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Enhancing Realism in Urban Simulations: A Mapping Framework for the German National Standard XPlanung and CityGML

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Abstract. 3D spatial data are widely used to simulate various urbanistic phenomena, thanks to their valuable semantic, geometric, and topologic information. CityGML is a highly adopted data standard for semantic 3D city models, providing a standardized description of the cityscape that enables interoperability across different stakeholders. When future scenarios for urban development are simulated, the simulation results can be visualized and further analyzed in synthetically generated 3D city models. However, land use and constructability regulations are often overlooked when generating synthetic 3D city models for simulation purposes, despite some regulatory urban constraints having a direct impact on simulation results. For instance, the roof shape is highly correlated with building solar energy potential, while the zoning maximum allowed number of apartments directly influences the buildings' urban density estimation. Therefore, integrating such constructability knowledge within 3D city models is crucial. This paper proposes a framework for mapping urban planning rules defined in the German XPlanung standard onto 3D city models structured in compliance with CityGML to ensure legislative validity and real-life applicability. We review related work, discuss the structure of CityGML and the main elements concerned by urbanistic laws, explain the main concepts of XPlanung, and investigate the mapping of regulatory information with CityGML entities.

Keywords: CityGML, XPlanung, Urban Simulation, 3D City model, urban regulations.

1 Introduction

Nowadays, 3D city models are increasingly deployed in a number of domains and applications beyond visualization [19]. Since they provide a well-structured description of the urban space, semantic 3D virtual city models are considered as a central asset to simulate various urban phenomena.

The standardization of 3D city models allows interoperability across different simulation domains. Adopting an open and common definition of the cityscape makes the interchange of data between urban planners at different levels possible [14]. CityGML models real-life urban objects by defining four aspects, i.e. geometry, semantics, appearance, and topological interrelationships [18]. Using the CityGML standard, 3D city models have been largely used for different urban simulations that have a spatial context. For instance, simulating the urban spatio-temporal growth [6, 15], measuring the impact of urban configurations on energy demand [17], evaluating the energy and environmental impacts of large residential building stocks throughout their life cycle [11], noise pollution [23], and traffic simulation [1]. The potential of urban simulations is increasing especially with the availability of tools that can generate synthetic virtual 3D city models for simulating possible future states of the city [4]. Procedural modelling is a commonly deployed approach to generate 3D city models [5, 21]. While procedural modelling focuses on translating input data and rules into 3D city models, land constructability regulations and limitations are usually disregarded [7]. Consequently, the generated synthetic model may not respect the current land regulations. Thus, the integration of such land constructability rules within the 3D city data model is crucial. Furthermore, the availability of standards that model land use and urban regulations makes the integration process more prominent.

XPlanung is a German national data standard and exchange format that models the urbanistic regulations within a specific scope area. This standardization aims for efficient, loss-free, and secure interchange of data between different actors, whether from the public or the private sector [20]. XPlanung harmonically integrates various land regulations. Some of these regulations have a nationwide impact, others are adopted locally. Namely, the development plan, the land use plan (derived from the German laws and regulations Baugesetzbuch (BauGB) and Baunutzungsverordnung (BauNVO) [3], the regional plan and state development plan, the landscape plan, as well as other spatial plans that contain additional relevant regulations.

As stated above, many urban simulations have been implemented based on CityGML. Therefore, it makes sense to use CityGML as a data model for generated synthetic 3D city models, that represent a possible state of a city or city district in the future. Thus, a question arises of how to link XPlanung and CityGML data models to make sure that each generated synthetic 3D city model is legislatively valid. This integrated modelling has the potential to make urban simulations more realistic and applicable in real-life use cases. It should be noted that we understand "realistic" in the context of this work not in the sense of photorealistic city models, but of functionally realistic models that could be transferred into reality from the perspective of urban planning rules.

This paper aims to develop ways for mapping urban planning rules defined in XPlanung into the 3D city models structured in compliance with the CityGML standard. The paper is structured as follows: after an introductory first section, section 2 presents related work focusing on integrating regulatory knowledge within 3D city models, while section 3 investigates the reasons behind a schema-level integration of urban regulations and 3D city models. The structure and the main CityGML concerned elements, as well as the relevant concepts of the German XPlanung standard, are presented in section 4. Section 5 investigates the mapping of regulatory information with CityGML entities. The paper ends with a discussion and conclusions.

2 Related work

The question of integrating land regulation knowledge for 3D urban simulation have been the focus of various works. [6] present a system that simulates urban expansion based on existing urban regulations. Constructability constraints were retrieved from two local land planning documents: PLU and POS (Plan Local d'Urbanisme and Plan d'Occupation des Sols in French). A multitemporal database has been developed to derive urban evolution rules based on the comparison between the urban configuration in different epochs. Subsequently, the urban density and fabric can be forecasted. A simulator has been developed to reach the target density. The simulator starts by selecting a suitable parcel based on attractivity and constructability requirements. Afterwards, the parcel is populated with buildings that respect the urban regulations. If the building does not verify the regulations, morphological modifications have to be made to cope with urbanistic rules. The process is repeated until reaching the target density. Figure 2 describes the workflow in more detail.

