

RESEARCH ARTICLE

# Towards harmonizing property measurement standards

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**Abstract:** Area and volume values of buildings and building parts have been used in many applications including taxation, valuation and land use planning. Many countries maintain a national standard for representing the measurements of floor areas in buildings. The national standards generally use similar basis for measuring building floor areas, in fact, areas specified in national standards often have semantic differences. Therefore, a number of international standards have been developed for harmonizing floor area measurements; however, they also have differences. This study aims at harmonizing the floor areas defined in the international property measurement standards by revealing the semantic relations between them and formalizing them with an ontological approach. To achieve this objective, the international property measurement standards were firstly examined in order to identify semantics, principles and practices in floor area measurements. Then, the obtained information were utilized to develop a set of measurement ontologies for harmonizing the property measurement standards. This paper also investigates 3D data standards to reveal whether they can be utilized for realizing the property measurement standards.

**Keywords:** property measurement standard, building floor area, knowledge organization system (KOS), ontology, property measurement ontology, 3D data standard

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## 1 Introduction

Area and volume values of buildings and building parts have been used in many applications such as taxation, valuation, land use planning, performance measurement of building, building cost planning and property transactions [32, 25]. The areas of property units or parts may be obtained from different sources, such as land registers, building

and dwelling registers and architectural projects, however, these sources generally do not provide explicit information on the semantics, procedures and methods used to compute them. Many countries have national standards for measurements of floor areas in buildings, e.g., DIN 277:2005 in Germany, NEN 2580:2007 in the Netherlands, ATASA in Spain, PCA Measurement Standard in Australia, and HKIS Code of Measuring Practice in Hong Kong.

A study conducted by the European Committee of Construction Economists (CEEC) shows that national measurement standards more or less use similar basis for measuring floor areas, but semantic differences between various types of areas specified in national standards often found highly misleading [13, 52, 53]. For instance, measuring a specific floor area in one building using different national standards results in variations up to 30% [13]. According to other resources, current measurement inconsistencies can create 24% difference in valuations between markets [29, 31]. Therefore, a number of international standards have been developed for harmonizing floor area measurements in local levels. These standards include:

- International Organization for Standardization (ISO), ISO 9836 2011 and 2017—Performance Standards in Building—Definition and calculation of area and space indicators [34, 35];
- The European Committee for Standardization (CEN), EN 15221-6—Area and Space Measurement in Facility Management, 2011 [13];
- The European Group of Valuers' Associations (TEGoVA), European Valuation Standards (EVS)—Code of Measurement of Distance, Area and Volume, 2012 and 2016 [53, 54];
- International Property Measurement Standards Coalition (IPMSC), IPMS for Office Buildings, 2014 [25], IPMS for Residential Buildings, 2016 [26]; IPMS for Industrial Buildings [27] and IPMS for Retail Buildings [28];
- Royal Institution of Chartered Surveyors (RICS), Code of Measuring Practice, 2007 [16]; Property Measurement, 2015 [47];
- The Council European Geodetic Surveyors (CLGE), The European Real Estate Area Label (euREAL), Measurement Code for the Floor Area of Buildings, 2012 [39];
- American Society for Testing and Materials (ASTM), E1836/E1836M-09—Standard Practice for Building Floor Area Measurements for Facility Management, 2006 [4] and 2016 [3];
- Building Owners and Managers Association (BOMA), Office Buildings: Standard Methods of Measurement (ANSI/BOMA Z65.1—2010 and 2017); Industrial Buildings: Standard Methods of Measurement (ANSI/BOMA Z65.2—2012), Gross Areas of a Building: Standard Methods of Measurement (ANSI/BOMA Z65.3-2009) ..., Mixed-Use Properties: Standard Methods of Measurement (ANSI/BOMA Z65.6—2012).

Although the objective of these international standards is to provide consistent basis harmonization in measurement practices, there are many differences amongst them. For instance, the above listed standards includes terms, definitions and rules for measuring building floor areas but only ISO 9836 [34, 35], CEN 15221-6 [13] and RICS [16, 47] have terms about building volumes, while TEGoVA [53], CEN 15221-6 [13] and RICS [16, 47] have a few terms for land measurement. Moreover, the mentioned standards apply different terminology, which causes international confusion [25]. For example, the standards generally have different term(s) and definition(s) on total (gross) floor area of a building.



Table 1 shows the terms used in the international measurement standards that represent total floor area of a building. More specifically, RICS [16,47] and TEGoVA [53] use the term “Gross External Area” for the representation of the total floor area, but their definitions are slightly different. On the other hand, “Total Floor Area” defined by ISO 9836:2011 [34] has same definition with “Gross External Area” defined by RICS [16].

Measurement standards	Terms representing total floor area of buildings
ISO 9836 (2011, 2017)	Total Floor Area
CEN 15221-6 (2011)	Gross Floor Area
TEGOVA (2016)	Gross External Area and Gross Floor Area
IPMS (2014)	IPMS 1
IPMS (2016, 2018a, 2018b)	IPMS 1 (External)
RICS (2007, 2015)	Gross External Area
CLGE (2012)	External Area and SEM
ASTM (2006, 2016)	Exterior Gross Area
BOMA (1996, 2009)	Exterior Gross Area

Table 1: Total (Gross) floor area terms of the international property measurement standards.

Until now, differences and commonalities between the terms representing floor areas of building parts defined in the international measurement standards have not been formally identified, and semantic relations between these terms have not been explicitly analyzed. This study focuses on development of a framework that may assist in harmonization of the floor area terms. The objective is to extract and reorganize information obtained from the international measurement standards, and reveal semantic relationships between terms of these standards through a knowledge organization system (KOS).

In order to formally represent floor areas and semantic relations between them, a KOS approach can be applied to the measurement standards. A KOS is a general term, which refers to tools that present the organized interpretation of knowledge structures [56]. It covers all types of schemes for organizing information and promoting knowledge management, such as (i) term lists (e.g., glossaries and dictionaries), (ii) classifications and categories (e.g., subject headings and taxonomies), and (iii) relationship lists (e.g., thesauri and ontologies) [22]. The literature presents a number of KOSs in different levels of detail related to Land Administration (LA), Building Information Modeling (BIM) and 3D city models. For instance, Çağdaş and Stubkjær [15] presented Cadastre and Land Administration Thesaurus (CaLAtHe) which provides a controlled vocabulary for the domain of cadastre and land administration. Sladic et al. [49] proposed a cadastral ontology for real estate cadastre based on ISO 19152:2012 Land Administration Domain Model (LADM) [33] and ISO 19100 series of standards. Soon [51] developed a formalized domain ontology for land administration based on ISO 19152:2012 LADM. Çağdaş et al. [14] provided a domain thesaurus for the development of a possible valuation component of LADM. In the BIM domain, an ontology-based approach for building cost estimation proposed by Lee et al. [37]; an ontology-based model for automated safety planning in order to analyze job hazards proposed by Zhang et al. [57]; a reference ontology for a formal mapping between Industry Foundation Classes (IFC) [32] and CityGML [41] was developed by El-Mekawy and Östman [18]. This research aims to contribute to knowledge in the field by providing relationship lists, namely ontologies for the international property measurement standards.

An ontology may provide a common understanding in a specific domain, reusing domain information and expressing definitions, relations and interrelations of the domain, explicitly [40]. In this study, a set of property measurement ontologies were developed based on the international measurement standards. The floor area terms, definitions, elementary portions (components) of the floor areas and hierarchical and semantic relations between the floor areas were firstly extracted from documentations of the standards. The outputs were utilized to develop formal ontologies for each measurement standard. The hierarchical relations between the floor area terms are identified via the semantic relations properties of Simple Knowledge Organization System (SKOS) in these ontologies. Then, the semantic relations between the floor area terms of the standards were matched in schema-level. The term Ontology Matching can be defined as “the process of finding relationships or correspondences between entities of different ontologies.” [19]. It may reduce semantic gap between different overlapping representations of the same domain [44]. The properties of Web Ontology Language (OWL) and Resource Description Framework Schema (RDFS) were used for matching the terms in the measurement ontologies. Furthermore, it is noted that an integrated property measurement ontology, which includes the floor area terms and component areas of them, was also developed. In other words, floor area measurements were decomposed into elementary floor area portions and an integrated measurement ontology was developed based on the portions to harmonize the measurement standards in component level. According to ontology classification based on formality presented by Roussey et al. [48], the developed property measurement ontologies can be classified as linguistic / terminological ontologies.

Information in a specific domain should be reused by other domains. Therefore, the terms and principles defined in the property measurement standards should be utilized by other relevant domains for providing interoperability. There is a number of 3D data standards, which include building and building part features in their data models that may be used to realize the property measurement standards. The semantic and spatial compatibility between “3D data standards” (e.g., OGC’s CityGML and LandInfra, IFC BIM, ISO LADM, INSPIRE Building Data Specification, etc.) and the “property measurement standards” should be ensured in order to achieve a full interoperability through these domains. In this context, the 3D data standards were investigated in terms of semantics and spatial aspects to reveal whether they can be utilized to measure the floor areas in accordance with the specifications of the property measurement standards.

The remaining part of this paper is organized as follows: Section 2 focuses on investigating the international property measurement standards of which the documentation about them is more reachable. The information obtained from previous section was utilized to develop property measurement ontologies in Section 3. This section gives detailed information on the structure of the ontologies. The next section investigates semantic and spatial compatibility between the 3D data standards and the property measurement standards. The last section presents discussion, concluding remarks and proposals for the further researches.

## 2 Property measurement standards

The property measurement standards were prepared with the aim of providing a consistent basis, assisting benchmarking and making easier interpretations in building parts measure-



ments. They provide terms, definitions, rules and principles for the measurement of floor areas.

All the measurement standards use floor-based measurements. A floor area is measured on the horizontal plane for each level of a building [3, 13, 25, 34]. If a floor's geometry is an inclined plane, then it is measured by the vertical projection onto a horizontal plane. When a floor area is measured, “the wall priority” and “boundary lines” should firstly be determined.

A building floor area may include the external wall thickness, part of the external wall's thickness (e.g., wall center method and median wall boundary) or exclude the external wall's thickness [25,55]. For example, with respect to floor area terms of the ISO 9836, while “Total Floor Area” includes floor area of external wall thickness, “Net Floor Area” does not include it. After wall priority is determined, boundary lines that delimit a floor area should be specified according to preferred measurement conventions. There are some different conventions in different markets, for example, one floor area can be measured to the wall-floor junction, midpoint of walls or dominant face of an inside finished surface [25]. Once the boundary lines that delimit a floor area are combined, a closed polygon is formed, which is used for computing a floor area value. The property measurement standards may specify different rules for determining boundary lines of a floor area. The next subsections examine measurement rules and principles of the floor areas defined in the international property measurement.

## 2.1 ISO 9836 performance standards in building—Definition and calculation of area and space indicators

ISO 9836 specify the calculation of area and volume values of all kind of buildings for performance measures [34,35]. ISO 9836 defines 25 different area types, 10 terms for building volumes and 16 height types (e.g., story height and building height). Figure 1 shows reference building floor areas defined in this standard. Figure 2 illustrates the building areas using floor plans.

