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Faculty of Informatics

Ontology Based Decision Support in Urban Energy Planning

DISSERTATION

zur Erlangung des akademischen Grades

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eingereicht von

Najd Ouhajjou MSc.
Matrikelnummer e1129870

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by

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Wien, 21. Dezember 2015

Najd Ouhajjou

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I am sticking to the conventional naming of this page, but I rather feel it like: gratitude, recognition, or simply "thank you" that we all say so often but -unfortunately- never take the time to fully meditate about and shape up in more expressive actions or words...

> *"The most beautiful things in the world cannot be seen or touched, they are felt with the heart."—Antoine de Saint-Exupéry*

Beautiful things in the world cannot be written either! "Beautiful Things" just exist, keep existing for ever, and grateful people just attempt to thank them in any way they can!

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Friends...

"I am looking for friends. What does that mean – tame?"
"It is an act too often neglected," said the fox. "It means to establish ties."
"To establish ties?"
"Just that," said the fox. "To me, you are still nothing more than a little boy who is just like a hundred thousand other little boys. And I have no need of you. And you, on your part, have no need of me. To you I am nothing more than a fox like a hundred thousand other foxes. But if you tame me, then we shall need each other. To me, you will be unique in all the world. To you, I shall be unique in all the world...."—Antoine de Saint-Exupéry

Each one of you (dear friends) is unique to me in the whole universe! How often we see and talk to each other is not as important as how much we are unique to each other... I am intentionally avoiding to talk about you one by one: this "aknowledgements" section would for sure go out of control!

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V , who hopefully someday would believe that candles are not dangerous, party confetti are not dirt, and roses always find some space in a piece of luggage. Sigh... indeed, tamed roses are unique.

> *"People have forgotten this truth," the fox said. "But you mustn, t forget it. You become responsible forever for what you, ve tamed. You, re responsible for your rose."—Antoine de Saint-Exupéry*

Thank you V... Du bist B!

Again, when I talk about friends, this applies as well to my family in Morocco. I love you too much to claim that I love you, recalling that most beautiful things are only felt with the heart. I am all yours, your son, your brother(/in-law), your cousin, your nephew, your uncle.

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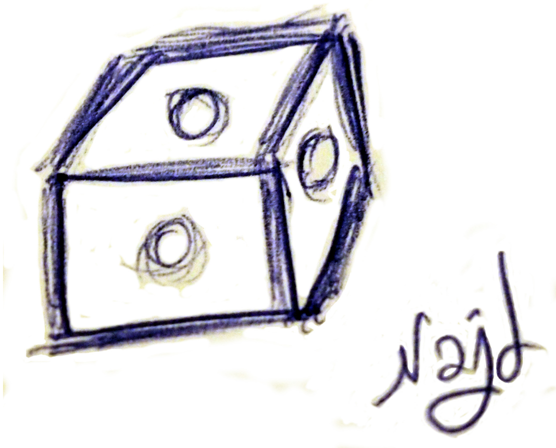
Inspired Antoine de Saint-Exupéry, I dedicate the "box" bellow to all of you. It contains all the beautiful things that we only feel with the heart. The "box" has an unlimited size, where came the idea to put some wholes on it: so that every time my heart feels a beautiful thing, I put it in there, for you all.



To the living memory of my grandparents that passed away during the time this work was being elaborated: Lmmima (Lalla Chrif Elhassani) and Bbassidi (Moulay Ali Yassine). I owe you so much to have given me such a great mother.

I miss your presence, but I feel your existence!

Abstract

Cities are emitting worldwide around 70% of all greenhouse gas emissions. To reduce this large share, cities aim to develop energy strategies, implemented as a set of measures to mitigate energy demand and ensure a sustainable energy supply for the built environment. A variety of city-level energy planning processes exists requiring the involvement of stakeholders (actors with different interests and matter of involvement). Cities are complex systems involving cross-dependencies and relationships between their elements in a wide problem space. Multiple domains have to be also considered involving different domain experts. These facts represent the challenges in modeling energy systems in cities for urban energy planning support purposes.

The objective of this thesis is to model a complex urban energy system for energy planning support. Several energy planning related tools exist, applied to suggesting and simulating solutions for these energy related problems. But developing a "master decision support system" is not easily feasible as the problem space shows a wide range and is related to data availability in cities, to changing requirements of stakeholders, and in general to the changing political environment where decision-support is required.

The dissertation suggests that the development of these systems is a continuous process. It always requires (i) updates to deal with the change in data availability and requirements and (ii) extensions to gradually include as much functionality as possible from a non-finite problem space, making the target decision support solution a self-sustaining, viable system. This thesis presents an ontology based approach for urban energy planning support for building-refurbishment and building-integrated PV-based energy generation. The adopted methodology works as an iterative, incremental process, step-wise integrating new planning decision. The process starts by the identification of the actors whose interests are affected by the decision, then developing/ adapting computation models that provide answers for their questions. Different models are integrated using a flexible ontology-based system. The adopted approach provides different actors with specific information related to their viewpoint of decision making.

Accordingly an incremental development methodology is proposed as a solution, where integration mechanisms, used computation models involved stakeholders, and their requirements are part of the system. This offers a transparency of the dynamics of the system and ensures the tractability of the requirements with regards to how they are fulfilled. The methodology was applied to develop an ontology-based decision support system for building-integrated solar PV. The same methodology was then applied for a second use case by including building refurbishment (integrated with solar PV) as

ontology-based planning support system.
The resulting system has been applied for the 4th district of the City of Vienna covering around 1200 buildings, but this approach is applicable to different cities, as the ontology also integrates extension and upgrade mechanisms that provide flexibility to cope with different data sets.

Kurzfassung

Städteemittieren weltweit rund 70 % der Treibhausgasemissionen. Um die Treibhausgasemissionen in deren Einflussbereich entsprechend zu reduzieren, werden Energiestrategien entwickelt und Maßnahmenpakete implementiert, damit die Energienachfrage effizienter und das Angebot in und für die gebaute Umwelt nachhaltiger gestaltet wird. Dafür existieren zahlreiche Energieplanungstools, doch diese beziehen die Beteiligten (lokale Akteure, Stakeholder) nicht immer ausreichend ein. Städte sind komplexe Systeme mit Abhängigkeiten und Beziehungen zwischen den Elementen in einem weiten Problemraum. Für die unterschiedlichen Aufgaben in den Städten sind eine Vielzahl von Experten zu beteiligen. Diese Herausforderungen sind bei der Modellierung der Optimierung städtische Energiesystemen als Entscheidungshilfe für Energieplanung zu berücksichtigen.

Diese Dissertation hat zum Ziel ausgewählte Elemente des komplexen Energiesystems einer Stadt als Unterstützung für städtische Energieplanung zu modellieren. Energetische Fragestellungen werden dabei von verschiedenen Energieplanungstools abgesprochen. Die Entwicklung eines "Master-Decision support-systems" ist schwierig, weil der Problemraum vielschichtig ist: er betrifft die zu erfüllende Aufgabe, die Datenverfügbarkeit, die sich ändernden Anforderungen der Stakeholder oder allgemein das sich wandelnde Politik-Umfeld, wo Entscheidungsunterstützung benötigt wird.

Diese Dissertation sieht die Entwicklung eines solchen Systeme als kontinuierlichen Prozess. Er ermöglich (i) Änderungen hinsichtlich Anforderung und Verfügbarkeit von Daten und (ii) Erweiterungen der Funktionalität um die Entscheidungsfindung flexibel zu unterstützen.

Diese Arbeit entwickelt einen Ontologie-basierten Ansatz für städtische Energieplanungs-Unterstützung für Gebäude-Sanierung und gebäudeintegrierte PV-basierte Energieerzeugung. Die angewandte Methode funktioniert als iterativer, schrittweiser Prozess. Der Prozess beginnt mit der Identifizierung der Akteure und deren Interesse, das Entwickeln oder Adaptieren von Berechnungsmodellen. Verschiedene Modelle werden dann unter Verwendung des flexiblen Ontologie-Systems zur Beantwortung der Fragen integriert. Der gewählte Ansatz liefert verschiedenen Akteure spezifische Informationen, um ihre Sicht in die Entscheidungsfindung einzubringen. Die Lösung ergibt sich durch eine stufenweise Integration von verwendeten Berechnungsmodellen zur Berücksichtigung der Ansprüche der Akteure.

Der erste Anwendungsfall betrifft die Entwicklung eines Ontologie-basierten Entscheidungsunterstützungssystems für den Einsatz gebäudeintegrierter Photovoltaik. Der zweite Anwendungsfall erweitert das System in Richtung energetische Gebäudesanierung.

Das entwickelte System wurde für den 4. Wiener Gemeindebezirk für etwa 1200 Gebäude angewendet. Aber es ist auf beliebige andere Städte oder Stadtteile übertragbar, da die Ontologie entsprechende Erweiterungen und flexible Gestaltung für unterschiedliche Problemstellungen und Datengrundlagen zulässt.

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CHAPTER 1

Introduction

1.1 Problem statement

The general objective addressed in this thesis is related to modeling and formalizing the complexity of urban energy systems. In theory, there is a large amount of elements that take part of an urban energy system. Furthermore, these elements interact with each other, causing chains of impacts that need to be captured as well. Finally, there is a variety of stakeholders that have interests being affected within urban energy systems. These interests are sometimes conflicting and need to be understood and formalized as well.

In practice, limited data availability in cities is an obstacle to carry out urban energy system modeling, as it requires a validation by confronting developed models to real data [Bat09]. At the level of cities, data are often not available at the desired level of detail. In other cases, the data are not accessible because of privacy issues (e.g. electricity consumption of households), or simply do not exist because no one has collected or calculated the data before. Modeling urban energy systems specially addresses urban energy planners. They need adequate tools (which model urban energy systems) to make informed decisions during their planning processes. In the absence of appropriate planning support tools, these strategies lack for integration (e.g. considering silos of planning decisions rather than integrated ones) and sometimes their impact is not assessed.

