bp.hs_mid = atb.address_id) as prt
```

Data Output Explain Messages Notifications

	id [PK] integer	objectclass_id integer	gmlid character varying (256)	gmlid_codespace character varying (1000)
1	20506001	26	lj_building.83	[null]
2	20725293	26	lj_building.100	[null]
3	20725296	25	lj_buildingpart.20725296	20725293
4	20725297	25	lj_buildingpart.20725297	20725293
5	20725313	25	lj_buildingpart.20725313	20725293
6	20725314	25	lj_buildingpart.20725314	20725293
7	20725316	25	lj_buildingpart.20725316	20725293

```sql
SELECT * FROM citydb.building
ORDER BY id ASC
```

Data Output Explain Messages Notifications

	id [PK] integer	objectclass_id integer	building_parent_id integer
1	20506001	26	[null]
2	20725293	26	[null]
3	20725296	25	20725293
4	20725297	25	20725293
5	20725313	25	20725293
6	20725314	25	20725293
7	20725316	25	20725293

Figure 41: creation of *buildingParts* (objectclass_id: 25) from cadastral data. Each *buildingParts* must have a *building_parent_id* that define to which *building* (objectclass_id: 26) it pertains to.

For the attribute *usage* of a building, where values can be residential, office building, post office, pharmacy etc. It was chosen to adopt a Code List from the CityGML standard document.

Table 5: Example of code list from the OGC CityGML Encoding Standard [50]

Code list of the *_AbstractBuilding* attributes *function* and *usage*			
http://www.sig3d.org/codelists/standard/building/2.0/_AbstractBuilding_function.xml			
http://www.sig3d.org/codelists/standard/building/2.0/_AbstractBuilding_usage.xml			
1000	residential building	1840	rubbish bunker
1010	tenement	1850	building for rubbish incineration
1020	hostel	1860	building for rubbish disposal
1030	residential- and administration building	1870	building for agrarian and forestry
1040	residential- and office building	1880	barn
1050	residential- and business building	1890	stall

```xml
<gml:name>_AbstractBuilding_usage</gml:name>
▼<gml:dictionaryEntry>
  ▼<gml:Definition gml:id="id1">
     <gml:description>residential building</gml:description>
     <gml:name>1000</gml:name>
   </gml:Definition>
 </gml:dictionaryEntry>
▼<gml:dictionaryEntry>
  ▼<gml:Definition gml:id="id2">
     <gml:description>tenement</gml:description>
     <gml:name>1010</gml:name>
   </gml:Definition>
 </gml:dictionaryEntry>
▼<gml:dictionaryEntry>
  ▼<gml:Definition gml:id="id3">
     <gml:description>hostel</gml:description>
     <gml:name>1020</gml:name>
   </gml:Definition>
 </gml:dictionaryEntry>
```

Figure 42: XML version of the *usage* code list suggested by Sig3D members[40]

[40] "Code List enumerating the values for the attribute *usage* of the feature type *_AbstractBuilding* in the module *building*" http://www.sig3d.org/codelists/standard/building/2.0/_AbstractBuilding_usage.xml. Accessed 2 Sep. 2020.

For this reason, the building *usage* code from the building cadastre was translated to the Sig3D code to show the implementation of code lists.

```
UPDATE building SET "usage" = CASE
WHEN usage =    '5000'  THEN    '1000'
WHEN usage =    '5001'  THEN    '1010'
...
WHEN usage =    '5057'  THEN    '2700'
WHEN usage =    '5058'  THEN    '1590'
ELSE NULL
END
```

Data Output Explain Messages Notifications

	id [PK] integer	objectclass_id integer	building_parent_id integer	usage character varying (1000)	usage_codespace character varying (4000)
1	20506001	26	[null]	1010--/\--1150--/\--1270--/\--2700	http://www.sig3d.org/codelists/standard/building/2.0/_AbstractBuilding_usage.xml
2	20725293	26	[null]	1010--/\--1370--/\--2700	http://www.sig3d.org/codelists/standard/building/2.0/_AbstractBuilding_usage.xml
3	20725296	25	20725293	1010	http://www.sig3d.org/codelists/standard/building/2.0/_AbstractBuilding_usage.xml
4	20725297	25	20725293	1370	http://www.sig3d.org/codelists/standard/building/2.0/_AbstractBuilding_usage.xml

Figure 43: translation of *buildingParts* (objectclass_id: 25) *usage* attribute values, and aggregation into the *building* (objectclass_id: 26) *usage* value

Once all the *buildingParts* were created with the relative *usage* code, the *usage* attribute relative to the whole building was created by aggregating the different usages of its *buildingParts* into a single attribute value, concatenating multiple values with a separator string "--/\--"[41]. The CityGML Importer/Exporter of 3DCityDB recognizes such attributes and maps CityGML files accordingly onto the corresponding database attribute values during import. Respectively, during export it generates multiple CityGML elements again of the same type, but with different values.

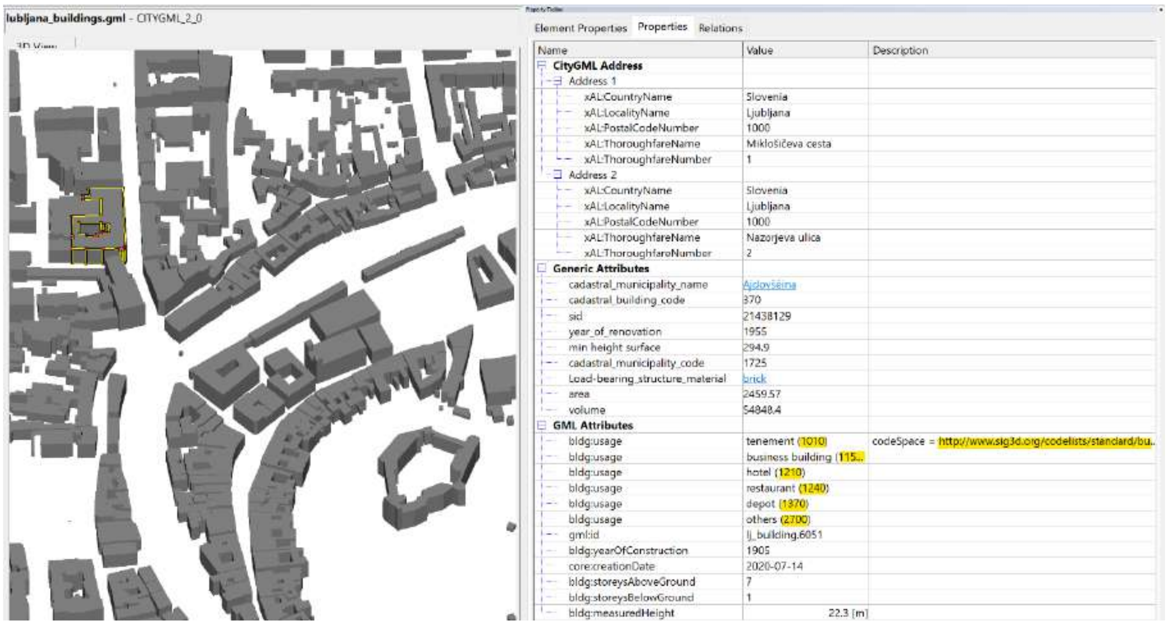


Figure 44: CityGML model in FZK Viewer[42], displaying the usages exported by the Importer/Exporter tool.

[41] "2.7.3.2. Core Model — 3dcitydb-docs 4.2.3 documentation." https://3dcitydb-docs.readthedocs.io/en/release-v4.2.3/3dcitydb/schema/module/core.html. Accessed 2 Sep. 2020.
[42] "Downloads - KIT - IAI." https://www.iai.kit.edu/1302.php. Accessed 2 Sep. 2020.

On the other hand, the export in KML/COLLADA/glTF formats does not account for the case that single attribute values might represent multiple CityGML values, as in the string "1010--/\--1150--/\--1210--/\--1240--/\--1370--/\--2700" in Figure 38). Therefore, one possibility to resolve this was to use the PostgREST API interface of the 3DCityDB Webmap Client[43]. To use the PostgREST API, it was necessary to create database views having three columns: *gmlid*, *attribute name*, *value*. The SQL statement to create such database views managed to store each attribute/value as a separate row, automatically mapping a single row from the *building* table containing an attribute value for the column *usage* like "1010--/\--1150--/\--..." onto multiple rows.