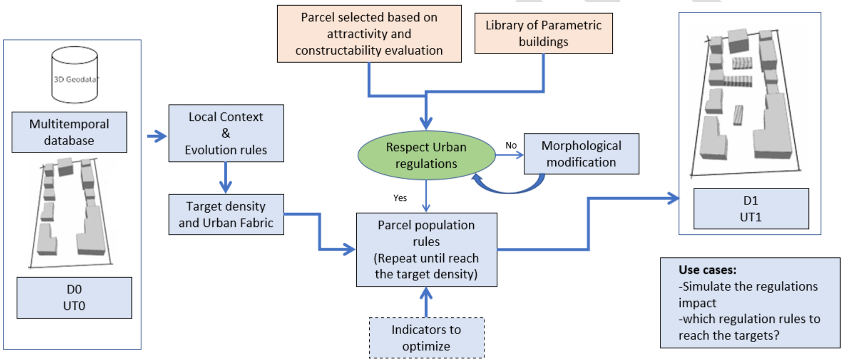

Fig. 1. Simulating the urban expansion based on 3D city model [6]

[7] define a model that represents knowledge contained in a land use regulation. The model focuses on regulations concerning buildings only. Hence, the regulation articles in regard to other objects as the road network and vegetation are omitted. The model is based on existing standards: themes relevant to buildings, relief and roads are adopted from CityGML2.0, whereas cadastral information (i.e, parcels, separation limits) are based on INSPIRE specifications for cadastral parcels [16]. Zoning elements are modelled based on COVADIS standards [9]. Furthermore, these standards are extended with additional classes, attributes, and relationships to cope with land regulation requirements, which is, in this case, the French regulation PLU. The urban rule is expressed, initially, through a textual attribute, and subsequently, through Object Constraint Language formalization. However, the proposed workflow is not intended to satisfy urban simulation requirements but rather perform posterior building permits compliance checks.

Various works have focused on the integration of CityGML with other data models for code compliance checking purposes. [12] have developed a multiscale framework for aligning spatial information with the local urban regulation plan PLU in order to generate a compliance report. Building Information Modeling (BIM) is deployed to check building construction rules while CityGML is adopted to verify subzones district restrictions. [2] have created a concept for a GML-based checking protocol for building license checking. Semantic and geometric information from BIM and CAD have been transformed to CityGML. These data were harmonized with urban planning data (XPlanGML) and a 3D city model (CityGML) to perform a regulation consistency evaluation. However, the proposed framework is more application-oriented (building permit check) rather than proposing a multidisciplinary general data model which can support various urban simulation use cases.

The above-mentioned work focuses on using geospatial data combined with regulatory urban information mainly for post compliance checking and building permit validation.

In contrast to the related work, this paper presents a conceptual framework that integrates urban regulation rules within 3D city models at the schema level with a focus on creating synthetic 3D city models for representing future states of the city for urban simulation purposes that comply with urban regulation rules.

3 Schema Level Integration of 3D City Models and Urban Regulations as a Requirement for Realistic Urban Simulations

Urban simulations impose different requirements compared to code compliance use cases. A schema-level harmonization of 3D city models and urban regulations is required based on the following reasons:

- Urban simulations are interdisciplinary and can touch various domains ranging from energy efficiency analysis to urban density simulations.
- 3D city models cover the geo context in regulation and have applicability to issues related to urban planning, the geo context is important for the automatic construction of city objects.

As an example, spatiotemporal urban growth analysis is a common GIS use case that aims to simulate the change of population density over space and time. Urban density change is due to a variety of reasons, including the job market situation and the presence of business structures. These urban internal forces can be well modeled using urban system dynamics for accurate population density predictions. [15] developed an approach that interconnects urban system dynamics modeling with 3D city models. A schema level integration is crucial regarding this use case due to the following reasons:

- To accurately simulate the housing demand growth by making use of input information related to the existing buildings with respect to their usage. Specifically, the number of buildings can enhance the estimation of the number of inhabitants, whereas the number of commercial and industrial structures can improve the estimation of available job opportunities. As a consequence, information regarding land use and building usage is required.

- To satisfy the urban housing demand growth resulting from the urban simulation, it is fundamental to incorporate information specifying possible vertical and/or horizontal building extension. Hence, knowledge regarding the maximum number of regularly allowed floors and appartments is needed.
- For horizontal densification, land use information about the urban zoning specification is required. Since any created building must respect the applicable constructability regulations. Information regulating the physical building plot location (construction window, building boundary), the allowed floor space ratios, the building use type, and the shape of the building (roof type and ridge direction) must be respected by a synthetic 3D city model, that results from an urban growth simulation.

4 Background on relevant standards

4.1 CityGML definition and applications

In order to guarantee interoperability across users, organizations, and their respective domains, an open standard to represent 3D city models is a must-have. The City Geography Markup Language (CityGML) is a standardized and open data model and XML-based format for the representation, storage, and interchange of 3D city models. CityGML has been developed to create a general definition of urban space. This is achieved by defining four aspects, i.e. geometry, semantics, appearance, and topological interrelationships. CityGML is adopted as a standard by the Open Geospatial Consortium (OGC) and the latest version of CityGML is 3.0, which was released in September 2021 to meet the requirements of new use cases. The latest version of CityGML has been enriched with new modules like Dynamizer, Versioning, Point Cloud, and Construction, whereas other modules have been revised as CityGML Core, Generics, Building, and Transportation [19]. CityGML eases the integration of urban spatial data for different applications.

Beyond visualization, 3D City models are being increasingly used in a number of domains and a wide range of tasks. [4] demonstrate that 3D city models can be deployed in at least 29 non-visualization use cases that are part of more than 100 applications. [22] categorized the 3D city models use cases into applications that make use of the geometry only; simulations based on geometry and semantic information, and analysis based on domain-specific extensions. An important issue that arises when generating 3D city models is the conformity of the generated model with the local constructability regulations. Consequently, the integration of regulation knowledge within such frameworks is a necessity. The Building, LandUse, and construction modules are the most prominent thematic CityGML parts to the case of generating synthetic 3D city models, that represent possible future states of the city in a realistic way. These modules will be discussed in more detail in the following sections. The new CityGML 3.0 concepts Space and Space Boundary can, e.g., be deployed to specify the regulatory occupied building space and the obligatory unoccupied spacing that has to be respected between buildings. Since these concepts are abstract core features, only the relevant thematic classes will be further discussed in the following sections.