In summary, this thesis addresses the problem of modeling complex urban energy systems. This problem is challenging due to the complex nature of these systems and the limited data availability in cities.

1.2 Background

1.2.1 Most of the energy of the world is consumed in cities

There is an increasing energy consumption in the world causing the growth of global CO_2 emissions, as depicted in Figure 1.1. This large amount of CO_2 emissions (31 734 Mt) threatens the achievement of the goal agreed upon by global leaders at the UN climate change talks in Cancun in 2010 i.e. limiting temperature increase to 2 °C [IEA11].

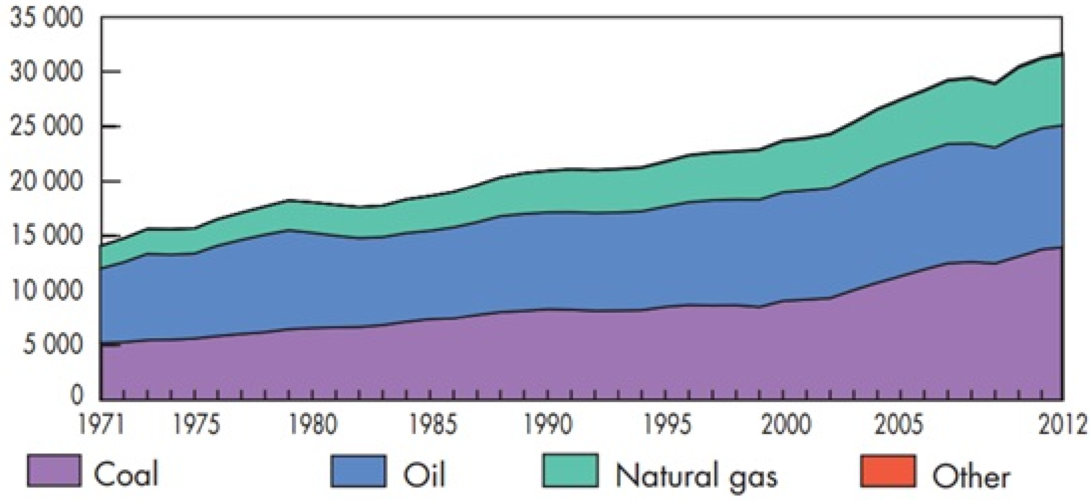


Figure 1.1: World CO_2 emissions from 1971 to 2012 by fuel (Mt of CO_2) [IEA14].

The highest energy consumption share is observed in cities. More than two-thirds of primary energy in the world is used in urban settlements [KSSW11]. This energy consumption results in approximately 71 percent of all energy-related direct greenhouse gas (GHG) emissions [IEA08].
Thus, cities represent a rich ground for taking action to reduce the amount of GHG emissions in general, or CO_2 emissions in particular. Therefore, decision makers, namely city administrations and governments, are developing strategies for CO_2 emissions reduction that are targeting cities. These strategies aim to reduce the energy demand of cities, as well as the promotion and integration of more renewable energy sources to cover the energy demand.

1.2.2 Cities are complex systems where quantifying the impact of decisions is challenging

Cities are complex systems regarding the amount of disciplines, components and interactions they comprise. They behave as socio-technical systems [Tri78], comprising both social and physical components and their (cross) relationships. Physical elements are, for example, buildings, streets, facilities, hardware etc. While social elements include the

different organizations and stakeholders whose interests are to be considered within the city.
The laws that regulate such systems are of two different natures as well, physical and social. While the physical laws define the behavior of the physical elements (e.g. energy conversion laws), the social laws represent regulations and behavioral patterns (e.g. funding regulations for buildings thermal insulation). Both laws affect the system as a whole [OFKVDP06], therefore, they need to be captured and formalized as well.
Models representing such systems are required to answer questions that are raised by certain users or involved stakeholders. Batty defines these models as functions and processes representations that generate urban spatial structure in terms of a variety of disciplines, enabling location theories to be tested against data and predictions [Bat09]. It is importing to adopt an integrated (i.e. systemic) approach when testing location theories. It helps understanding their impact on the whole system and its side-effects. For example, installing solar photovoltaics (PV) systems in a given building might be interesting for the building owner but this measure might have undesired technical side-effects on the electric grid. Therefore, it is necessary to have an integrated assessment that makes sure that the location theories are tested within the whole system, capturing their systemic behavior that cannot be obtained by looking at isolated parts [Ber68].
In the specific case of developing CO_2 emission reduction strategies, several options are available. The options are different measures that the planners would like to implement in order to reduce CO_2 emissions e.g. integrating renewable energy sources such as solar PV systems, solar thermal collectors, wind turbines or reducing the energy demand of the city by refurbishing buildings. Any combination of measures triggers different chain effects within the system. Choosing the right combinations of measures requires not only knowing their impacts on the system but also on each other. For example, introducing electric vehicles will increase electricity demand, reducing the production of waste will also reduce the energy available from incineration, introducing a large amount of PV will require interventions on the local electricity grid. On the other, hand measures can compete over limited available resources, e.g. PV modules and solar thermal collectors will compete for a limited available roof area.
Accordingly, making informed decisions in a complex environment such as a city is challenging. It requires understanding the side-effects of decisions on the different social and physical elements of the system. Furthermore, it requires understanding the impact of the different decisions on each other.

1.2.3 Modeling a large, complex integrated system

Urban energy systems are large and complex, and require the knowledge of experts from different domains. Cities are large entities in terms of the space they occupy. To illustrate the scale being addressed in modeling urban systems, capturing the physical aspects of cities is taken as an example. There are several techniques to construct and populate a city spatial model (only containing the geometries of the city). Examples of these techniques include light detection and ranging (Lidar) sensing technology, described in [Ren00], where an aircraft that carries a Lidar system flies over a target area, it emits pulses and measures their reflection. Another example is ground laser scanning, discussed by Zhao and Shibasaki [ZS03] or Fruh and Zakhor [FZ01], which is based on scanning buildings using a vehicle (e.g. truck) that is equipped with cameras. Both technologies are illustrated in Figure 1.2. Other large-scale urban modeling approaches and technologies are described in more details by Hu et al [HYN03].

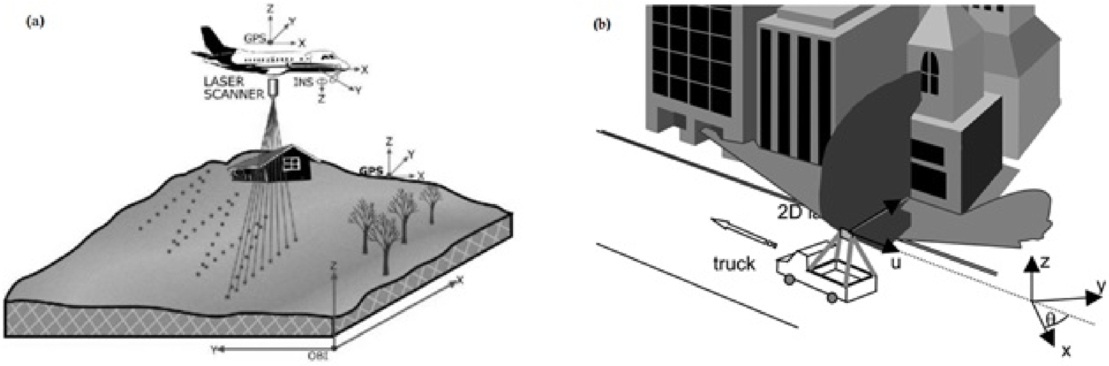


Figure 1.2: (a) Lidar scanning [Ren00] (b) ground laser scanning [FZ01].

The large size of urban systems with their vast number of elements is a challenge in modeling them. Not only the computational support requirements or the accuracy of models are challenging but also data acquisition is an obstacle. As described previously, important resources are required to scan a whole city just to obtain its geometric data. Concerning the scope of urban energy system, it is due to the heterogeneous data it integrates. Thus modeling an urban energy system requires different expertise from several domains, including, for example, electrical engineering, thermal engineering, building physics, mobility, etc. It is important to note that different domain experts do not necessarily adopt the same modeling approaches but still share the same goal of modeling a complex comprehensive system. Different modelers, from different backgrounds, consider those modeling approaches they are used to [LJ06] - as the purpose of the applied model focuses on their specific questions.
Accordingly, modeling a complex urban energy system is challenging because (i) of the heterogeneous nature of the disciplines it encompasses and (ii) also because modelers (from different disciplines) do not necessarily share the same modeling approaches that might be challenging to combine.
The scope of the system is difficult to delimit i.e. stating which parts of the system are to be modeled and which others are to be left out of the modeling scope. The modelers, supporters of the General System Theory [Ber68], confront the dilemma of where to foster reductionism over holism. In practice, it is difficult to develop a model that exactly replicates the reality in all its small details. Hence, only interesting parts of the system from the perspective of the user of the model are to be captured. In the particular case of urban energy system, there is a large amount of stakeholders whose interest are involved, thus a large amount of perspectives is to be considered. This affects the scope of the

modeling and makes it very large.
The above constraints impact the modeling process of urban energy systems in three different ways: (i) modeling large system would require large resources (in terms of time and effort). (ii) Modeling a multidisciplinary system requires the integration of different modeling approaches and heterogeneous data sources. (iii) The large amount of perspectives (of stakeholders) within the system, makes the scope grow large and require a special attention to the scalability of the system.

1.2.4 The viability of complex urban system models

Beer refers to a viable system as one "maintaining its identity independently of other such organisms within a shared environment" [Bee84]. The viable system model (VSM) [Bee85] describes the sub-parts of a system that ensure its viability. This model is based on Ashby's law [Ash56] stating that the stability of a system requires that the number of states it is designed to control shall be greater or equal than the ones it is stimulated by. The main concept of VSM is to deal with the number of states (variety) regardless of the environment and conditions of use of the system. Figure 1.3 illustrates the essence of VSM in a simplified way, as described in [Bee85]. It shows a system composed of operations and management that deals with the variety of the environment by attenuating the variety it receives from it and amplifying its ability to deal with it (through operations). Similarly, the management maintains the same relationships with the operations.

