Sustainable Cities and Society 14 (2015) 223–235

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Data structuring for the ontological modelling of urban energy systems: The experience of the *SEMANCO* project

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ARTICLE INFO

Article history:
Available online 1 October 2014

Keywords:
Urban energy systems
Energy standards
Ontologies

ABSTRACT

Semantic web technologies can help to integrate heterogeneous data sources, and to make them accessible to the stakeholders involved in the urban energy planning.

In the *SEMANCO* project, semantic technologies have been used to create models of urban energy systems able to assess the energy performance of an urban area. A semantic energy information framework brings together the data sources at different scales and from different domains (e.g. urban planning, energy management), as well as some energy simulation and assessment tools that interact with the semantically modelled data. An ontology based on a vocabulary of concepts shared by experts has been created through the following process: capturing the experts knowledge about a specific problem regarding the energy efficiency of an urban area and the data needed to model it; creating an informal vocabulary through the terms referred to technical standards, and creating a formal vocabulary according to the Ontology Web Language specifications.

This ontology has been applied to three case studies in the *SEMANCO* project. The ontology can be reused in other cases dealing with modelling of urban energy systems using semantic technologies and its underlying methodology – knowledge capturing, informal vocabulary creation, ontology building – could be replicated in other domains.

1. Introduction

1.1. Urban energy systems: modelling approaches

The problem of reducing CO_2 emissions in cities involves multiple domains and actors, and cuts across established geographic and administrative boundaries. Its solution requires a systemic approach to grasp "the combined process of acquiring and using energy to satisfy the demands of a given urban area" (Keirstead & Shah, 2013, p. 273) by means of an urban energy system model, that is, "a formal system that represents the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area" (Keirstead, Jennings, & Sivakumar, 2012, p. 6). Different approaches to devise urban energy system models have been summarised by Keirstead et al. (2012). In spite of their differences, these approaches all tackle certain common issues: understanding model complexity, data quality and uncertainty, model integration and policy relevance.

One of the challenges of creating a model of an urban energy system is the integration of components that act at different scales to understand, for instance, the influence that building energy consumption might have on a particular urban area (a neighbourhood, a district, a municipality). In such cases, the aspects that are relevant for the analysis – such as building form, climatic and socio-economic characteristics of the locations of interest – may differ across scales (Sorman & Giampietro, 2011).

Traditional approaches to the modelling of the energy behaviour of building stocks in urban areas are usually based on top-down or bottom-up models, as pointed out by Heiple and Sailor (2008). According to these authors, a number of urban climate researchers have used building survey data, or utility-scale load data, to estimate the temporal and spatial variability of energy consumption in cities following a top-down approach. This requires scaling some relatively coarse resolution data down to a finer temporal and/or spatial dimension. Unlike top-down approaches, in bottom-up processes the energy performance of representative buildings is first assessed, and the resulting energy consumption data are then aggregated or scaled-up to the required resolution. The latter

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http://dx.doi.org/10.1016/j.scs.2014.09.006
2210-6707/

technique is applied more frequently. Some examples of the application of the bottom-up approach are building prototypes, building clustering (Jones, Lannon, & Williams, 2001) and district clustering (Yamaguchi, Shimoda, & Mizuno, 2007).

In order to model the energy consumption of building stocks, other cross-sectorial studies use regression models that relate energy consumption to the physical, economic, and social aspects of the urban environment. The dependent variables in these models are usually energy or emission indicators. Parshall et al. (2010) suggest that local policy makers would benefit from a national "high resolution inventory" of energy consumption and their related carbon emissions which would help them to make better informed decisions regarding energy supply and demand, fossil fuel consumption and climate change mitigation considered at multiple scales.

Recent studies have taken an integrated approach, which embraces complex interactions in urban areas, such as energy flows, environmental indicators, and social and economic factors. These holistic approaches are enabled by transdisciplinary science and computer technology (Laniak et al., 2013). According to the US Environmental Protection Agency (2008), an integrated approach should include a set of interdependent science-based components (models, data, and assessment methods) which together form the basis for constructing an appropriate model of an urban energy system. Urban energy modelling processes and methods could be implemented with different assessment tools.

A fundamental property of integrated systems is the congruency among the components. This is necessary to facilitate the exchange of information between them (Laniak et al., 2013). Often, information about the elements of a system is only available in form of raw datasets, which have been collected in different contexts and different countries for different purposes, using different tools and formats that usually cannot be combined. This creates serious limitations when it comes to analyse the data, especially if the analysis is carried out in a holistic manner requiring data from different realms (e.g. technical, political, social, economic, environmental). Furthermore, the difficulties to access multiple data sources and integrate them in a unified data model increase in the case of having (Nemirovskij, Nolle, Sicilia, Ballarini, & Corrado, 2013):

- large volumes of data stored in data sources that support different data models,
- data that describe the characteristics of similar items using different standardisation systems,
- different units of measure applied to the same physical quantities.

To overcome these obstacles which hinder the integration of the system's components, a mediator is required to bring together data from different sources and domains with the purpose both of delivering the data to the tools as a homogeneous cross-referenced data set and facilitating an effective data processing. Lately, the role of such a mediator has been increasingly assigned to ontologies, namely, formal specifications based on a vocabulary shared by the experts of the domains to be integrated. Also in the field of urban energy systems, a shared ontology can facilitate interoperability between data models which have been built by different experts from various domains using multiple techniques (van Dam & Keirstead, 2010).

1.2. Using ontologies to create models of urban energy systems

As stated by Gruber (1993), an ontology is an explicit specification of a conceptualisation, that is, a set of objects representing a knowledge domain by means of a vocabulary of terms and the explicit relationships between them. In such an ontology, concept definitions associate the names of entities in the universe of discourse (e.g. classes, relations, functions, or other objects) with human-readable texts that describe what the names are meant to denote, and formal axioms that constrain the use of these terms. Ontology creation is a process through which, by capturing the base terminology, the knowledge of a particular domain or domains is made explicit in terms of concepts and relations.

Building ontologies requires the standardisation of terms and units of measures and the application of a terminology that is accepted by a community of users. At the same time, technical standards represent the consensus of experts concerning the terms used in a domain and their structure. Ontologies make it possible to integrate data from multiple domains which have been defined in accordance to some prevalent technical standards. The structuring/standardizing of data and the structuring/standardizing of knowledge are interrelated processes. When designing an ontology, both aspects have to be taken into account.

In this context, the main object of this article is to present the process followed within the *SEMANCO* project (Madrazo, Gamboa, Nemirovskij, Sicilia, & Crosbie, 2012) to design an ontology representing the knowledge that multiple experts have about an urban energy system. This process involves the creation of:

1. an informal vocabulary of terms – defined in accordance with technical standards facilitated by international official classifications and previous research projects – which are compiled in Excel sheets, and
2. a formal vocabulary, namely, the ontology, built from the terms defined in the Excel sheets. The ontology has been coded in the *DL-Lite*$_A$ a formalism of the Ontology Web Language (OWL) which outperforms most of the other description logic formalisms in the context of managing data distributed in heterogeneously structured sources.