4.2 CityGML structure

The CityGML LandUse module provides means of defining objects that describe portions of the earth's surface that are either dedicated to a particular land use or possess a specific land cover, with or without vegetation. The LandUse objects in CityGML can account for concepts related to land use (human activities) and land cover (physical/ biological land cover) and can be utilized to depict various features such as parcels, spatial planning objects, recreational spaces, and physical characteristics of an area in 3D. The top-level feature type LandUse is the sole class of the LandUse module and represents these LandUse objects in the CityGML data model.

Buildings in CityGML are considered as self-supporting, free-standing, normally roofed, and location-fixed constructions. A building can be decomposed logically into building units (BuildingUnit and Storey features) and functionally into building parts (BuildingPart feature). In CityGML, rooms represent the interior of the building, which includes installations and furniture. Installations are usually conceived as permanent parts of the building, like balconies and stairs, whereas furniture is freely movable objects. Structurally speaking, various types of surfaces can bound a building. This includes outer façade elements such as the roof surfaces, ground surfaces, and outer ceiling surfaces. Additionally, indoor room surfaces can be semantically distinguished into interior wall surfaces, floor surfaces, and ceiling surfaces.

Any object that can be manufactured from construction materials, intended to be permanent, and connected to earth is considered a construction object. The CityGML construction module defines concepts to represent construction objects. The purpose of this module is to integrate elements that consist of various categories of construction, namely buildings, tunnels, and bridges. In the Construction module, additional terms such as Furniture, Installations, and Constructive Elements are elaborated on. Installations refer to fixed components of a structure that have a significant impact on its exterior or interior appearance and cannot be relocated, such as balconies, chimneys, or stairs. Conversely, furniture pertains to portable objects within a structure, such as tables and chairs. The outer and inner elements of the constructions are differentiated in a similar way to the building module.

4.3 XPlanung as an urban plan content standard

XPlanung is a German data standard and data exchange format that provides models to describe information related to land use and urban planning. XPlanung is mainly adopted to formalize the content that is related to urban planning, aiming for a loss-free transfer of urban plans between the different actors [20]. Starting from 2017, it is mandatory to introduce the XPlanung standard for Information Technology (IT) projects used in the planning and approval procedures [20] for all German municipalities. The main goal of XPlanung is to provide a standardized digital data exchange format to enable simple, fast, and secure interexchange between the different administrative levels and the land planning actors.

UML is used for XPlanung data modelling, whereas the encoding rules have been adopted from ISO 19118 and ISO 19136. XPlanGML is the exchange format derived from the XPlanung data model using the encoding rules mentioned above. XPlanGML is based on GML 3.2.1 [3]. The latest version 6.0.2 was released in November 2022. XPlanung and XPlanGML are derived from ALKIS/NAS German standard, which is mainly used in the field of surveying and land registration. Accordingly, XPlanung basic schema uses only one geometry type, which corresponds to the ALKIS model “common geometry” [3]. XPlanung is based on the following land use and regulation documents:

- Urban development plan (**BPlan**) according to BauGB and BauNVO;
- Land use plan (**FPlan**) according to BauGB and BauNVO;
- Regional plan and state-wide spatial development plan (**RPlan**) according to Raumordnungsgesetz (ROG);
- Landscape plan (**LPlan** core model) in accordance with the Federal Nature Conservation Act.

Besides the nationwide regulations mentioned above, the data model includes a feature called SoPlan for other spatial plans that may contain additional relevant legal foundations. These regulations differ by scope and geographical extent. Thus, XPlanung came to integrate these documents within one standardized data model. Since our focus is on building constructability regulations, we will concentrate on regulations according to BauGB (German national building code) and BauNVO (zoning regulation code), which are modeled by the feature Bplan. These documents define the building constructability rules and the urban planning guidelines at the municipality level.

XPlanung models a spatial planning document as an instance of the plan class. Each specific planning document mentioned above has its own plan class (BP_Plan, FP_Plan, RP_Plan, LP_Plan, SO_Plan), all of which are derived from a common superclass XP_Plan. These plan classes refer to one or more areas that are specific to the respective planning document (BP_Area, FP_Area, RP_Area, LP_Area, SO_Area). These areas may have their own scope and can structure the plan geographically and/or thematically. All classes used for modeling these areas are derived from an abstract superclass XP_Area. Visualizing the plan involves graphically representing the areas using their own maps.

5 Mapping XPlanung and its regulations on relevant CityGML classes

5.1 Land use plan (Flächennutzungplan) and Urban Development Plan (BebauungsPlan)

The German Building Code (BauGB) stipulates that municipalities are entitled to publish a land use plan (Flächennutzungsplan) and development plans (Bebauungsplan). The land use plan outlines the land use type zoning resulting from the projected urban development projects as well as the vision and needs of the municipality. Development plans extend the land use plan with more structural stipulations, the type and extent of the land use areas, the dimensional limitations of the constructable areas, as well as regulations regarding public and private green spaces. It is important to note that no substantial contradiction in terms of the content of the development plan and the land use plan is allowed. Consequently, the zoning stipulations of the land use plan are present in the development plan with more details in order to make it legally binding for citizens, for building permits allowance, for example:

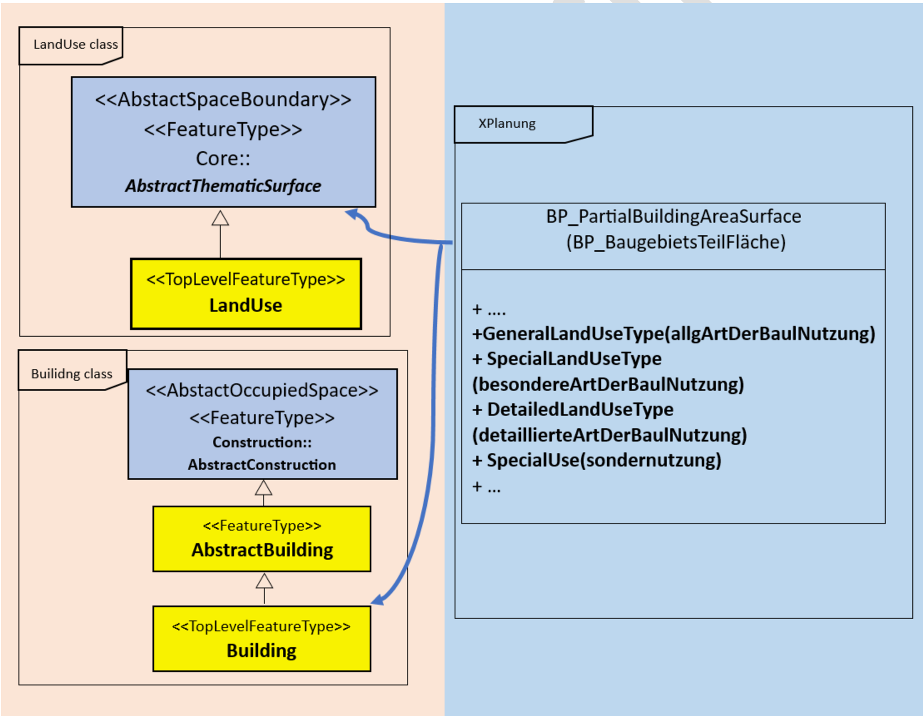

Fig. 2. Relation between land use regulations defined in XPlanung and CityGML classes. The blue arrows show the relations between CityGML classes on the left and an XPlanung class on the right

Land use knowledge is modeled in detail within the XPlanung land use plan FPlan (Flächennutzungplan) module. This sub-plan section models the following areas:

- areas intended for urban development FP_DevelopmentArea (FP_BebauungsFläche),
- areas that are reserved for waste disposal, excavations, and mineral resources FP_Landfill_Excavation_Mineral resources (FP_Aufschuettung_Abgrabung_Bodenschaetze),
- areas that are concepted for community needs and sports facilities FP_Community_needs_and_SportFacilities (FP_Gemeinbedarf_Spiel_und_Sportanlagen),
- zoning dedicated for agriculture activities and green spaces FP_Agriculture_Forest_GreenSpace (FP_Landwirtschaft_Wald_und_Grün),
- subareas subject to the nature conservation acts FP_NatureConservation (FP_Naturschutz).

Nevertheless, the crucial land use and zoning types are also modeled within the development plan BPlan (BebauungsPlan). As the right part of figure 2 shows, the feature class BP_PartialBuildingAreaSurface (BP_BaugebietTeilFläche) includes attributes that specify land use information. The latter XPlanung feature is used within the planning area of a development plan to specify partial areas with a consistent building use, such as purely residential or commercial areas. This XPlanung feature incorporates additionally BauNVO semantic land use information. Namely, the attribute GeneralLandUseType (allgArtDerBaulNutzung) which models the general type of land usage; possible values are Residential building area, Mixed building area, Commercial building area, Special building area, and other building area type. SpecialLandUseType (besondereArtDerBaulNutzung) specifies special area designations including industrial area (code 1800) and rural residential areas (code 1450). Table 1.1 presents the possible attribute values. In case detailed zoning information is required the attribute DetailedLandUseType (detaillierteArtDerBaulNutzung) can be deployed by defining a corresponding code list. The SpecialUse (sonderNutzung) attribute is used regarding zones that have special characteristics. For instance, if the value 2000 is assigned, the zoning is preserved for military purposes, the SpecialUse codelist is presented in table 1.2.

Before a simulation creates a synthetic building model at a specific location in the city using the CityGML standard, verifying if the object’s land parcel is legally buildable and under which conditions is a necessity. The CityGML LandUse objects can be used to model various features such as parcels and spatial planning objects. Linking the LandUse object with the municipality-imposed zoning information can be achieved by creating a relationship between the LandUse feature and the XPlanung BP_PartialBuildingAreaSurface (BP_BaugebietTeilFläche) feature as figure 2 illustrates. As a consequence, buildings can be enriched with zoning information. Thus, this integration can serve for defining consistency rules in order to make sure that a building is constructed on a buildable area in compliance with the land use plan implications.

Table 1. SpecialLandUseType codelist (upper left). SpecialUse codelist (upper right). GeneralLandUseType codelist (bottom right)

XP_Enumerationen :: **SpecialLandUseType (Besonder-eArtDerBaulNutzung)**
Small residential area = 1000
Pure residential area = 1100
General residential area = 1200
Special residential area = 1300
Village area = 1400
Rural residential area = 1450
Mixed area = 1500
Urban area = 1550
Core area = 1600
Commercial area = 1700
Industrial area = 1800
Special recreation area = 2000
Other special area = 2100
Weekend cottage area = 3000
Special area = 4000
Other area = 9999

XP_Enumerationen :: **SpecialUse (Sondernutzung)**
Weekend cottage area = 1000
Vacation home area = 1100
Campground area = 1200
Spa area = 1300
Other special recreation area = 1400
Retail area = 1500
Large-scale retail area = 1600
Shop area = 16000
Shopping center = 16001
Other large-scale retail area = 16002
Wholesale special area = 1650
Traffic training area = 1700
Port area = 1800
Renewable energy special area = 1900
Military special area = 2000
Agricultural special area = 2100
Sports special area = 2200
Health and social special area = 2300
Clinic area = 23000
Golf area = 2400
Cultural special area = 2500
Tourism special area = 2600
Office and administration special area = 2700
Judicial special area = 2720
University research special area = 2800
Fair special area = 2900
Other special use area = 9999