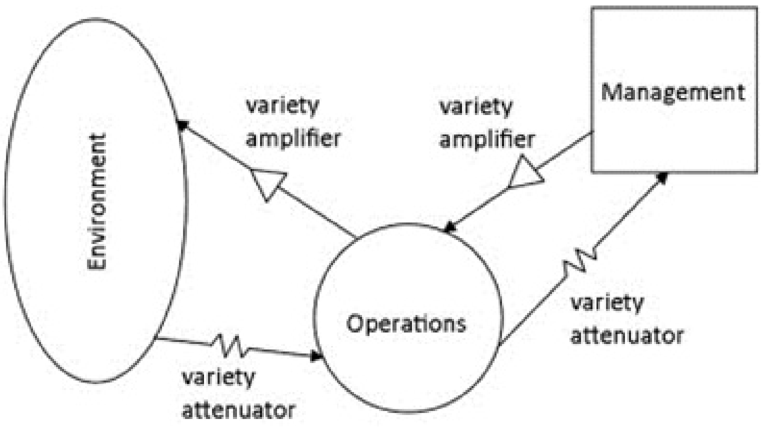


Figure 1.3: System variety [PSH13].

In the specific context of this research viable systems are defined as self-sustaining ones that are able to adapt to the changing environment they are being used in i.e. different data availability, usage processes, and requirements. The modelers of urban energy systems cannot know beforehand (all the cities) where the developed models are going to be used. Therefore, the variety that the modeled urban energy systems face is very high, similarly to what is described in Figure 1.3, where the management cannot

know all the what happens in the operations [Bee85].
Data availability is significantly varying frpm a city to another. [CB13] Within the European project SEMANCO, a report has been published on accessible energy data in three different cities - Manresa, Newcastle, and North Harbour [CB13]. A synthesis of this data collection has been performed to check the similarities between the different collected data parameters. The percentage of similarities has been calculated as the following: number of similar parameters in one city data collection compared to the other two cities divided by the total number of parameters in the data collection of the city in question. The results of this comparison are shown in Table 1.1.

Data category	**Number of parameters**			**Percentage of similarities**		
	North Harbour	**New-castle**	**Manresa**	**North Harbour**	**New-castle**	**Manresa**
Energy	5	6	2	0%	0%	0%
Energy cost	2	0	2	50%		50%
Climatic	6	4	3	33%	50%	33%
Building technical	4	30	32	50%	23%	25%
Geographical	0	6	6	-	0%	0%
Land use	4	0	8	0%	-	0%
Urban planning	1	0	6	0%	-	0%
Socio-economic	6	14	3	33%	0%	67%
Demographic	4	0	7	100%	-	57%
Legislative constraints	0	0	1	-	-	0%
Not classified	0	5	6	-	0%	0%
All data together	**32**	**65**	**76**	**34%**	**14%**	**21%**

Table 1.1: Data availability comparison North Harbour, Newcastle, Manresa [OPS+13]

Another type of variety that urban energy system models face is due to the changing requirements (i.e. what information the users expect from the system). The competency questions of the system depend on its users. Since the urban energy system models are used for decision support purposes, they shall consider the perspectives of the involved stakeholders that are different from a city to another. For example, in some cases the city administration does not provide subsidies for installing solar PV systems. Therefore, modeling a tailored urban energy system model for this case makes it face a variety in other cities where the city administration does provide subsidies for installing solar PV systems.
Finally, when using the system for decision support in energy planning, there are different

processes and approaches cities adopt (for energy planning). Therefore, this increases the variety that the system shall deal with. The users of the system are not predefined and not necessarily the same in all the cities. For example, in the context of nationally funded projects [The11] for developing energy strategies for the cities of Vienna, Amstetten, and Linz in Austria, the set of stakeholders that participated in the process was different from city to another.
The viability of models is important given the large resources (time and effort) they require to be developed. Therefore, it is crucial that the developed urban energy system models can be adapted to different environments so that the development efforts and the allocated resources are saved.

1.3 Research questions

As described above, this research addresses modeling the complexity of urban energy systems, for decision support purposes in urban energy planning. Aligned with the background section that describes the environment where energy planning support is required, the following research questions (RQ) are defined:
RQ: Is it possible to develop an ontology of an urban energy system to support decision making i.e. the choice of adequate measures in the process of developing a sustainable energy master plan?

- **RQ1**: How can a georeferenced urban energy system be represented within an ontology?
- **RQ2**: How can an urban energy system ontology be used in urban energy-related decision support?
- **RQ3**: What mechanisms need to be integrated within the ontology so that it copes with the variety of data availability, requirements, and use?
- **RQ4**: What software architecture is needed to implement an ontology based tool for decision support in urban energy planning?

1.4 Methodology

This section describes the research process framework. It explains a meta-methodology rather than detailed steps to develop the desired urban energy planning support ontology, described in chapter 3, or its applications, addressed in chapters 4, and 5.
The general research framework that has been adopted to achieve this work is the Design Science in Information System Research [HMPR04]. It is considered to be a system development based science [NJC90]. The principal goal of the Design Science is to do research through designing and creating systems [Gre11], [MS95], [Iiv07]. In contrast with other classical research methods that are based on observation of phenomena to reveal problems [SHP+11] , design science starts from being aware of pre-existing

problems [JAS14] that are solved by developing new systems [VKJ07].
Konda argues that information systems research borrowed its concepts from older research disciplines such as physics or chemistry [Kon12]. Furthermore, he argues that the main challenge that has been encountered is finding the right trade-off between, in the one hand, relevance that characterizes the applicability requirement of information systems and research rigor, on the other hand, which is required in classic research methods [Kon12].
The choice of Design Science as a framework for this research is due to its explicit guidelines that address both research rigor and relevance. Figure 1.4 shows the information system research framework. It requires both rigor and relevance that Konda has discussed [Kon12]. The relevance is ensured by considering the domain needs by taking into account people, organizations, and technology that together constitute the research environment [SMB95] that defines the problem space [Sim96]. Concerning the rigor of the research, it is brought through the knowledge base i.e. foundations (e.g. theories, frameworks, instruments, etc.) and methodologies (e.g. data analysis, techniques, formalisms, etc.).

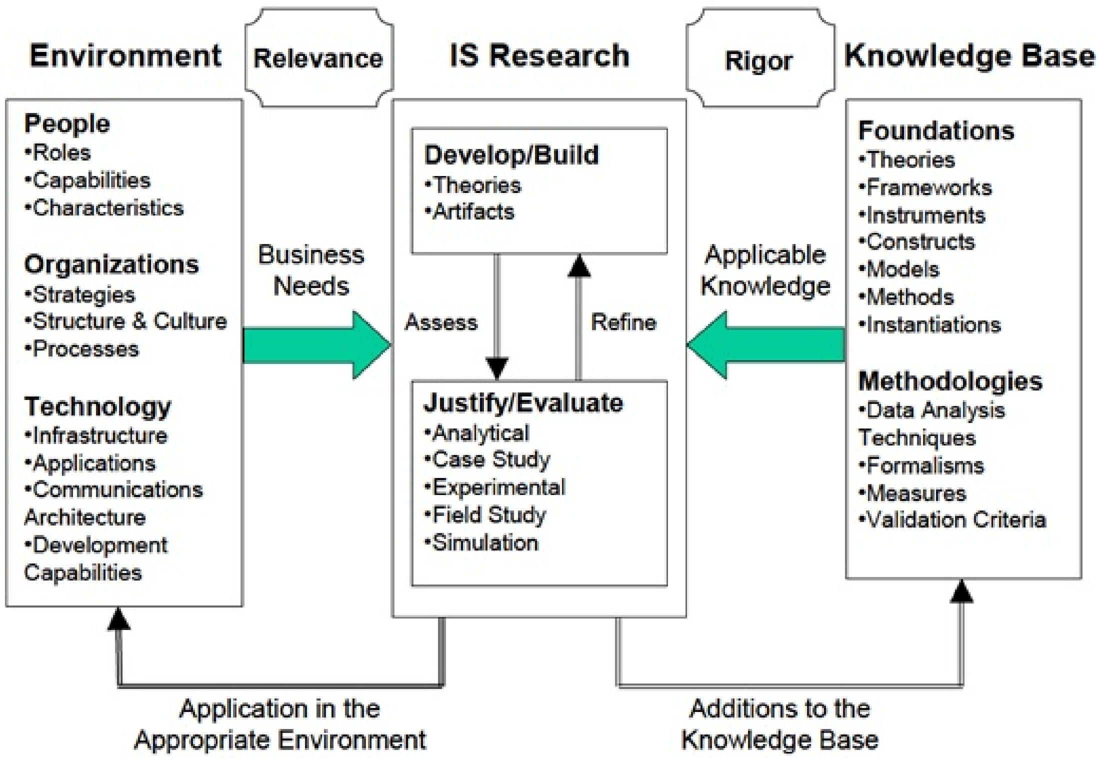


Figure 1.4: Information Systems Research Framework [HMPR04].

Design Science defines seven explicit guidelines that constitute the research framework [HMPR04]. Each guideline contributes in ensuring either the relevance of the research to the environments (i.e. applicability) or its rigor, in terms of the theoretical background and methodology. The guidelines state that the research must output a concrete artifact, which is relevant to a real business problem. Moreover, the artifact has to be evaluated via proper methods. The research must contribute in the area of the design artifact and rely on rigorous methods for both constructing and evaluating the artifact. Furthermore, the research process requires exploiting available methods while still obeying the laws of the environment of problem. Finally, the research must be communicated adequately to both technical-oriented and management-oriented audiences. The full set of these guidelines is listed in table 1.2.

Guideline	**Description**
Guideline 1: Design as an Artifact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

Table 1.2: Design Science research guidelines [HMPR04]

CHAPTER 2

Urban Energy Planning Support

There exist numerous definitions of urban energy planning [MDG13]. The focus of this chapter considers integrated long-term urban energy planning that relies on supporting (software) models [MLKK09].

