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Extending CityGML for Urban Solar Potential Estimation: A Semantically Enriched Model Informed by UAV-Derived Analysis

Jarence David D. Casisirano[1], Alexis Richard C. Claridades[1]

[1]Department of Geodetic Engineering, University of the Philippines Diliman, Quezon City, Philippines – {jdcasisirano, acclaridades}@up.edu.ph

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Abstract

Urban solar potential is often estimated using digital surface models (DSMs) and surface-based tools. These work well for rooftops but fall short when it comes to vertical surfaces, shadow dynamics, and simulation-ready attributes. In this study, we explored these limitations using a UAV-derived point cloud of the NIMBB building in UP Diliman. We generated a DSM and ran ArcGIS Pro's Raster Solar Radiation tool to estimate rooftop solar potential under standard atmospheric assumptions. While the output highlighted high-potential zones on flat roof areas, it entirely excluded facade and ignored surface-level variables like panel orientation or shading over time. These are factors that influence real-world solar performance. These limitations point to the need for a more structured, object-based approach that can support detailed, surface-specific attributes and semantically link energy values to building components. In response, we proposed a conceptual extension to the CityGML data model. We introduce new classes such as SolarPanelInstallation, ShadowCastLog, and SolarPotentialAnalysisResult to represent the physical, contextual, and temporal dimensions of solar analysis. This model was designed to follow CityGML's modular structure and can be integrated into semantic modeling workflows. The proposed model bridges the disconnect between 3D urban geometry and energy simulation, providing a clearer path for incorporating meaningful attributes into solar suitability assessments.

1. Introduction

As cities grow denser, they become more energy dependent. This pushes urban planners and researchers to look into renewable energy sources that meet sustainability goals. Among these, solar energy has emerged as a practical and scalable option, especially in tropical regions where sunlight is abundant. However, identifying which buildings are suitable for solar panel installations requires more than just surface-level observation. It demands detailed three-dimensional representations of building geometry, orientation, and environmental context, such as surrounding obstructions or vegetation (Gawley & McKenzie, 2022; Reffat & Ezzat, 2024).

CityGML, a widely adopted standard for 3D city modeling, provides a structured way to represent buildings, terrain, and other urban features across different Levels of Detail (LoD). Its modular architecture allows for semantic enrichment, making it valuable not just for visualization, but also for analysis and simulation. However, CityGML's default configuration focuses primarily on geometric and structural representation. This limits its direct applicability for application-specific analyses like those related to environmental assessment and renewable energy planning. For instance, in solar potential estimation, many critical attributes such as shadow effects, urban obstruction, and nearby vegetation are not explicitly represented in the standard model.

To address this limitation, researchers have explored ways to adapt and extend existing 3D building models to support specialized applications. This approach enables the reuse of established standards while tailoring them to meet specific analytical needs. For example, Noardo (2018) proposed a CityGML extension for representing architectural heritage information. Noardo demonstrated how domain-specific concerns can be addressed through semantic model enrichment. Building on this idea, we focus on a different but equally application-driven context: solar potential estimation. In this study, we enhance the CityGML data model by introducing new classes that capture physical and contextual features that directly influence a building's solar energy suitability.

Accurately assessing the solar potential of facades and rooftops supports informed decision-making in sustainable urban planning. Factors such as roof geometry, surface orientation, tilt, and exposure to nearby obstructions influence how much solar energy a building can harness. However, many solar assessments still rely on generalized datasets or simplified building footprints. This limits their usefulness for local-scale planning and implementation. In rapidly urbanizing areas, especially in tropical countries where sunlight is abundant, the ability to pinpoint which surfaces are most viable for solar panel installation is essential for scaling renewable energy solutions efficiently.

This study tackles that need by proposing a domain-specific extension of the CityGML data model tailored for solar potential estimation. By embedding new semantic classes such as solar panels, mechanical rooftop units, trees, and other shadow-casting features into a unified UML structure, the model supports both geometric detail and contextual awareness. Integrating these features enhances the ability of 3D models to support urban analyses without discarding compatibility with existing standards. In doing so, this work contributes to the growing demand for interoperable, analysis-ready building models that can be applied in GIS-based solar simulation workflows. The extended model provides a foundation for future applications in energy mapping, rooftop prioritization, and decision support systems for renewable energy adoption.

This study aims to develop a domain-specific CityGML extension that supports solar potential estimation in urban environments. It introduces new semantic classes that represent photovoltaic elements, shadow-casting features, and analytical solar attributes that are not sufficiently captured in the standard schema. The proposed model is designed to remain compatible with existing CityGML modules while enabling more detailed and application-specific representations of building elements relevant to solar energy analysis. UAV-derived data will serve as the geometric basis for demonstrating the limitations of conventional surface-based tools and for informing the design of the extended model. Ultimately, this study aims to provide a structured and reusable modeling framework that enhances the capacity of 3D urban data for renewable energy planning and simulation.