XP_Enumerationen :: **GeneralLandUseType (AllgArtDerBaulNutzung)**
Residential building area = 1000
Mixed building area = 2000
Commercial building area = 3000
Special building area = 4000
Other building area = 9999

5.2 XPlanung restrictions on the building plot

Within the BPlan submodel of the XPlanung standard, there are various classes that have spatial reference and can define areas where buildings can be constructed. This includes the features BP_BesondererNutzungszweckFlaeche (BP_SpecialPurpose-UseArea), BP_SpielSportanlagenFlaeche (BP_SportsFacilitiesArea), BP_-GemeinbedarfsFlaeche (BP_CommunityRequirementsArea), BP_GruenFlaeche (BP_GreenArea), BP_VerEntsorgung (BP_DisposalArea), BP_StrassenVerkehrs-

Flaeche (BP_RoadTrafficArea), BP_VerkehrsflaecheBesondererZweckbestimmung (BP_SpecialPurposeTrafficArea), BP_WohngebaeudeFlaeche (BP_Residential-BuildingArea), and BP_UeberbaubareGrundstuecksFlaeche (BP_Buildable Area).

The feature classes BP_FestsetzungenBaugebiet (BP_BuildingAreaDeterminations) and BP_ZusätzlicheFestsetzungen (BP_AdditionalDeterminations) are crucial and model the building’s dimensional constructability regulations.

Table 2. Relation between attributes of the XPlanung class BP_FestsetzungenBaugebiet (BP_-BuildingAreaDeterminations) and CityGML classes, the attributes define constraints for instances of the CityGML classes

Attribute	Description	Concerned CityGML feature
BM	Maximum allowed construction mass.	Building
BM_Ausn	Exceptionally maximum allowed construction mass.	Building
Bmax	Maximum width of building plots.	GroundSurface
Bmin	Minimum width of building plots.	GroundSurface
BMZ	Maximum permissible structural mass.	BuildingPart
BMZ_Ausn	Exceptionally maximum permissible structural mass.	Building
Fmax	Maximum size (area) of a building plot.	GroundSurface
Fmin	Minimum size (area) of a building plot.	GroundSurface
GF	Maximum allowed floor area.	FloorSurface
GF_Ausn	Exceptionally maximum allowed floor area.	FloorSurface
GFmax	Maximum allowable floor area for an area release.	FloorSurface
GFmin	Minimum allowable floor area for an area release.	FloorSurface
GFZ	Floors/plot surface area ratio.	FloorSurface
GFZ_Ausn	Maximum Floors/plot surface area ratio.	FloorSurface
GFZmax	Maximum allowable Floors/plot surface area ratio.	FloorSurface
GFZmin	Minimum allowable Floors/plot surface area ratio.	FloorSurface
GR	Building footprint area	FloorSurface
GR_Ausn	Maximum building footprint area as an exception.	FloorSurface
GRmax	Maximum building footprint area.	FloorSurface
GRmin	Minimum building footprint area.	FloorSurface

GRZ	Percentage of the building footprint over the size of the building plot	FloorSurface
GRZ_Ausn	Exceptionally maximum permissible GRZ.	FloorSurface
GRZmax	Maximum percentage of the building footprint over the size of the building plot	FloorSurface
GRZmin	Minimum percentage of the building footprint over the size of the building plot	FloorSurface
MaxZahlWoh-nungen	Maximum number of apartments in resi-dential buildings.	BuildingUnit
MinZahlWohnein-heit	Minimum number of apartments in resi-dential buildings.	BuildingUnit
Tmax	Maximum depth of building plots.	WallSurface
Tmin	Minimum depth of building plots.	WallSurface
Z	Maximum number of full floors above ground.	BuildingUnit
Z_Ausn	Maximum number of full floors above ground as an exception.	BuildingUnit
Z_Dach	Maximum number of additional permit-ted floors that are also full stories.	BuildingUnit
Z_Staffel	Maximum number of full floors set back above ground as stacked floors.	BuildingUnit
Zmax	Maximum allowable number of storeys above ground.	BuildingUnit
Zmin	Minimum permissible number of full stories above ground.	BuildingUnit
ZU	Maximum allowed number of under-ground storeys.	BuildingUnit
ZU_Aus	Exceptionally maximum permissible number of floors below ground level.	BuildingUnit
ZUmax	Maximum allowable number of under-ground storeys.	BuildingUnit
ZUmin	Minimum permissible number of floors below ground level.	BuildingUnit
ZUzwingend	Mandatory number of underground floors.	BuildingUnit
Zzwingend	Mandatory number of full stories above ground.	BuildingUnit

Table 2 presents the attributes of the XPlanung class BP_FestsetzungenBaugebiet (BP_BuildingAreaDeterminations) in more detail. BP_BaugebietTeilFläche (BP_PartialBuildingAreaSurface) models development plan areas with consistent building types as commercial buildings, and residential building areas.

BP_ÜberbaubareGrundstücksFläche (BP_BuildableArea) represents the area of the land parcel that can be built on. These entities inherit the properties of the classes BP_GestaltungBaugebiet (BP_DesignBuildingArea), BP_Flächenschlussobjekt (BP_ClosureAreaObject), BP_ZusätzlicheFestsetzungen (BP_Additional-Determinations), and BP_FestsetzungenBaugebiet (BP_BuildingAreaDeterminations).