This chapter gives an overview of the problem space [Sim96] of this research and illustrates its relevance to real-world problems [HMPR04] i.e. what process it supports and what constraints it encounters. In section 2.1, an overview of urban energy planning processes is given. In section 2.2, a description of the most prominent urban energy planning process is given (more than 5000 cities and municipalities as users). Then, based on this process, necessary conditions in urban energy planning support systems are derived and detailed in section 2.3. Finally in section 2.4, state-of-the art tools in urban energy planning support are listed and discussed against the necessary conditions in urban energy planning support systems.

2.1 Overview of urban energy planning processes

As previously stated, the scope of this research considers integrated and long-term urban energy planning, which usually relies on supporting software tools [MLKK09]. According to Mirakyan and De Guio, urban energy planning is defined as the process of finding solutions to the best mix of energy demand and supply in a given area. The solution shall support a sustainable development of the area in a long-term run, and at the same time shall be socially acceptable and institutionally sound [MDG13]. Regarding the nature of the process, Mirakyan and De Guio emphasize on the fact that urban energy planning is a participatory and transparent process. It offers the opportunity to the planners to simplify and present complex issues in a structured way, taking account the system as a whole. Therefore, decision makers have a better understanding of the issues and are supported regarding their planning decisions [MDG13].

According to Mingers and Brocklesby [MB97], a more generic definition is associated to

this process. Thus, it is defined as a set of guidelines and / or activities to support a target group of people in performing their tasks [MB97]. The planning process can be undertaken using various methods and techniques adequate to the specific contexts of the decision making [MDG13]. The urban energy planning process has the primary goal of putting the decision making in a conceptual framework, thus, putting some structure concerning what is needed to be accomplished. Accordingly, more emphasis is respectively rather on the process and actors than the content and the structures [Wil02].
There exists a large variety of energy planning processes that resulted from different projects that were related to specific case studies. Such energy planning processes include the work of Jank [Jan00], which aimed to apply different tools and models to describe complex municipal energy system. Thus, aligning the planning process with the available tools and models [Jan00]. Another urban energy planning process designed by the IEA [IEA94] aimed to plan energy efficient communities. Thus methods of local energy planning have been developed consisting of (i) finding the right software tools that are adequate for energy planning (ii) then modeling the calculations of the impacts of different decisions on the environment. (iii) Then, advertising the potential planning solutions (scenarios) among the target communities. (iv) Finally, implementing the results of the planning procedures [IEA94]. Similar planning processes that list the phases and steps to be undertaken in urban energy planning include the work of Linkov et al [LVJ+05], Hewitt [Hew95], and Josefsson et al [JJW96].
Several platform for sharing energy planning experiences and best practices are also available [MDG13]. The aim of these platforms is to create planning communities and maintain relationships between the different people and organizations that are operating in the same field. Examples of such platform are : [Sus12], [Eur14a], [Eur14b], [Eur14c], [Cli], [INT13], [The14a], [The14b], [EC14], and [ICL14].
More literature exists about different energy planning methodologies, which are considered to be process-based [BH07]. However, Mirakyan and De Guio [MDG13], have derived a generic process of integrated energy planning in cities, as shown in Figure 2.1. The process is structured into four phases (i) Preparation & orientation, (ii) Detailed analysis, (iii) Prioritization & Decision, and finally (iv) Implementation & Monitoring.

In the preparation & orientation phase, a general understanding of the problems to be solved is achieved. Problems are formulated, structured, and then goals to be reached are defined. This phase is conducted in the presence of the decision makers, planners, and experts.
In the detailed analysis phase, a deeper understanding of the problems is achieved and solution scenarios are defined. This phase requires data processing and software tools to assess the impact and effectiveness of the different proposed solutions. This phase involves the participation of the planners and domain experts. The decision makers do not participate in this phase as it is mainly about data processing and scenarios preparation.
In the prioritization & decision phase, different potential solution scenarios are compared, and then best solutions are chosen. This phase requires the participation of all the affected stakeholders besides the decision makers, planners, and domain experts. Decisions are

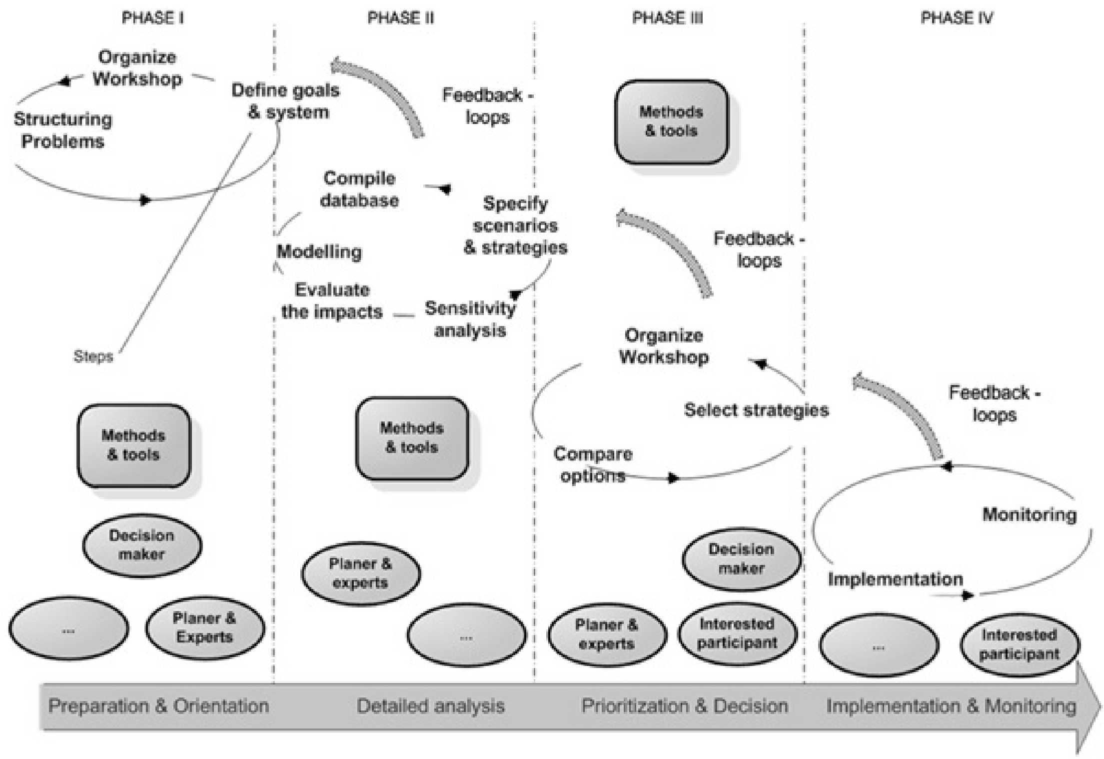


Figure 2.1: Generic process of integrated energy planning in cities [MDG13]

made in workshops, where different scenarios are discussed, based on the data and information that have been processed in the detailed analysis phase.

The last phase, implementation & monitoring, involves mainly the realization of the outcome of the prioritization and decision phase. The strategies that have been defined previously are implemented and coordinated. Furthermore, the progress is monitored and goes in a feedback-loop together with the implementation. The participation of the affected stakeholders in this phase is necessary.

As mentioned before, there is a large variety of urban energy planning processes. However, there is a common pattern that re-appears in most of them as shown in Figure 2.1, in the form of common phases and participants. The Sustainable Energy Action Plan (SEAP) [Eur10] [BCMdR10], is one of these processes that obey to the generic meta-model shown in Figure 2.1 [MDG13] and it is very widely spread across Europe. The rest of this research is based on this process and the results can be generalized over all energy planning processes that implement the meta-model that is described by Mirakyan and De Guio [MDG13].

2.2 The SEAP process

The findings of this research are based on the SEAP process. The choice of the SEAP process is due, on the one hand, to the fact that it obeys to the generic meta-process-model of urban energy planning as described by Mirakyan and De Guio [MDG13]. On the other hand, the findings of this research are directly addressing the large community of the SEAP process users (more than 5000 cities and municipalities). Thus, as described in section 1.4, the designed artifact addresses a real world problem and eventually is relevant to its environment [HMPR04].
Concerning the history of the SEAP process, it was created to support cities to develop sustainable energy action plans. After committing to the Climate and Energy Package [Eur12] in 2008, the European Commission initiated the Covenant of Mayors [Cov13] in order to support cities and local authorities developing energy strategies to reduce their CO_2 emissions. Ambitious targets in terms of CO_2 emission reduction, energy efficiency, and share of renewable energy use have been set. Different cities can join the Covenant of Mayors and benefit from the support of the EC. Thus, the Covenant of Mayors describes a process of how to develop a Sustainable Energy Action Plan (SEAP) [Eur10] that lists the main steps and guidelines that need to be executed.
The SEAP process is a largely spread reference process in Europe and other countries, such as Argentina, Kyrgyzstan, and Morocco. It is has been adopted, until the second semester of 2014, by more than 6000 signatories representing more than 193 million inhabitants [Cov13]. It is to be noted that the number of signatories is constantly increasing by more than 500 adherents per year, as it is shown in Figure 2.2.

Figure 2.2: Signatories number over time [Cov13]

Figure 2.3.shows a district of the map of the signatories of the Covenant of Mayors. The signatories are distributed all over Europe, with a higher concentration especially in Spain and Italy.