This paper is organized as follows. The next section reviews related work on 3D city modeling standards, solar potential estimation techniques, and the integration of UAV-derived data in urban analysis. The following section presents a DSM-based solar assessment of a real-world building using UAV-derived imagery. This analysis serves as a diagnostic baseline to explore the limitations of surface-only methods in capturing vertical exposure and contextual features. Building on these findings, the subsequent section introduces a conceptual extension to the CityGML data model, designed to address these gaps through semantically enriched representations of solar-relevant components. The final section presents the study's conclusions and outlines directions for future implementation and validation.

2. Review of Related Work

2.1 3D City Modeling Standards and CityGML

CityGML is an open data model and XML-based encoding standard developed by the Open Geospatial Consortium (OGC) to represent the geometry, semantics, and topology of urban environments in 3D. It organizes city objects, such as buildings, vegetation, roads, and terrain, into thematic modules, each capable of being modeled at different Levels of Detail (LoD), from simple building footprints (LoD0) to detailed indoor structures (LoD4) (Open Geospatial Consortium, 2021). This hierarchical structure makes CityGML a widely used framework for city-scale modeling, offering interoperability and consistency across various geospatial applications.

One of the core strengths of CityGML is its semantic structure. Each object in the model carries not only its geometric representation but also attributes related to its identity, function, and relationships with other objects. This semantic dimension enables a range of analytical applications beyond mere visualization, including simulations, infrastructure planning, and network modeling (Saran et al., 2018). However, the standard was not originally designed with domain-specific applications in mind. While it provides foundational modules for buildings and constructions, it does not include detailed representations of features critical for specialized analyses, such as solar energy modeling or simulations.

To address these limitations, researchers have developed various Application Domain Extensions (ADEs) that build upon the base CityGML schema. These extensions aim to tailor the model to specific fields by introducing new classes and relationships. For instance, Noardo (2018) proposed an ADE for architectural heritage to support conservation workflows. This enabled detailed semantic representations of historical structures. Similarly, Agugiaro et al. (2018) introduced their own energy ADE, which extends CityGML to support urban-scale energy simulations. The Energy ADE incorporates classes for building physics, occupant behavior, material properties, and energy systems, allowing the model to represent energy demand and supply more accurately across buildings and cities. These examples highlight the flexibility and extensibility of the CityGML framework, demonstrating its adaptability for specialized applications such as heritage conservation, energy modeling, and, as this study proposes, solar potential estimation.

2.2 Solar Potential Estimation and GIS-Based Approaches

As cities pursue renewable energy goals, estimating solar potential at the building or surface level has become an important aspect of urban energy planning. Traditional approaches often rely on two-dimensional building footprints and Digital Surface Models (DSMs) to derive metrics such as solar irradiance, usable rooftop area, and shading loss (Chompoosri et al., 2024; Hu et al., 2023). While useful for large-scale assessments, these methods tend to oversimplify rooftop geometry and ignore contextual features such as rooftop installations or nearby obstructions.

To overcome these limitations, researchers have turned to three-dimensional data sources, such as LiDAR and drone-based photogrammetry, to produce detailed 3D models of urban structures (Setyawan et al., 2022). These datasets enable more accurate modeling of roof tilt, azimuth, and shading conditions, which are essential for surface-level solar estimation. Several tools and platforms, including ArcGIS Solar Analyst, GRASS r.sun, and PVGIS, incorporate terrain and building data into solar radiation models. However, these tools often operate on raw geometry or rasterized surfaces and lack integration with structured data models that support semantic querying, interoperability, or lifecycle documentation.

This gap has led to a growing interest in combining 3D geometry with semantic data modeling. Studies have shown that semantically enriched 3D models can improve the accuracy of solar potential estimation by enabling simulations that account for surface types, dynamic obstructions, and solar technologies in use (Krapf et al., 2022; Willenborg et al., 2018). However, many existing models for solar estimation use their own formats and are not based on established standards. This makes them difficult to integrate with other urban datasets or planning tools.

2.3 Integration of UAV-Derived Data in Urban Modeling

While GIS tools provide powerful analytical capabilities, their accuracy is constrained by the quality and granularity of the input data. UAV-derived models offer an increasingly viable solution to this challenge. Unmanned Aerial Vehicles (UAVs) are increasingly used in urban modeling due to their ability to capture high-resolution, close-range imagery from flexible flight paths. Compared to traditional airborne LiDAR or satellite imagery, UAV-based photogrammetry allows for detailed reconstruction of building facades, rooftops, and environmental features using Structure-from-Motion (SfM) techniques (Malihi et al., 2018). These capabilities are especially useful for identifying elements that influence solar suitability, such as rooftop clutter, tree canopies, and irregular roof geometries.