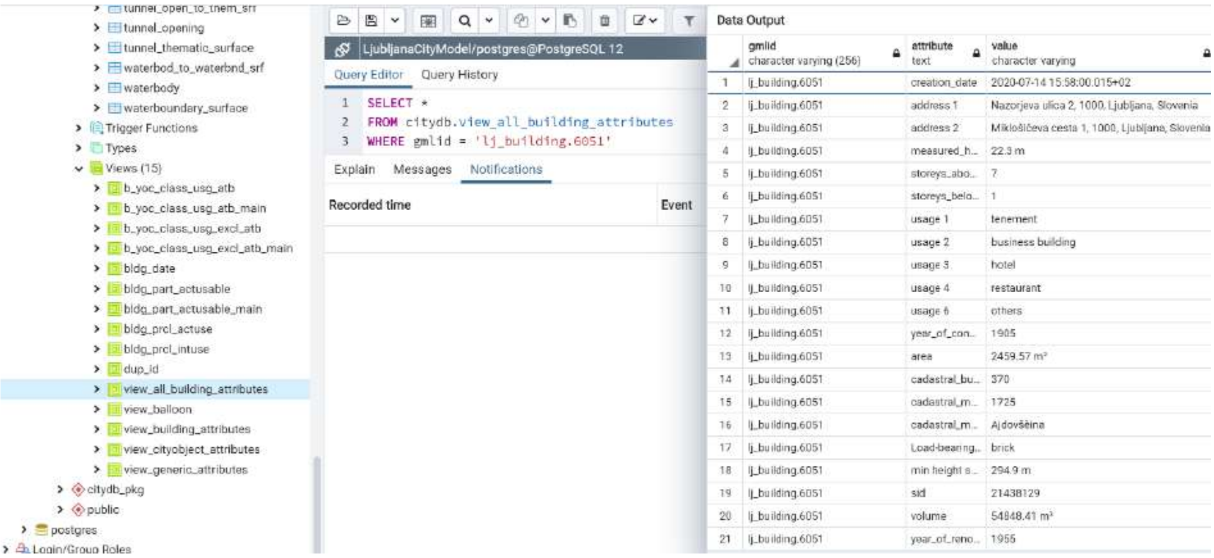


Figure 45: database view *all_building_attributes* correctly displaying all the building data

[43] "Releases · 3dcitydb/3dcitydb-web-map · GitHub." https://github.com/3dcitydb/3dcitydb-web-map/releases/tag/v1.8.1. Accessed 2 Sep. 2020.

Notes on the semantic enrichment for the CityGML Energy ADE

From the constructed city model, it is possible to proceed and mapping the data required to perform and urban-scale energy assessment according to the Energy ADE. A list of possible classes and related attributes that could be populated is shown in Table 6, modified from [51].

Table 6: Useful Energy ADE attributes for urban scale energy assessment. Modified from [51]

Energy ADE Module	Energy ADE Classes	Attributes
	AbstractBuilding	Building ID
Building Physics	ThermalZone	Gross floor area
	ThermalBoundary	Type
		Size
		Area
Occupancy	UsageZone	Type
	Occupants	Type
		Number
Constructions and Materials	Construction	U-value
Energy System	ConversionSystem	Number
		Nominal efficiency
	PerformanceCerfication	Rating
Time Series	FinalEnergy	Time series

Attributes with grey background were not found online, but could be modelled referencing the data from the TABULA project

Each building can be modelled only as a single thermal zone (*ThermalZone* class) since there are no detailed data to specify the rooms inside the buildings. For each building the surfaces that compose the external envelope have to be distinguished as *ThermalBoundary* class. The areas of use within the buildings (*UsageZone*) can be derived from the different usages associated with each the *buildingPart*. Unfortunately, no data relevant to the building occupants was easily accessible online, therefore the *Occupants* class of the Energy ADE could not be enriched with any data. This severely affects any consideration regarding buildings' energy loads. The transmittance values associated with each building can be modelled as *Construction*, assuming the values derived from the TABULA[44] project starting from the time of construction. The efficiency values of the heating systems could be obtained from TABULA as well, and modelled using one of the several classes available in the Energy System module. Finally, the consumption data could be modelled as *FinalEnergy* class.

Unfortunately, the inability to import/export energy information from the 3DCityDB, due to lacking support of the Importer/exporter tool, is a major obstacle which prevented the enrichment of the database with such data.

[44] "IEE Project TABULA (2009 - 2012)" https://episcope.eu/iee-project/tabula/ Accessed 24 Jul. 2020

5.2.2 Bottom-up approach

This section proposes a bottom-up approach that foresee the creation of a BIM model for design intents, which is subsequently enriched by data relevant for energy assessments. The exchange of information for a multiscale understanding of energy performances requires data integration procedures which span across multiple data schemas, such as IFC, CityGML, Shapefiles and excel spreadsheets. This is mainly due to the different software and file format that are used to work at different scales. This approach has been divided into three steps, concerning:

- the preparation of the BIM model for the energy assessment,
- the energy demand assessment, the export procedure and
- the integration of the geometric and semantic information into the 3DCityDB.

The first step will detail the process to inform the BIM model with the requirements for a "Baseline Building"[52] used to assess the potential for future energy-saving solutions. The second step will present an overview of some of the possibilities offered by Graphisoft tools to perform integrated Building Energy Performance Analysis, using the Archicad add-on EcoDesigner STAR[45]. The analysis proposed will evaluate the building energy loads, therefore information regarding building systems will not be considered. The last step will present data integration strategies to enrich a cityGML database with geometry and semantic information at different Level of Detail extracted from IFC models.

[45] "Eco Designer Star" https://graphisoft.com/downloads/ecodesigner. Accessed 1 Sep. 2020

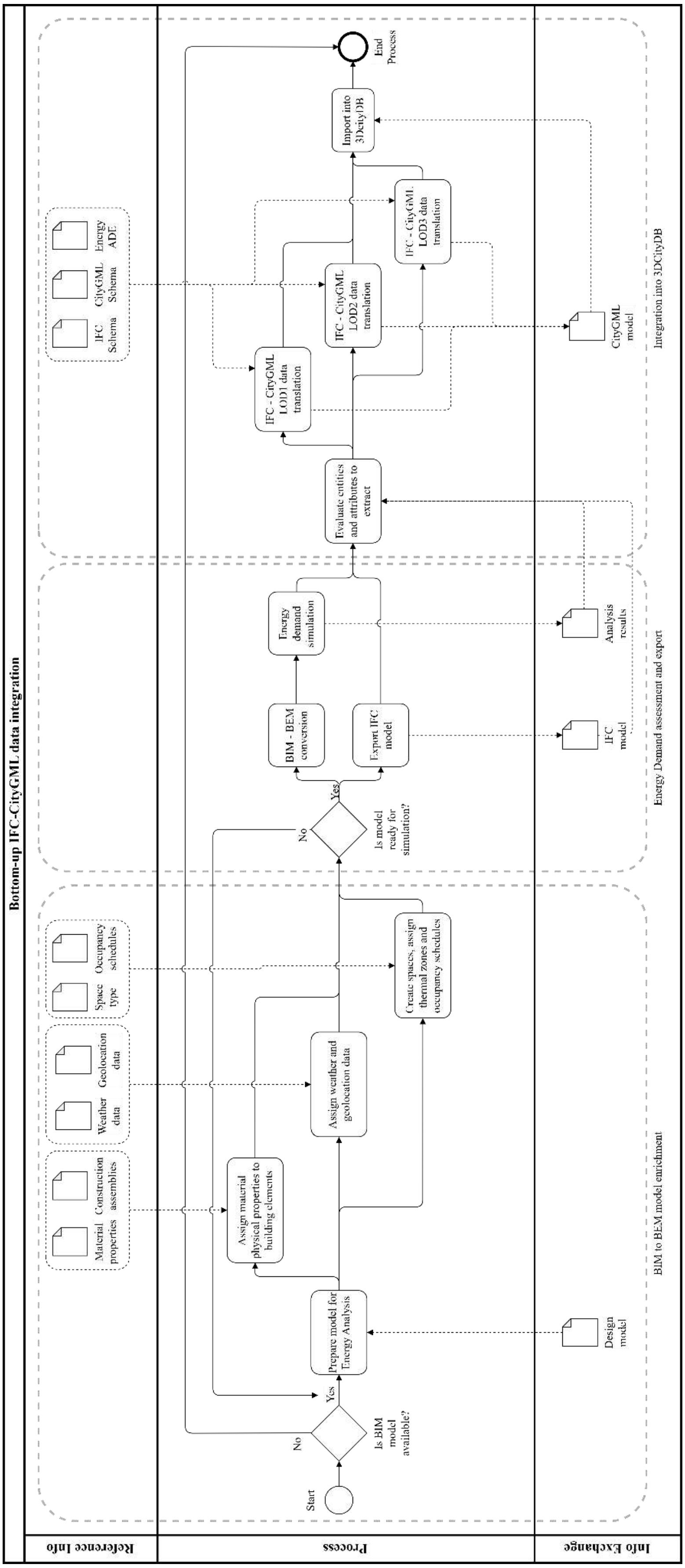


Figure 46: Bottom-up IFC-CityGML data integration process

Prepare the BIM model for the energy evaluation

ARCHICAD models must be prepared in such a way that they can perform a precise energy simulation in EcoDesigner Star. The more precise the model, the more accurate the energy calculation. Geometry, building materials and priority-based connections must be set up correctly to model all the details of the building. At the moment of writing, the project is still in an early stage, where most of these characteristics are still not specified.

This section propose the creation of a “Baseline Building”, that is a version of the model used to evaluate the feasibility of energy-saving solutions, adopting an approach called Sensitivity Analysis [52]. The overall morphology and space distribution are agreed, but the detailed construction technology, assemblies and façade details can be enhanced where required. The building’s system at this stage are not specified.