The SEAP is a flexible process that leads to an action plan of a dynamic nature and which is continuously subject to revision and improvement.
Regarding the scope of the SEAP process, it focuses on concrete measures, which implementation leads to a certain target reduction in CO_2 emissions. For example,

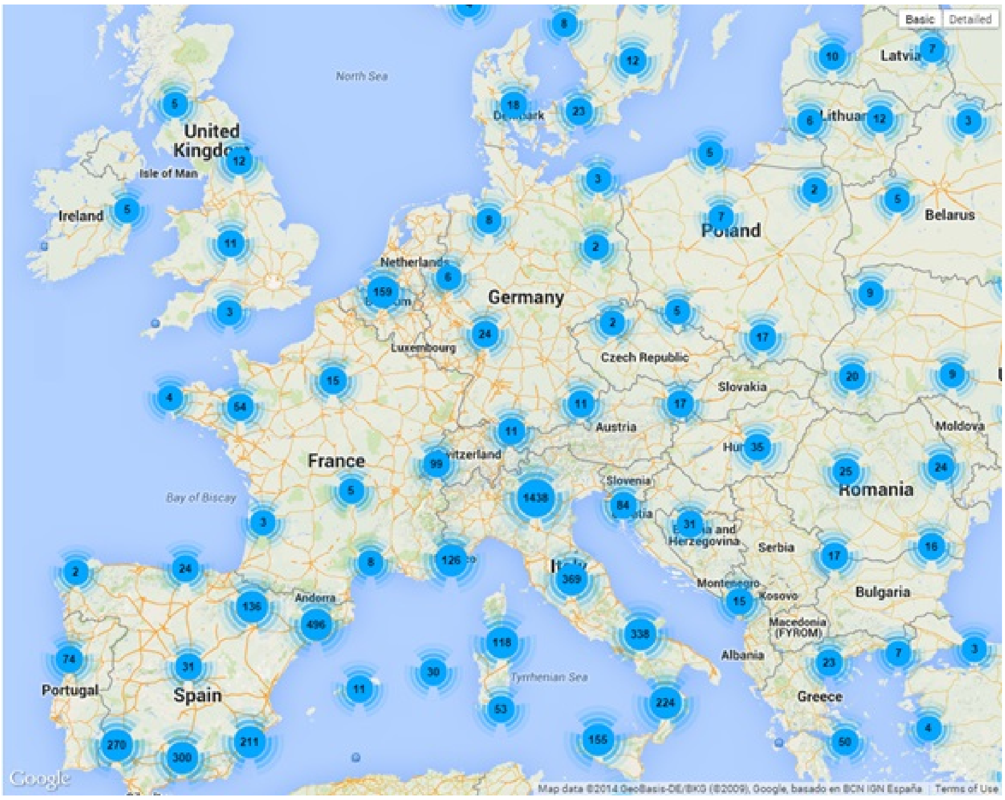


Figure 2.3: Signatories of the Covenant of Mayors map fragment [Cov13]

installing solar PV systems or refurbishing buildings. Moreover, it is bounded to actions and decisions that can be made at a local level (i.e. by the authorities of cities or municipalities). The measures that the SEAP addresses are related to the categories of energy efficiency and local energy supply. The energy efficiency measures are mainly related to the sectors of buildings, transport, and equipment/facilities. The local energy supply measures include actions to produce locally electricity and heating/cooling either in a decentralized way (e.g. building or bloc of buildings level) or in centralized way (e.g. city level Combined Heat and Power (CHP) plants). Concerning the time horizon of the SEAP process, it was designed to develop long term strategies with the only condition that the resulting strategies have to state the intermediate targets for 2020. Therefore, a city can use this process to develop energy strategies that go until 2050 or even farther. Table 2.1 summarizes the scope of the SEAP process by listing what it covers in terms of four main components: Planning horizon, space frame, measure types, and sectors addresses.

The SEAP process, as illustrated in Figure 2.4, is composed of four main phases. The process typically goes by the following phases in a sequential manner: initiation, planning, implementation, and finally monitoring and reporting. However, it is possible to start steps that belong to different phases in parallel.

Planning horizon	Space frame	Types of measures	Sectors
Long term	Municipality	Energy demand	Buildings
Medium term	City	Energy supply	Transportation
	Regional		Equipments/facilities

Table 2.1: The scope of the SEAP process

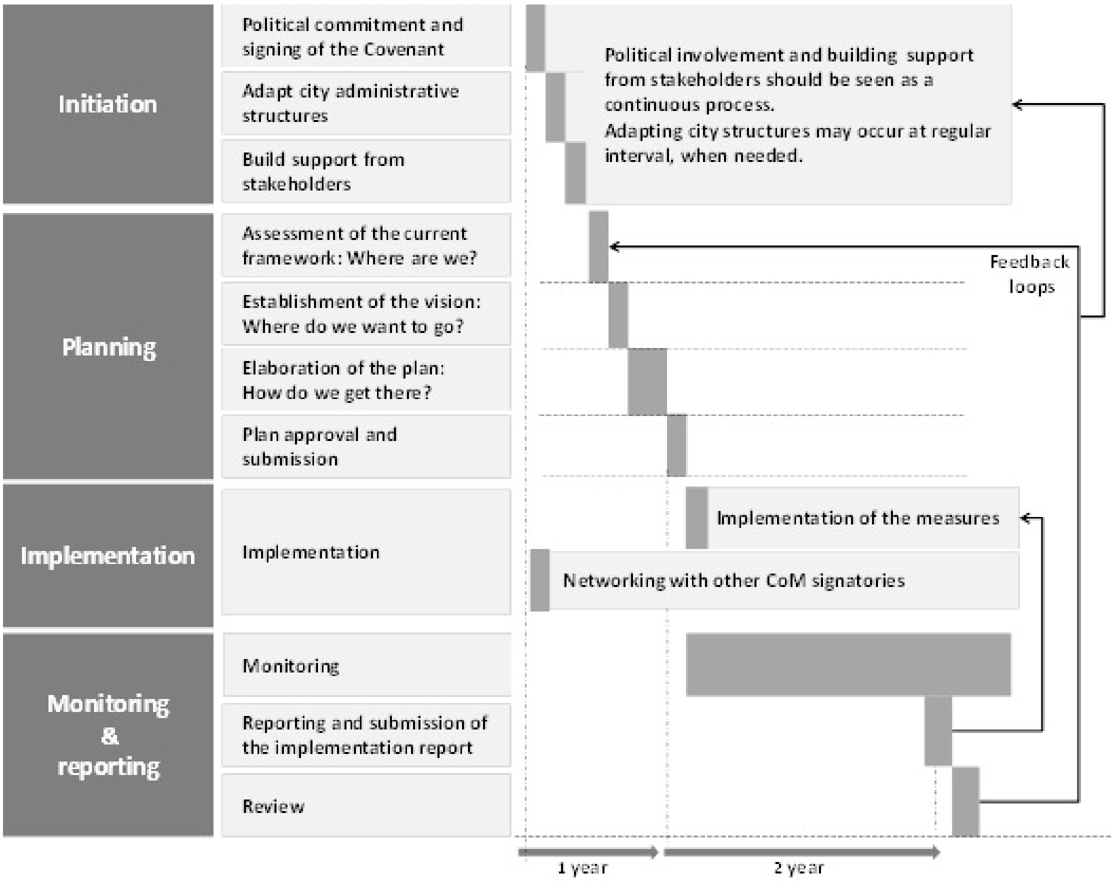


Figure 2.4: The main phases and steps of the SEAP process

The initiation phase: the goal of this phase is to build the political involvement of the concerned authorities in city as well as the support of all important stakeholders. This phase is the starting point of the SEAP process. However, its activities continue all along the lifetime of the process. The main steps to achieve the initiation phase of the SEAP process are as the following:

- Political commitment and signing of the Covenant
- Adapt city administrative structures

- Build support from stakeholders

The planning phase: the goal of this phase is to come up with a sustainable energy strategy that clearly defines how to reach a certain target in terms of CO_2 emissions reduction (compared to the levels of 1990). Optionally, other targets might also be set such as the energy efficiency or the share of renewable energies compared to the total energy supply of the city. The energy strategy that is developed within this phase is based on the current situation of the city. Therefore, in order to assess the situation of the city, a Baseline Emissions Inventory is set besides the potentials of the city in terms of implementing different measures. It is important in this phase to make sure that the developed strategy is a working instrument for the implementation phase (the following phase). Moreover, it serves as a shared ground for understanding the content to be implemented and it serves for communication, especially toward the stakeholders. Therefore, the level-of-detail of the description of this strategy needs to be sufficient to fulfil the requirements of the above issues. The SEAP process does not state explicitly the small details of developing a sustainable energy strategy, since it is rather generic and addressed to a large community with different specificities. Therefore, it only states the major steps that lead to developing the desired strategies, as described below:

- Assessment of the current framework (Including the elaboration of the CO_2 Baseline Emissions Inventory): In which situation is the city?

- Establishment of the vision: Where does the city want to go?

- Elaboration of the plan: How to reach the targets?

- Plan approval and submission: initiating the process of moving towards the targets

The implementation phase: the goal of this phase is to realize the actions that constitute the strategy, which was defined in the planning phase. Therefore, the implementation phase is the one with the longest lifecycle. Moreover, it is challenging because of the effort and financial resources it requires. Hence, it is important to perform actions that ensure the continuous political commitment and involvement of all the stakeholders. Moreover, it is necessary to ensure a proper internal communication during this phase.
The monitoring phase: the goal of this phase is to stay up to date about the progress status of the implementation of the developed strategy. The most critical aspect to monitor is the status of the CO_2 emissions and how the Base line emission inventory is affected by the progress of implementation phase. Thus, it is necessary to keep an updated Monitoring of the Emission Inventory. The frequency of updating the Monitoring Emission Inventory shall be at least four years. The monitoring reports also include the status of the implemented actions. Optionally, depending on the nature of the implemented actions, other indicators can be monitored.

2.2.1 Actors in the process

The actors that participate in the SEAP process fall in three different categories. They include the municipal council (or an equivalent body, depending on the city where the process takes place), the local administration, and finally the stakeholders. It is to note that an actor can belong to more than one category and play different roles depending on this latter. For example, the transport companies of a city can be both stakeholders and local administration. For the sake of flexibility and preserving the generic nature of the SEAP process, instead of describing the roles of specific actors, the Covenant of Mayors describes the roles of "categories of actors".

The municipal council: it refers to the local authority that has the ability to make political and strategic decisions within the city. The main role of the municipal council is to ensure the continuous political commitment of the city during the process lifecycle.

The local administration: it refers to the bodies that manage and regulate the key services in the city. It includes local energy agencies, transport companies, the urban planning agency, etc. Their main role in the SEAP process is to lead its planning and ensure its proper implementation.