Several studies have demonstrated the successful use of UAV-SfM point clouds in producing semantically structured 3D city models. For example, Van et al. (2023) used UAV and TLS data to generate CityGML-compliant LoD2 and LoD3 models of mining infrastructure, highlighting how drone-derived point clouds can support both geometric accuracy and semantic enrichment. Their results confirm the suitability of UAV-based datasets for integration into structured modeling frameworks such as CityGML, especially when high-resolution surface-level details are required.

2.4 Semantic Enrichment of 3D Models

However, even highly detailed 3D reconstructions are limited without semantic attributes that define how surfaces function or interact with solar energy systems. While geometric accuracy is essential for 3D city modeling, geometry alone is often not sufficient for complex spatial analysis. Many real-world applications, such as solar estimation, energy simulation, and emergency planning, require additional information about the function, type, and behavior of building components. This additional layer of information is referred to as semantic data. It allows models to represent not only the shape of a building but also what each part means, how it is used, and how it interacts with other features. Semantically enriched models can, for example, distinguish between different types of surfaces, identify objects such as solar panels or air conditioning units, and store properties like tilt, orientation, and material. These attributes are critical for simulation-based workflows and decision-support systems that require more than just 3D geometry. Without semantic enrichment, models remain purely visual and offer limited analytical value.

Agugiaro (2016) demonstrated how semantic enrichment of a CityGML-based 3D model for Vienna allowed for more precise urban energy simulations. By introducing the Energy (ADE), the study embedded energy-relevant information such as solar irradiance, system installation attributes, and time-series data into the model structure. It also highlighted the role of UML as a formal mechanism for defining new classes and relationships. Importantly, the study emphasized that extending an existing standard like CityGML allows cities to create energy-aware models without discarding the benefits of structured, open, and scalable data formats.

In this study, we follow the same principle of semantic extension but apply it specifically to solar energy applications. By introducing new classes our model enables analysis of solar suitability. These additions provide the necessary contextual data to support surface-level solar estimation while remaining aligned with the CityGML standard.

3. DSM-Based Analysis and Its Limitations

To explore the limitations of surface-based solar estimation methods commonly used in GIS workflows, we applied the Raster Solar Radiation tool in ArcGIS Pro to a digital surface model (DSM) derived from drone imagery. This approach is representative of typical solar potential assessments that rely solely on topographic surfaces to approximate incoming solar radiation. By using this method on a real-world building with complex geometry, we aim to demonstrate how such tools, while efficient, fall short to account for critical spatial and semantic details, particularly on vertical surfaces such as facade. The insights gained from this exercise serve as the motivation for the extended CityGML-based data model proposed in the later sections of this paper.

3.1 Study Area and Data Acquisition

The study was conducted at the National Institute of Molecular Biology and Biotechnology (NIMBB) within the University of the Philippines Diliman campus in Quezon City (Figure 1). The building's complex geometry, featuring elevated rooftops, multiple facade, and surrounding vegetation, makes it an ideal case for evaluating surface-level solar suitability.

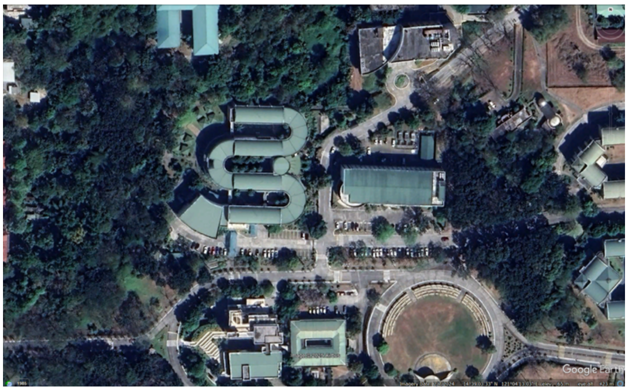

Figure 1. Study Area (Google Earth, 2025)

To capture its full 3D structure, aerial imagery was acquired using a manually piloted DJI Mini 3 Pro drone. The data acquisition followed a segmented flight strategy, covering five target views: one nadir (top-down) and one oblique view for each of the four cardinal facade. This method allowed for vertical sweeping of facade and flexible positioning to avoid obstructions such as trees and overhangs. A total of 1,392 images were captured under clear daylight: 50 nadir images and over 1,300 oblique images, with higher densities at the front and rear facade due to their height and complexity. Manual flight maintained an estimated 60% forward and side overlap. Nadir images were collected at approximately 50 meters altitude, while façade views were captured at varying distances to ensure coverage and safety.

This approach enabled the reconstruction of a complete 3D building envelope suitable for rooftop and façade-level solar analysis. While vertical surfaces were not represented in the DSM used for solar estimation, they were captured in the point cloud and are available for future integration using the extended CityGML model.

3.2 DSM-Based Solar Potential Estimation

To explore the capabilities and limitations of conventional solar estimation techniques, we used a digital surface model (DSM) generated from the drone-derived point cloud. This DSM includes rooftops, tree canopies, and surrounding terrain features. But like most surface models, it does not represent vertical building elements such as facade. It served as the input for ArcGIS Pro's Raster Solar Radiation tool which estimates the total incoming solar radiation across a surface based on slope, orientation, and topographic shading.