Figure 47: 3D View of the BIM model

The following suggestions should be followed to avoid incorrect results. To create a Building Energy Model is required a view in which are visible the building envelope and the openings, as well as the most important internal structures constituting significant heat storage mass. All the elements of the zone boundaries should be displayed, whereas beams, columns, etc. must be on a hidden layer. Those walls or slabs which are not considered to be zone boundary elements must also be on a hidden layer. Avoid using several parallel components such as walls, slabs or roofs to model composite structures. If such structures are present, ensure that only one of the parallel components is visible in the energy model and that the adjacent zones touch this component. Creating a "Zones Only" view can help to drag zones into thermal blocks, and to identify unused zones.

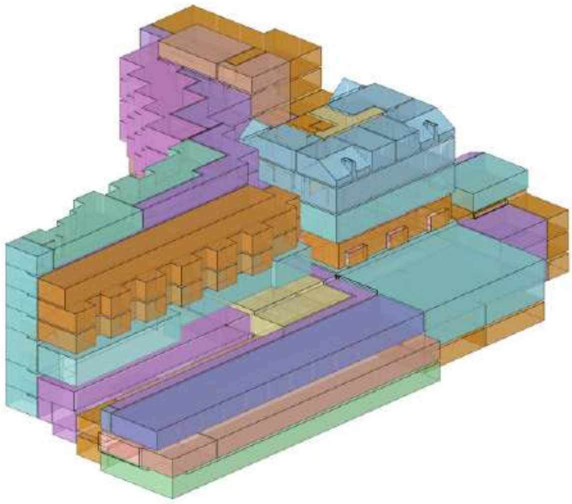
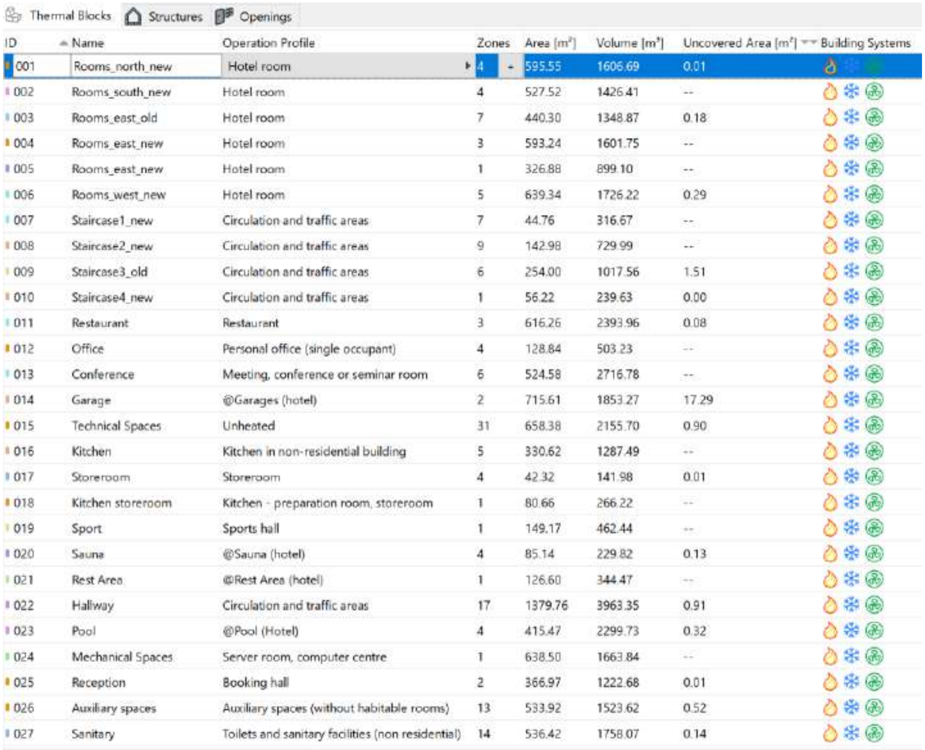


Figure 48: 3D view of the thermal zones

Energy performance analysis

The building was analysed using EcoDesigner STAR, a Graphisoft add-on that allows users to assess building energy performances. The tool permits designers to model building systems and assign them to multiple thermal blocks, allowing to evaluate energy demand and consumption, carbon footprint and other characteristics related to greed building practice. For the purpose of this research, the features and workflows presented concern only the initial steps to evaluate building energy loads. In fact, Archicad and EcDesigner STAR offer a deeper and more detailed workflow, to be referred to for further information [52].

Several thermal blocks were created in the model, as shown in the image above. Each thermal block is defined by grouping rooms with the same orientation, operational profiles, and temperature conditions. The BIM model is then converted in BEM thanks to an automated process that happen within Archicad, using the geometries and the materials properties already present in the model to generate information needed for the analysis.



ID	Name	Operation Profile	Zones	Area [m²]	Volume [m³]	Uncovered Area [m²]
001	Rooms_north_new	Hotel room	4	595.55	1606.69	0.01
002	Rooms_south_new	Hotel room	4	527.52	1426.41	--
003	Rooms_east_old	Hotel room	7	440.30	1348.87	0.18
004	Rooms_east_new	Hotel room	3	593.24	1601.75	--
005	Rooms_east_new	Hotel room	1	326.88	899.10	--
006	Rooms_west_new	Hotel room	5	639.34	1726.22	0.29
007	Staircase1_new	Circulation and traffic areas	7	44.76	316.67	--
008	Staircase2_new	Circulation and traffic areas	9	142.98	729.99	--
009	Staircase3_old	Circulation and traffic areas	6	254.00	1017.56	1.51
010	Staircase4_new	Circulation and traffic areas	1	56.22	239.63	0.00
011	Restaurant	Restaurant	3	616.26	2393.96	0.08
012	Office	Personal office (single occupant)	4	128.84	503.23	--
013	Conference	Meeting, conference or seminar room	6	524.58	2716.78	--
014	Garage	@Garages (hotel)	2	715.61	1853.27	17.29
015	Technical Spaces	Unheated	31	658.38	2155.70	0.90
016	Kitchen	Kitchen in non-residential building	5	330.62	1287.49	--
017	Storeroom	Storeroom	4	42.32	141.98	0.01
018	Kitchen storeroom	Kitchen - preparation room, storeroom	1	80.66	266.22	--
019	Sport	Sports hall	1	149.17	462.44	--
020	Sauna	@Sauna (hotel)	4	85.14	229.82	0.13
021	Rest Area	@Rest Area (hotel)	1	126.60	344.47	--
022	Hallway	Circulation and traffic areas	17	1379.76	3963.35	0.91
023	Pool	@Pool (Hotel)	4	415.47	2299.73	0.32
024	Mechanical Spaces	Server room, computer centre	1	638.50	1663.84	--
025	Reception	Booking hall	2	366.97	1222.68	0.01
026	Auxiliary spaces	Auxiliary spaces (without habitable rooms)	13	533.92	1523.62	0.52
027	Sanitary	Toilets and sanitary facilities (non residential)	14	536.42	1758.07	0.14

Figure 49: BIM Model thermal blocks

It is therefore possible to evaluate the physical characteristics of the building's elements that are required for the analysis, such as U-values, thickness, orientation, thermal block, infiltration and solar absorptance. These properties are automatically filled from the BIM model, but can easily be refined. For example, where required it is possible to edit the U-value of the technology packages for roofs, slabs and walls, according to the values proposed in the built-in material library.

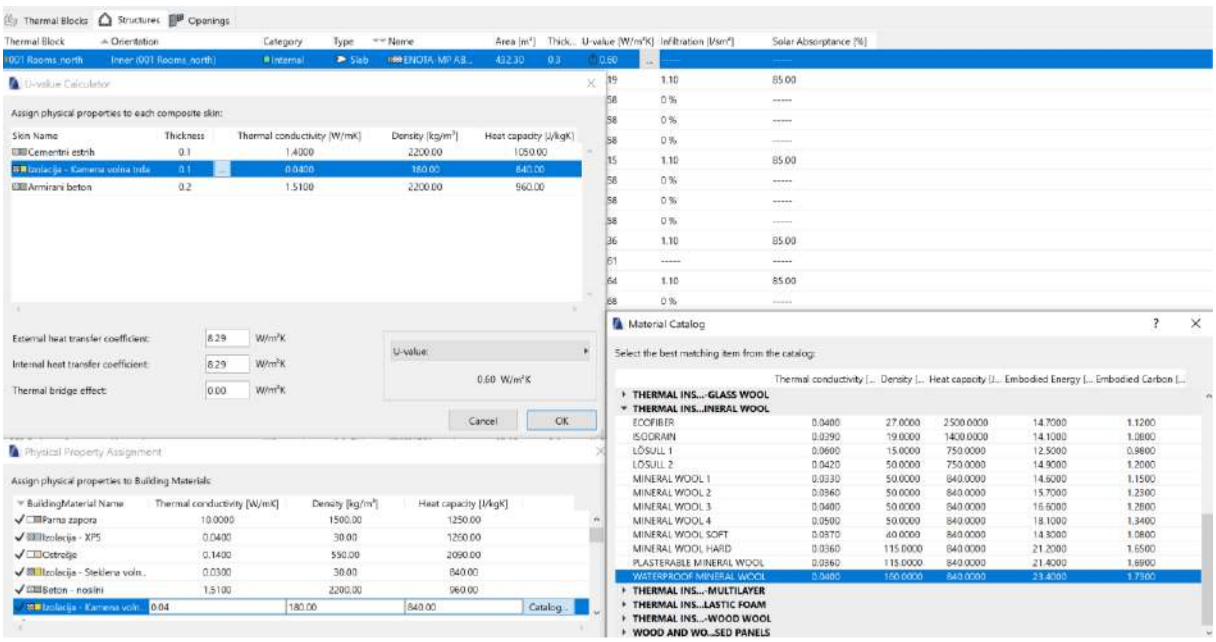


Figure 50: Editing of slab insulation material properties

Another possibility offered by the EcoDesigner Star add-on is to perform solar irradiation analysis on transparent components, taking into account building's geometry and orientation. The image below shows the different solar irradiation on two windows. In this diagram, the horizontal axes represent the period of the year, while the vertical one display the daily hours. The colours represent the percentage of direct sunlight on the windows.