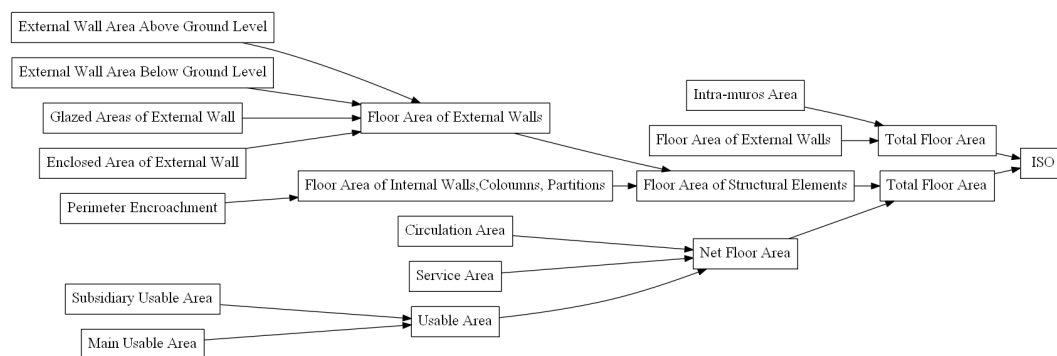


Figure 1: The reference building floor areas of ISO9836:2017.

As presented in Figure 1, the “Total Floor Area” is the sum of “Net Floor Area” and “Floor Area of Structural Elements” or “Intra-muros Area” and “Floor Area of External

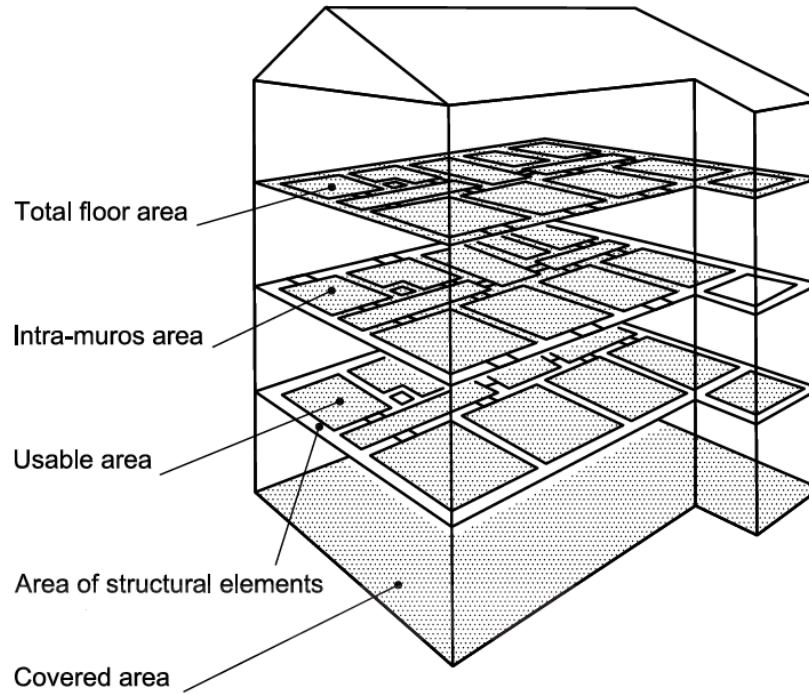


Figure 2: ISO 9836 floor area types illustrated as floor plans [32, 33].

Walls". It can be defined as total gross area including internal and external walls. "Total Floor Area" in ISO 9836 is represented by different terms in other standards, i.e., "Gross External Area" in RICS [16] and "Level Area" in CEN 15221-6:2011 [13]. "Intra-muros Area" is the gross floor area minus the floor area taken up by the external walls, namely floor area of the building envelope [34,35]. If the "Intra-muros Area" is enclosed and covered on all sides, it would be termed as "Gross Internal Area" in RICS Code of Measurement [34,35]. "Intra-muros Area" is different from "Internal Floor Area" defined in CEN 15221-6 [13], since the latter excludes voids above technical areas.

According to ISO 9836, "Net Floor Area" is the sum of "Usable Area", "Service Area", and "Circulation Area". The sum of "Effective Building Loss Area", "Effective Floor Area for Occupants" and "Service Area" is also equal to "Net Floor Area" [34,35]. "Net Internal Area" defined in RICS corresponds to "Net Floor Area", but it excludes "Services Area", "Circulation Area", common areas, toilets, cleaners' rooms, and areas with a headroom of less than 1.5 meters [34,35]. In euREAL, "Internal Area" is used for referring to "Net Floor Area". However, it should be noted that "Internal Area" does not include construction features and fixed partitions contrary to "Net Floor Area".

Next floor area terms defined in ISO 9836 are "Service Area" and "Circulation Area". While the former refers to net floor area with technical installations in the building (e.g., water supply, gas installation, elevator, etc.), the latter covers stairwells, corridors, internal ramps, waiting areas, etc. [34,35]. "Service Area" and "Circulation Area" in ISO 9836 cor-

responds to “Technical Area” and “Circulation Area” types in CEN 15221-6, respectively. If “Service Area” and “Circulation Area” are extracted from the “Net Floor Area”, the remained part is named as “Usable Area” according to ISO 9836.

“Covered Area” is measured by the vertical projection of the external dimensions of the building onto the ground [34]. It complies with “Building Footprint Area” type specified in CEN 15221-6.

“Area of Structural Elements” is defined as area within total floor area of the enclosing elements such as external and internal load bearing walls. The columns, pillars, piers, chimneys and partitions are not included, when calculating the “Area of Structural Elements” [34,35]. The sum of “Interior Construction Area” and “Exterior Construction Area” specified in CEN 15221-6 corresponds to “Area of Structural Elements” in ISO 9836. “Constructed Area” type defined in euREAL is quite similar to “Area of Structural Elements” in ISO 9836, but it also includes walls, pillars, supporting walls, breast walls, and alcoves.

Lastly, ISO 9836 defines a number of floor volumes and one of them is “Net Volume above Intra-muros Area” that is defined as “the product of the intra-muros area and the height between the surface of the floor and the underside of the ceiling.” [34, 35]. This volume is identical with the “Cubic Content” in the RICS Code of Measurement [16].

## 2.2 CEN EN 15221-6—Area and space measurement in facility management

CEN 15221 contains series of standards related to facility management. CEN 15221-6 provides terms, definitions and principles about measurement of floor areas in building [13]. Although this standard is mainly related to facility management, it can also be employed in entire construction industry [13]. CEN 15221-6 defines 9 different distance types (e.g., length, width, and height), 34 different building areas and 2 volume types (gross and net volume), as detailed below. Figure 3 presents the principal floor areas defined by CEN 15221-6.

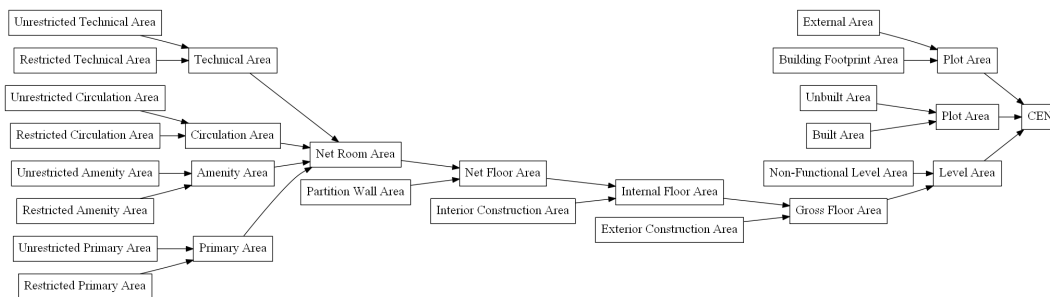


Figure 3: CEN EN 15221-6 principal building floor areas.

“Level Area” is measured from external permanent finished wall surfaces. It is composed of the “Gross Floor Area” and “Non-functional Level Area” [13]. “Level Area” is similar to “Gross External Area” defined by RICS Code of Measurement [13].

According to CEN 15221-6, “Gross Floor Area” is calculated by extracting “Non-Functional Level Area” from “Level Area”. It is different from “Gross Internal Area” spec-

ified in RICS, due to the wall thickness and external projections [13]. Next area term in CEN 15221-6 is the “Internal Floor Area”, which is the sum of “Net Floor Area” and “Interior Construction Area”. While “Internal Floor Area” does not include “Non-functional Level Area”, “Gross Internal Area” includes service voids and areas with a height below 1.5 meter [13]. “Net Floor Area” can be decomposed into “Net Room Area” and “Partition Wall Area” (e.g., non-structural walls, flexible, and movable partitions). The “Net Room Area” consists of “Primary Area”, “Technical Area”, “Circulation Area”, and “Amenity Area” [13]. Among these floor area portions, “Primary Area” corresponds to “Net Internal Area” defined by RICS [13].

CEN 15221-6 also provides a number of definitions for areas outside of buildings, such as “Building Envelope Area”, “Building Footprint”, “Building Area Above Ground”, and “Building Area Below Ground” (see Figure 4). “Building Envelope Area” and “Building Footprint” specified in CEN 15221-6 correspond to “Building Envelope Area” and “Covered Area” defined by ISO 9836.

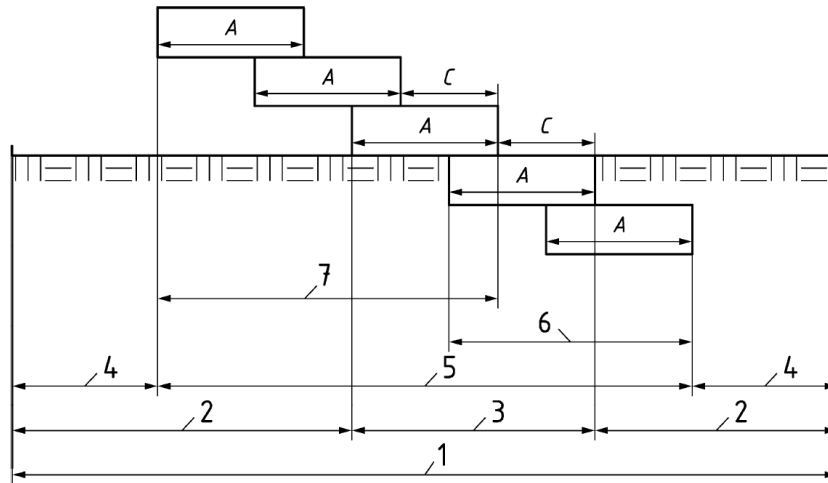


Figure 4: Measurement areas outside of building: 1. Plot area, 2. External area, 3. Building footprint, 4. Un-built area, 5. Building envelope, 6. Building area below ground, 7. Building area above ground, A. spaces which are entirely covered and enclosed on all sides up to their full height, C. spaces which are not covered, but contained within components [13].