The stakeholders: it mainly refers to the bodies whose activities either affect the SEAP process or affected by it. Moreover, stakeholders also include the organizations that participate in the implementation of the SEAP process and supplying the necessary information during the process lifecycle.

2.2.2 Measures implemented in SEAPs

As it was described earlier in the terminology section, measures are together with their quantities and planned time frame the building blocks of urban energy strategies (or action plans in the SEAP process terms). They represent specific actions that can be achieved with the purpose to reduce a certain amount of CO_2 emissions. The Covenant of Mayors signatories, for example, submit an action plan that outlines all the measures that they plan to implement in order to reach a certain target of reduction (typically greater or equal to 20 percent) in CO_2 emissions. The Covenant of Mayors website [Cov13] offers public access to the action plans that have been submitted (more than 4000 Sustainable Action Plans available by the end of 2014). A review of the proposed measures by the different cities includes the ones on Table 2.2. It presents a sample list of measures related to both energy demand and energy supply. The list is a not an exhaustive set of measures. However, it represents the most redundant measures in most of the presented action plans.

2.2.3 Analysis of the SEAP process

The main elements of the SEAP process are phases, steps, resources, actors and their roles. The structure of the SEAP process is illustrated through its meta-model that have been derived, as shown in Figure 2.5. The process is structured in four phases: initiation, planning, implementation, and finally monitoring & reporting. Each phase is composed

Energy demand measures	Energy supply measures
Building refurbishment	Solar photovoltaic
Building system refurbishment	Building integrated wind energy
New buildings standards	Micro hydro power
Efficient artificial lighting	Geothermal energy
Energy efficient behavior	Energy production from waste
Optimized automated building control systems	Gas and Steam Power Plant
Smart grid	Biomass Power Plant
Smart electric grid demand side management	Low temperature district heating
Incentives for non-motorized individual transport	Biogas for heating/cooking
Disincentives for motorized individual transport	expand existing district heating
Mobility on demand	Heat recovery from industrial processes
Optimize city logistics	Solar thermal collectors
Increase use of biofuels	Heat pumps
Increase use of electric vehicles	Hydro power storage
Increase public transport use for commuting	Electrical storage
Car Sharing	Micro thermal grids
Optimize transport Occupancy	-
Incentives for public transport	-

Table 2.2: Sample energy demand and supply measures

of a number of steps, each of which requires resources and involves a certain number of actors.
The part of the SEAP process belonging to the scope of our interest is the planning phase, as it results in the development of an energy strategy, and requires computational support. The planning phase starts by an assessment of the current situation of the city, which leads to a CO_2 emissions' inventory that shows the different sources of energy and their breakdown over the main sectors (e.g. buildings, transport, industry, etc.). Then, a vision is established in terms of quantifiable objectives that the city aims to reach, such as a certain percentage of CO_2 emissions' reduction. Finally, an energy strategy is defined based on the current situation of the city in order to reach the targets that are defined in the vision.

Figure 2.6 presents the structure and the main constituting blocks of the energy strategies that are developed within the planning phase of the SEAP process. An energy strategy is composed of a set of measures, i.e. quantifiable actions with a certain potential to reduce the CO_2 emissions at the level of the city. Each measure is bound to an implementation sequence, which states what quantity of the measure is to be implemented at what time horizon. For example, installing solar photovoltaic systems in buildings is a measure. It can have an implementation sequence of 100,000 m^2 each decade from 2020 until 2050. The implementation of an energy strategy results in an impact on the city that is measured through a predefined set of key performance indicators (KPIs), such as CO_2 emissions and costs. The evaluation of a strategy is achieved by comparing its resulting KPIs against its objectives defined in the vision phase.

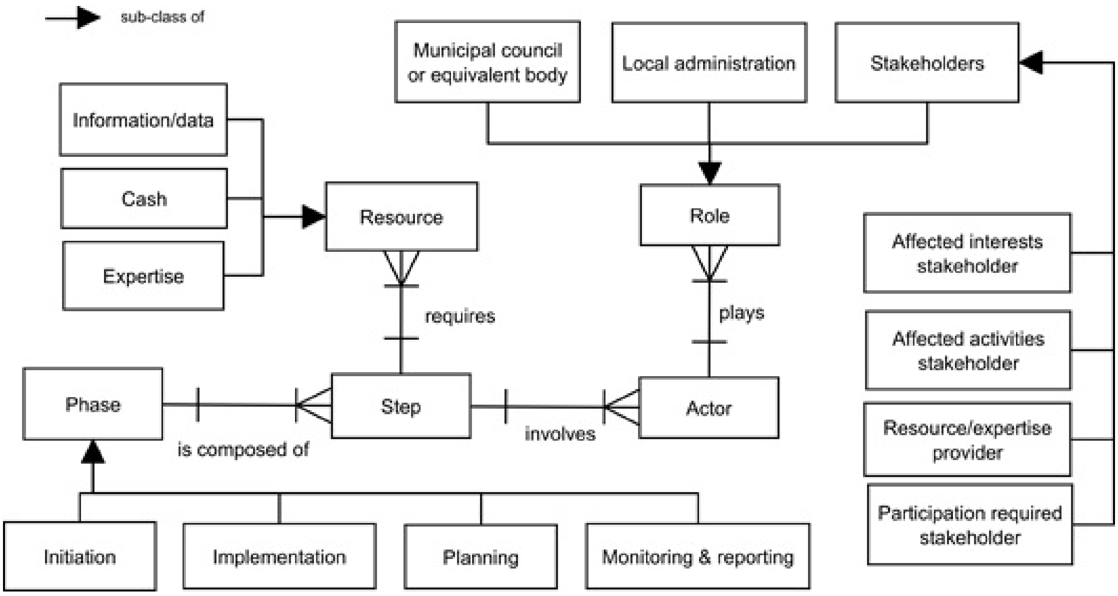


Figure 2.5: SEAP process meta-modelmodel [OPS+13]

A study [Ivn09] concluded that using planning support tools have a positive impact on the energy planning process in terms of legitimacy, scope, and the quality and comprehensiveness of the assessment. Thus, in the next section, an analysis of the SEAP process is performed so that the main characteristics of urban energy planning support systems are derived.

2.3 Urban energy planning support conditions

The following necessary conditions in urban energy planning support systems represent the objectives of the target ontology-based decision support system in this thesis. These conditions resulted from the analysis of the SEAP process and data availability analysis in different cities.

1. **Supporting the perspectives of different actors (stakeholders):** the decision making process must involve all the stakeholders that have potentially affected interests and provide them with specific information, from their different perspectives.
   Developing an energy strategy requires the collaboration of several actors from different fields of expertise, as shown in Figure 2.5. The actors that take part in this process have different views of the problem and expect a support that is specific to their point of view. The planning support software is supposed to be usable by all the actors and explicitly implement their points of view.
   Furthermore, even in the meta-process of urban energy planning [MDG13] shown in

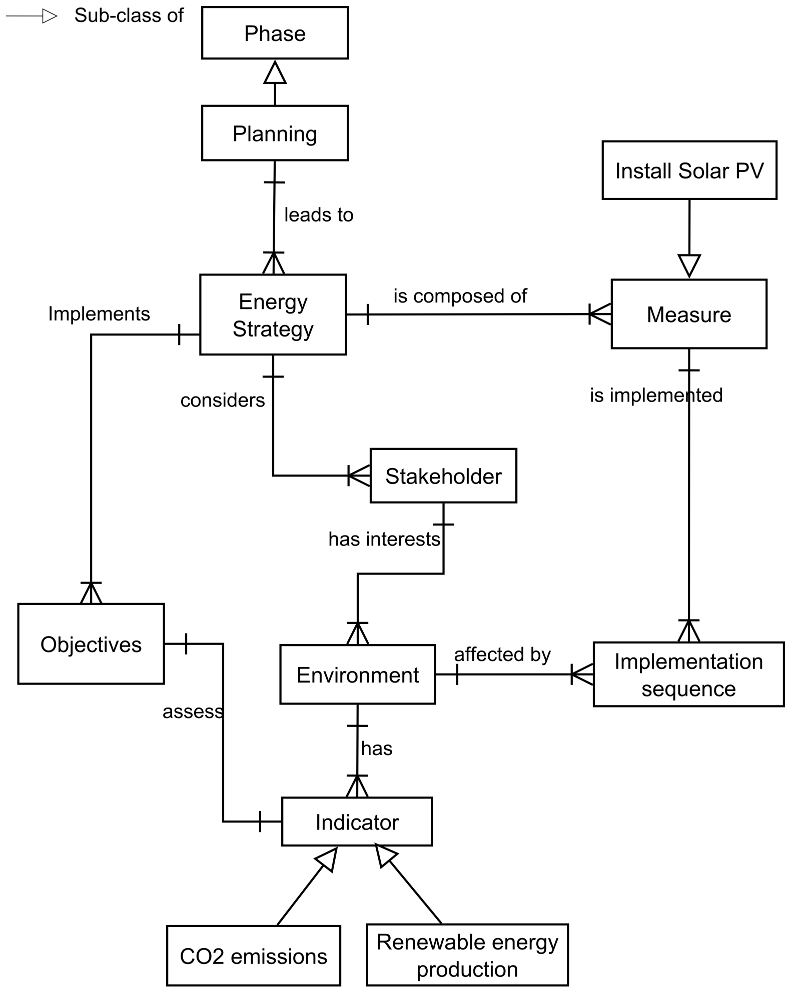


Figure 2.6: Energy strategies structure

Figure 2.1, the participation of the stakeholders (decision makers) is required. They participate in the prioritization & decision phase that precedes the implementation, meaning that they have the “last word” (accept or not) the proposed strategies by domain experts.