The analysis was performed for a full calendar year, from January 1 to December 31, 2025, using the default UTC time setting. Because the tool was configured to use only date ranges without specifying time of day, no additional time adjustments were necessary. The atmospheric settings were left at their defaults: a uniform sky model, a diffuse proportion of 0.3, and a transmittivity of 0.5. These parameter values intended to approximate average clear-sky conditions. No analysis mask was applied, allowing the tool to evaluate the entire rooftop extent within the DSM.

To convert solar radiation (in kWh/m²/year) into estimated solar energy output, we calculated solar potential per pixel using Equation 1.

$$Potential = Radiation \times Pixel\ Area \times System\ Efficiency \quad (1)$$

A system efficiency of 19.5% was used, based on the configuration reported by Cruz et al. (2023). Given the 5 cm × 5 cm pixel size of the raster (0.0025 m² per pixel), each pixel's potential energy output was derived using a raster calculator expression. This yielded a new raster representing solar potential in kWh/year per pixel, reflecting the usable energy that could be harnessed under the given efficiency and radiation conditions.

3.3 Visual Interpretation of Solar Radiation and Potential

The results of the DSM-based solar analysis reveal distinct spatial patterns in solar energy distribution across the rooftop and surrounding areas of the study building. As shown in Figure 2, the highest solar radiation values, approaching 1,748.1 kWh/m²/year, are concentrated on flat, unobstructed rooftops that directly face the sky. These areas receive consistent year-round sunlight under clear-sky conditions, making them ideal candidates for conventional rooftop solar installations.

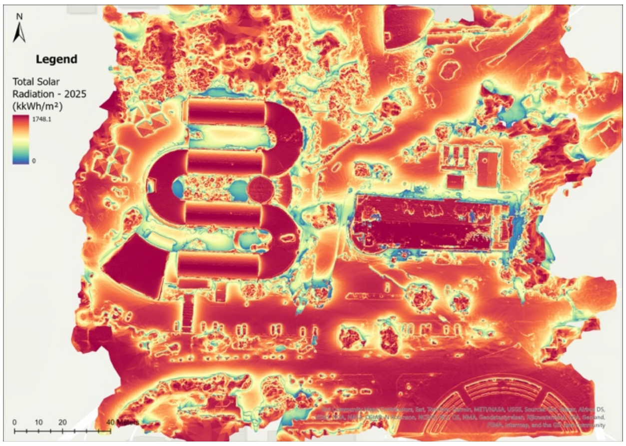

Figure 2. Estimated 2025 Solar Radiation over the NIMBB Building Using DSM Input (kWh/m²)

Conversely, lower radiation values appear along building edges, near vegetation, and in narrow corridors between structures, where slope, aspect, and topographic shading reduce direct sunlight. These patterns align with expectations based on how the Raster Solar Radiation tool models incoming solar energy using surface orientation and obstruction data from the DSM. The output also reveals subtle irradiance variation between rooftops at different elevations, highlighting the tool's sensitivity to height differences and rooftop geometry.

The raw solar radiation of NIMBB was translated into a usable solar potential raster. The resulting map, shown in Figure 3, displays solar potential per pixel in kWh/year. The brightest zones correspond to values up to 0.85 kWh/pixel/year, reflecting areas with the highest irradiance and energy harvesting potential under the assumed system configuration. While both maps effectively highlight rooftop-level trends in exposure and energy potential, it is immediately apparent that vertical surfaces such as facade are excluded from the analysis. These surfaces were captured in the original 3D point cloud but are not represented in the 2.5D DSM raster used by the solar tool. As a result, any potential energy gain from façade-mounted systems or wall-integrated photovoltaics is entirely overlooked. This omission becomes especially significant in dense or multi-story urban environments where vertical surfaces offer valuable and often underutilized solar real estate.

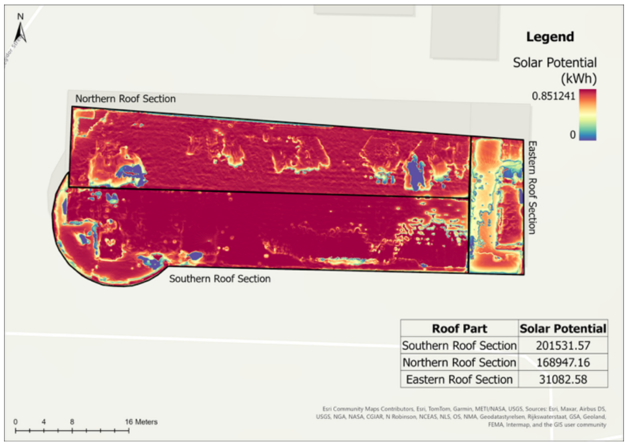

Figure 3. Estimated Solar Potential per Pixel Based on System Efficiency

3.4 Estimated Rooftop Solar Potential

To summarize the energy generation potential of the building, the calculated pixel-level solar potential values were aggregated by roof section. As shown in Figure 3, the southern roof section yielded the highest annual solar potential at 201,531.57 kWh, followed by the northern section at 168,947.16 kWh, and the eastern section at 31,082.58 kWh. This results in a total estimated rooftop solar potential of 401,561.31 kWh/year.