### 2.3 TEGoVA, EVS—Code of measurement of distance, area, and volume

European Code of Measurement, which is a part of European Valuation Standards published by the European Group of Valuers’ Associations (TEGoVA), provides methods used for measuring properties for valuation purposes [53,54]. Totally, 19 different areas related to land and building parts are defined in this code. Figure 5 presents the principal floor areas defined by TEGoVA measurement code.

The terms and principles of this measurement code have been informed from CEN 15221-6 [53]. Therefore, the terms and definitions of this code are almost identical with the CEN 15221-6.





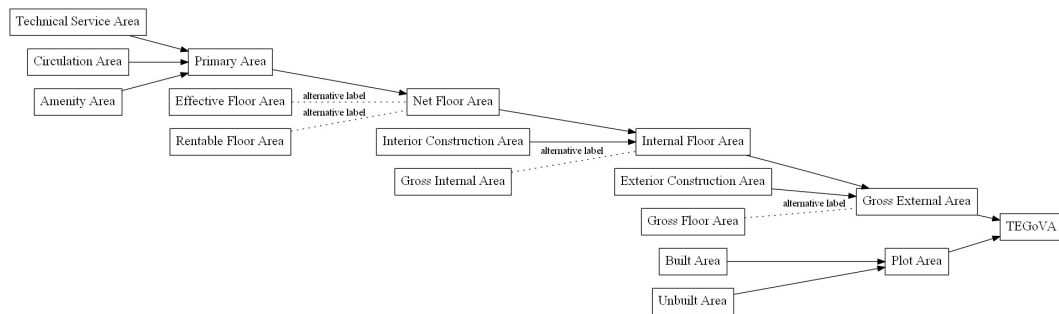


Figure 5: The reference floor areas of TEGoVA.

Since the EVS is a valuation standard, it focuses on measurements that may affect the value of properties. For example, the EVS specifies some distances related to land and building, such as depths from the building's frontage since the built depth may affect the monetary value of a property particularly in the retail sector. It is stated that these distances should be included in the valuation reports [51, 52]. Finally, the EVS stated that while "Gross External Area" can be used for cost estimation, insurance valuation, planning and zoning; "Gross Internal Area" can be employed for especially in valuation of office and industrial buildings [53,54].

## 2.4 IPMS for office buildings and IPMS for residential buildings

The International Property Measurement Standards Coalition (IPMSC) comprises the organizations including RICS, CLGE, BOMA, International Federation of Surveyors (FIG) and International Association of Assessing Officers (IAAO). It aims "to bring about the harmonization of national property measurement standards through the creation and adoption of agreed international standards for the measurement of Buildings" [26]. The IPMSC specifies different terms and principles according to building usages. Accordingly, it published four standards: IPMS Office Buildings [25], IPMS Residential Buildings [26], IPMS Industrial Buildings [27] and IPMS Retail Buildings [28]. It is noted that IPMSC may develop standards for other types of property (e.g., mixed, school, hospital, hotel, and student accommodation) in the future [30]. The members of IPMSC have started to put the IPMSs into practice. For example, RICS made a statement to its members that IPMS Office Buildings and Residential Buildings is mandatory for RICS members [47]. Furthermore, the standard BOMA for Office Buildings was prepared fully compatible with IPMS Office Buildings and it is noted that BOMA will be incorporating the IPMS standards in all its standards [2]. In this subsection, the published standards of IPMSC were examined.

Thirty terms concerning to building floor areas are defined in IPMS Office Buildings. Figure 6 presents the floor areas defined by IPMS Office Buildings that specifies three reference floor areas: "IPMS 1", "IPMS 2—Office" and "IPMS 3—Office". The first floor area is "IPMS 1" that is measured outer surface of external wall for each level of building [25]. It includes the areas of balconies, covered galleries, accessible rooftop terraces, but not covers the areas of open light wells, upper level voids, open external stairways, patios and decks at ground level and external car parking. Figure 7 (left) shows a floor plan illustrating the

areas included in the “IPMS 1”. The “IPMS 1” is slightly different with “Gross External Area” of RICS, since it covers the external balconies and rooftop terraces [47].

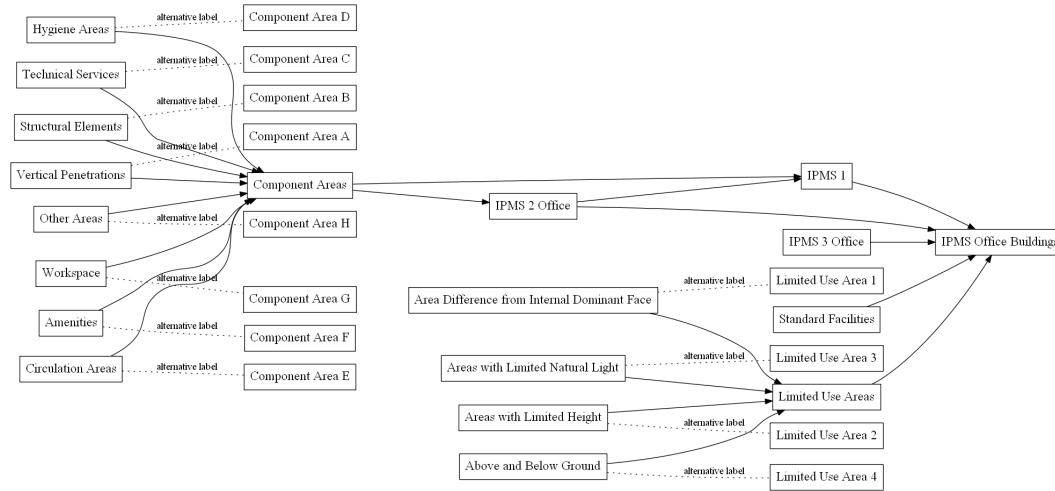


Figure 6: IPMS Office Building reference floor areas.

“IPMS 2—Office” is measured from “internal dominant face” for external walls or otherwise horizontally at wall-floor junctions, ignoring skirting boards, heating and cooling units, and pipework [25]. It includes internal walls, columns, enclosed walkways, balconies, covered galleries [25]. Figure 7 (right) shows the eight component areas of “IPMS 2—Office” [25]. It is reported on a component-by-component basis for each floor of a building and used in applications such as facility management, valuation, and transactions [25]. It is slightly different with “Gross Internal Area” defined in code of RICS. While “Gross Internal Area” defined in RICS includes internal balconies and roof terraces, “IPMS 2—Office” does not cover these areas [47].

“IPMS 3—Office” is not directly related to “IPMS 1” or “IPMS 2—Office” and it is for measuring the occupation of floor areas in exclusive use. While all internal walls and columns are included within ‘IPMS 3—Office”, standard facilities and shared circulation areas such as stair, toilet, fire refuge area, and maintenance room are excluded [25]. It is calculated on an occupier-by-occupier or floor-by-floor basis for each building [25]. This can be used by parties such as occupiers, asset managers, facility managers, property managers, researchers, and valuers [25].

In order to measure some of the IPMS floor areas, boundary lines that delimit a specific floor area are determined according to “internal dominant face”. The IPMSC defines the internal dominant face as “the inside finished surface comprising 50% or more of the surface area for each Vertical Section forming an internal perimeter” [25, 26]. While the “vertical section” refers to each part of a window, wall, or external construction feature, “finished surface” refers to wall surface directly above the horizontal wall-floor junction [25, 26]. If the internal dominant face is not vertical or vertical but no face exceed 50%, the wall-floor junction should be selected as a vertical section starting or ending point [25]. Columns, skirting boards, heating and cooling units, and pipework are ignored when the measure-



Figure 7: “IPMS 1” (Left): a. Covered gallery, b. Balcony, c. Open light well/upper level void of atrium, d. Open external stairway; “IPMS 2—Office” (Right): A. Vertical penetrations, B. Structural elements, C. Technical services, D. Hygiene areas, E. Circulation areas, F. Amenities, G. Workspace, H. Other Areas [25].

ment should be to the wall-floor junction [25]. Figure 8 shows the process of determining vertical sections and internal dominant faces. This method is applied in all the IPMSs.

The other standard published by IPMSC is about Residential Buildings. There are 43 terms about floor areas and two different height types (i.e., clearance and full heights). Figure 9 presents the floor areas of this standard. The measurement principles are same with the IPMS Office Buildings. IPMS Residential Buildings specifies five reference floor area terms: “IPMS 1 (External)”, “IPMS 2—Residential (Internal)”, “IPMS 3A—Residential”, “IPMS 3B—Residential” and “IPMS 3C—Residential”.

“IPMS 1 (External)” is measured outer perimeter of the external walls and generally used for planning purposes [26]. This area is equal to sum of all component areas defined in this standard (see Figure 9 and Figure 10). While the area of columns, balconies, verandas, internal catwalks, sheltered areas and internal permanent mezzanines are included in “IPMS 1 (External)”, the areas of temporary mezzanines, open light wells and open exter-

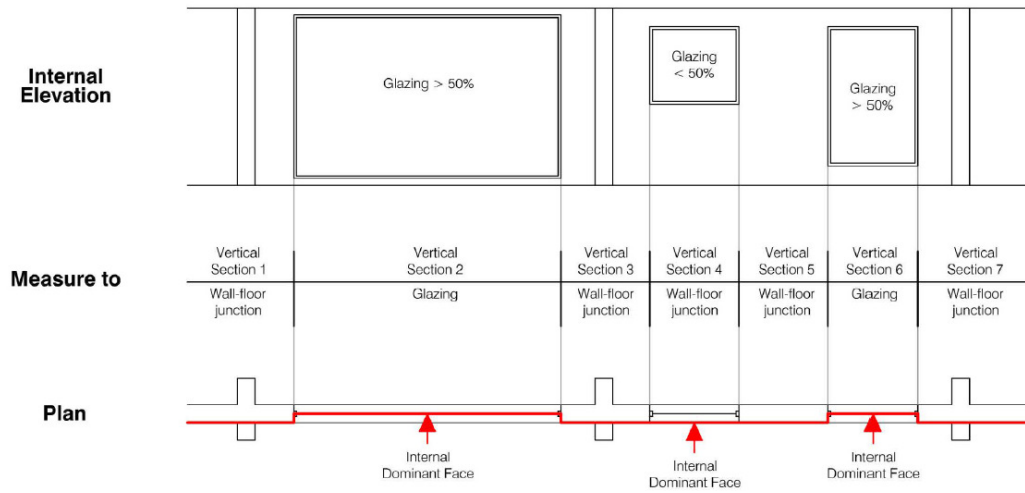


Figure 8: Determining the internal dominant faces of vertical sections [25–28]

nal stairways are excluded [26]. In some instances, “IPMS 1 (External)” may be the same with “IPMS 3A—Residential” [26]. The “IPMS 2—Residential (Internal)” is equal to the aggregate of the component areas minus external wall area [26]. The measurement of “IPMS 2—Residential (Internal)” is to be taken to internal dominant face of the each floor [26]. In some instances, “IPMS 2—Residential (Internal)” may be the same with “IPMS 3B—Residential”. Moreover, it is quite similar with “Internal Floor Area” in CEN 15221-6 but it includes internal columns, partitions and non-structural walls.