2. **Common understanding and quantifiable impact of decisions:** the assessment of the impact of energy strategies must be quantifiable. The output results must be aggregated to a level of abstraction that is understandable by all the different actors (i.e. stakeholders). The assessment of the impact of energy strategies shall be quantifiable and comparable to predefined objectives. Figure 2.6 shows that an energy strategy implements objectives that are defined prior to the beginning of this activity. Therefore, the assessment of all measures shall obey to a common

output format that is comparable to the predefined objectives. It is to note that each measure can also have an additional output that is specific to its context and that addresses particular needs of the actors that it involves.
Additionally, as shown in Figure 2.7, the decision making process requires the negotiation of different stakeholders and decision makers [OLA+14]. Therefore, it is necessary that the participants in the process understand each other and that they present information to each other in a manner that does not require domain experts to explain it further.

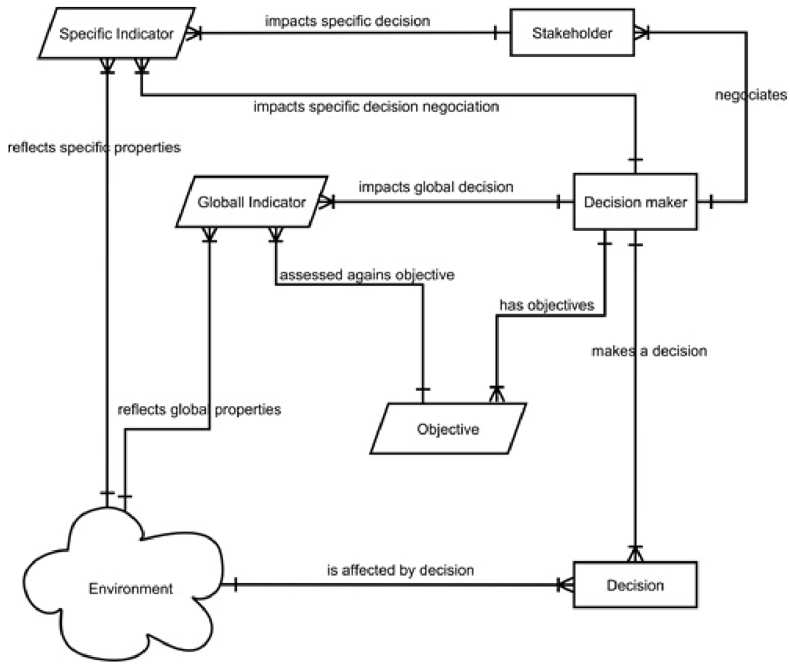


Figure 2.7: The decision making meta-process [OLA+14]

3. **Measures integration and resources negotiation:** the assessment of the impact of energy strategies must consider the inter-dependencies between different components and calculations e.g. installing solar PV reduces the surface areas where solar thermal collectors can be installed.
   The assessment of the impact of an energy strategy depends on the integrated assessment of the impacts of its constituting measures. Indeed measures impact on each other and this needs to be considered when assessing the overall performance of an energy strategy. Figure 2.6 highlights that the interest is in an assessment at the strategy level, not at the level of single measures. Measures can impact on each other in a causal way e.g. introducing electric vehicles will increase electricity demand, reducing the production of waste will also reduce the energy available from incineration, introducing a large amount of PV will require interventions on the local electricity grid. On the other, hand measures can compete over limited

available resources e.g. PV systems and solar thermal collectors will compete for a limited available roof area.

4. **System viability through robustness against data availability problems:** The system must be flexible to be used within different conditions of data availability and levels of detail.
As a part of a previous related work [OPS+13], a data availability analysis in four different cities has been performed. The data collection that has been analyzed was in the context of projects of developing city-level energy strategies for the cities of Vienna, Linz, Amstetten in Austria [The11], and Nanchang in China. The findings of this analysis that are of interest are related to data unavailability types. Four data unavailability types have been identified as shown in the Table 2.3. Different people interchangeably refer to data as unavailable when they fall in one of these four types.

Data unavailability type	**Description**
Inaccessible	Existing data but no access rights to obtain them
Non-existing	Never censed or calculated data
Low level-of-detail	Existing data but lower level of detail than the desired one
Non-synthesized	Data elements exist but need to be synthesized to obtain the desired data

Table 2.3: Data unavailability types

The first type of data unavailability is inaccessible data i.e. the data exist but there are no proper access rights to obtain them. For instance, usually the locations of the electricity grids' transformers are not accessible for territorial security reasons.
The second type of data unavailability is non-existing data i.e. it occurs when the desired data simply do not exist. It might be due to two reasons: either that no one has collected these data before (e.g. number of commuters from a specific sub-urban area) or the desired data requires specific computation that has never been performed (e.g. the solar radiations of a specific location).
The third type of data unavailability is low level-of-detail of data. It happens when data are not available in the sense that they do not exist at the desired level-of-detail e.g. water consumption not existing at a household level but rather as a national average consumption per capita.
The last type of data unavailability is non-synthesized data. This is rather a minor data unavailability problem. It occurs when the elements to obtain the desired data are available but not synthesized e.g. existing population data and existing income data, while the income per capita data is required and missing.
Batty argues that urban modeling includes confronting the model to data as part of the modeling process [Bat09]. Therefore, data unavailability affects modeling complex urban systems in two different ways:

a) During the modeling process, data unavailability forms a "bottleneck", as the developed model has to be confronted to data at the end. Thus, it is possible to do only as much modeling as the data availability allows. In other words, only the parts of the system about which data are available can be modeled, even if it compromises its accuracy. For instance, it is possible to develop a model that requires 3D spatial data about buildings; however, it will fail if it is to be used where no such data exist.

b) During the use/re-use of a complex urban system model, even if it has been already confronted to data beforehand, it does not guarantee its usability in other different data availability environments (e.g. cities with different data availability than the ones it has been confronted to). Indeed, confronting a complex urban system model to data validates its theoretical validity and usability. However, if the model is to be used in a city where the data (or part of data) it requires do not exist, it becomes invalid again. This is a problem because large amount of resources (time and effort) are invested to develop models that potentially apply only to specific data availability environments.

Data availability in cities is significantly varying between cities as described earlier in Table 1.1. Concerning the signatories (cities and towns) of the Covenant of Mayors, it is noted that about 88% of them are small cities with less than 50,000 inhabitants, as shown in Figure 2.8 [Cov13]. According to previous work in collecting data in different Austrian cities [OPS+13], the smaller the cities are the less data are available due to less internal human resources to collect or less budget for empirical studies and analysis of finally less interest in providing this information. For example, in the city of Vienna a solar cadaster is available [Mag13] whereas the cities of Amstetten and Linz did not have one.

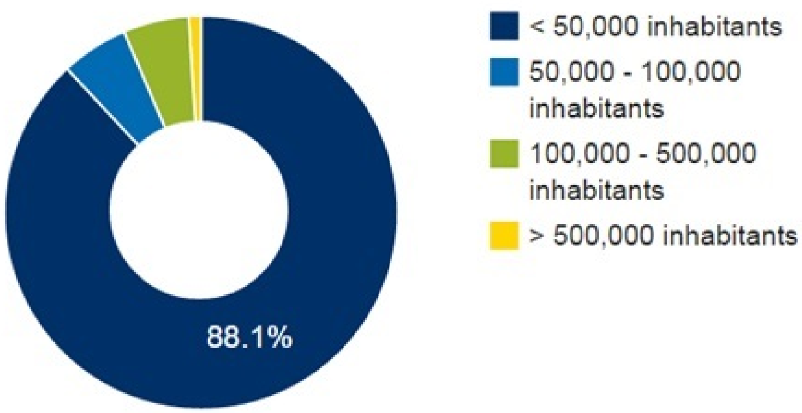


Figure 2.8: The Covenant of Mayors signatories profiles [Cov13].

Different initiatives worldwide have been started to collect environmental data at different spatial scales, given their importance in the decision making process [LOG+13]. Sample data collection initiatives are listed by Laniak et al [LOG+13] as shown in Table 2.4, proving that collecting data at large scales (such as cities) is a permanent work rather than a simple phase in a project.

Initiative	**Description**
Global Earth Observation System of Systems (GEOSS)	International initiative for,the coordination of monitoring large scale data and predicting the behavior of,the earth system
Infrastructure for Spatial Information in the European,Community (INSPIRE)	EU initiative aiming to,collect special information in Europe (regarding seventeen themes) with the,goal to assist environmental policy making.
European Shared Environmental Information System (SEIS)	EU initiative to share,environmental data owned by public information providers.
Water Information,Service for Europe (WISE)	EU initiative related to the,collection of water data for the purpose to serve several stakeholders
Environmental Resources Information Network (ERIN)	Australian,initiative aiming to integrate information,from several data sources and providing specific tools for interfacing with,the information.
Environmental Dataset Gateway (EDG)	US initiative a gateway for,interacting with environmental datasets, developed by the US Environment,Protection Agency. It also includes geospatial tools.
National Ecological Observation Network (NEON)	US initiative it includes,data collected across the US regarding the impacts of climate change. It aims,to forecast ecological changes at a continental level.
US based Consortium of Universities for the Advancement of Hydrologic,Science, Inc. (CUAHSI)	US initiative aiming to share,hydrologic time series data contributed by a wide range of providers, including,the National Water Information System of the US Geological Survey.

Table 2.4: Examples of data access initiatives of relevance to IEM (adapted from [LOG+13]).

2.4 Urban energy planning support tools

Since the mid-1990s, many researchers have been engaged in developing tools for urban energy planning. Connolly et al. [Ren00] define seven categories of tools, where a tool can belong to more than one category including simulation, scenario, equilibrium, top-down, bottom-up, operation optimization, and investment optimization. Today, there is a wide variety of tools that address different aspects of urban energy planning with different levels of details. The focus in this section is on tools that belong to the scenario type [Ren00]; therefore, the level of details of input and output information that they respectively require and produce. It is to note that a tool that is needed at the stage of defining an urban energy master plan is a one that copes with input data that can be obtained at an early stage and at a broad scale i.e. low level of detail-input data.