The feature BP_UeberbaubareGrundstueckeFlaeche (BP_Buildable Area) is the essential overlay XPlanung class that presents the building structural area and dimensional regulations. It contains specifications regarding the building alignment (BP_BauLinie) and the building boundary (BP_BauGrenze). These entities are pivotal elements of the development plan. In addition, the building alignment and the building boundary restricts the structure of the building according to Paragraph 1 No. 2 BauGB, §22 - 23 BauNVO. As illustrated in Fig. 3, the building site must not exceed the building boundary area (BauGrenze) and the outer building surfaces must be aligned with the imposed building alignment (BauLinie). Consequently, the CityGML features GroundSurface as well as OuterFloorSurface must cope with the Building alignment and the building boundary. In addition, the CityGML GroundSurface is restricted by the maximum and minimum width of the building plot Bmax and Bmin.

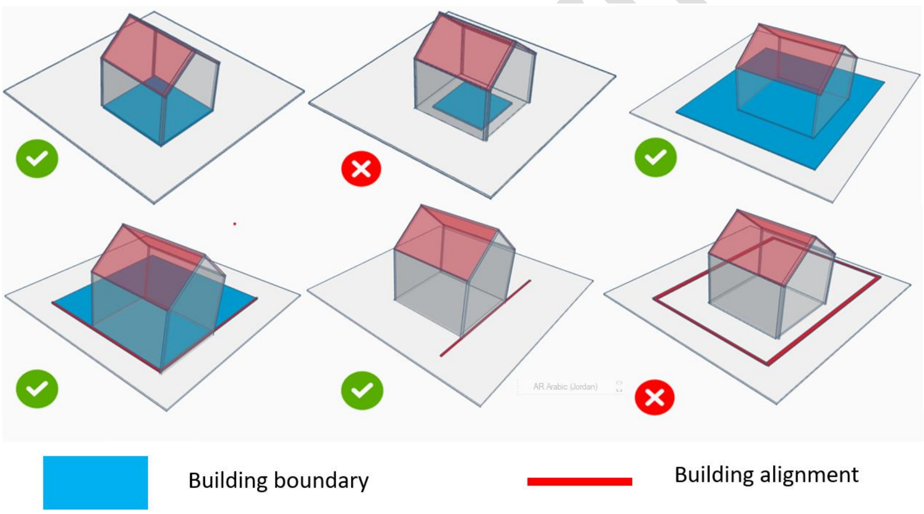

Fig. 3. Building alignment (BauLinie) and Building boundary (BauGrenze) as building site constraints

5.3 XPlanung restrictions on the building underground components

The CityGML feature Building is subject to constraints regarding the maximum and minimum number of underground floors (ZUmax and ZUmin), and if applicable the mandatory number of underground ZUzwingend. Furthermore, the maximum and minimum building depth must also be considered referring to the attributes Tmax and Tmin.

5.4 XPlanung restrictions on the building overground components

A CityGML building can be subdivided functionally into building units and storeys, as well as structurally into Building constructive elements. These elements are subject to dimensional regulatory conditions. Thus, a link to the XPlanung classes BP_FestsetzungenBaugebiet (BP_BuildingAreaDeterminations) and BP_Zusätzliche-Festsetzungen (BP_AdditionalDeterminations) must be concepted. This is illustrated in Table 2 as well as Fig. 4. The building GroundSurface must respect conditions related to the maximum and minimum area size of the building plot (Fmax and Fmin). The CityGML Building attribute StoreysAboveGround as well as the feature class Storey are subject to limitations regarding the maximum and minimum number of appartments (MaxZahlWohnungen and MinZahlWohneinheit respectively) and maximum and minimum permissible number of floors above ground (Zmax and Zmin), as well as the mandatory aboveground floors (Zzwingend). The CityGML constructive features FloorSurface and GroundSurface objects are subject to regulatory limitations regarding the maximum and minimum allowed floor area (Gfmin and Gfmax), the maximum and minimum floor area ratio (GFZmax and GFZmin), the maximum and minimum portion of the building plot that can contain buildings (GRmin and GRmax), and the maximum and minimum percentage of the building areas over the size of the building plot (GRZmax and GRZmin). These different area limitations are illustrated in more detail in Fig. 4. Additionally, the building alignment (BauLinie) and building boundary (BauGrenze) attribute elevation (Höhenangabe) specifies the maximum height of the building. Thus, this will restrict the CityGML attributes height and storeyHeightsAboveGround of the Building class and also its geometry.

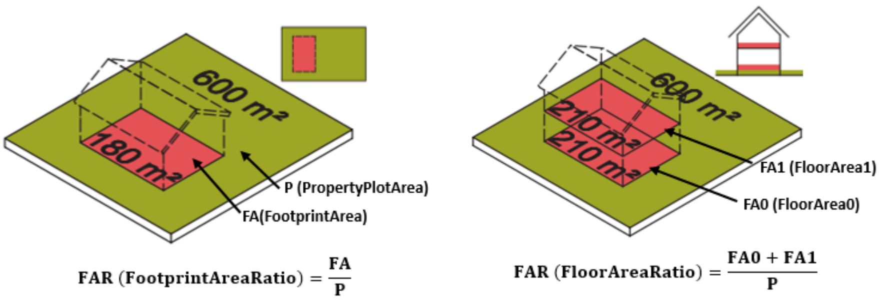

Fig. 4. BauNVO building area constraints ([20], edited)

5.5 XPlanung restrictions on the building roof

The feature BP_GestaltungBaugebiet (BP_DesignBuildingArea) models some of the building design characteristics as the ridge direction and the roof design parameters (BP_Dachgestaltung) (BP_RoofDesign). These attributes constrict the CityGML constructive object RoofSurface as well as the building class attribute roofType. These limitations as well as the above mentioned regulations are illustrated in Fig. 5 and 6.