“IPMS 3—Residential” is the floor area available on an exclusive basis to an occupier [26]. There are three variations of it. “IPMS 3A—Residential” includes the areas of attics, basements, balconies, and verandas in exclusive use and enclosed garages; however, it does not include the areas of patios, unenclosed parking areas, staircase openings, vertical penetrations, and voids greater than 0.25 m<sup>2</sup> [26]. When “IPMS 3A—Residential” is measured, the wall priority is determined according to dwelling type. For example, in a detached dwelling “IPMS 3A—Residential” is measured outer face of external walls, while, it is measured outer face of external walls and centre-line of shared walls in an attached dwellings [26]. “IPMS 3B—Residential” is measured from internal dominant face and finished surface of internal perimeter walls. “IPMS 3B—Residential” includes the floor area occupied by internal walls and columns. Lastly, “IPMS 3C—Residential” excludes the floor area occupied by full-height, permanent, internal walls, and columns [26]. The variations of “IPMS 3—Residential (Occupier)” share close definitions with “Net Floor Area” of ISO 9836 and “Internal Area” of euREAL.

The IPMS Industrial Building is another standard of IPMSC. There are 46 terms on floor areas and three different height types (i.e., clear, full, and internal heights) in this standard [27]. Figure 11 presents the floor areas of this standard. IPMS Industrial Buildings specifies four different reference terms for floor areas: “IPMS 1 (External)”, “IPMS 2—Industrial (Internal)”, “IPMS 3A—Industrial (External: Exclusive Occupation)”, and “IPMS 3B—Industrial (External: Exclusive Occupation)”.

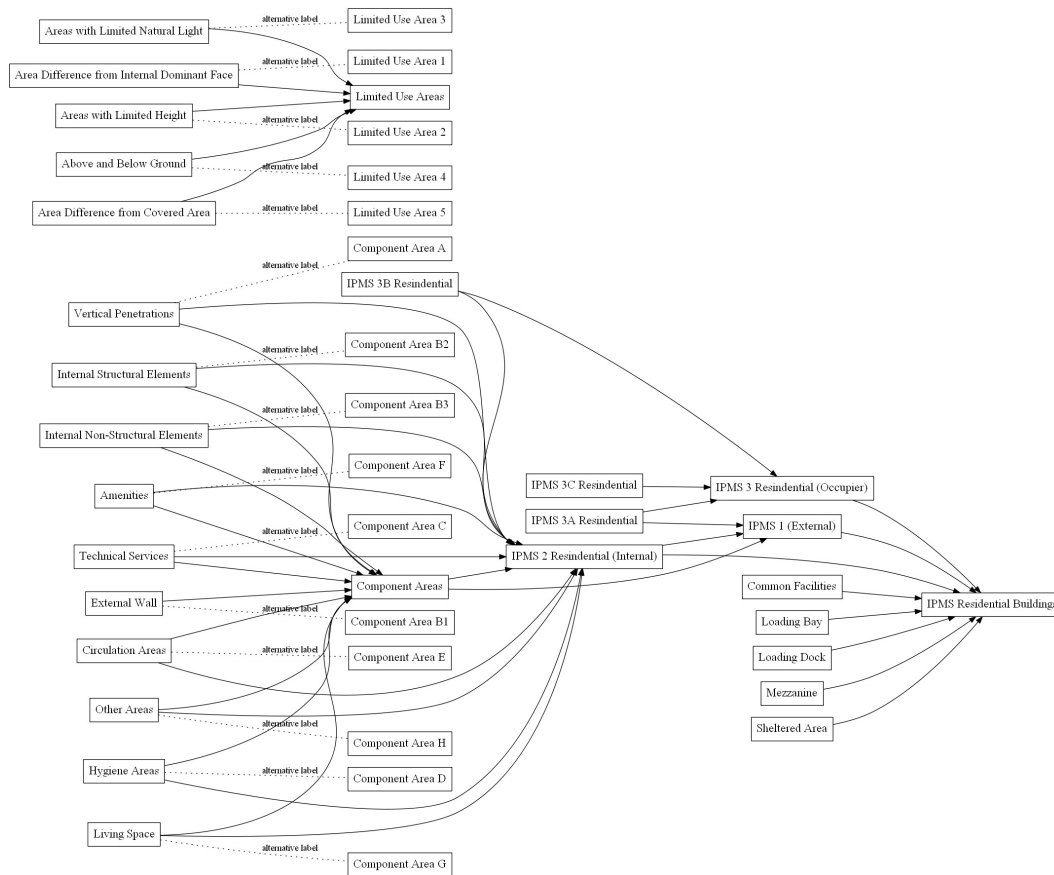


Figure 9: IPMS Residential Buildings floor areas.

“IPMS 1 (External)” floor area term of IPMS Industrial Buildings has almost same definition with the other IPMSC standards. It is measured from the outer perimeter of external walls, sheltered areas and balconies [27]. This standard has 11 different component area types and the aggregate of these component areas must equal the “IPMS 1 (External)” [27]. Figure 12 shows the component areas of the “IPMS 1 (External)” at ground level. “IPMS 2—Industrial (Internal)” is measured to the internal dominant face of all external walls and balconies on each level of a building [25]. It includes internal walls and columns but excludes external wall, namely “Component Area B1” [27]. The areas of balconies, internal loading bays, and mezzanines are included in “IPMS 2—Industrial (Internal)”.

“IPMS 3A—Industrial (External: Exclusive Occupation)” and “IPMS 3B—Industrial (External: Exclusive Occupation)” are used for measuring the occupation of floor areas in exclusive use [27]. These areas not directly related with the “IPMS 1 (External)” and “IPMS 2—Industrial (Internal)” [27]. “IPMS 3A—Industrial” is measured to the outer boundary of external wall of the area in exclusive occupation [27]. The center-line of shared walls between occupants is used to measure the “IPMS 3A—Industrial” in an attached or partially

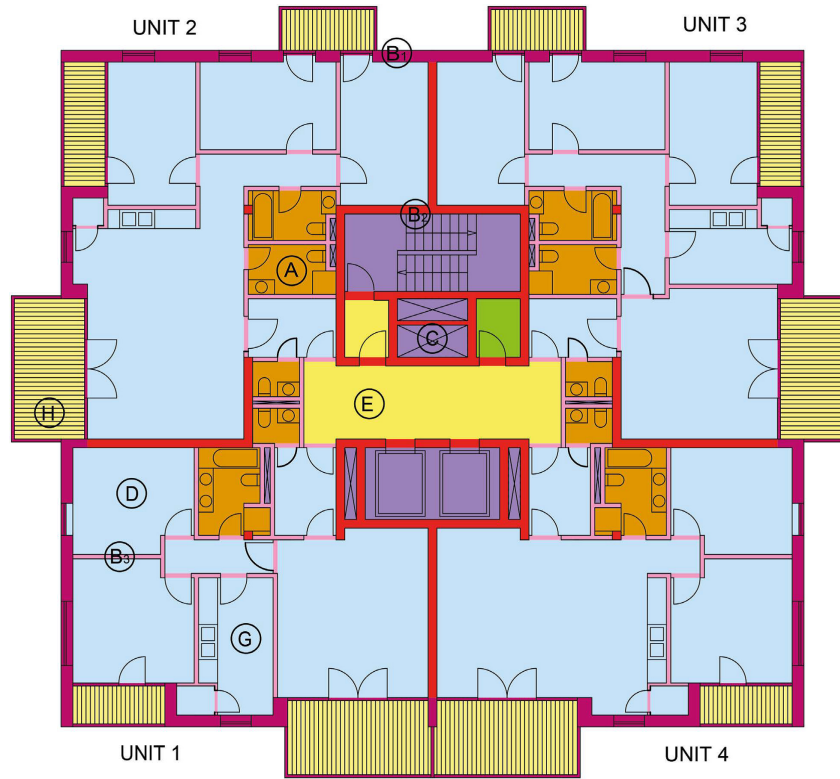


Figure 10: IPMS 1—Residential Apartments Component Areas: A. Vertical penetrations, B1. External wall, B2. Internal structural elements, B3. Internal non-structural elements, C. Technical services, D. Hygiene areas, E. Circulation areas, F. Amenities, G. Living space, and H. Other areas [26].

attached building [27]. “IPMS 3B—Industrial” is measured to the internal dominant face of all external walls and balconies on each level of a building [27]. “IPMS 3B—Industrial” excludes floor area of temporary structures and any areas outside external wall [27].

The IPMS for Retail Buildings is the last standard that the IPMSC has planned to publish. There are 46 different area terms in this standard (see Figure 13). Apart from the other IPMSs, it includes a definition on shop line that is defined as “the notional line established as the maximum potential extent of the retail area in exclusive use” [28]. The shop line corresponds to gross frontage defined in the RICS [47]. It has five reference floor areas, namely “IPMS 1 (External)”, “IPMS 2—Retail (Internal)”, “IPMS 3A—Retail (Occupier)”, “IPMS 3B—Retail (Occupier)” and “IPMS 3C—Retail (Occupier)” [28].

“IPMS 1 (External)” is used for measuring the area of a building including external walls, while “IPMS 2—Retail (Internal)” is used for measuring the interior boundary area of a building [28]. The difference between the floor areas is the external wall thickness and areas outside the external wall such as sheltered areas and external loading bays [28]. The “IPMS 3—Retail” is used for measuring the occupation areas in exclusive use, similar to the other IPMSs. The primary intended use for “IPMS 3—Retail” is transactional purposes and