2. Theory and method

In the *SEMANCO* project (*Semantic Tools for Carbon Reduction in Urban Planning*) an integrated platform, which enables to model multiple urban energy systems of an urban area using a set of tools which interact with semantically modelled data, has been developed. This integration of data from multiple sources with different tools is handled by a *Semantic Energy Information Framework* (SEIF), a key technological component developed in the project. The SEIF facilitates the retrieval of urban energy systems related data distributed in different data sources that employ diverse structural schemas, access methods and data semantics. Furthermore, a major goal of the SEIF is to ensure data access interoperability: it makes it possible that tools or users formulate data queries without knowing the technical details concerning the access methods that are supported by single sources, the content of the sources, and the data schemas or specific semantics employed by each source. The ontology developed in *SEMANCO* is one of the central elements of the SEIF. It is used as a mediation mechanism for all the schemas employed by the multiple data sources integrated in the SEIF.

2.1. The ontology building process in the SEMANCO project

As introduced in Section 1.2, the ontology design process developed in *SEMANCO*, which is described in Nemirovskij et al. (2013) and Nolle and Nemirovskij (2013), can be divided into two stages:

1. Informal vocabulary building, whose goal is to define terms, data categories and relations between them. The terms of the vocabulary are based on selected technical standards.

2. Coding and integration, which is aimed at the creation of a formal specification from the informal vocabularies.

At the stage of informal vocabulary building, a use case approach has been adopted to obtain from experts of different disciplines knowledge and information about a particular problem related to a specific policy framework. By means of some forms created in the project, experts have defined a use case, specifically, the problem to be solved, the methods and tools to be used, the data needed (Madrazo et al., 2012). Each use case description contains a set of activities that are interconnected. Since an activity can occur in several use cases, a network of activities emerges (Fig. 1). A use case defined in this way helps ontology designers (both ontology engineers as well as domain experts, working in partnership) to understand the users' requirements, the needs for data and their semantics, the vocabulary and the desired level of value aggregation.

The use case forms encapsulate the understanding experts of different specific domains have about a compound domain of discourse – a problem to define and solve within an urban energy systems – and, in particular, they help them to understand the role that the data from a particular domain play in the use case. The terms provided through the use case forms have been compiled in the *Energy Standard Tables* (see Section 3). These tables stand for the informal vocabulary which precedes the construction of the formal vocabulary, that is, the ontology.

The *Energy Standard Tables* are implemented as a set of spreadsheets (see Section 3), where the terminology, descriptions, units of measures and relationships between concepts are described. The diagram presented in Fig. 2 shows the role of the *Energy Standard Tables* in the overall ontology design process. The *Energy Standard Tables* act as a connection between the available information (e.g. in the form of permanently stored data) and the knowledge of experts as expressed in technical standards and use case specifications. Therefore, these tables stand for a conceptualisation of an interdisciplinary domain (i.e. an urban energy system) by providing the definition of the terms which experts consider to be relevant to the problem at stake as well as the relationships between concepts.

The initial vocabulary is enhanced by mapping its terms onto the data sources that are being integrated. In order to maintain a correspondence between the data names used in the data sources and the terms provided in the initial vocabulary, some tables are provided (*Mapping Tables*). This process of relating existing data structures to a vocabulary is the collaborative work of ontology designers and domain experts (Corrado & Ballarini, 2013b). Ontology designers contribute with their knowledge about representation techniques, while domain experts bring their expertise in the practical application of the data and tools involved in the process.

An ontology building process encompassing the creation of informal and formal vocabularies has been carried out in three case studies in Manresa (Spain), Copenhagen (Denmark) and Newcastle (UK). In each case, a vocabulary has been derived from the information contained in the use case descriptions.

2.2. Structuring data

Because of the different origins and the large numerical quantity of data necessary to develop an energy and environmental analysis encompassing multiple scales and domains, it is necessary to collect data and classify them in categories before starting the informal vocabulary building. The data categories and the information package (data fields) were defined from the heterogeneous information provided in the data sets of the *SEMANCO* case studies. The following data categories were identified:

- *Energy data*, referring to energy quantities (e.g. primary energy, delivered energy, exported energy, produced renewable energy, CO_2 emissions, etc.).
- *Energy cost data*, which can be grouped into "energy costs", or more generally "running costs", and "investment costs" (European Committee for Standardisation, 2007c). The "running costs" mainly refer to the cost of the consumed energy and the cost of the building operation and maintenance related to energy. The "investment costs" on the other hand refer to new construction or refurbishment interventions on the existing building stock, linked to both the building envelope and to the technical building systems.
- *Climatic data*, which define the climatic conditions of a given geographical area (e.g. air temperature, solar irradiance, wind speed, relative humidity, vapour pressure).
- *Environmental data*, which refer to the principal air pollutants in the urban area (e.g. total suspended particulate matter, sulphur dioxide, nitrogen dioxide, carbon monoxide, ozone, lead, etc.) (Daly & Zannetti, 2007).
- *Building technical data* on building and its technical systems. This category can be divided into several sub-categories, because of the wide range of data covered. Examples of sub-categories are: building general data, building geometry, building construction, technical building systems.
- *Legislative constraints*, which encompass the requirements fixed by legislation that have to be applied to new constructions or existing buildings. The legislative constraints usually refer to data

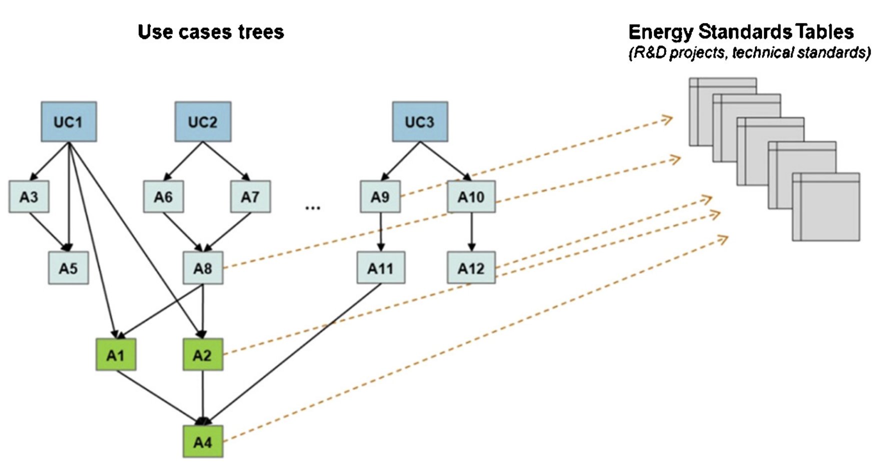

Fig. 1. Use case trees and *Energy Standard Tables*.