This quantitative estimate represents the usable solar energy that could be harvested annually from the building's rooftop surfaces, assuming continuous exposure and full panel coverage across the eligible area. While these values are valuable for building-scale solar planning, they remain limited to horizontal roof areas and do not account for potential solar contribution from vertical surfaces. This limitation reinforces the need for more advanced modeling approaches.

3.5 Observed Limitations of the DSM-Based Method

While the DSM-based solar radiation and potential maps effectively capture spatial variations in sunlight exposure across horizontal surfaces, they present several critical limitations when applied to detailed solar suitability assessments.

As shown, a key limitation is the omission of vertical surfaces such as facade, which, though captured during drone-based data acquisition, are not represented in the DSM raster. This significantly impacts estimation accuracy, especially in dense urban areas where facade can receive substantial solar exposure. Despite the growing adoption of façade-mounted photovoltaic systems and building-integrated solar technologies (Mangherini et al., 2023), raster-based tools remain restricted to horizontal analysis and cannot account for vertically oriented solar opportunities. In addition, raster cells lack surface-specific attributes such as panel orientation, tilt angle, efficiency, or material properties essential to solar energy modeling. All surfaces are treated as anonymous and uniform, overlooking rooftop clutter, mechanical obstructions, or tracking systems that directly affect actual energy yield (Ni et al., 2024). The method also provides static annual values without capturing temporal variation, irradiance fluctuations, or seasonal shifts, limiting its use in time-sensitive simulations such as forecasting or adaptive panel control. Finally, raster-based tools do not support semantic linkage between solar potential and specific architectural components. Solar values cannot be directly attributed to individual roof elements or construction objects, creating a disconnect from BIM workflows, digital twins, and other structured data models.

These limitations underscore the need for a semantically enriched, interoperable data model that represents both the geometric and functional characteristics influencing solar suitability, not only for rooftops, but for all relevant building surfaces including vertical surfaces.

This study did not include a formal accuracy assessment against ground-based measurements or established models (e.g., PVGIS, Solar Analyst). The DSM-based analysis primarily aimed to reveal limitations in representing vertical surfaces and contextual features. Future work will incorporate comparative evaluations using reference datasets and alternative modeling tools to assess accuracy and to fully populate the proposed CityGML extension for both rooftops and facade.

4. Conceptual Extension of CityGML for Solar Potential Estimation

The results of the DSM-based solar estimation demonstrate the effectiveness of surface-level analysis for quantifying rooftop solar potential. However, such methods are inherently limited in their ability to represent vertical surfaces, attribute-specific performance factors, and temporal shadow behavior. These gaps highlight the need for a semantically enriched data model that can accommodate detailed attributes of solar systems and building elements beyond what raster-based methods can offer. To address this, we propose an extension to the CityGML standard, introducing new classes specifically designed for solar suitability analysis.

4.1 Overview of the Base CityGML Structure

CityGML is a widely adopted standard for modeling the geometry, topology, semantics, and appearance of 3D urban objects. It provides a modular framework for representing city elements at multiple Levels of Detail (LoD), enabling both visualization and analytical use cases across disciplines. Among its thematic modules, the Building and Construction modules are among the most foundational and frequently used, particularly in applications involving structural representation and above-ground features.

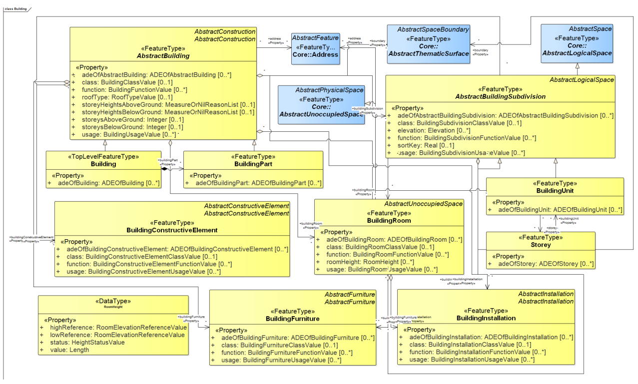

Figure 4. CityGML Building Module

The Building module, shown in Figure 4, defines the AbstractBuilding class, which serves as a base for more specific types like Building and BuildingPart. These classes describe the overall structure of a building, including its function, usage, height, and subdivision into units, rooms, and stories. Semantic granularity is achieved through subclasses such as BuildingUnit, BuildingRoom, BuildingInstallation, and Storey, allowing buildings to be represented at LoD2 through LoD4 depending on the detail required. These entities are linked through well-defined object properties, allowing the model to express not only physical hierarchy but also functional relationships among spaces.