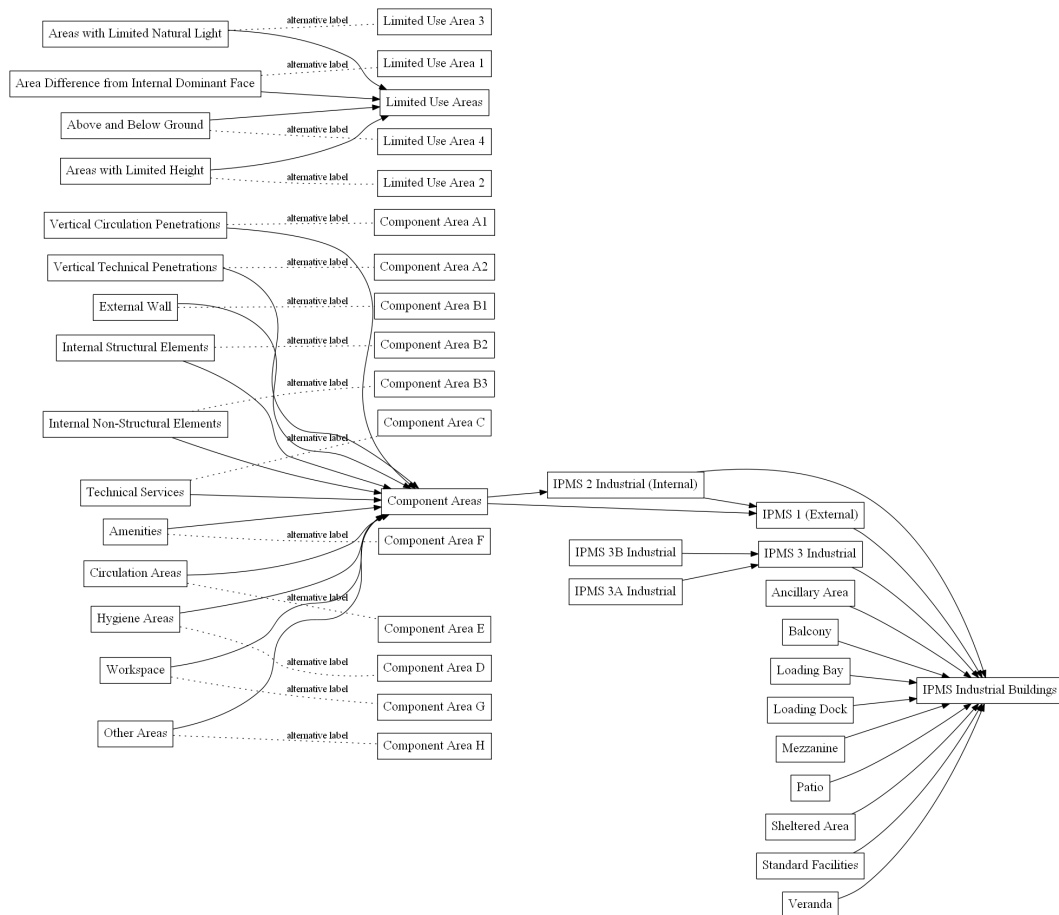


Figure 11: IPMS for Industrial Buildings floor areas.

there are three variation of it [28]. The difference between “IPMS 3A—Retail (Occupier)” and “IPMS 3B—Retail (Occupier)” is the floor area of external walls. “IPMS 3C—Retail (Occupier)” also excludes the floor area of internal walls and columns [28]. It is noted that the consultation draft of this standard was published but it is not approved at the time of writing.

## 2.5 RICS code of measuring practice

RICS is a professional body that accredits professionals within the land, property and construction sectors worldwide. The practice areas of RICS are geomatics, environment, planning, construction, and valuation. RICS Code of Measuring Practice defines building floor areas for using in commercial processes, valuation, management, conveyancing, planning, taxation, sale, letting, and acquisition [16,47].

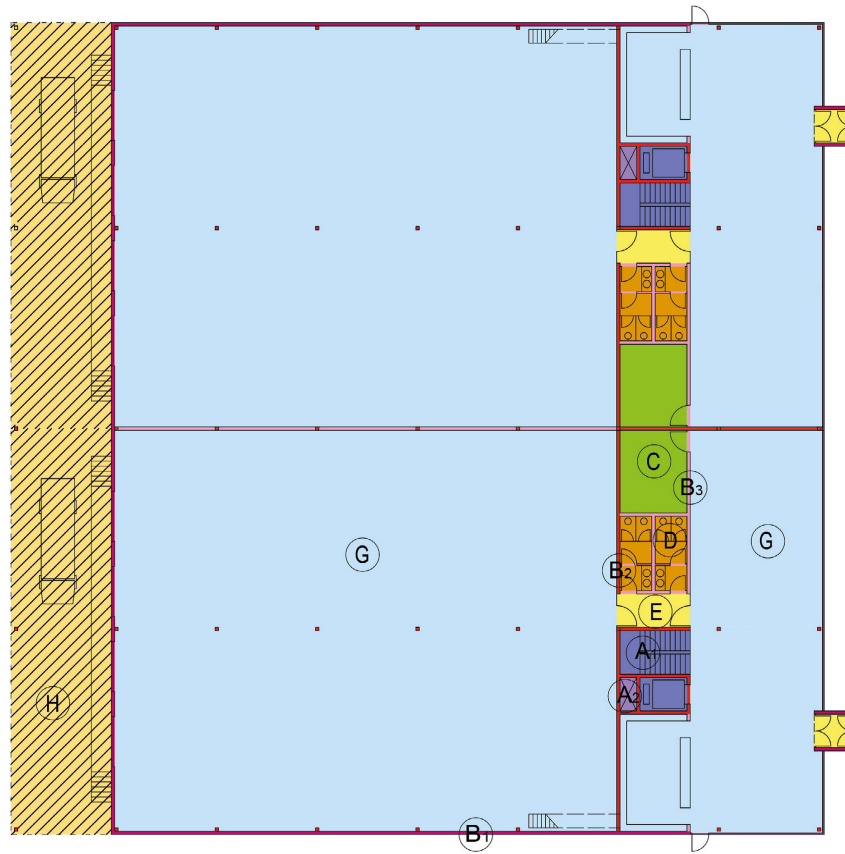


Figure 12: IPMS—Industrial—Ground Floor (Level 0)—Component Areas: A1. Vertical Circulation Penetrations, A2. Vertical Technical Penetrations, B1. External Wall, B2. Internal Structural Elements, B3. Internal Non-Structural Elements, C. Technical Services, D. Hygiene Areas, E. Circulation Areas, F. Amenities, G. Workspace, H. Other Areas [27].

This code defines three reference area terms: “Gross External Area”, “Gross Internal Area”, and “Net Internal Area” as illustrated in Figure 14. Besides the reference areas, it provides eight more floor area definitions, e.g., shops, residential, and leisure properties [16,47]. In addition, several height types are defined including ceiling, eaves (external, internal), maximum internal, clear internal and raised floor heights. The only volume type is the “Cubic Content” that is defined as the product of the “Gross Internal Area” and the appropriate internal height [16,47].

“Gross External Area” is defined as “the area of a building measured externally at each floor level” [16,47]. It excludes open balconies, terraces, parking areas, canopies, and voids [16]. The “Gross External Area” is used for building cost estimation, valuation, property management, and town planning [16,47]. “Gross Internal Area” is measured internal face of the walls for each floor and excludes the wall thicknesses and external projections [16,47]. “Net Internal Area” is measured from the internal dominant face of the walls and it specifies the usable area within each floor of building [16,47]. “Net Inter-



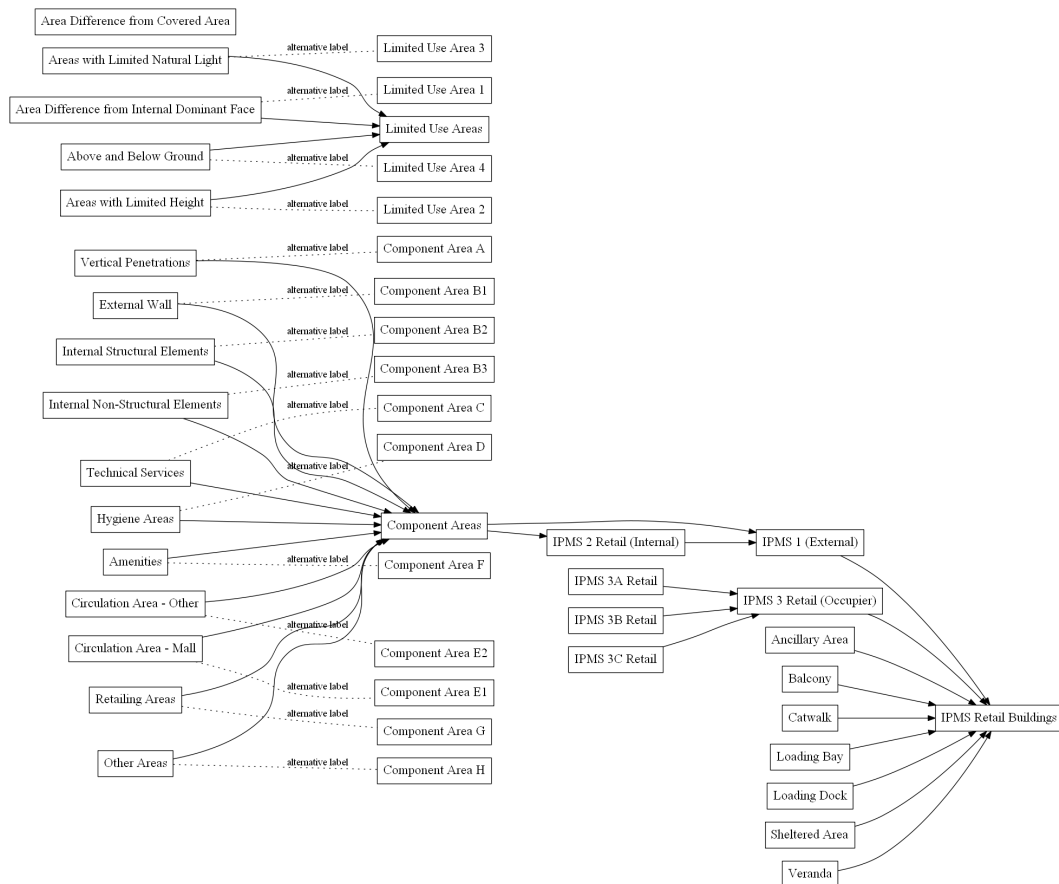


Figure 13: IPMS Retail Buildings floor areas.

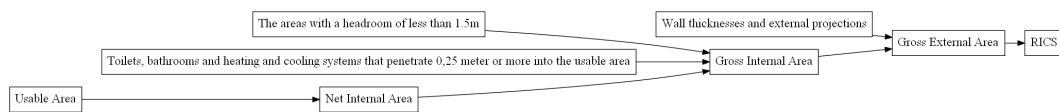


Figure 14: RICS reference building floor areas.

nal Area" excludes the areas with a headroom of less than 1.5m, toilets, bathrooms, and heating and cooling systems that penetrate 0.25 meter or more into usable areas [16, 47]. "Gross External Area", "Gross Internal Area", and "Net Internal Area" of RICS are slightly different from "IPMS 1", "IPMS 2 Office", and "IPMS 3 Office" respectively. It is noted that the RICS prepared an infographic [46] and second version of its standard [47] to show difference between the reference floor areas of the RICS and IPMS Office Buildings, and IPMS Residential Buildings.

## 2.6 CLGE euREAL measurement code for the floor area of buildings

The initiative called euREAL constituted by CLGE for specifying the definitions and rules of building area measurement [39]. The main aim of the euREAL standard is to provide rules and definitions for the measurement of all kinds of buildings, irrespective of their use [39].

The standard defines three reference areas and totally 12 different floor area terms. Figure 15 presents principal floor areas defined by the euREAL. There is no term about volume measurements. “External Area” is measured outer perimeter of building walls [39]. When “External Area” is measured at ground floor level, the areas of decorative voids, airshafts, and atria are included. However, these areas are excluded from “External Area” at upper floor level.