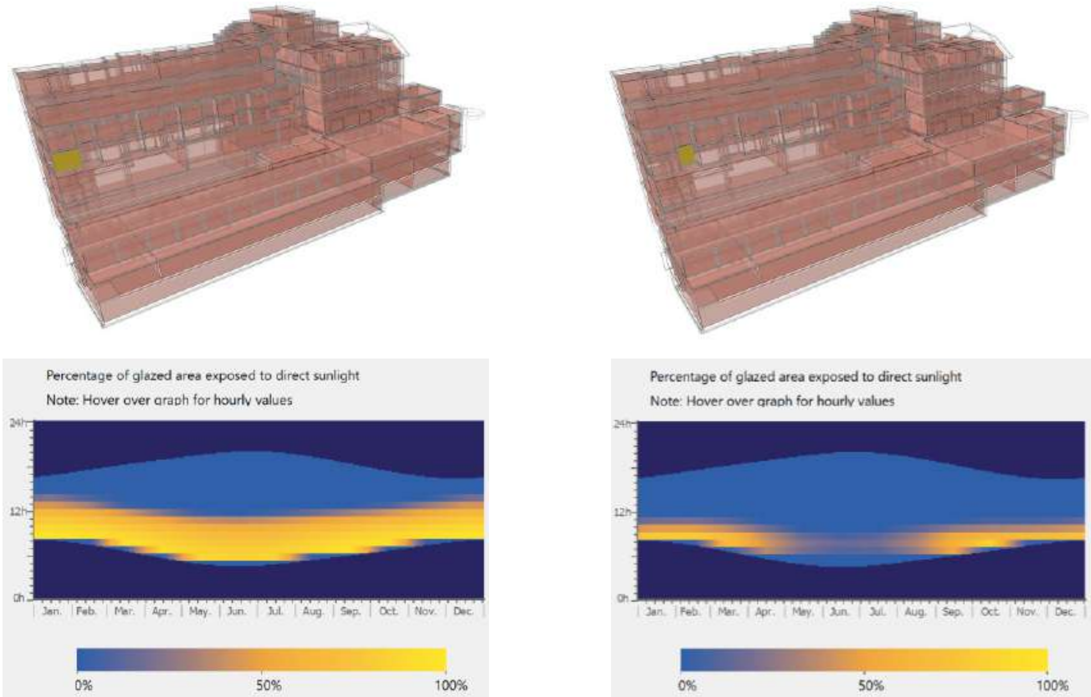


Figure 51: Different solar irradiation on two windows caused by overhangs

To run the energy demand calculation, the building systems are not specified, but it is needed to indicate if they exist or not. This is because the building's energy loads are closely related to the architectural features of the building, and therefore this is a key indicator to assess the relevance of green building strategies. However, operation profiles are needed, as this is a relevant information to be attached to thermal blocks.

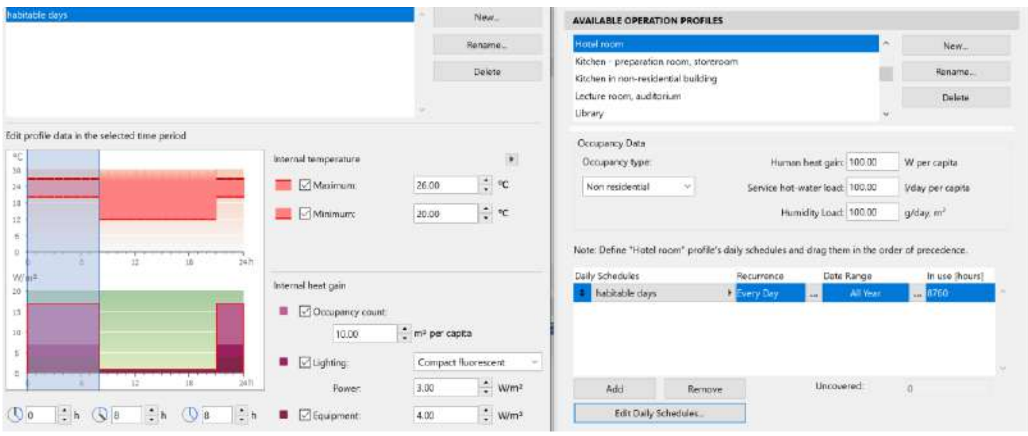


Figure 52: Operation profile for hotel rooms

After all relevant information is provided, it is possible to start the energy performance assessment. The program provides the possibility to export a report in pdf format and to export the results in Excel spreadsheet.

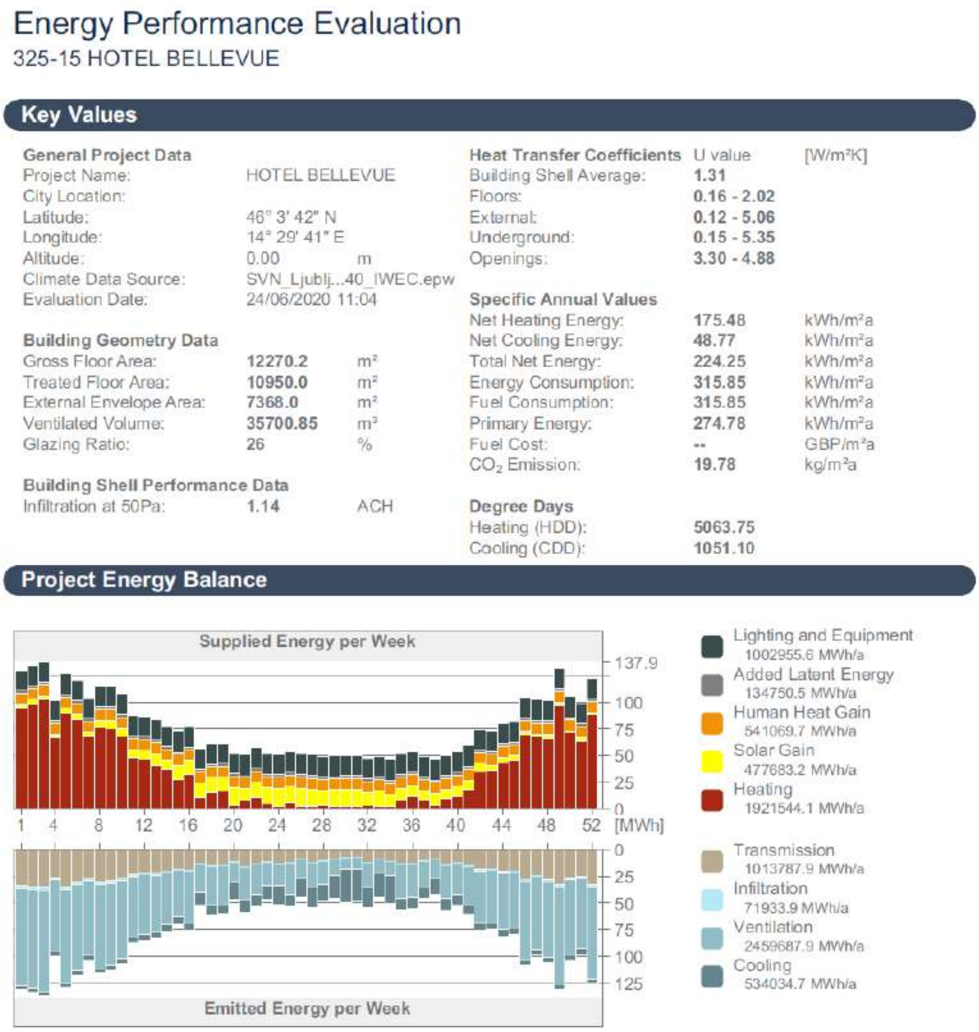


Figure 53: baseline building, energy performance evaluation report.

As mentioned at the beginning of this section, this analysis results are related to a “baseline building”. The aim of these values is to provide a reference to evaluate strategies for further improvements. For this reason and other technical issues concerning the geo-referencing of the project, better explained below, the values cannot be considered reliable. The results provide however some information that could be useful in a bottom-up data integration process moving from the building scale to the urban scale.