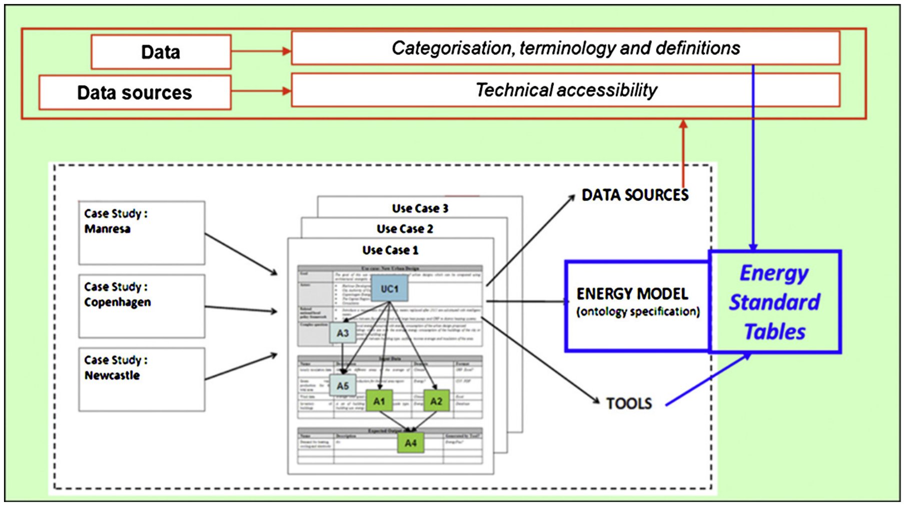

Fig. 2. Role of the *Energy Standard Tables* in the process of information and knowledge capturing.

belonging to other data categories, for instance to the *Energy data* category, or *Building technical data* category.

- *Geographical data* are usually provided through a "Geographic Information System" (GIS). A GIS is designed to capture, store, manipulate, analyse, manage and present all types of geographical data. In *SEMANCO*, a spatial database informs the *Semantic Energy Information Framework* (SEIF) about geometric and typological data. The former group is related to the cartographic representation of objects, such as the shape (point, line, polygon), the size and location. The latter group is related to the mutual relationships between objects (connection, adjacency, inclusion, etc.). Other complementary geographic data (numerical, text) are associated to each object and some of them can be structured semantically. These data include, for instance, latitude, longitude, height above sea level, etc. They are not usually applied at a building scale but at a higher territorial level.
- *Land and buildings registry data*, which refer to the cadastre, for different scales or levels of analysis. The land registry data can be divided into the following sub-categories: land parcels, land tenure, land value (International Federation of Surveyors, 1995). The buildings registry data is considered a parallel category of the land registry data.
- *Urban planning data*, which traditionally come from the land registry land category (Koh, 2001). Therefore, as urban planning data are generally related to land use, land use can be considered one of the main attributes of land.
- *Socio-economic data*, which include the basic overall social and economic data pertaining to the population (at country, municipality and neighbourhood scales) and to housing (at a building scale).
- *Demographic data*, which include the basic overall data on population size, density, gender, age, origin, language, education, etc.

The data included in the described categories could be further grouped into:

- Energy systems, energy quantities and boundary condition data ("Energy data", "Climatic data", "Building technical data").
- Energy-related data or contextual data ("Energy cost data", "Environmental data", Legislative constraints", "Geographical data", "Land and buildings registry data", "Urban planning data", "Socio-economic data", "Demographic data").

In order to perform an ontological modelling of data at different territorial scales, it is necessary to refer each data category to a well-defined area. The categories of the above described data are listed in Table 1, with reference to the different areas to which the categories could be applied (i.e. country, region, municipality, neighbourhood, building). Furthermore, these areas were structured into three major groups:

- a *micro scale*, which encompasses analysis at the building level;
- a *meso scale*, which can be considered as a district, a ward, a neighbourhood or a city. In the latter case, the city is considered as the main urban area of a municipality, excluding industrial zones and rural areas;
- a *macro scale*, which is defined as an area or region beyond the city, that is, a municipality (e.g. urban, rural and industrial areas), a province or some other aggregation of the *meso*-scale categories.

Table 1
Application level of the categories of data.

Data category	Areas and related scales				
	Country (macro)	Region (macro)	Municipality (macro)	Neighbourhood (meso)	Building (micro)
Energy data	x	x	x	x	x
Energy cost data	x	x	x	x	x
Climatic data		x	x		
Environmental data	x	x	x	x	
Building technical data					x
Legislative constraints	x	x	x	x	x
Geographical data	x	x	x		
Land and buildings registry data				x	x
Urban planning data				x	
Socio-economic data	x	x	x	x	x
Demographic data	x	x	x	x	x

Table 2
Common data fields and specific data fields.

Data field name	Data field type	Example
Category	Common	"Energy data"
Name	Common	Primary energy
Long name	Common	Primary energy for space heating
Description	Common	Primary energy for space heating of different building uses, normalised on the heated floor area
Symbol	Specific	$Q_{p,H}$
Unit	Specific	Wh
Way of data determination	Specific	Measured
Way of data aggregation	Specific	Sum
Temporal scale	Specific	Annual
Temporal range	Specific	01/01/2012–31/12/2012
Geographical area	Specific	Piedmont Region (Italy)
Scale of the data (e.g. building, municipality, region)	Specific	Building
Data file format	Common	.xls
Source name	Common	"Database of the energy performance certificates"
Owner	Common	Piedmont Region (Italy)
Author	Common	Building energy performance certifier
Access type	Common	Export from a web portal
Availability (i.e. accessibility level)	Common	Public with authorisation
Reliability (i.e. trustworthiness level)	Common	Medium
Relevance for the purpose	Common	High
Reference (e.g. technical standard, national regulation)	Common	ISO/IEC FDIS 13273-1:2014
Validity conditions (applicable for "Legislative constraints")	Specific	–

The data collected from different data sources have been organised with additional information, which is necessary for the data interpretation. The information package includes common data fields and specific data fields. The former are applicable to all the data, the latter are specific of some types of data. A list of common and specific data fields and some examples are provided in Table 2. The "name" of the datum has to be defined through international standards, or other official references, in order to guarantee that the ontological modelling is developed through an official and shared terminology. The main references used for fixing the terminology are described in Section 2.3.

2.3. Use of technical standards for semantic modelling

Typically, technical standards are the means by which experts agree on a common vocabulary in a particular domain.

As regards the energy assessment in urban areas, a new ISO technical committee (TC 268) was established in the field of Sustainable Development in Communities in 2012. This committee is focused on the development of a management system standard, and a global city indicator standard pertaining to city services and the quality of life, which will help harmonise performance indicators in these fields. In parallel, an ISO working group (TC 257/WG2) is dealing with general energy efficiency and saving calculation methods for countries, regions or cities. A recent draft standard (International Organisation for Standardisation, 2014c) provides a general framework to calculate energy savings, considering both energy indicators (e.g. mean gas consumption per dwelling) calculated from statistical data, and the saving effect of policy measures or measures taken by other stakeholders to enhance energy efficiency.

A new standardisation mandate, to support European Smart Grid deployment, has just been issued at a European level. According to this mandate, ICT should be deployed to increase energy efficiency in buildings and beyond, including urban planning.

Significant efforts have been made regarding the standardisation of data over the last few years in the urban energy sector, and in other relevant domains, such as real estate marketing or climate research. However, the task of integrating the various standards into an universal vocabulary that is acceptable by experts of different, although related, domains still remains to be resolved. High-level data models (vocabularies and ontologies) need to be developed to provide interoperability between sectors and considering the whole value chain. Although standards on energy efficiency already exist, there is still a need to specifically focus on the urban domain.