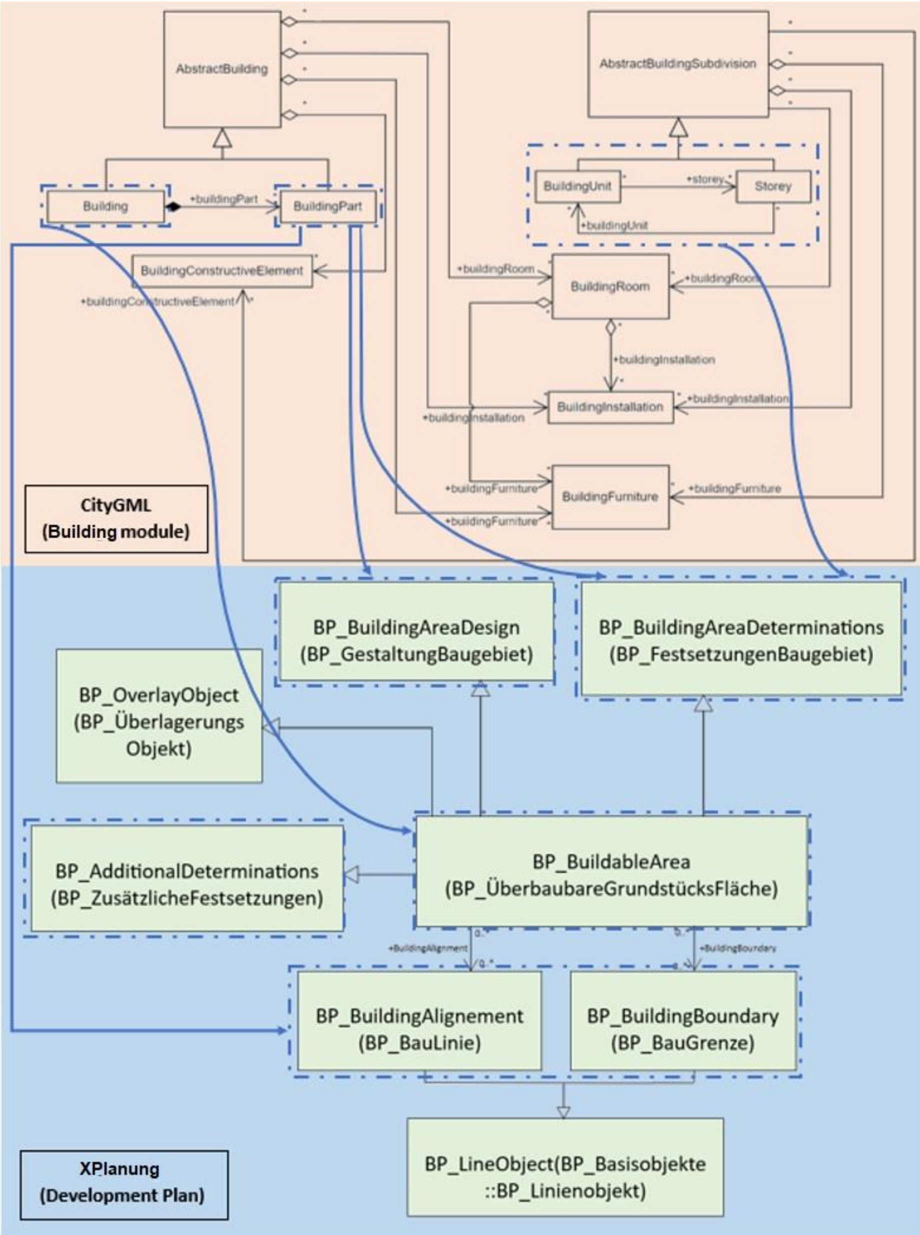

Fig. 5. , XPlanung restrictions of classes from the CityGML building module. The blue arrows demonstrate the association between the XPlanung regulations and the corresponding classes in CityGML