Bottom-up multiscale data integration

The BIM model designed in Archicad is exported in IFC according to the settings of the IFC Translator. An IFC Translator identifies the elements to be exported and how they should be interpreted. In the IFC Translator, beside the IFC Schema and the MVD selection, there are two essential mapping definitions: the Type Mapping and the Property Mapping. The Type Mapping manage the display of IFC properties in Archicad, where the displayed properties depend on the IFC Type that is mapped to the Archicad element. During IFC export, Type Mapping assigns IFC Types to the exported elements, based on their Archiad Classifications, according to the requirements of the receiving party. Here, after selecting the Classification System, it is possible to define the IFC Type and IFC Product to be associated with the IFC model elements. The Property Mapping provides a set of IFC Properties used for functions related to IFC data in Archicad, and allows to define and optimize the element mapping table for IFC export. These properties are based on the IFC Types previously received from the IFC Type Mapping.

In short, an IFC Type is associated with the elements, based on the Classification System and through the Type Mapping. Then, IFC properties are associated with the elements through the Property Manager based on their IFC Type.

Because the BIM model was constructed referencing a geolocated CAD survey that uses the "EPSG:3912 MGI 1901/Slovene Nation" CRS, the model is placed far from the Archicad Project Origin. At the same time, the location of the project was set with precise coordinates referring to the building position. This means that the Archicad Project Origin referred to the exact geographic location of the facility, but the model itself was located very far from it.

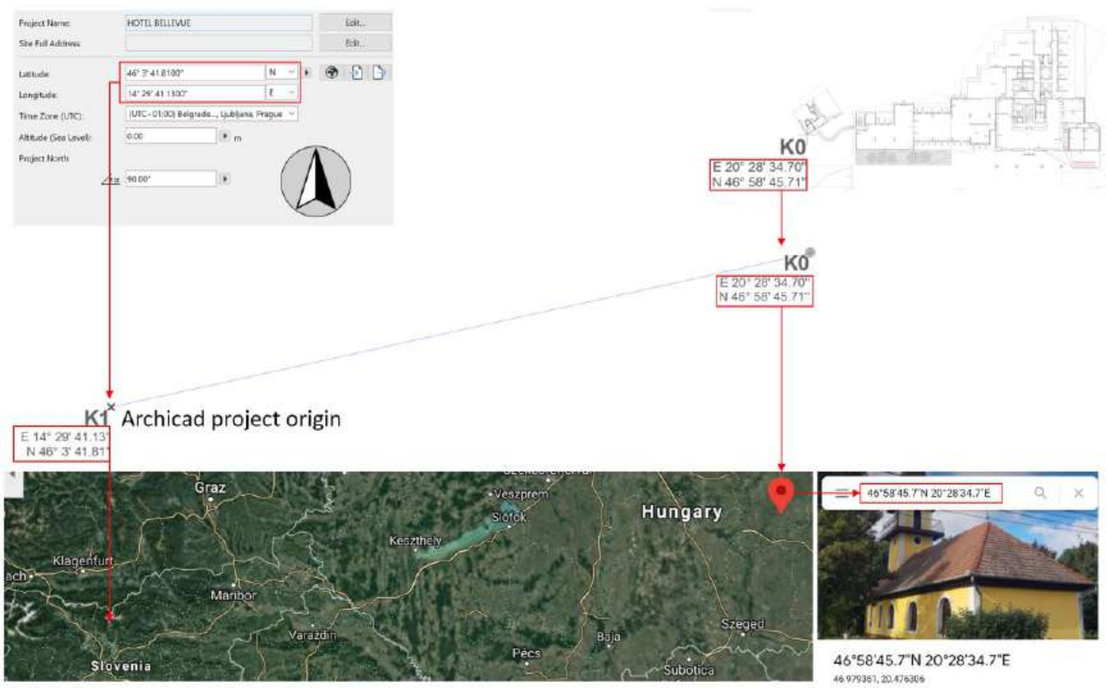


Figure 54: Project location and georeferenced CAD survey

This caused very high values in the local coordinate system, but no other problem during the design process. On the other hand, it was not possible to perform reliable energy assessment without a time-consuming reconstruction of the model. This would require splitting the design information in at least two separate files containing one the site information, and the other the model of the building.

Without corrections, the data stored in the model could have prevented a correct geo-referencing process. Therefore, for a usable IFC export, the project longitude and latitude had to be set equal to 0, and the IFC Site Location was matched with a Survey Point with known location. The Survey Point can be used as shared reference to facilitate models' coordination: its position and rotation defines the global coordinate system of the IFC model. When defining this point position, it is advised to consider the True North direction, so that in the IFC this parameter defines the Y axis in the global coordinate system.

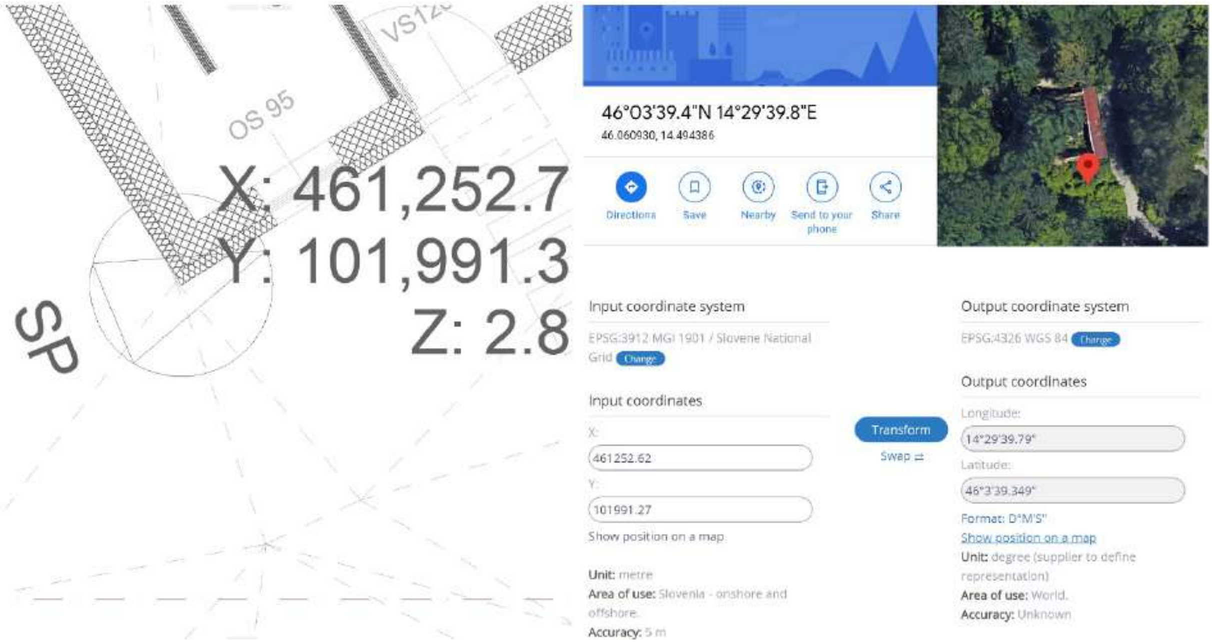


Figure 55: Archicad Survey Point coordinates in EPSG:3912 and its transformation in EPSG:4326

The IFC 2×3 was chosen because it is the certified schema for export, with the Coordination View MVD. The 2nd level space boundaries were exported along with the material characteristics. All properties have been selected to obtain to the material data and schedules for the CityGML LOD3 transformation.

Figure 56: IFC export of the BIM model

IFC to CityGML LOD 1

The workflows for data integration between IFC and CityGML at different Level of Detail follows a similar structure, that expands according to the granularity of the data of interest. These workflows are practically implemented through ETL procedures using FME and following advices on the FME community[46]. At LOD1, buildings are represented as a generic extrusion of their footprint.

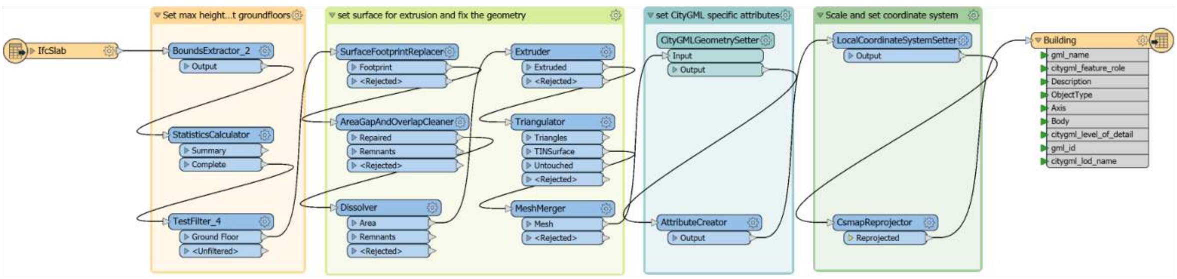


Figure 57: IFC to CityGML LOD1. FME workspace.