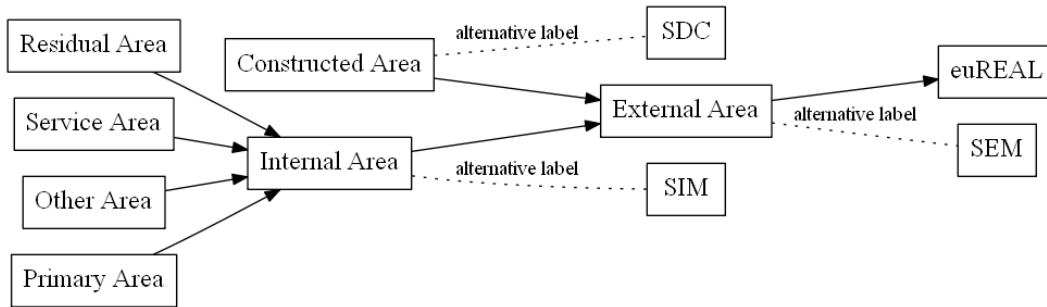


Figure 15: CLGE euREAL reference floor areas.

“Internal Area” is measured as “the interior perimeter of all construction features or fixed partitions” [39]. The “Internal Area” consists of “Primary Areas”, “Residual Areas”, “Service Areas”, and “Other Areas” [39]. The “Internal Area” is slightly different with “Net Floor Area” defined in CEN 15221-6 since it excludes construction features and fixed partitions. The “Primary Area” is defined as “areas with a headroom higher than 2.10 meters associated with the principal uses of the building” [39]. The “Primary Area” of the euREAL is quite similar with the “Primary Area” of CEN 15221-6. Lastly, the “Constructed Area” is defined as the difference between the external area and the internal area [39].

## 2.7 ASTM standard practice for building floor area measurements for facility management

ASTM is an international standard setting-body for materials, products, systems and services. One of its standard is about building floor area measurements for facility management under the fixed designation E1836/E1836M. The code is for measuring floor areas in office facilities including research, laboratory, or manufacturing buildings [3].

There are 27 different building area terms in the standard. There is no term about volume measurements. ASTM specifies four different reference areas: “Exterior Gross Area”, “Interior Gross Area”, “Plannable Gross Area”, and “Plannable Area”. Figure 16 presents the principal area terms defined in this standard.

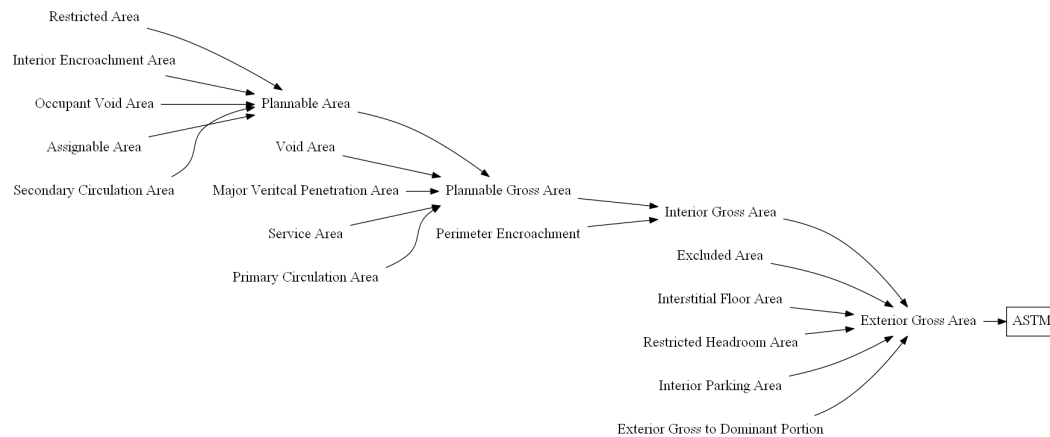


Figure 16: ASTM principal building area types.

“Exterior Gross Area” is measured to the outside face of external walls [3]. The “Exterior Gross Area” minus “Exterior Gross to Dominant Portion”, “Excluded Areas”, “Interstitial Areas”, “Restricted Headroom Areas”, and “Interior Parking” is equal to “Interior Gross Area” [3]. When “Perimeter Encroachments” are deducted from “Interior Gross Area”, the result is equal to “Plannable Gross Area”. “Plannable Gross Area” minus “Void Areas”, “Major Vertical Penetrations”, “Service Areas”, and “Primary Circulation” is equal to the “Plannable Area”, which includes the “Restricted Areas”, “Interior Encroachments”, “Occupant Void Areas”, “Assignable Areas”, and “Secondary Circulation” [3]. It is noted that most of the terms defined in ASTM code share copyrights with Standard Method for Measuring Floor Area in Office Buildings ANSI/BOMA Z65.1-1996 [1], such as “Interior Gross Area”, “Primary Circulation Area”, and “Major Vertical Penetration”.

### 3 Property measurement ontologies

This section describes the development of the property measurement ontologies for harmonization of the property measurement standards. The property measurement ontologies are available online at <http://www.cadastralvocabulary.org/propertymeasurementontologies/>.

To harmonize the property measurement standards, a number of ontologies were developed within the scope of this study. In order not to harm and fully represent the general structure and principles of the measurement standards, a formal ontology was developed for each of the examined standards. The focus in these ontologies is floor area terms, hierarchical relations between the terms and the semantic interrelation between the terms. Furthermore, an integrated property measurement ontology, which covers all the measurement standards, was also developed. The integrated measurement ontology is based on elementary parts of the reference floor areas. In other words, the floor area measurements were decomposed into elementary floor areas (components) in order to represent included

and excluded portions of reference floor areas more precisely and fully integrate the floor area terms.

The open source ontology editor, Protégé is used as development environment for the property measurement ontologies. The OWL was chosen due to richness of language and powerful mechanisms for defining semantic relations between the terms of different vocabularies [20]. The OWL can be used together with the SKOS to model different parts of the same conceptualization [8]. An OWL ontology may include classes, properties, instances of classes and relations between instances. A class in OWL refers to classification of a thing. Every individual is the member of `owl:Thing` class in the OWL and each defined class is subclass of `owl:Thing` [50]. The characteristic of classes are determined with properties and constraints. There are two different types of property in OWL. If a property relates individuals to individuals, it is an object property; if it relates individuals to literals, then it is named as a datatype property. In addition to these, there are value and cardinality constraints in the OWL. While the value constraints are used for restricting the range of the properties when they applied to the class description, cardinality constraints are used to limit the number of values a property can take [17]. The `owl:allValuesFrom` and `owl:someValuesFrom` are the types of value constraints. The ontology languages provide extra properties that do not contribute to the logical knowledge but give additional information for enriching the ontology with annotations and document information such as `owl:versionInfo`, `owl:sameAs`, and `rdfs:seeAlso` [21]. The `owl:sameAs` property provides links between two Uniform Resource Identifier (URI) references that actually refer to the same thing [38]. The `rdfs:seeAlso` property is used for providing additional information about the resource [12]. Furthermore, SKOS vocabulary is used to provide semantic links between concepts. While the SKOS semantic relation properties `skos:broader` and `skos:narrower` are used to assert a direct hierarchical link between concepts, SKOS mapping properties (e.g., `skos:closeMatch`, `skos:exactMatch`, `skos:broadMatch`, `skos:narrowMatch`, and `skos:relatedMatch`) are used to state mapping links between concepts in different schemes [9]. The `skos:closeMatch` and `skos:exactMatch` properties are positioned in part as alternatives to `owl:sameAs`. In this study, only the SKOS semantic relations were used to specify hierarchical relations between the terms of the property measurement standard. The `owl:sameAs` and `rdfs:seeAlso` were chosen to specify semantic relations between the floor area terms of the measurement standards since they are more overused than the SKOS mapping properties [7].

In order to develop the property measurement ontologies, classes of ontologies were firstly specified. The classes `Land`, `Building`, and `Floor` were defined as superclass and were represented with `owl:Class` definition. The `Area`, `Boundary`, and `Volume` classes were also created in the ontologies. The areas, volumes and boundaries of the measurement standards were defined as subclasses of these classes.

After the classes of the ontologies were determined, the object properties `has`, `hasFloor`, and `hasBuilding` were identified for each of the property measurement ontologies. The expression of `Building→hasFloor only Floor` defined to the `Building` class. It means that all the instances of `Building` class that have `hasFloor` property, only can have the instances of class `Floor`. Figure 17 shows the OWL Turtle syntax of the expression. In a similar manner, `Land→hasBuilding only Building` expression was defined for the `Land` class. Furthermore, the expressions `Building→has some Area` and `Volume`, `Floor→has some Area` and `Volume`, and `Land→has some Area` were added to the all measurement ontologies.

```

http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/Building
<http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/Building>
a owl:Class ;
    rdfs:subClassOf
    <http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/ISO9836:2011>
    , _:genid1 .
_:genid1 a owl:Restriction ;
    owl:onProperty
    <http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/hasFloor>
    ;owl:allValuesFrom
    <http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/Floor> .

```

Figure 17: Snippet of ISO 9836 Ontology—all values from constraint.

```

<http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/Floor> a
owl:Class ;
    rdfs:subClassOf
    <http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/ISO9836:2011>
    , _:genid6 .
_:genid6 a owl:Restriction ;
    owl:onProperty
    <http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/
hasTotalFloorArea> ;
    owl:qualifiedCardinality "1"^^xsd:nonNegativeInteger ;
    owl:onDataRange xsd:decimal .

```

Figure 18: Snippet of ISO 9836 Ontology—qualified cardinality constraint.

Next, datatype properties and their ranges were specified. The property measurement standards have a number of terms about distances, areas and volumes. These terms were specified as datatype property and their ranges are specified with a numerical datatypes such as decimal and integer. Since the measurement standards use floor-based measurement, most of terms were related to building floor areas. Therefore, there are many expressions in the Floor class in the ontologies. For example, Floor→has TotalFloorArea exactly 1 xsd:decimal expression means that a floor has exactly one total floor area with a decimal value. Figure 18 shows that the OWL Turtle syntax of the expression.

The hierarchical relations between the terms of each standard were specified with the skos:broader and skos:narrower properties in the Area and Volume classes. For example, IntraMurosArea class in ISO 9836 ontology have broader hierarchical relation with TotalFloorArea and narrower relation with NetFloorArea. Therefore, the following expressions IntraMurosArea→has broader exactly 1 TotalFloorArea and IntraMurosArea→has narrower exactly 1 NetFloorArea were specified in the IntraMurosArea class.

The boundary lines that delimit the floor areas were represented by various types of boundary lines in the measurement ontologies. The Boundary class has some sub-classes that specifies the boundary types, for example, ExternalWallBoundary and InternalWallBoundary. The relations between the boundary types and the floor areas are provided with the skos:related semantic property. For example, “Total Floor Area”

```

http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/TotalFloorArea
:TotalFloorArea rdf:type owl:Class ;
    rdfs:subClassOf :Area ,
        [ rdf:type owl:Restriction ;
          owl:onProperty
            <http://www.w3.org/2004/02/skos/core#related> ;
          owl:someValuesFrom :ExternalWallBoundary ] .