Complementing this, the Construction module in Figure 5 defines building elements at the surface level, such as RoofSurface, WallSurface, DoorSurface, and WindowSurface, which inherit from AbstractConstructionSurface. These features provide the geometric faces of the building shell and are essential for structural articulation and façade modeling. The AbstractFillingSurface subclass introduces elements like DoorSurface and WindowSurface, further enabling thematic differentiation of building envelopes. The model also includes attributes for roof type, elevation, construction events, and surface orientation at higher levels of detail, although these are primarily intended for architectural or construction-oriented applications rather than environmental or energy analysis.

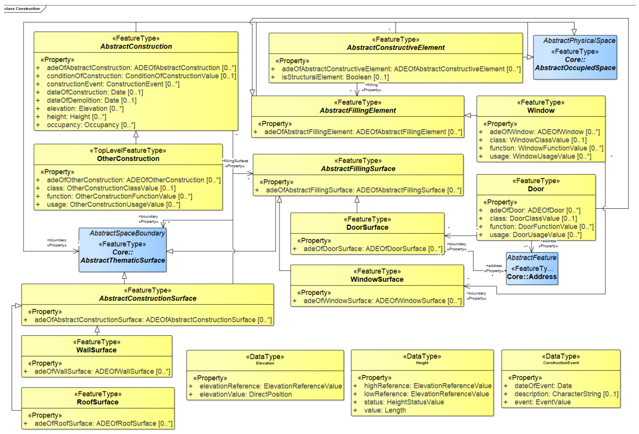

Figure 5. CityGML Construction Module

4.2 Motivation for Extending the Model

While CityGML provides a solid foundation for geometric and semantic modeling of buildings, its core schema lacks the domain-specific constructs needed for accurate and efficient solar potential estimation. The standard Building and Construction modules do not account for key environmental or energy-related elements such as the presence of solar panel installations, shadow-casting rooftop objects, or vegetation that may obstruct sunlight (Bachert et al., 2024). As a result, surface-level solar analysis using default CityGML models often depends on inferred or supplemental data reducing accuracy and hindering standardization.

Additionally, while CityGML 3.0 introduces the Dynamizer module to support time-dependent properties, it does not prescribe domain-specific structures for storing simulation-derived solar attributes such as irradiance exposure. Without explicitly defined semantic classes for solar installations, obstructions, and analysis logs, users are left to encode these values in generic or external formats. This limitation presents a challenge for solar modeling workflows which require structured, high-resolution data linked to building elements under changing environmental conditions. Attributes like panel azimuth, tilt angle, obstruction type, and cumulative shading effects are essential for accurate energy yield estimation, yet they are not fully captured by the base CityGML schema or even by the generalized Dynamizer mechanism alone.

While some application domain extensions (ADEs) have been proposed for broader energy modeling such as those focusing on thermal zones, HVAC systems, or consumption behavior, they do not adequately address solar-specific concerns like direct surface exposure, panel-level geometry, or localized shadow sources (Agugiaro et al., 2018). This leaves a gap for solar-centric ADEs that can integrate both the physical and contextual characteristics necessary for rooftop suitability assessments. Recognizing this gap, we propose a targeted extension to the CityGML Building and Construction modules by introducing new semantic classes specifically designed for rooftop solar potential analysis. Our extension retains compatibility with the core CityGML structure while adding the precision and domain relevance needed to support urban-scale and building-scale energy planning.

4.3 Design of the Solar Extension Model

To address the semantic limitations of the existing CityGML Building and Construction modules for solar potential analysis, we developed a UML-based extension that introduces new classes tailored to this application domain which is shown in Figure 6. The extended model integrates seamlessly with the core CityGML structure by preserving class hierarchies and adopting consistent naming conventions. It introduces three major categories of new elements: (1) solar infrastructure and analytical output classes, (2) obstruction and contextual classes, and (3) shadow modeling classes. Together, these additions provide the semantic depth needed for rooftop-level solar suitability evaluation while maintaining compatibility with existing CityGML workflows and tools.

4.3.1 Solar Infrastructure and Analytical Output Classes: The class SolarPanelInstallation represents individual photovoltaic systems physically mounted on building surfaces. It includes key attributes such as areaCovered, currentAzimuth, currentTilt, efficiency, installationDate, panelType, tiltAngle, and trackingType. These parameters play a critical role in accurately estimating solar energy yield and evaluating panel performance. Notably, currentAzimuth and currentTilt support dynamic modeling of adjustable systems, allowing the representation of real-time configurations in solar tracking technologies.