The terms used in the *Energy Standard Tables* have been derived from existing technical standards, European projects and international official classifications. These sources supply the proper terminology, the descriptions, the relationships between concepts and, if applicable, the symbols and the units of the defined quantities. The harmonisation of the language used by different experts is a prerequisite for the subsequent construction of the formal shared vocabulary (i.e. the ontology).

The technical standards identified and applied in the *Energy Standard Tables*, mostly referring to buildings, are described in the subsections below.

2.3.1. Energy systems, energy quantities and boundary condition data

The main International technical standards pertaining to the structuring of data on energy systems, energy quantities and boundary conditions, which are included in the "Energy data", "Climatic data" and "Building technical data" categories, are parts 1 and 2 of ISO/IEC FDIS 13273:2014 (International Organisation for Standardisation, 2014a,b). These parts contain transversal concepts and their definitions in the fields of energy efficiency and renewable energy sources. According to these standards, energy terms can be grouped in different sets, such as:

- *energy*, which includes energy source, primary energy, secondary energy, energy storage, energy loss, energy carrier, final energy, energy use, etc.
- *energy management*, which includes energy policy, energy target, etc.
- *energy performance*, which includes energy performance indicator, benchmarking, etc.
- *energy efficiency*, which includes energy efficiency improvement, energy efficient design, etc.
- *energy demand*, which includes energy demand, energy supply, etc.

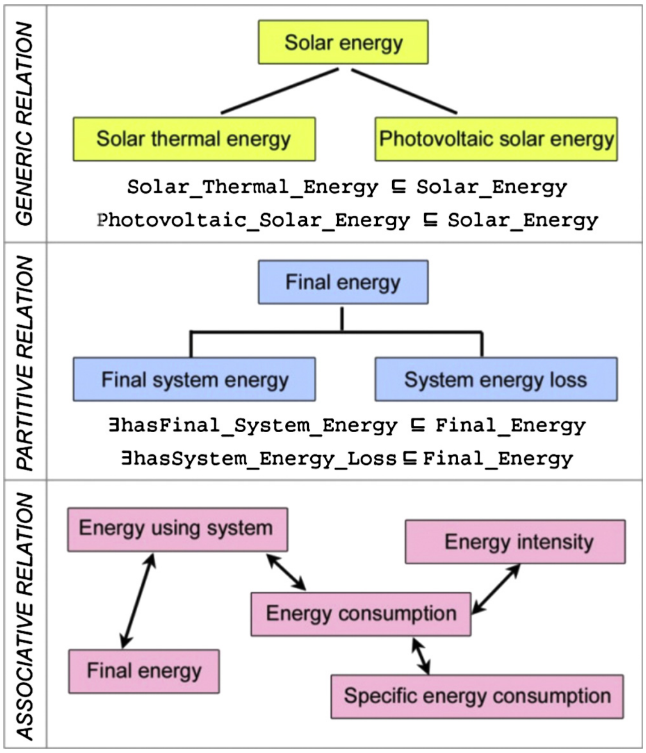

Fig. 3. Primary forms of concept relationships according to ISO/IEC FDIS 13273:2014.

- *renewable energy*, which includes bioenergy, hydro energy, marine energy, solar energy and geothermal energy.

Three primary forms of concept relationships are considered in terminology work: the *generic relation*, the *partitive relation* and the *associative relation*. In the *generic relation*, the subordinate concepts within the hierarchy inherit all the characteristics of the superordinate concept, and contain descriptions of these characteristics which distinguish them from the superordinate (parent) and coordinate (sibling) concepts. In the *partitive relation*, subordinate concepts within the hierarchy form constituent parts of the superordinate concept. The *associative relation* is helpful in identifying the nature of the relationship between one concept and another within a concept system (e.g. cause and effect, activity and location, tool and function, material and product, etc.). Examples of the three forms are shown in Fig. 3, with the related axioms of the formal specification.

The terminology on energy systems, energy quantities and boundary condition data is also fixed in some European technical standards, such as FprEN 15603:2014 (European Committee for Standardisation, 2014), EN ISO 13790 (European Committee for Standardisation, 2008b), and the EN 15316 (European Committee for Standardisation, 2007b) series.

The *Overarching Standard EPBD* FprEN 15603 is intended to replace EN 15603:2008 and parts of other EN or EN-ISO standards published in 2007–2008 under the M/343 mandate on the EPBD (European Union, 2003). This standard draft deals with the framework of the overall energy performance of buildings, and also covers common terms, definitions, symbols as well as building and system boundaries. It enables the modelling of data in the fields of *buildings* (e.g. building, technical building system, building services, space heating, space cooling, conditioned space, etc.), of *technical building systems* (e.g. system thermal loss, recovered system thermal loss, etc.), of *energy* (e.g. energy source, energy carrier, delivered energy, exported energy, renewable energy, primary energy, CO_2 emission coefficient, etc.) and of *energy calculation* (e.g. heat gains, etc.).

The EN ISO 13790 technical standard (*Energy performance of buildings. Calculation of energy use for space heating and cooling*), which specifies the calculation methods for the building annual energy use of space heating and cooling, provides the definitions and the terminology of several energy data, such as *time step*, *periods and seasons* (e.g. heating or cooling season, etc.), *spaces*, *zones and areas* (e.g. conditioned space, unconditioned space, conditioned area, etc.), *temperatures* (e.g. internal temperature, external temperature, etc.), *energy* (e.g. energy need, technical building system, technical building subsystem, etc.), *building heat transfer* and *building heat gains* (e.g. internal heat gains, solar heat gains, etc.).

The modelling of data pertaining to technical building systems is mainly covered by the EN 15316 standard series (*Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies*), which provide data descriptions of space heating systems, space cooling systems, domestic hot water systems, etc. with the related technical subsystems. Terminology on renewable energy sources is also provided.

Besides these technical standards, some technical reports also provide terminology and definitions, thus enabling the identification of relationships between energy concepts; the European Technical Report CEN/TR 15615 (European Committee for Standardisation, 2008a) and the corresponding International Technical Report ISO/TR 16344 (International Organisation for Standardisation, 2012) are examples of these references. Moreover, ANSI/ASHRAE/IESNA Standard 90.1 (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007) allows data to be modelled concerning building envelope, energy systems and boundary conditions.

The EN ISO 15927-1 technical standard (European Committee for Standardisation, 2002) includes definitions of climatic data and specifies procedures for calculating and presenting the monthly values of some climatic parameters which can be used to model the “Climatic data” category in the ontology structure. The standard covers all the main climate variables, such as *air temperature*, *atmospheric humidity*, *wind speed*, *precipitation*, *solar radiation* and *long-wave radiation*.

Other references on energy data vocabulary could be obtained from European projects. In this context, the “Intelligent Energy Europe” *TABULA* project (*Typology Approach for Building stock Energy Assessment*) provides terminology on building typologies, with reference to the residential building stock. *TABULA* was a three-year project (2009–2012) whose objective was to create a harmonised structure for “European building typologies” in order to estimate the energy demand of residential building stocks at a national level and, consequently, to predict the potential impact of energy efficiency measures and to select effective strategies for the upgrading of existing buildings. Shared definitions of geometrical data, of typical constructions and of technical systems are provided.