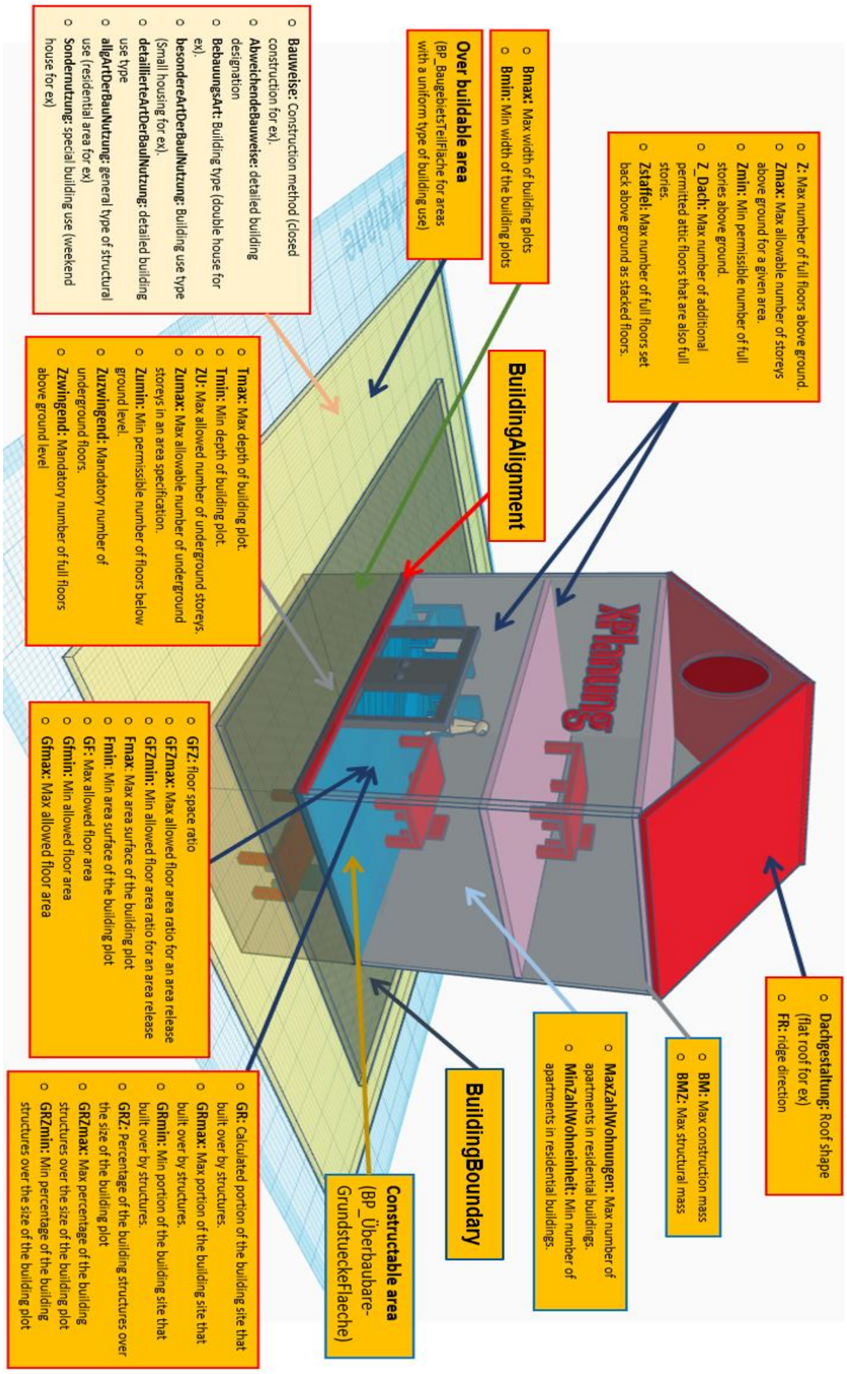

Fig. 6. Dimensional and constructability regulations regarding the building element

6 Discussion and conclusion

This paper aims to provide a schema-level integration of land planning regulatory information modeled in the German data model standard XPlanung and the 3D city model data standard CityGML as a base for constraining the generation of synthetic 3D city models in urban simulations. This integration is conducted through an investigation process to answer the pivotal research question: "What XPlanung objects constrain semantically and dimensionally a CityGML Building entity?".

Our integration process starts by investigating land use areas where buildings are allowed to be built on. The XPlanung feature BP_PartialBuildingAreaSurface (BaugebietTeilFläche) incorporates attributes that specify the landscape zoning allocations following the land use plan of a municipality (Flächennutzungplan). This can be conceptually linked to the CityGML LandUse class, which should be linked to the Building class. This harmonization makes sure that a CityGML building is legislatively allowed in the parcel area. In addition, the building plot is constrained by regulations related to the building alignment (BauLinie) and the building boundary (BauGrenze); these features include the maximum allowed height information as well as limitations on the plot area. The building's underground and above-ground entities are subject to regulations relevant to the maximum and minimum over-ground and under-ground FloorSurfaces and buildingUnits. The various floor area constraints that are outlined in the BauNVO legal document are attributed to the XPlanung class BP_BuildingAreaDeterminations (BP_FestsetzungenBaugebiet). Hence, these features will constrain the CityGML constructive FloorSpace elements. The CityGML RoofSurface class object is not neglected within XPlanung and subject to constraints related to the roof shape and the ridge direction. Such integration of landscape regulatory knowledge with 3D city data model ensures the real-life applicability of any urban simulation workflow. Making sure that the synthetic building model generated as part of an urban simulation respects the binding land use regulation enhances the importance of using semantic 3D city model for urban planning use cases.

In addition to the building example, both standards can provide support for other aspects, such as the city's streets and green space area. This integration framework enhances the semantic and topological richness of CityGML 3D models with constructability regulation knowledge provided in the German standard XPlanung. Accordingly, synthetic 3D city models generated by urban simulations will incorporate urban regulations limitations which gives them more realism. Urban simulation results will be in accordance with the urban applicable land use regulations. This includes energetic simulations and solar irradiation potential estimation, which are highly impacted by the roof shape, the height of the building, as well as the building orientation. The latter building features are legally binding and cannot be freely designed. Urban growth simulations must cope with the land use limitations, the maximum and minimum floor space and number of storeys etc.. Synthetic 3D city models generated for proposing smart and optimized cityscape configurations must follow the land use and the development plan guidelines. If not, transforming them into real-life projects remains doubtful. Various use cases can benefit from CityGML-XPlanung harmonization, the proposed schema-level integration can be used to study the impact of the development and land use plans on different factors that have a spatial context. This covers for instance, the impact of building ridge direction and the roof shape on the energy consumption as well as the influence of the adopted building alignment (BauLinie) and building boundary (BauGrenze) on the traffic areas and the indoor perceived noise.

Future work will build on this mapping and focus on extending it with Object Constraint Language (OCL) rules to ensure that any CityGML entity generated by an urban simulation respects its relevant urban constraints. This will lead to the development of a 3D city logical model that includes urban regulation knowledge, enabling the generation of synthetic 3D city models for proposing smart and optimized cityscape configurations that follow land use and development plan guidelines. Based on an implementation for the use case urban expansion, we intend to evaluate the conceptual mapping and demonstrate the benefits of our concept.

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