To facilitate comprehensive data-driven assessments, the model also introduces two additional classes: ShadowCastLog and SolarPotentialAnalysisResult. The ShadowCastLog class stores detailed irradiance and shadow geometry parameters, including coverageRatio, shadowAngle, shadowLength, sunAltitude, sunAzimuth, and a timestamp, which collectively reflect transient shading conditions. Meanwhile, SolarPotentialAnalysisResult aggregates analytical outcomes such as annualIrradiation, optimalAzimuthAngle, optimalTiltAngle, seasonalDistribution, and shadingLossPercentage, alongside an associated surfaceId. These outputs enable the semantic model to preserve temporal and surface-specific solar performance evaluations, serving both simulation workflows and long-term urban energy monitoring.

4.3.2 Obstruction and Contextual Classes: Accurate modeling of solar potential necessitates the explicit representation of physical obstructions that may cast shadows on solar-receiving surfaces. The class UrbanObstruction serves as a generalized feature type to capture both anthropogenic and natural elements that interfere with solar access. Its attributes include distanceFromSurface, height, obstructionType, orientation, and shadowImpact, enabling geometric and semantic characterization of shadow-casting behavior.

Two specialized classes extend from this base: Tree and MechanicalUnit. The Tree class provides a biologically-informed abstraction for vegetative obstructions, incorporating properties such as canopyDiameter, distanceToFacade, height, species, and trunkDiameter, thereby supporting seasonally-sensitive shadow simulations (Tian et al., 2023). In contrast, the MechanicalUnit class captures rooftop infrastructure including HVAC systems, antennas, and satellite dishes through attributes such as footprintArea, height, material, and unitType. These components are often absent in conventional LoD2 CityGML representations, yet their inclusion is vital for fine-grained solar analysis, particularly on densely equipped rooftops.

4.3.3 Shadow Modeling Classes: To support time-sensitive and surface-aware shading analysis, we introduce ShadowCastingEntity and ShadowCastLog. The former refers to any building or obstruction that generates a shadow at a given time, while the latter records temporal and spatial details of the shadowing event. ShadowCastLog includes fields such as castTime, targetSurfaceID, sunPosition, and shadowArea, enabling reconstruction of irradiance loss due to shading. These elements are critical for simulating variable solar conditions across days, months, or seasons.

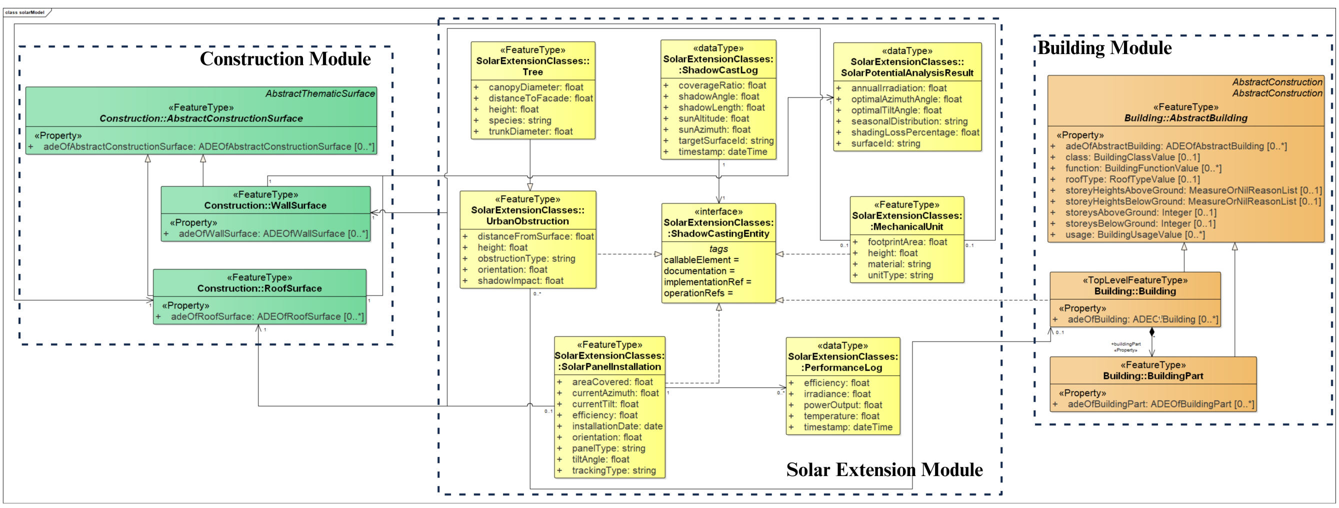

Figure 6. Proposed Solar Energy Extension to the CityGML 3.0 Data Mode

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4.4 Integration with the Base Model

To maintain interoperability and consistency with the CityGML standard, we designed the extended model using formal UML practices defined by the Open Geospatial Consortium (OGC). All newly introduced classes reference or associate with existing CityGML elements without modifying the core schema. This approach allows the model to preserve the integrity of the base modules while enabling new functionalities specific to solar energy applications.