On a similar topic, the “Intelligent Energy Europe” *DATAMINE* project (*Collecting Data from Energy Certification to Monitor Performance Indicators for New and Existing buildings*) offers a coherent structure of the uses of buildings, together with their descriptions. *DATAMINE* (2006–2008) was aimed at constructing a knowledge base using the information given on the energy performance certificates that are issued when buildings are constructed, sold or rented.

2.3.2. Energy-related data

The references on the semantic modelling of contextual data are provided in the present section for each category of energy-related data introduced in Section 2.2.

As far as the “Energy cost data” category is concerned, the analysis of the concepts referred to as “running costs” and “investment costs”, together with the related definitions, is provided by European technical standard EN 15459 (European Committee for Standardisation, 2007c). The standard offers a calculation method for the economic issues of heating systems and other technical systems that are involved in the energy demand and energy consumption of a building. The main items of the standard are the definition and the structure of the types of costs, including those that should be taken into account for the calculation of the economic efficiency of saving options in buildings (e.g. insulation, better performing generators and distribution systems, efficient lighting, renewable sources, combined heat and power). The definitions of the terms provided by EN 15459 can be considered in the ontological modelling of energy cost data.

The “Environmental data” category takes into account all the data that refer to the principal air pollutants in urban areas. As stated by Daly and Zannetti (2007), six principal pollutants can be included in this data category. They are “criteria” pollutants that are regulated by the United States Environmental Protection Agency (US-EPA) and by most countries throughout the world. The six principal air pollutants are: total suspended particulate matter (TSP, e.g. PM10 and PM2.5), sulphur dioxide (SO_2), nitrogen oxides (NO and NO_2), carbon monoxide (CO), ozone (O_3) and lead (Pb).

The same environmental pollutants are taken into consideration in European Directive 2008/50/EC (European Union, 2008) on ambient air quality and cleaner air in Europe. This Directive provides the definition of air pollutants, such as PM10, PM2.5, nitrogen oxides, volatile organic compounds (VOC), as well as definitions of pollutant concentrations, such as level, limit value, critical level, margin of tolerance, target value, long-term objective, upper assessment threshold, lower assessment threshold and average exposure indicator. These attributes are all necessary to structure and model environmental data.

The “Legislative constraints” category includes the performance requirements fixed by the legislation that has to be applied to new constructions or existing buildings. The legislative constraints usually refer to data belonging to other data categories, for instance to the “Energy data” category, or the “Building technical data” category, etc. The main reference of contemporary legislative constraints in the field of building energy efficiency is European Directive 2010/31/EU (European Union, 2010) on the energy performance of buildings. This Directive establishes the application of the minimum requirements of the energy performance for new buildings, for existing buildings subject to major intervention, for building elements when they are retrofitted or replaced, and for technical building systems whenever they are installed, replaced or upgraded.

Another important reference on this subject is European Directive 2012/27/EU (European Union, 2012). This directive establishes a common measure framework for the promotion of energy efficiency within the Union, in order to ensure the achievement of the Union’s 2020 20% headline target on energy efficiency. The promotion of the use of energy from renewable sources is the subject of European Directive 2009/28/EC (European Union, 2009). According to these directives, the energy performance requirements and the reference values that are necessary to comply with European objectives are established by each Member State through their own legislative dispositions.

As far as the ontological modelling of legislative constraint data is concerned, guidelines are specified by international standard EN 15217 (European Committee for Standardisation, 2007a) to express the overall indicators of the energy performance of buildings and to express the energy requirements for the design of new buildings or the renovation of existing buildings. Two main types of energy performance requirements are defined in the standard:

- overall energy performance requirements (e.g. the primary energy as an indicator),
- specific requirements (e.g. energy use or energy need for one specific purpose, heat transfer coefficient of the building envelope, technical system efficiency, thermal transmittance of walls, efficiency of boilers, lighting power density, etc.).

In addition, the requirements may be written so as to modify (e.g. reduce, neutralise, correct or normalise) the impact of some parameters, i.e. the reference values that have to be complied with are provided in function of different parameters, such as the climate, the building function, the building size and/or the shape, the energy carrier, etc. These parameters should be indicated in the ontology as attributes of the energy performance requirements.

The information on “Geographical data” is usually provided through a “Geographic Information System” (GIS), as has been done in *SEMANCO*. The references on spatial information are European Directive 2007/2/EC (European Union, 2007) and its related technical guidelines which are currently under publication. The Directive concerns the establishment of an “Infrastructure for Spatial Information in the European Community (INSPIRE)” and is focused on the creation of metadata for spatial data sets and services. CityGML, a common model for the representation and the exchange of 3D city models, which focuses on the semantics of objects and its structures (aggregations, relations), plays an important role in INSPIRE. CityGML defines the geometry, semantics and appearance of topographic objects in urban or rural regions. These objects are divided into thematic modules: the building module, the vegetation module, the transportation module, the water body module, the city furnishings module and the digital terrain model module.

In order to perform the semantic modelling of data belonging to the “Land and buildings registry data” and “Urban planning data” categories, the “Statement on the Cadastre” (International Federation of Surveyors, 1995) can be taken as a reference. The document provides a classification of land information, and determines the principal attributes of land, such as *land parcels* (including the concepts of land location, land surface, etc.), *land tenure*, *land value* (including the concepts of land quality, land type, land buildability and the economic value of land).

Urban planning data are generally related to land use (Koh, 2001), and the land use might have different classifications. In this context, the “Land-Based Classification Standards (LBCS Standards)” (American Planning Association, 2001) is a consistent model for the classification of land uses, on the basis of their characteristics. The model extends the notion of classifying land uses by refining traditional categories into multiple dimensions, such as activities (i.e. the actual use of land on the basis of its observable characteristics), functions (i.e. the economic function or type of establishment using the land), structures (i.e. the type of structure or building on the land), site development character (i.e. the overall physical development character of the land), and ownership constraints (i.e. the relationship between use and its land rights). Each dimension has its own set of categories and subcategories that have to be considered as subsumptions of land uses in the semantic modelling.

A reference classification for the semantic structuring of the socio-economic and demographic data of the related data categories is provided by the United Nation Statistics Division, under the “Demographic and social topics” section, and by the UK Office for National Statistics. Owing to the close relationship between these topics, the two data categories can be considered in the same structure in the ontological modelling of data.

The vocabulary on demography and social aspects could be differently in relation to an area (such as a region, a municipality, etc.) or to a building (with reference to the housing aspects). In this regard, two different topics should be taken into account:

- *population* (related to a territory), which includes data on size, density, gender, age, origin, language, etc.
- *housing* (related to a building), which includes data on tenure, price, etc.

In addition, both these topics include information, each of which refers to a different scale, regarding households and families, economic activity, income and poverty, learning and education, etc.