The workflow requires to import only the IfcSlab elements from the IFC file. From here, the slabs positioned at the ground floor are isolated and extruded to form the LOD1 building. A Boundary Extractor transformer is used to calculate the boundaries of all the elements, from which the maximum hight (value on Z axis) is extracted using the Statistic Calculator transformer, with the parameter "Statistics to calculate" pointing to the attribute "_zmax" and the check on the "max" box. The Test Filter transformer is used to identify and isolate the slabs at the ground floor. This is done selecting all the slabs that reference the ground floor story through their "ifc_parent_id". The selection is further

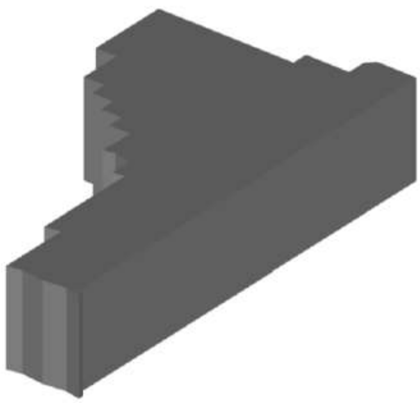
[46] "Adding Different Textures to a 3D City Model". https://community.safe.com/s/article/writing-citygml-example. And "Creating a Textured CityGML Model". https://community.safe.com/s/article/creating-a-textured-citygml-model. Accessed 18 Aug. 2020

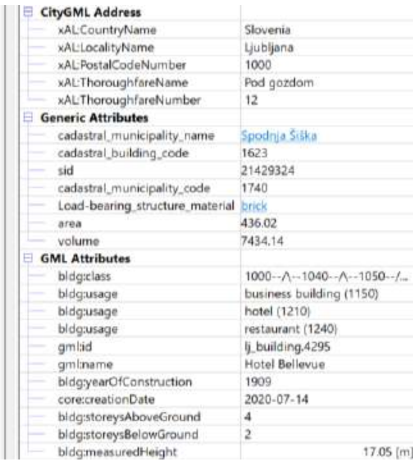
refined by filtering the slabs named “PL - 001”, thus avoiding selecting also slabs which represent building’s site arrangement.

The next part of the workflow aims to set the surface for the extrusion and manage the geometry to be correctly stored in CityGML schema. Here, a Surface Footprint Replacer transformer replaces the three-dimensional geometry of the selected slabs with planar surfaces at a predefined elevation set to 0. An Area Gap and Overlap Cleaner transformer fix the geometry by eliminating internal gaps and aligning overlapping boundaries, whereas the Dissolver transformer merges the separate geometries in a unique shape. The Extruder transformer with vertical direction and distance equal to the maximum height generate the three-dimensional solid. The Triangulator transformer decomposes the geometry into triangular sections, and the Mesh Merger transformer recomposes the features into a single geometry.

To adhere to the CityGML standards, the CityGML Geometry Setter transformer allows to choose the CityGML Lod Name, “lod2MultiSurface”, and the Feature Role, “cityObjectMember”. The Attribute Creator transformer creates other attributes for which it is not required to adhere to the CityGML standards. These are the level of detail, the id and the name of the building.

For the appropriate dimension and geographical position of the building Scaler, Local Coordinate System Setter, and CsMap Reprojector transformers are required. As the IFC model scale is in millimetres, while the CityGML model is in meters, the Scaler transformer scales the geometry accordingly. To determine the geographical location of the building, the “Origin X” and “Origin Y” in the Local Coordinate System transformer are matched with the Archicad Survey Point in the “EPSG:4326 WGS 84” as in Figure 55. Subsequently, the building model is reprojected in the 3DCityDB CRS, that is the “EPSG:3794 Slovenia 1996 / Slovene National Grid”, using the Csmap Reprojector transformer.





CityGML Address	
xAL:CountryName	Slovenia
xAL:LocalityName	Ljubljana
xAL:PostalCodeNumber	1000
xAL:ThoroughfareName	Pod gozdom
xAL:ThoroughfareNumber	12
Generic Attributes	
cadastral_municipality_name	Spodnja Šiška
cadastral_building_code	1623
sid	21429324
cadastral_municipality_code	1740
Load-bearing_structure_material	brick
area	436.02
volume	7434.14
GML Attributes	
bldg:class	1000--/\--1040--/\--1050--/...
bldg:usage	business building (1150)
bldg:usage	hotel (1210)
bldg:usage	restaurant (1240)
gml:id	lj_building.4295
gml:name	Hotel Bellevue
bldg:yearOfConstruction	1909
core:creationDate	2020-07-14
bldg:storeysAboveGround	4
bldg:storeysBelowGround	2
bldg:measuredHeight	17.05 [m]

Figure 58: CityGML Building in LOD1.

The CityGML writer finally writes the transformed data in a CityGML compliant file, according to the name and the path specified in its parameters. Follows a table with a summary of the transformers, their parameters and the value used in the transformation.

Table 7: IFC to CityGML LOD 1. Main transformer, parameters and attributes

Transformer	**Parameter**	**Value**
StatisticCalculator	Attribute	_zmax
	Max	X
TestFilter	Test Condition, If	Value(ifc_parent_id) = g.f. id
		Value(Name) = PL - 001
	Output Port	Ground Floor
SurfaceFootprintReplacer	Elevation	0
AreaGapAndOverlapCleaner	Tolerance	0.001
	Aggregate Handling	Deaggregate
	Connect Z Mode	Average
	Fill all Gaps	Yes
Extruder	Direction	Vertical
	Distance	_zmax.max
Triangulator	Aggregate Handling	Deaggregate
CityGMLGeometrySetter	CityGML Lod Name	Lod1MultiSurface
	Feature Role	CityObject Member
AttributeCreator	citygml_level_of_detail	1
	gml_id	lj_building.4295
	gml_name	Hotel Bellevue
Scaler	Scale Factor X, Y, Z	0.001
LocalCoordinateSystemSetter	Origin Coordinate System	EPSG:4362
	Origin X	14.494386
	Origin Y	46.060930
CsmapReprojector	Destination Coordinate System	EPSG:3794

IFC to CityGML LOD 2

To generate a CityGML LOD 2 building a similar workflow was generated, albeit with some additions. This followed the instruction found in the FME community, albeit with some customization.

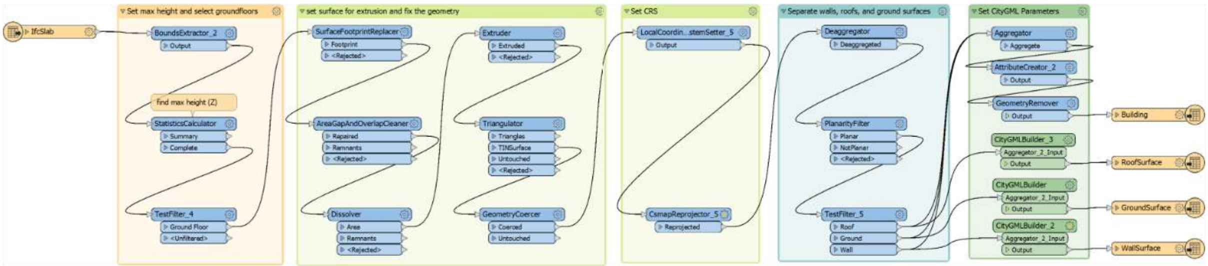


Figure 59: IFC to CityGML LOD2. FME workspace.

Also in this case from the IFC file only the IfcSlab elements are imported, because these are the only elements needed to create a LOD 2 building: the extrusion of the slabs will provide enough geometry and semantic information to differentiate among ground surfaces, walls and roofs. This is in fact the main discriminator that distinguish CityGML buildings LOD1 from buildings LOD2. The IFC elements have to be merged into a single geometry that represents the CityGML building: even if in CityGML it is possible to separate the historical construction from the new addition, and representing the facility as composed by two Building Parts, for the purpose of this workflow these were considered as a single building entity .

The workflow is similar to the generation of a CityGML LOD 1 building, but instead of merging all the geometries in one single mesh, here these are divided and classified according to what they represent: wall, ground floor slabs and roof slabs. After the extrusion and the triangulation, the resulting geometries type is forced to be a Composite Surface using a Geometry Coercer transformer. The procedure to set and reproject the CRS are similar as above, however, a Deaggreagator transformer is used after this to decompose the geometries in single components. These single geometries are then tested against a Planarity Filter transformer, to check the direction of their normal vector and therefore determine its function using a Test Filter.

To set the CityGML parameters accordingly to the standard for LOD 2 buildings, it is needed to maintain roofs, walls, and ground surfaces as separated features, which are children of the building entity. To do so, the geometries are aggregated together using an Aggregator transformer, and new attributes of gml_id and gml_name are created to define the building feature. The geometries are then removed using the Geometry Remover transformer to create the building entity as an empty "container". With the use of a custom transformer called CityGMLBuilder[47], walls, roofs and ground surfaces are separately aggregated by function, then enriched with appropriate attributes for mandatory parameters such as citygml_level_of_detail, citygml_lod_name and citygml_feature role. Among these attributes, the one defining the geometry type (citygml_lod_name) need to be copied to a geometry trait using the Geometry Propery Setter transformer. Furthermore, each feature composing a CityGML file needs to

[47] "Creating a Textured CityGML Model". https://community.safe.com/s/article/creating-a-textured-citygml-model. Accessed 18 Aug. 2020

have a unique id; this is provided by the UUID Generator transformer, and is subsequently concatenated with the prefix "GML_" and stored as new attribute gml_id using the String Concatenator transformer. To define the parent id for the features, an Attribute Creator transformer is used, with the id of the building.