```

Figure 19: Snippet of ISO 9836 Ontology—the boundary of the “Total Floor Area”.

term of ISO 9836 includes the floor area of external and internal wall thicknesses. In other words, it is measured from the “ExternalWallBoundary”. Therefore, *TotalFloorArea* and *ExternalWallBoundary* classes were related with the *skos:related* property, as presented in the Figure 19.

The semantic links between the developed ontologies were specified with the *owl:sameAs* and *rdfs:seeAlso* annotation properties. If a term refers to the same fact with another term, *owl:sameAs* property was used; if a term is slightly different with another term, *rdfs:seeAlso* property was used in the ontologies. For example, the term “Total Floor Area” of ISO 9836 shares same definition with the “Gross External Area” of RICS; however, the “Gross Floor Area” definition of CEN 15221-6 is slightly different from them. Therefore, the expressions *TotalFloorArea*→*owl:sameAs* *GrossExternalArea* and *TotalFloorArea*→*rdfs:seeAlso* *GrossFloorArea* were defined in the *TotalFloorArea* class. The semantic links between the terms were manually specified by means of mapping tables. Once the semantic links between the ontologies were specified, the ontologies were enriched with other annotations. For example, *owl:versionInfo* property was used for specifying ontology version. Moreover, the properties of commonly used ontologies were also used for enriching the ontologies. For instance, *dcterms:description* property of the Dublin Core Metadata Ontology was used for expressing floor area definitions.

All the resources of ontologies are identified with a URI. The URIs are good identifiers since they create globally unique names and enable to access the information about a resource on the Web [10]. In this study, <http://cadastralvocabulary.org/propertymeasurementontologies/> was selected as domain URI. <http://cadastralvocabulary.org/propertymeasurementontologies/OntologyName/ClassOrProperty> URI pattern was used for the identification of the resources. For example, while the ontology of the ISO 9836 standard has the URI <http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/>, the *TotalFloorArea* class of the ISO 9836 has the URI <http://cadastralvocabulary.org/propertymeasurementontologies/ISO9836/TotalFloorArea>.

As mentioned earlier in this section, an integrated property measurement ontology was also developed to represent the semantic relations between the reference floor areas of the standards more clearly by means of decomposing the reference floor areas into components, namely floor area portions. The same modeling methodology was applied when developing the integrated measurement ontology that has three superclasses named *Area*, *Boundary*, and *PropertyMeasurementStandards*.

The *Area* class has a number of subclasses, namely *FloorArea*, *ComponentArea*, *FloorAreaInExclusiveUse*, and *LimitedUseArea*. The *FloorArea* in the integrated ontology represents the total floor area of a normally horizontal, perma-

ment, load-bearing structure for each level of a building. The `ComponentArea` class specifies the components (parts) areas of a floor. It has some subclasses such as `ExternalWall` (`ComponentAreaB1`), `CirculationArea` (`ComponentAreaE`) and `TechnicalServiceArea` (`ComponentAreaC`). Since the IPMSC has been supported by a large number of organizations and IPMSs have received wide acceptance in the domain, the component area classification of the IPMSs were chosen as basis when determining component areas. The `ComponentArea` class has some subclasses that represents the instances (examples) of component areas. For example, `ComponentAreaC` has subclasses named `Lift-ElevatorMotorRoom`, `MaintenanceRoom`, and `PlantRoom`. It is noted that the component area instances may not be limited to the areas defined in the integrated measurement ontology and can be extended. Therefore, not only component area instances of IPMSs, but also component area instances of the other measurement standards were specified in the ontology to develop a more detailed and comprehensive integrated measurement ontology.

The occupation of floor areas in exclusive use is needed when measuring some of the reference floor areas such as “IPMS 3—Residential” and “IPMS 3—Industrial”. Therefore, the `FloorAreaInExclusiveUse` class was introduced to the integrated ontology. In certain markets, there may be areas in buildings that are incapable of legal or effective occupation due to local or national legislation [25,26]. Since these limited use areas should take into consideration when measuring a floor area, the `LimitedUseArea` class was created in the integrated ontology. The `LimitedUseArea` class has some subclasses to represent the limited area types such as `AreasWithLimitedHeight` (`LimitedUseArea2`) class. It represents a floor area with restricted height that may affects the floor area measurement. For example, floor areas with a headroom of less than 1.5 meter is excluded in the `NetInternalArea` of the RICS, while, the ASTM is specified the restricted headroom height as 2.0 to 2.3 meters. The `LimitedUseArea2` class of the integrated ontology represents these restrictions with a number of subclasses.

The `Boundary` class stands for the boundary types that are important in measurement practices. According to the examined measurement standards, different boundary types are needed when measuring different types of buildings (e.g., residential and retail). The boundary types defined in the different standards were represented as subclass of the `Boundary`. For example, internal dominant face boundary is used when measuring some floor areas defined in IPMSs and ASTM. Therefore, `InternalDominantFace` class was created in the integrated measurement ontology.

Another superclass of the integrated measurement ontology is the `PropertyMeasurementStandards`. It has some subclasses to represent the examined measurement standards and their reference floor area terms. For example, there is a class named `IPMSOfficeBuildings` and it has three subclasses named `IPMS 1`, `IPMS 2-Office`, and `IPMS 3-Office` to represent reference floor areas. The reference floor areas classes include a large number of expressions to define included and excluded floor area portions (component areas) and boundary types. These expressions were created with `hasIncluded`, `hasExcluded` and `hasMeasured` object properties. For example, the `IPMS 1-Office` is measured from external wall boundary and it is not include the area of open light wells. In order to specify these characteristics to the ontology, `IPMS1→hasMeasuredFrom` some `ExternalWallBoundary`, `IPMS1→hasIncluded` some `FloorArea`, and `IPMS1→hasExcluded` some `OpenLightWell` expressions were defined in the `IPMS 1-Office` class. Moreover,

the class has some data property expressions, for example,  $IPMS1 \rightarrow floorArea$  some `xsd:decimal` expression specifies value of the floor area in a specific unit, while  $IPMS1 \rightarrow floorLevel$  some `xsd:integer` expression represents the measured floor level. The characteristics of reference floor areas of the measurement standards were specified in the ontology in a similar way. The classes, hierarchical and semantic relations between the classes of the integrated property measurement ontology is represented in the Figure 20. It is noted that the Visual Notation for OWL Ontologies (VOWL) extension of Protégé ontology editor was used for the visualization.

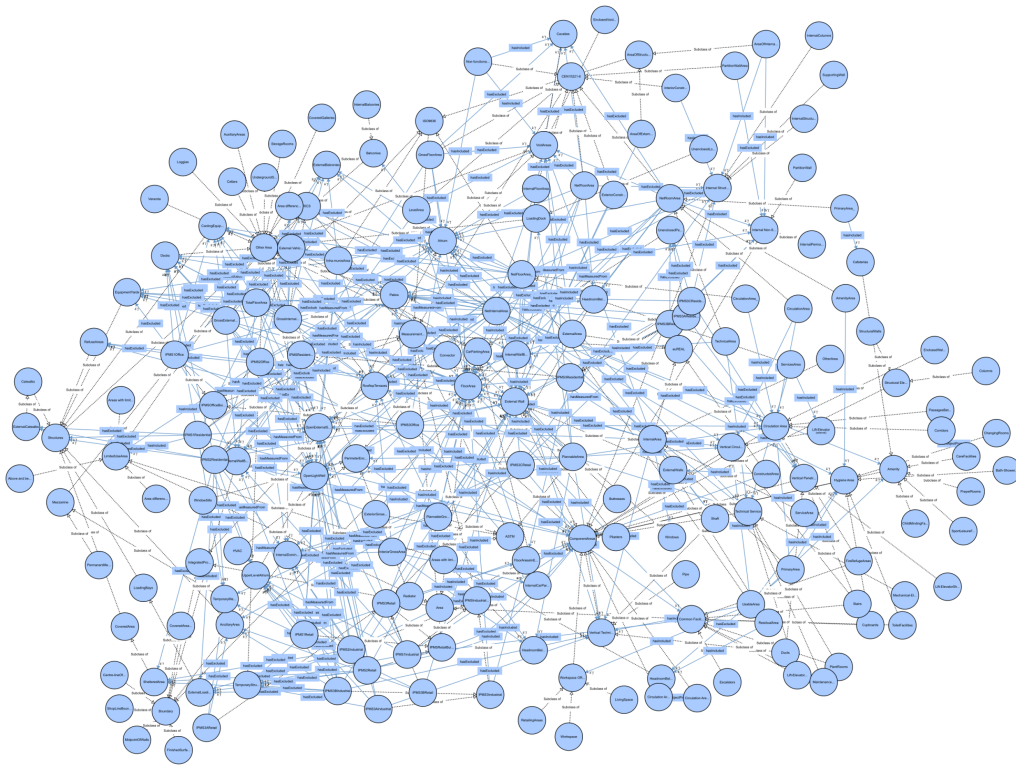


Figure 20: An overview of the integrated property measurement ontology.

The property measurement ontologies in OWL turtle format and their HTML representations are available online for inspection and feedback at <http://cadastralvocabulary.org/propertymeasurementontologies/>.

In this section, the property measurement standards were examined and reorganized as ontologies. Next section investigates the 3D data standards from the perspective of property measurement standards.





## 4 The role of 3D data standards in building floor area measurement

In order to put the property measurement standards into practice, the floor areas can be measured in field or in a digital environment. Architectural projects, plans, Computer Aided Design (CAD) drawings, or BIM data can be utilized as source data for the floor area measurements in the digital environment. However, these data sources may not be sufficient to measure the floor areas. More specifically, 2D drawings and plans may not include semantic and textual information about properties and even some 3D information models are not capable of distinguishing whether the boundary lines are located interior, exterior or median of a wall [5, 6]. Furthermore, it is challenging to find the component areas of a floor area (e.g., common areas, technical areas, and amenity areas) from “2D drawing” and “not semantically enriched” 3D information models [5]. These can create confusion in measuring the floor areas and volumes since the location of boundary line (wall priority), dominant wall surface and the component areas included in a floor area plays a fundamental role.

Some BIM software, such as Revit and ArchiCAD, enable measurement of the reference floor areas of ASTM and ANSI/BOMA measurement standards, if a data source provides sufficient information in accordance with the principles of the measurement standards. Moreover, the 3D data standards, which have feature in their data models to represent building and building parts, may play a significant role in realizing the property measurement standards. However, the investigations shows that the property measurement standards were not generally taken into consideration in the modeling phases of 3D data models. More clearly, the 3D data standards does not include the terms and definitions about the building floor areas. Moreover, they may not provide semantically enriched data on component areas of a floor area. Furthermore, spatial characteristics of properties defined in the 3D data standards may not fulfill the measurement requirements of the property measurement standards. For example, the 3D data standards may not include required boundary types and geometry types for the floor area measurements. The integration of the property measurement standards and the 3D data standards may provide more accurate and harmonized data about the floor areas. Therefore, a number of international 3D data standards were briefly investigated in order to evaluate whether entities of the standards can be utilized for the floor area measurements.