As far as the economic activity is concerned, a reference data structure is provided by the "International Standard Classification of Occupation (ISCO)" (International Labour Organisation, 2008). Being part of the international family of economic and social classifications of the United Nations, the ISCO is a classification structure for the organisation of data on labour and jobs. In addition, information about the learning and education topic is provided in the "International Standard Classification of Education (ISCED)" (Educational, Scientific and Cultural Organisation, 2011), which is part of the international family of economic and social classifications of the United Nations. The ISCED is a classification structure that can be used to organise education and training concepts.

3. Results and discussion

The *Energy Standard Tables* introduced in the previous sections represent a key component in the ontology building process and are, therefore, one of the main outputs of the *SEMANCO* project.

In the *Energy Standard Tables*, concepts are structured according to two components, objects and attributes. Each concept can be defined through an object that specifies what the concept *is* and through properties, which are attributes of the concept (i.e. what the concept *has*). For instance, *building* is a concept that has many properties, such as *use* and *geometry*. In this way, the *building has use*, the *building has geometry*, and so on. In addition, *use* is a concept and it can be described through objects, such as *residential*, *office*, and *commercial*.

According to these rules, which are the foundations of formal concept analysis, the *Energy Standard Tables* are elaborated by including a concept (datum) in each row and by prepending the *is* (subsumption) or *has* (attribute) field to each datum name. Information is provided for each concept in different columns, as follows:

- the datum name or the acronym, which can be made of different words separated by underscores;
- the description of the concept, which is obtained from the official reference (standards, projects, classifications, etc.);
- the reference that provides the description. An asterisk should be added near the reference to highlight that the description is adapted according to the scope;
- the type of datum, whether descriptive (e.g. string, logic), or numeric (e.g. integer, real);
- the unit, if applicable;
- the name of other *Energy Standard Tables* (sheets), in which that concept is further detailed (identification of relationships with other concepts).

An example of an *Energy Standard Table* from the *SEMANCO* project is shown in Fig. 4 for some of the data that are included in the "Energy data" category (name of the sheet: "energy_quantities"). One of the main classifiable concepts of energy data is: "Energy_Consumption_And_Energy_Saving_Related_To_Building_Services".

Two objects could be associated to this concept, "Energy_Consumption" and "Energy_Saving". Both have "Energy_Quantity_And_Emission" as an attribute, which can be "Delivered_Energy", "Exported_Energy", "Primary_Energy", or "Produced_Renewable_Energy", etc. Each of the objects under the "Energy_Quantity_And_Emission" concept could in turn have different attributes, such as:

- "Energy_Carrier" (e.g. natural gas, electricity, heat, etc.),
- "Energy_Source" (e.g. sun, wind, biomass, etc.),
- "Energy_Service" (e.g. space heating, space cooling, domestic hot water, etc.),
- "Duration", with reference to the time interval to which the value refers. The "Duration" concept also refers to another *Energy Standard Table* sheet, named "TIME", in which concepts of time are structured.

As far as the association between a data category and an *Energy Standard Table* is concerned, it is necessary to point out that one *Energy Standard Table* sheet does not necessarily structure all the data of a single category, i.e. a data category might have concepts that are modelled in different *Energy Standard Table* sheets and, at the same time, an *Energy Standard Table* sheet might include data belonging to different data categories. This is mainly due to the ascription of some concepts to different territorial scales (*micro*, *meso*, *macro*). For instance, "Land and buildings registry data" and "Urban planning data" are both categories that provide the properties of the "land" concept, and a single *Energy Standard Table* sheet is usually sufficient to model this concept with these properties. On the contrary, both *housing* data (for the micro scale) and *population* data (for a higher scale) belong to the same "Socio-economic data" category, but convey different information due to the different analysis levels; in this case, two different *Energy Standard Table* sheets should be provided. The correspondence between the data categories, the related *Energy Standard Tables* (sheet names) and the application areas in *SEMANCO* can be observed in Table 3.

Apart from the ordinary *Energy Standard Tables*, two complementary *Energy Standard Table* sheets, named "TIME" and "SPACE", are provided to structure the concepts of time (e.g. duration, period) and space (e.g. orientation). In the ordinary *Energy Standard Tables*, the time and/or space concepts are recalled by the data that have them as attributes. As the *Energy Standard Tables* should be linked to each other in order to guarantee the structuring of all the concepts, a particular *Energy Standard Table* should be provided to connect all the sheets to the geographical area that is the subject of the analysis. To this aim, an *Energy Standard Table* sheet, named "TERRITORY", has been created (see Fig. 5). This sheet includes the concepts of "region", "municipality", "neighbourhood" and "building" as well as their attributes, which are modelled in the related *Energy Standard Tables*. The connections between all the *Energy Standard Tables* in *SEMANCO* are shown in Fig. 6.

The ontology building process has concluded with the creation of the *SEMANCO* ontology – formal vocabulary coded in accordance with the Ontology Web Language (OWL) specifications – which encompasses 987 terms defined in the *Energy Standard Tables.*

The number of terms contained in the *Energy Standard Tables* refer to 18 technical standards, covering 25 different domains. Each standard provides from 1 to 52 terms to the vocabulary (see Fig. 7). In relation to the total number of terms defined in the *Energy Standard Tables* and included in the ontology, each standard provides from 1% to 5.3% of all terms. However, one term can refer to multiple standards. The standards which have been most applied in the *Energy Standard Tables* are ANSI/ASHRAE/IESNA Standard 90.1, SAP, LBCS Standards, ISO/TR 16344, FprEN 15603, EN 15316, DATAMINE and TABULA (determining more than 30 terms each).