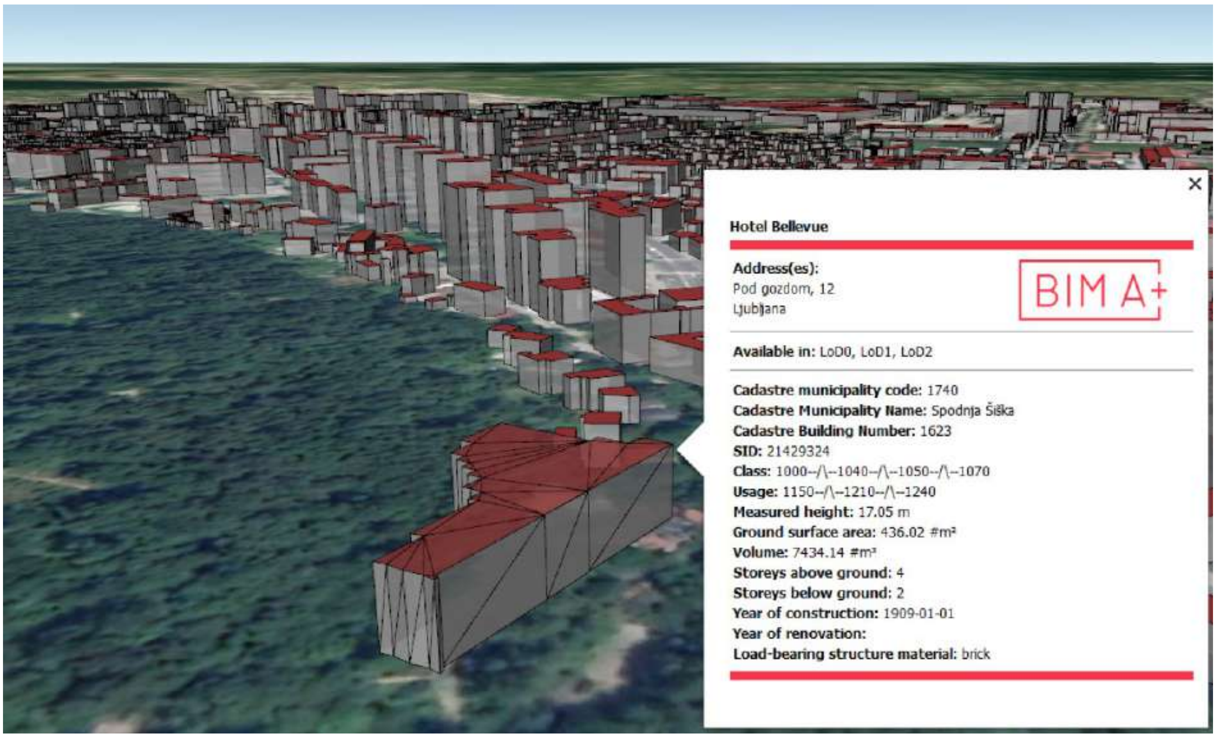


Figure 60:The CityGML model of the building in the 3DCityDB

Ultimately, before writing to CityGML using the appropriate writer's features, these require to be cleaned, removing all the unnecessary User Attributes that the IFC have still attached, leaving only the CityGML feature role. In Format Attributes only expose the gml id, lod name and parent id. The building also requires deleting all User Attributes except the gml name and expose the gml id. The features are finally saved as a CityGML compliant file, according to the name and the path specified in its parameters. Follows a table with a summary of the transformers, their parameters and the value used in the transformation.

Table 8: IFC to CityGML LOD 2. Main transformer, parameters and attributes

Transformer	Parameter	Value
StatisticCalculator	Attribute	_zmax
	Max	X
TestFilter	Test Condition, If	Value(ifc_parent_id)=g.f. id
		Value(Name)= PL - 001
	Output Port	Ground Floor
SurfaceFootprintReplacer	Elevation	0
AreaGapAndOverlapCleaner	Tolerance	0.001
	Aggregate Handling	Deaggregate
	Connect Z Mode	Average
	Fill all Gaps	Yes
Extruder	Direction	Vertical
	Distance	_zmax.max
Triangulator	Aggregate Handling	Deaggregate
GeometryCoercer	Geometry Type	Fme_composite_surface
LocalCoordinateSystemSetter	Origin Coordinate System	EPSG:4362
	Origin X	14.494386
	Origin Y	46.06093
CsmapReprojector	Destination Coordinate System	EPSG:3794
Deaggregator	Mode	Flatten One Level
	Split Composites	Yes
	Explode Instances	Yes
PlanarityFilter	Expose Surface Normal	Yes
TestFilter	Test Condition, If	Value(surfaceNormalZ)>1e-5
	Output Port	Roof
	Test Condition, Else If	Value(surfaceNormalZ)<-1e-5
	Output Port	Ground
	Else	<All other conditions>
	Output port	Wall
AttributeCreator (Building)	gml_id	lj.building.4295
	gml_name	Hotel Bellevue
AttributeCreator (CityGMLBuilder)	citygml_level_of_detail	2
	citygml_lod_name	lod2MultiSurface
	citygml_feature_role	boundedBy
GeometryPropertySetter (CityGMLBuilder)	Property to set	Traits From Attributes
	Source Attributes	Citygml_lod_name
StringConcatenator (CityGMLBuilder)	Constant	GML_
	Attribute Value	_uuid
AttributeCreator (CityGMLBuilder)	gml_parent_id	lj_building.4295

IFC to CityGML LOD3

The data translation process to generate a CityGML LOD3 from an IFC file is more complex than the two workflows proposed above. As the others, this process is derived from a tutorial published in the FME community webpage[48], and it is customised according to the specific needs and peculiarities of the project. The reason for this growing complexity resides in the hierarchical configuration of the two data models. When these are compared to match features from one to the other, it appears how the IFC schema is more convoluted and layered compared to the CityGML schema.

This FME workspace contains two IFC readers: one reads all the features contained in the file (<All>), while the other reads each feature and its attributes separately (IfcBuilding, IfcSpace, etc.). This approach is required to remove the connection to intermediate features, that are present in the IFC data model but are not part of the CityGML schema. As an example, in IFC the doors are connected to the walls through an IfcOpening, whereas this is not the case for the CityGML. For this reason, the <All> reader browses all the IFC elements and create a look-up table with elements and parent IDs, and another one with parent element types.

To set up the data translation process it is used the IFC reader that addresses the elements separately. In the case of the IfcBuilding, this means to delete all the geometries and rename the IFC id to the GML id. To convert the others IFC elements, all the geometries need to be transformed to a geometry type that can be stored in CityGML. As this is an intermediate step required by all other features, a customised transformer is conceived to repeat the process. This will separate the geometry from the property sets and handle the geometry's conversion. Another process that is repeated several times in the workflow is the setting of the CRS according to the Archicad Survey Point coordinates, and its reprojection in the EPSG: 3794.

In IFC, many features are linked to the storey they pertain to, which in turn is a spatial container that define the data structure within a building. This means that features such as windows and doors are not directly connected to the building, as it is the case for the CityGML data model. To allow such a connection, another customised transformer encapsulates some passages that need to be repeated through the workflow. It will allow to jump intermediate connections using the look-up tables previously created.

Prior storing the data in CityGML format, there are properties that must be properly set according to the schema standard: the Lod Name and the feature role. For this purpose, it is available a transformer that allow to choose the property values using a drop-down menu, to prevent any misspelling. Generally, the workflow to convert an IFC feature to a CityGML feature can be schematised as in Figure 61.

[48] "BIM to GIS (Intermediate)". https://community.safe.com/s/article/bim-to-gis-intermediate-ifc-lod-300-to-lod-4-cityg. Accessed 18 Aug. 2020

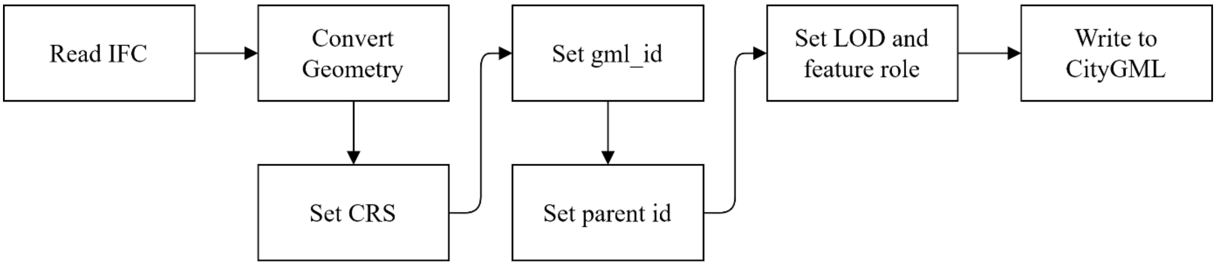


Figure 61: general workflow to transform IFC features to CityGML

Most of the building's feature are correctly transformed in CityGML format, despite some errors that are worthy to mention. Some of the features that required to shift their parent connection from wall to building are exported with inconsistencies, such as the windows and doors in the historical building. The cause for these errors could be related to a different modelling workflow adopted in the BIM authoring tool, to represent these features. In fact, in the existing building several strategies are adopted to represent and account for demolition and reconstruction activities during the design process, mostly to derive accurate bills of quantities.