The extension links key classes, such as SolarPanelInstallation, to existing building surfaces, most commonly RoofSurface or WallSurface, via aggregation. This mirrors the real-world configuration in which photovoltaic units physically attach to external building surfaces. In the UML model, the design specifies these links using composition or association relationships with clear cardinality. For example, one RoofSurface may contain zero or more SolarPanelInstallation instances. This design supports seamless querying and traversal between surfaces and their solar-related attributes during analysis.

Obstruction-related entities, including Tree, MechanicalUnit, and UrbanObstruction, are likewise linked to their spatial context using geometric references and surface attachment logic. They are semantically positioned to act as contextual modifiers of solar performance and are integrated through surface adjacency or proximity relationships. Their roles are further enhanced through participation in ShadowCastingEntity associations which formalize their capacity to affect irradiance through shading.

The model links obstruction-related entities, including Tree, MechanicalUnit, and UrbanObstruction, to their spatial context using geometric references and surface attachment logic. The design positions them semantically as contextual modifiers of solar performance and integrates them through surface adjacency or proximity relationships. The model, again, further enhances their roles by incorporating them into ShadowCastingEntity associations.

The use of standard UML syntax and structure ensures that the proposed model can be serialized using GML-based encodings or implemented in CityGML-compatible databases. This makes it suitable for integration with tools like 3D City Database, GeoServer, or other CityGML-compliant platforms. As a result, the model retains extensibility and forward compatibility while introducing the application-specific depth required for rooftop solar assessment.

4.5 Advantages of the Proposed Extension

The proposed extension to the CityGML data model offers several advantages for domain-specific applications focused on solar potential estimation. First, it introduces a rich semantic structure that allows building surfaces to be characterized not only by their geometry but also by their functional roles in solar energy production. By incorporating classes such as SolarPanelInstallation, ShadowCastLog, and SolarPotentialAnalysisResult, the model supports a level of analytical precision that is not achievable with CityGML's default schema.

Second, the extension maintains full compatibility with existing CityGML modules by adhering to the ADE framework. This ensures that the model can be integrated into existing urban digital twins, 3D geodatabases, or GIS workflows without requiring major structural revisions. It also supports interoperability with simulation tools that rely on standardized GML encoding or UML-derived model parsing.

Third, the model is designed to be reusable and adaptable. While the focus of this work is on rooftop solar analysis, the classes introduced—particularly those handling obstructions, temporal shadows, and irradiance logs—can be applied to other domains such as urban heat island studies, facade shading analysis, or climate-responsive design. This generalizability supports long-term integration of energy-aware modeling practices into 3D city planning.

The proposed CityGML extension can support LGUs in mapping rooftop and façade solar potential at the parcel or barangay level, enabling targeted PV deployment programs. Energy agencies could use the surface-linked attributes to design feed-in tariffs, track compliance with solar-ready building regulations, and monitor performance over time. Because outputs are stored in an interoperable, queryable format, they can be integrated into GIS-based planning systems, smart city dashboards, or national renewable energy databases.

Finally, the extension bridges the gap between geometry-focused 3D models and simulation-ready representations. The proposed schema is scalable and transferable to different urban contexts regardless of the primary 3D data source. By adhering to the CityGML ADE framework, it can integrate attributes from UAV photogrammetry, airborne LiDAR, satellite DSMs, or existing 3D building models such as BIM. The analytical results stored in classes like SolarPotentialAnalysisResult are compatible with outputs from various solar modeling tools, enabling adoption in cities with different data availability and resources. This capability allows integration into LGU planning workflows—such as mapping priority PV sites at parcel or barangay scales, designing incentives, or enforcing solar-ready building codes—and supports national energy agencies in monitoring renewable energy adoption through GIS-based platforms and smart city dashboards.

5. Conclusion and Future Work

This study justified the need for extending the CityGML data model to support solar potential estimation. Using a high-resolution UAV-derived point cloud, we reconstructed the geometry of a complex urban building and generated a digital surface model (DSM). The DSM served as input for conventional surface-based solar estimation tools. While this method provided useful rooftop-level insights, it inherently excluded vertical facade and lacked support for semantic attributes critical to solar energy analysis.

To address these limitations, we designed a conceptual extension of the CityGML schema that introduces new classes specifically targeted at solar suitability modeling. These include representations for photovoltaic installations, shadow behavior, and surface-level irradiance outcomes, components not supported by the default CityGML schema. The proposed model follows the modular principles of CityGML.

The results of this work suggest that semantic modeling can offer a more complete, flexible, and analytically powerful approach to urban solar assessment than surface-only raster tools. By enriching building models with attributes like panel configuration, shading logs, and irradiance analytics, the proposed extension can bridge the gap between 3D geometry and simulation-ready data environments.

As a direction for future work, we plan to implement the proposed model in a real semantic use case using the same UAV-derived dataset. This will involve encoding the new classes, populating them with actual attribute data, and evaluating their usefulness in facilitating facade-level solar analysis. Such a case study will serve as a practical validation of the model and support its integration into data-rich urban planning workflows.

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