Table 2 presents an overall evaluation of the selected 3D data standards from the perspective of the property measurement standards. The floor area terms row indicates whether the 3D data standard is included the floor area terms of the measurement standards, while the next row show whether the 3D data standards are semantically enriched in the context of component areas of a floor. The boundary types (i.e., external, median and internal wall boundaries) supported by the 3D data standards are given in the third row. The next two rows indicates corresponding entities for the floor area measurement and supported geometry types for representing boundary, floor area and volume of the 3D data standards, respectively.

ISO 19152:2012 LADM is an abstract model focusing on the legal and spatial aspects of LA [33]. Its Spatial Unit Package and Surveying and Representation sub-package deal with spatial units (e.g., cadastral parcel), and their geometric / topological representation based on ISO 19100 series of standards [33]. It offers a cadastral viewpoint on buildings, namely legal space buildings but semantic and physical representation of buildings are considered

	ISO 19152	OGC CityGML	INSPIRE Building	IFC BIM	OGC LandInfra	OGC Indoor GML
<b>Floor area term</b>	-	-	CLGE euREAL	Partly, yes (own terms)	-	-
<b>Floor area component</b>	-	Partly, yes	Partly, yes	yes	-	-
<b>Floor measurement boundary</b>	-	External wall and internal wall boundary	External and internal wall boundary	External, median and internal wall boundary	External wall boundary	-
<b>Entity for computation</b>	-	BoundarySurface Building BuildingPart	BoundarySurface Building BuildingPart	IfcBoundedSurface IfcBuilding IfcBuildingElement	BoundingElement BuildingPart	-
<b>Boundary, surface and volume geometry</b>	-	MultiCurve MultiSurface MultiSolid	MultiCurve MultiSurface MultiSolid	MultiCurve MultiSurface MultiSolid	IfcRepresentation	-

Table 2: An overview of the 3D data standards from perspective of the measurement standards.

out of scope of LADM. Therefore, the LADM does not include semantic and geometric information regarding the measurements of building floor areas. In order to define relationships between land registries and building registries, `ExtPhysicalBuildingUnit` class were created. It is noted that `LA_BoundaryFace` class, which has `GM_MultiSurface` characteristic, can be used for 2D and 3D representation of boundaries of a spatial unit of LADM [33].

CityGML is another 3D data standard for the storage and exchange of virtual 3D city models through a number of thematic modules [41]. Its Building Module allows representation of thematic and spatial aspects of buildings and building parts [41]. The Building Module allows for the representation of thematic and spatial aspects of buildings and building parts in five levels of detail, LOD0 to LOD4 [41]. The `_BoundarySurface` class provides important information for the floor area measurements such as floor surface, wall surface and interior wall surface [41]. It is noted that the floor surface must only be used in the LOD4 interior building model for modelling the floor of a room [41]. Therefore, only the LOD4 can be employed for measuring floor areas. On the other hand, Boeters [11] has shown that CityGML LOD2 can be automatically extended to cover floor surface, slabs and wall thicknesses and the extended model can be used for computation of internal net area of the NEN 2580:2007. CityGML supports boundary representation (B-rep) of solid modeling that allows defining topological links between surfaces. It also supports specification of 3D physical boundaries such as interior and exterior boundaries, but median wall boundaries are not be represented [5]. The floor area terms defined in property measurement standards are not included, while some of the floor area component are implicitly included in the CityGML. Lastly, it also allows computing volumes of building and building parts with appropriate height data.

The Infrastructure for Spatial Information in Europe (INSPIRE) Directive aims to create a European Union spatial data infrastructure. In accordance with this purpose, data

specifications and models have been specified for the 34 different spatial data themes. While INSPIRE Cadastral Parcel Data Specification allows 2D representation of cadastral parcels [23], INSPIRE Building Data Specification allows 3D representation of physical boundaries of buildings and building parts with surface and solid geometry types [24]. It also specifies semantic information about buildings. It is noted that the INSPIRE Building Data Specification adopted some concepts from the CityGML, for example, LOD concept and the classes building part, building installation and room. The floor areas defined in the CLGE's euREAL standard was utilized in modeling phase of the standard. `BuildingAndBuildingUnitInfo` feature class includes a characteristic named `CLGE_OfficialAreaReferenceValue` that details the floor area terms of the euREAL standard [24]. INSPIRE Building Data Model is the only model which is semantically linked to a property measurement standard. On the other hand, this part of the INSPIRE model should be updated in accordance with the IPMSs since CLGE is one of the main partners of the IPMSC.

ISO 16739:2013, the Industry Foundation Classes (IFC), specifies data schema and an exchange file format for BIM data [32]. The standard provides semantically and geometrically enriched data model. In other words, it provides detailed component floor area definitions, semantic information about the boundary types and as well complex geometry types. It supports constructive solid geometry (CSG) that can enable modeling complex spatial objects and the computing volume of 3D properties [6]. The semantic information about geometries can be stored together with geometry in BIM object models, which in turn may provide basis for more accurate property measurement. IFC data model can be employed for computing all the floor areas defined in property measurement standards. On the other hands, this standard does not include any floor area term defined in the measurement standard, however, several individual floor area terms (e.g., gross floor area and net wall area) are specified in the "Quantity Set" data schemas of the standard.

LandInfra is a conceptual data model focusing on land and civil engineering facilities [43]. It allows volumetric representation of spatial units with surface and solid geometry types. It has building and building part classes; however, they do not provide semantically enriched data about boundary and floor area components information to measure the building floor areas. Moreover, it is noted that the standard does not include any floor area term about building measurements.

Finally, IndoorGML is related to specification of interior space of buildings from geometric, cartographic, and semantic viewpoints [42]. It has limited capabilities for property measurements, since the focus is to provide description of indoor spaces for indoor navigation [42]. IndoorGML has complementary standards (e.g., IFC and CityGML), for example, IndoorGML does not include information about wall thickness but needs it for computing the WiFi signal strength and takes that value from IFC model [42]. Therefore, it does not provide any geometric data for floor area measurement. Moreover, it does not specify any semantic data on physical building boundaries and floor areas.

Briefly, it was found out that semantically and geometrically most enriched 3D data standards for realizing the property measurement standards are ISO 16739:2013, OGC CityGML, and INSPIRE Data Specification on Buildings. It is noted that the only 3D data standard that is semantically linked to a property measurement standard (i.e., CLGE euREAL) is the INSPIRE Building Data Specification.

## 5 Discussion and conclusion

The floor area measurements of buildings and building parts may have many legal and financial uses including taxation, valuation, land use planning, building cost planning and property transactions. The international and regional standardization bodies have already created a number of measurement standards for formalizing and representing the floor area measurements of properties in consistent and transparent basis. However, the measurement standards in use have different terms and principles that may create confusion. It is noted that floor area definitions and measurement principles might create dramatic variances in practice, even among terms that have very close definitions. For instance, as pointed out by Pugh [45], one of the IPMS floor area, “IPMS 3—Office”, may differ up to 9% with “Net Internal Area” of RICS Code of Measurement Practices.

This study examines a number of international measurement standards, and reveals their commonalities and differences through developed measurement ontologies. In this context, ten individual property measurement ontologies were developed that focus more on the floor area terms, hierarchical and semantic relations between them, while an integrated property measurement ontology was developed that focus more on the floor area components of the reference floor areas. These ontologies may assist in harmonizing the property measurement standards. It is noted that harmonization and standardization together may improve performance of the measurement practices, increase accuracy of the measurements and lower cost of measurements.

The investigation of the measurement standards shows that the IPMSs will be widely accepted and adopted all over the world since they have been developed with the participation of a large number of international organizations in order to create one international property measurement standard. Actually, some of the organizations have started to put IPMSs into practice and have prepared IPMSs compliant measurement standards. For example, RICS has published the second version of the RICS property measurement that compares the floor areas defined in the RICS with the IPMS Office Buildings and IPMS Residential Buildings [47]. Moreover, BOMA Office Buildings [2] standard prepared fully compatible with the IPMSs. BOMA also stated that it would be incorporating the IPMS standards in all its standards. It can be stated that both local and international measurement standard setting bodies may consider reorganizing their specifications according to IPMSs in order to provide more transparent and interoperable measurement data to the market. Since the concepts and principles of the other measurement standards have taken into consideration when developing the IPMSs (e.g., dominant face definition of BOMA), the conversion between the floor areas of the standards may easily be addressed both in theory and in practice.

There are a number of studies to put IPMSs into practice. For example, [36] proposed a LADM based data model in order to provide reliable and accurate spatial information on 3D underground properties. The definitions of IPMS Office Buildings are included in the data model to enhance the value of a 3D underground parcel by registering semantic information on the utilized and developed architectural space composition [36]. On the other hand, the RICS has developed XML schemas to encapsulate the characteristics and elements of the IPMS measurement in order to aid adoption of IPMS by users and external parties and to provide consistency for software developers and applications [47]. Moreover, it launched an IPMS Office Buildings converter tool that converts floor areas measured in IPMS for Office Building Standard into the local standards [47]. It is noted that the property



measurement ontologies may also assist to develop tools that convert a floor area measured in one standard into another standard. Such converters are important in the measurement domain to save time and resources.

The 3D data standards are also investigated in this study from a property measurement point of view. It turns out that the property measurement standards can be realized using the 3D data standards such as IFC BIM and OGC CityGML. However, more effort is required to provide full interoperability between these domains. It may be recommended that the further versions of the 3D data standards would provide means to represent the semantic information required in the property measurements.

One of the findings of this research is that the analyzed measurement standards generally consider out of scope the measurements of building volumes. Only the ISO 9836, CEN 15221-6, and RICS define a few terms about floor volumes, however, they do not specify detailed principles for measuring them. For example, inclusion and exclusion of component areas (e.g., interior partitions, ventilation, balconies, and void areas) when measuring different volumes in a building part have not been determined. Moreover, it is not specified that how perimeter encroachments in different heights area taken into consideration in measurement. Future version of the measurement standards may include a part that specifies usage areas and measurement principles of volumes of building and building parts.

Finally, it is noted that terminological property measurement ontologies were developed in this study. Therefore, the focus is hierarchical and semantic relations between the floor area boundaries, floor area terms and component areas of them; not to realize the measurement standards. As a future work, it may be useful to develop an IFC BIM based application ontology (e.g., ifcOWL) for IPMSs in order to provide geometrically and semantically more detailed information on building and building parts. Another research focus may be to develop a CityGML Application Domain Extension (ADE) that compute the floor areas according to IPMSs. Moreover, it may be considered to create a graph database that not only store floor areas but also utilize them to convert a floor area measured in one standard to another.

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