Name/Acronym					Description	Reference	Type of data	Unit	Reference to other sheets
Energy_Consumption_And_Energy_Saving_Related_To_Building_Services					energy referred to building services	-	-	-	-
is	Energy_Consumption				quantity of energy applied	ISO/IEC CD 13273-1	string	-	-
is	Energy_Saving				reduction of energy consumption following implementation of an end-use action intented to improve energy performance	ISO/IEC CD 13273-1	string	-	-
has	Energy_Quantity_And_Emission				-	-	-	-	-
	is	Delivered_Energy			energy, expressed per energy carrier, supplied to the technical building systems through the system boundary, to satisfy the uses taken into account (heating, cooling, ventilation, domestic hot water, lighting, appliances etc.) or to produce electricity	ISO TR 16344 EN 15603	real	J Wh kWh/m^2	-
		is	Final_Energy		the total purchased energy (fossil, electric) excluding renewables consumed to achieve the required building performance and comfort over a given period of time	ISO TR 16344	real	J Wh kWh/m^2	-
	is	Exported_Energy			energy, expressed per energy carrier, delivered by the technical building systems through the system boundary and used outside the system boundary	ISO TR 16344 EN 15603	real	J Wh kWh/m^2	-
	is	Primary_Energy			energy that has not been subjected to any conversion or transformation process	ISO TR 16344 EN 15603 ISO/IEC CD 13273-1	real	J Wh kWh/m^2	-
	is	Produced_Renewable_Energy			energy produced by technical building systems using renewable energy sources, which are not depleted by extraction	ISO TR 16344*	real	J Wh kWh/m^2	-
		is	Produced_Renewable_Thermal_Energy		thermal energy produced by technical building systems using renewable energy sources, which are not depleted by extraction	ISO TR 16344*	real	J Wh kWh/m^2	-
		is	Produced_Renewable_Electrical_Energy		electrical energy produced by technical building systems using renewable energy sources, which are not depleted by extraction	ISO TR 16344*	real	J Wh kWh/m^2	-
	is	CO2_Emissions			for a given energy carrier, quantity of CO_2 emitted to the atmosphere	ISO TR 16344* EN 15603* CEN/TR 15615*	real	g	-
	has	Energy_Carrier			substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes	ISO TR 16344 ISO 13600	string	-	-
		is	Electricity		-	-	string	-	-
		is	Natural_Gas		-	-	string	-	-
		is	Heat		-	-	string	-	-
		is	Gasoil		-	-	string	-	-
		is	Coal		-	-	string	-	-
		has	CO2_Emission_Coefficient		for a given energy carrier, quantity of CO_2 emitted to the atmosphere per unit of delivered energy	ISO TR 16344 EN 15603 CEN/TR 15615	real	g/kWh	-
	has	Energy_Source			source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process	ISO TR 16344	string	-	-
		is	Not-Renewable_Energy_Source		not-renewable energy source	-	string	-	-
			is	Gasfields	-	-	string	-	-
			is	Oilfields	-	-	string	-	-
			is	Coal_Mines	-	-	string	-	-
		is	Renewable_Energy_Source		renewable energy source	-	string	-	-
			is	Sun	-	-	string	-	-
			is	Wind	-	-	string	-	-
			is	Water_Power	-	-	string	-	-
			is	Geothermal	-	-	string	-	-
			is	Biomass	-	-	string	-	-
	has	Energy_Service			related to the services provided by the technical building systems and by appliances to provide the indoor climate condition, illumination and other services related to the use of the building	UNI TR 16344* EN 15603*	string	-	-
		is	Space_Heating		process of heat supply for thermal comfort	UNI TR 16344 EN 15603	string	-	-
		is	Space_Cooling		process of heat extraction for thermal comfort	UNI TR 16344 EN 15603	string	-	-
		is	Domestic_Hot_Water		process of heat supply to raise the temperature of the cold water to the intended delivery temperature	UNI TR 16344* EN 15603*	string	-	-
		is	Ventilation		process of supplying or removing air by natural or mechanical means to or from a space	UNI TR 16344 EN 15603	string	-	-
		is	Lighting		process of supplying the necessary illumination	UNI TR 16344 EN 15603	string	-	-
		is	Electrical_Appliances		services supplied by energy consuming appliances	UNI TR 16344 EN 15603	string	-	-
		is	Cooking		process of food preparation	-	string	-	-
	has	Duration			time interval to which the value refers	-	string	-	"TIME"

Fig. 4. Example of *Energy Standard Table* structuring some concepts included in the "Energy data" category. Extract from the *SEMANCO* project (Corrado & Ballarini, 2013b).

Name/Acronym						Description	Reference	Type of data	Unit	Reference to other sheets
Territory						a geographical domain	-	string	-	-
is	Country					a territory of a nation or state	-	string	-	-
is	Region					an administrative division of a country	-	string	-	-
is	Municipality					a political unit, such as a city, town, or village, incorporated for local self-government	-	string	-	-
is	Neighbourhood					a geographically localised community within a larger city, town or suburb	-	string	-	-
has	Territorial_Information					-	-	-	-	-
Country						a territory of a nation or state	-	string	-	-
has	Region					an administrative division of a country	-	string	-	-
	has	Climate				climate that defines areas of size up to 200 km linear extension	-	-	-	"climate"
	has	Municipality				a political unit, such as a city, town, or village, incorporated for local self-government	-	string	-	-
		has	Local_Climate			climate that defines areas of size up to 10 km linear extension	-	-	-	"local_climate"
		has	Neighbourhood			a geographically localised community within a larger city, town or suburb	-	string	-	-
			has	Land		a topographically or functionally distinct tract	-	-	-	"land"
				has	Building	construction as a whole, including its envelope and all technical building systems, for which energy is used to condition the indoor climate, to provide domestic hot water and illumination and other services related to the use of the building	EN 15603	-	-	"building"
Territorial_Information						-	-	-	-	-
has	Geographic_Coordinate					coordinate describing geographical location	-	-	-	"geographic_coordinate"
has	Population					the body of inhabitants of a place	-	-	-	"population"
has	Pollution					substances present in ambient air and likely to have harmful effects on human health and/or the environment as a whole	Directive 2008/50/EC*	-	-	"pollution"
has	Cost_Related_To_Energy_Performance					cost that shall be taken into account for calculation of the cost effectiveness of energy efficiency measures in buildings	EN 15459	-	-	"cost_related_to_energy"
has	Energy_Consumption_And_Energy_Saving_Related_To_Building_Services					energy referred to building services	-	-	-	"energy_quantites"
has	Energy_Indicator					indicator of building energy performance	-	-	-	"energy_quantites"
has	Requirement_Related_To_Energy_Performance					minimum level of energy performance that is to be achieved to obtain a right or an advantage: e.g. right to build, lower interest rate, quality label	EN 15217*	-	-	"requirement_related_to_energy"

Fig. 5. *Energy Standard Table* named "TERRITORY" in the *SEMANCO* project (Corrado & Ballarini, 2013a).

The *Energy Standard Tables* have been used to create urban energy models in three case studies (Manresa, Spain; Copenhagen, Denmark; and Newcastle, UK) using the *SEMANCO* integrated platform (Madrazo, Nemirovski, & Sicilia, 2013). To create these models, it has been necessary to link the concepts (i.e. terms) of the *Energy Standard Tables* to the available data sources. A total of 116 concepts have been used for this purpose.

In the urban model of Manresa, 16 domains (65% from the total) have been defined using the terms of the *Energy Standard Tables* ("TERRITORY", "land", "climate", "housing", "population", "building", "building_system", "energy_quantities", "energy_generator", "cs_geometry", "cs_envelope", "cs_internal_partitions", "cs_occupancy", "cs_indoor_air_temperature", "cs_internal_heat_gains", "TIME") and 87 concepts have been applied (9% of the total).

In Newcastle, 13 domains (52% of the total) are included ("TERRITORY", "land", "housing", "population", "building", "building_system", "cs_geometry", "cs_envelope", "cs_ventilation", "cs_internal_partitions", "cs_occupancy", "cs_internal_heat_gains", "TIME") and 39 concepts used (4% of the total).

Finally, 9 domains (36% of the total) have been integrated in the urban model of Copenhagen ("TERRITORY", "land", "building", "building_system", "energy_quantities", "energy_generator", "energy_refurbishment", "requirement_related_to_energy", "cost_related_to_energy") and 22 concepts (2% of the total available) applied.

With regard to the integration of scales and boundaries, it has been possible to address this issue in Manresa and Newcastle, since in both cases the data sources to be integrated corresponded to different territorial scales. In Manresa, at the building level there were data about the year of construction and the type of building, and at the urban level data from the cadastre, census and socio-economic conditions of the neighbourhoods. In Newcastle, the building data was provided by the SAP (Standard Assessment Procedure) records facilitated by the city, and the urban data included socio-economic information about fuel poverty and deprivation levels.