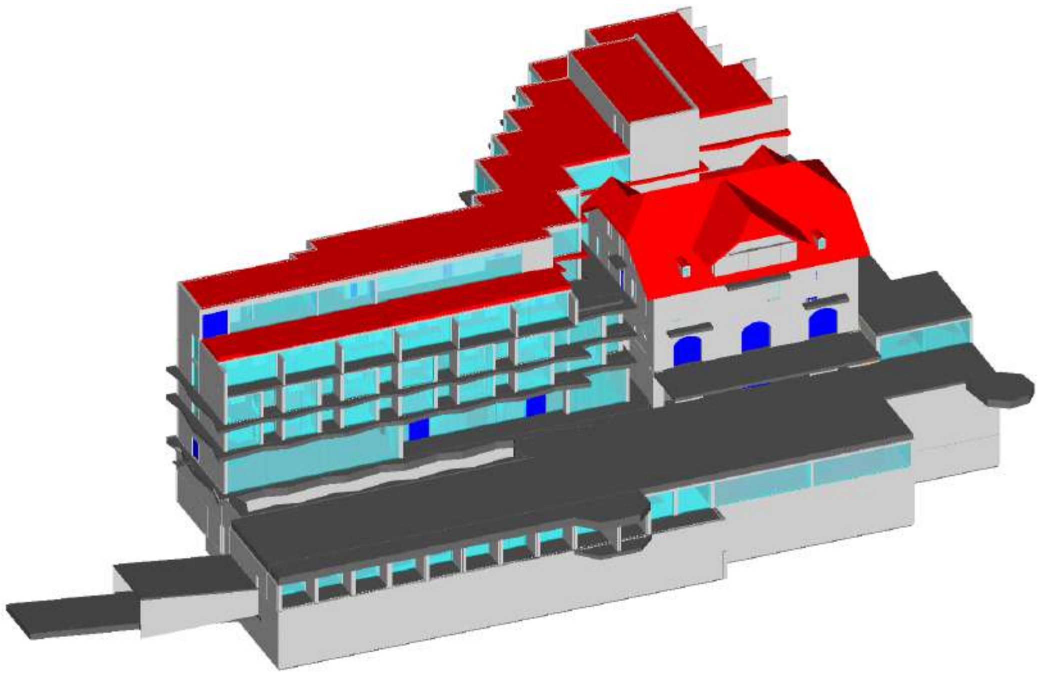


Figure 62: The building in CityGML format

While the data translation process can be considered successful for what concern basic geometry and attributes information, a more profound research is needed to assess the ability of this workflow to handle domain-specific semantic information. As previously mentioned, the possibility to transfer such data adopting the IFC schema requires a non-trivial process, and sometime is still limited. Therefore, the corresponding conversion in CityGML format adds a level of complexity that is worthy to be further investigated.

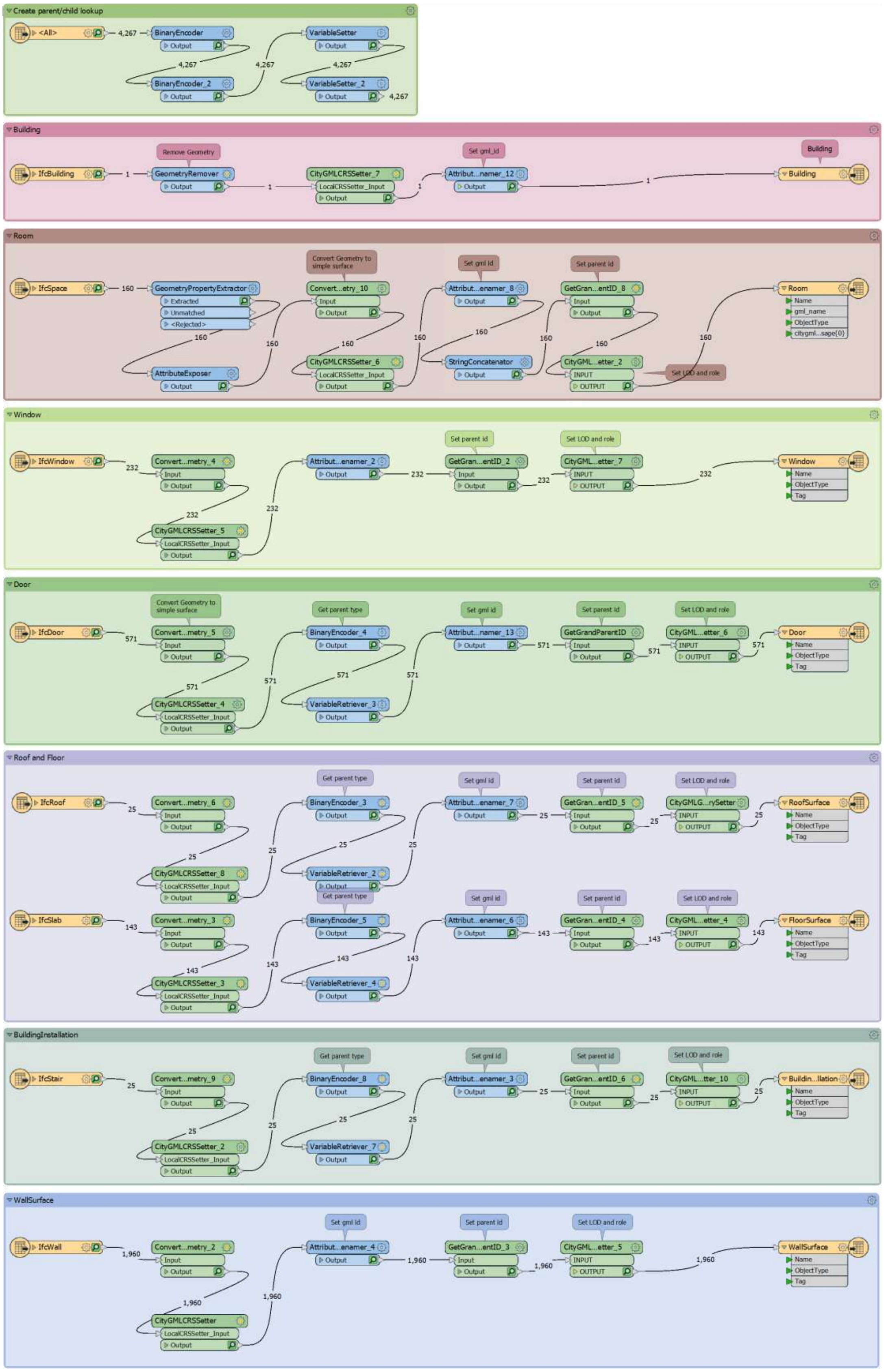


Figure 63: IFC to CityGML LOD2. FME workspace.

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6 CONCLUSION

A multiscale analysis of the built environment, with particular emphasis on energy consumption is possible, albeit with some limitation which are listed below.

The creation of a semantic 3DCity model is feasible with a reasonable effort in terms of data collection and harmonization. It has to be said that a solid knowledge of data schemas, GIS tools and Relational Database Management System is not common among architects and engineers. Therefore, the complexity of the CityGML schema itself and its implementation for practical use is only one of several obstacles that could prevent widespread implementation among practitioners.

Another barrier resides in the fragmented, dispersed and non-coherence of the spatial and semantic data publicly available. If on one side, geometric data – mainly shapefile usable with GIS tool – were easy to understand and interpret, the semantic attributes, mostly distributes as tabular data, were difficult to grasp, particularly referring to the Slovenian building cadastre. The institutional platform mentioned in the research offered however a relatively easy access to data. Nonetheless, these datasets were mostly in Slovenian language and needed to be translated in English before any analysis or usage.

The unavailability of data regarding building energy consumptions and occupants were the major limitation that prevented a fully enriched urban model, which otherwise could be used to perform urban scale energy assessment.

At the building scale, there are still major limitation when dealing with the capability of open standards to capture and interpret data for energy performance assessment. On one side, buildingSMART is making considerable effort to enrich and simplify the IFC schema. However, it appears that it is still not mature enough for sharing information with BEM tools and practitioners. On the other hand, gbXML appears to be the preferred choice to transfer information for energy analysis purposes, on the expenses of geometry correctness.

BIM and BEM interoperability is still not fully developed, resulting with some information being loss during the process. If the simulation is done through different tool than the BIM authoring software, are still required iterations of changes, export and import procedures. Adding to this technical limitation, the major obstacle here is the lack of uniform BEM standards in BIM workflows.

A multiscale information integration process is feasible, but it requires solid knowledge of two data model which are renowned to have very complex schemas. In order to perform a successful data integration workflow, one need to understand the underlying structures of the datasets to devise how of entities and their relationships are organised. The operations to map different data formats between building and urban scale also require understanding and overcome differences among coordinate systems, and align levels of information at different scales. It goes without saying that these are other skills that are not common among AEC professionals.

It must be acknowledged, however, that the possibilities exist and are available to whom is prepared to study, research and – sometimes - fail. The professions are changing, and so should be the attitude of a successful professional.

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