The methodology to use the *Energy Standard Tables* in the ontology has succeeded. The ontology enabled semantic tools to access the data stemming from different domains and applications. Not many terms of the Energy Standard Tables have been used in the case studies, because only few use cases have been developed to become urban energy models. Anyway, this is not a shortcoming of the vocabulary, rather it shows that it has more potential than the one covered by the implemented cases.

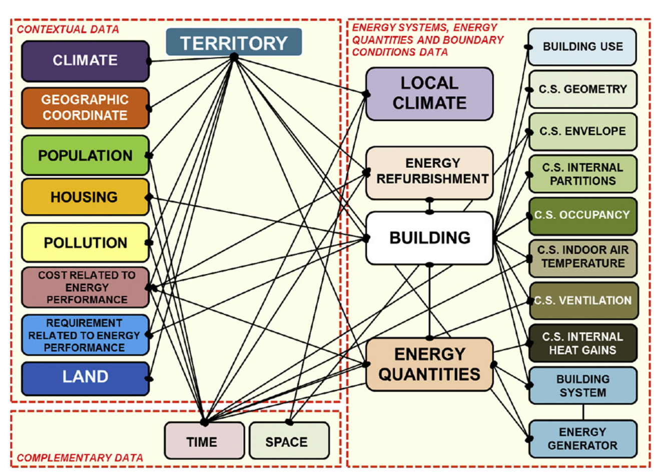

Fig. 6. Connections between the *Energy Standard Table* sheets in the *SEMANCO* project.

Table 3
Correspondence between data categories, *Energy Standard Tables* and areas in the *SEMANCO* project.

DATA CATEGORY	*ENERGY STANDARD TABLE* (ref. sheet names)	KIND OF AREA			
		Region	*Munic.*	*Neighb.*	*Building*
Energy data	"energy_quantities"	x	x	x	x
	"energy_refurbishment"	x	x	x	x
Energy cost data	"cost_related_to_energy"	x	x	x	x
Climatic data	"local_climate"		x		
	"climate"	x			
Environmental data	"pollution"	x	x	x	
Building technical data	"building"				x
	"b_use"				x
	"cs_geometry"				x
	"cs_envelope"				x
	"cs_internal partitions"				x
	"cs_occupancy"				x
	"cs_indoor_air_temperature"				x
	"cs_ventilation"				x
	"cs_internal_heat_gains"				x
	"building_system"				x
	"energy_generator"				x
Legislative constraints	"requirement_related_to_energy"	x	x	x	x
Geographical data	"geographic_coordinate"	x	x		
Land and build. registry data	"land"			x	
	"building"				x
Urban planning data	"land"			x	
Socio-economic data	"housing"				x
	"population"	x	x	x	
Demographic data	"housing"				x
	"population"	x	x	x	
-	"TERRITORY"	-	-	-	-

The *Energy Standard Tables* are published on the *SEMANCO* website, while the ontology is publicly available on a dedicated page (http://www.semanco-project.eu/ontology.htm).

The terms and definitions included in the *Energy Standard Tables* can be enhanced in the future as a result of new applications. The vocabulary provided in the *Energy Standard Tables* and the subsequent ontology can be used to model other cases, aside from those reported, which deal with the modelling of urban energy systems at various scales.

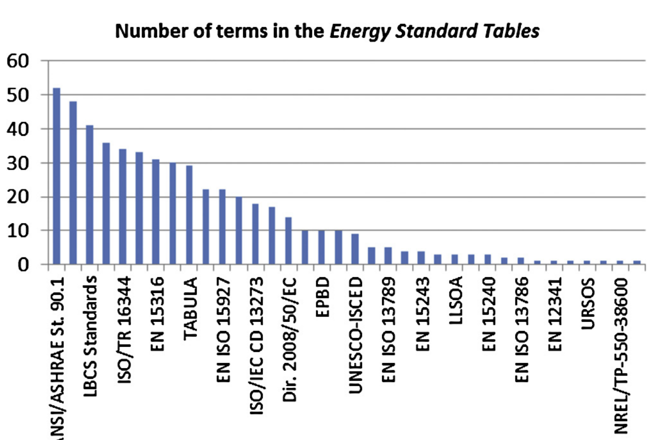

Fig. 7. Number of terms in the *Energy Standard Tables* by reference (technical standard, research project, etc.).

4. Conclusions

The *Energy Standard Tables* are a key component of the ontology building process carried out in the *SEMANCO* project. They have enabled to construct an ontology which integrates multiple domains and facilitates access to the contents of disperse data sources. They are part of a methodology to conceptualise a multidisciplinary domain – e.g. to create a model of an urban energy system – using ontologies. The tables encapsulate the knowledge gathered from the various experts involved in the definition of an urban energy model, using existing technical standards to create the basis for a shared language. The construction of the *Energy Standard Tables* is a multidisciplinary process in itself, since it involves the collaboration of ontology engineers and domain experts working together in the task of re-defining the terms facilitated by experts using the vocabulary of the technical standards. An effective collaboration is necessary to ensure a successful application of the ontology for solving a particular problem related to a specific policy framework.

In the process of building the *Energy Standard Tables*, it has been necessary to dedicate considerable efforts to eliminate contradictions and inconsistencies between different standards. Hence, this research work can be considered as a step forward towards further standardisation in the urban energy system domain.

Furthermore, it has taken into account the specifics of energy systems applied at different urban scales (neighbourhood, district, municipal). Different types of energy data at different scales (neighbourhood, municipal and regional) have been considered: supply and consumption at a district/national level, pollution maps, district GIS maps of the urban environment, population/occupancy data and climate data, and energy consumption in buildings and neighbourhoods. In this regard, the *Energy Standard Tables* provide a base for the creation of urban models which take into consideration the aggregation of data throughout multiple scales.

The vocabulary has been used to create urban energy models in three case studies using the *SEMANCO* integrated platform. The process followed to create the *Energy Standard Tables* can be replicated in other projects, and the vocabulary applied to other cases. In this regard, the *Energy Standard Tables* can be considered as a tool, and their implicit methodology could also be applied for vocabulary building in other domains besides modelling urban energy systems.

Some further practical applications of this work would concern the activities of agents operating during different phases of urban planning processes, to assess the current situation with regard to CO_2 emissions as well as the social, economic and political context in urban scenarios.

A main limitation of the developed methodology concerns its relation with the framework of the technical standards about energy. These standards, especially those regarding the urban domain, are in the process of being developed and updated. For this reason, the concepts, the definitions, the symbols and the relations introduced in the *Energy Standard Tables* are not unmovable, but they will need a continuous review in the next years. That makes necessary a continuous update of the *Energy Standard Tables* and, consequently, of the ontology.

Acknowledgements

This work has been developed as part of the *SEMANCO* project (http://semanco-project.eu/), which has been co-financed by the European Commission within the 7th Framework Program of the European Union, under the coordination of the research group ARC from the School of Architecture and Engineering, Ramon Llull University, Barcelona (Spain).

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