SUNtool [RCG+07] and its later successor **CitySim** [PKW+11], [RHK+09] attempt to model and simulate energy flows of buildings in a neighbourhood context. CitySim takes into consideration several parameters to allow a micro simulation of energy flows in buildings in terms of both demand and supply. It has a set of integrated energy demand and supply calculation models: thermal model, radiation model, occupants' behavioral model, and finally plants and equipment models. CitySim comprises a Graphical User Interface to facilitate the buildings' 3D shape for urban districts (making it possible to work with several hundred buildings) and attribute the buildings' thermo-physical properties as well as the visualizing simulation results. It also includes a CitySim Solver for simulating buildings' energy supply and demand for space conditioning. Energy supplies from renewable sources can be determined for the buildings, including radiation exchange driven by the urban environment, making it possible to work at different temporal resolutions. A range of graphical tools support energy consumption analyses to identify the buildings' performance improvement potential [WBG+15]. The developers of CitySim plan the extension of the tool to integrate wastes and water models. Furthermore, a coupling of CitySim with a MATSim [BRM+09], [BMR+08], a transport micro simulation tool, is under development in order to have a comprehensive urban energy simulation tool. In conclusion, CitySim allows a micro simulation of urban energy and gives accurate visual results, regarding the level of detail of the input datasets that do not uniquely rely on statistical data but also on an integrated set of calculation models. In brief, CitySim requires a high level of detail input data, e.g. u-values of buildings envelopes, and produces also detailed output that might exceed the requirements of information during the master planning stage.

EnerGis [GMD+10] is a tool that is based on the methodology of pinch analysis and energy integration [DL93]. The main concept in this tool is that it calculates the minimum annual heat demands of buildings and displays the results in a georeferenced context with different colors representing the corresponding categories of heat demand. The results are summarized at the level of zones, which comprise a number of buildings. The heat demand is broken down into different categories, including heating, hot water production, and cooling. Unlike CitySim which uses detailed equations, EnerGis calculates the energy demands based on statistical analysis of measured buildings. When such data do not exist, proxy data - like typical heating energy consumptions for representative building types are applied. In brief, EnerGis provides information that meets the required level of details during the stage of defining an urban energy master plan. Moreover, the input information is flexible since standard datasets can be applied in the absence of specific measured data. EnerGis considers heating from a demand perspective. It gives an overview about the heat demand of a city but it does not support decision making about specific measures to reduce energy demand.

Urban Strategy [BSL+09], [SSW07], is developed at the Netherlands Organization for Applied Scientific Research (TNO). It is an interactive urban planning and scenario development tool not limited to energy planning comprising the following modules: traffic, sound/noise, air quality, livability, ground water, durable nature, external safety, and costs. All those modules are integrated and are dynamically interrelated. For each of the listed modules, there is a set of indicators that evaluate user defined scenarios, from different perspectives. This tool does not simulate urban development as an automatic generation process, but makes it possible to conduct impact assessment of urban planning decisions, applying a set of models which simulate traffic, energy use, air quality, noise, groundwater and other topics addressing sustainability. The tool must be commercially obtained by TNO [WBG+15]

Scenario 360 [KB01], a scenario development and GIS based decision support tool for land-use planning, is an extensions of the GIS software ArcGIS. It evaluates the impact of different scenarios by calculating a set of indicators that are related to a variety of aspects: greenhouse gases emissions, commercial floor area, commercial energy use, jobs, labor force population, residential energy and water use, school children population, vehicle trips per day, etc. The accuracy of the indicators depends on the quality of the datasets that are configured at the beginning of the process. No dedicated energy demand or supply calculation models are coupled with Scenario 360. All calculations regarding energy are based on average demand values that need to be configured beforehand. The tool allows evaluating how energy is affected by different land-use planning scenarios. However, no specific energy planning measures can be evaluated by the tool. The indicators that assess the different user defined scenarios are mainly land-use driven.

UrbanSim [Wad02] [Wad11] [WU04] is on open source tool for urban development scenario simulation. UrbanSim is a state-of-the art simulation system for supporting planning and analysis of urban development, incorporating interactions between land use, transportation, economy and the environment. UrbanSim adopts a micro-simulation approach: households, businesses or jobs, buildings, and land areas are represented through individual agents, addressing different spatial entities to be selected, ranging from buildings and parcels to grid cells and districts. The model simulates urban development dynamics through the interaction of many actors, making decisions within the urban markets for land, housing, non-residential space and transportation.

The user interacts with the tool to create scenarios, specifying alternative population and economic development expectations, land use policy assumptions, and other exogenous inputs. The tool is thus intended for use by planning authorities and researchers interested in exploring the effects of planning policy choices, including transport modes and accessibility, housing affordability, greenhouse gas emission targets or open space and habitat protection [WBG+15]. Results can be viewed through a GIS based results browser addresseing a city from a holistic perspective.The spatial granularity can be selected individually depending on data availability - ranging from census districts to 150 x 150 meters grid cells.

SynCity [KSS10] is a scenario development, simulation, and optimization tool that is used at a city scale, with a resolution that goes until energy technologies in buildings, implemented in its resource-technology network (RTN) model. It focuses on urban energy systems and its goal is to identify where it is possible to achieve large reductions concerning the energy intensity of cities. It has a bottom up approach to tackle urban energy systems, where it simulates energy demand and supply at smaller levels of granularity, compared to other tools. Therefore, SynCity could be used for more detailed decision support, in the latest phases of the urban energy planning process. On the other hand, it requires more input data and more time for data preparation and integration, compared to tools that support decision making at earlier phases, during urban energy master planning.

SEMERGY literature describing this tool in more details is found in [FHN+14, GPM+14, MPS+12, PGS+14, WGP+14]. It is a decision support tool that is specialized in building refurbishment decision making. It supports decision makers to define strategies concerning the optimization of the configuration of building components by finding an optimal trade-off between energy efficiency and cost. SEMERGY supports three different types of use, which mainly depend on three different levels of detail of input data. It includes, first, manually entered summarized data about a building; second, CAD generated models; third, GIS format data. The goal of the last use case of SEMERGY is to support decision makers in defining building refurbishment strategies, by evaluating the impact of different scenarios in terms of a predefined set of indicators.

Smart City Spreadsheet Tool is a spreadsheet-based tool that provides a quantitative support to urban energy planners, when developing energy strategies. The input of the system is quantities of measures to be implemented and the output is their global impact on the environment, in terms of CO_2 emissions, energy efficiency, renewable energy production, and modal split (i.e. the percentages of transportation media used in the city). This tool provides a large variety of measures, addressed in a low level-of-detail. The measures that are implemented include energy demand and energy supply such as building refurbishment, efficient lighting, energy efficient behavior, increase transport occupancy rate, solar PV, solar thermal collectors, biomass, etc.

Table 2.5 shows an overview of how the above tools fulfill the main features in urban energy planning that have been derived from the analysis of urban energy planning processes in the previous section.

Thus, existing tools in urban energy planning have different foci and - referring to data available for developing/configuring the respective tools - different levels of detail of input and output data. A more comprehensive review of more general tools can be found in [WBG+15], [CLML10]. A comparison of energy planning-related tools with their main features, partially described by Collony is shown in Table 2.6. Some of these tools do not consider urban aspects that might influence the decision making process as they are supporting national energy system control processes like Balmoral, Times/Markal, Primes. Some others require levels of detail of input data that are not available at a city scale, as they are dealing with single building analysis and enhancement (e.g. TRANSYS) or are focusing on other topics besides energy use (like Landexplorer/Galileo). In most of cases, tools that require specific levels of data level of detail deliver output data pf the same spatial resolution but do not often consider detailed stakeholder behavior with respect to energy consumption,. Therefore, even if there are many tools that address issues that are related to urban energy planning, they are not specifically dedicated to support decision making in during the urban energy planning phase.

Tool	Related Literature	Support of the main features in urban energy planning support tools* [OPS+13]			
		I	**II**	**III**	**IV**
SUNtool	[RCG+07]		(partially)	x	
CitySim	[PKW+11], [RHK+09]		(partially)	x	
EnerGis	[GMD+10]		(partially)	x	
Urban Strategy	[BSL+09, SSW07]	x	(partially)	(partially)	
Scenario 360	[KB01]	x	x	(partially)	
UrbanSim	[Wad02, Wad11, WU04]	x	(partially)	(partially)	
SynCity	[KSS10]		(partially)	x	
SEMERGY	[FHN+14] - [WGP+14]		x		
Smart City Spreadsheet tool	Not,available		x		

Table 2.5: Related energy planning support tools[a]

[a]* I Supporting the perspectives of different actors II Shared understanding and quantifiable impact of decisions III Measures integration and resources negotiation IV System viability through robustness against data availability problems

Tool name	**Tool type**		**Features**					
			Energy demand		**Energy supply**		**Transport**	**Costs**
	GIS interface	**Dynamic**	**Electricity**	**Heat**	**Electricity**	**Heat**		
AEOLIUS		x	x	-	x	-	-	-
BALMOREL	-	x	x	Partialy	x	Partialy	Partly	x
BCHP Screening Tool	-	x	limited	limited	limited	limited	-	-
COMPOSE	-	-	x	x			x	x
E4cast		-	x	x	x	x	Partly	x
EMCAS		x	x	-			-	x
EMINENT	-	-	x	x			-	x
EMPS		-	x	-			-	x
EnergyPLAN	-	x	x	x			x	x
energyPRO	-	x	x	Partialy			-	x
ENPEP-BALANCE			x	x	x	x	x	x
GTMax	-	x	x	Partialy			Partly	x
H2RES	-	x	x	x			Partly	under dev
HOMER		x	x	x			-	x
HYDROGEMS		-	x	-			-	-
IKARUS		-	x	x			x	x
INFORSE		-	x	x			x	-
Invert		x	x	x			Partly	x
LEAP	x	x	x	x			x	-
MARKAL/TIMES		-	x	x	x	x	x	x
Mesap PlaNet		-	x	x			x	-
MESSAGE		-	x	x	x	x	x	x
MiniCAM		x	x	Partialy	x	Partialy	x	x
NEMS		-	x	x	x	x	x	x
ORCED		x	x	-	x	-	-	x
PERSEUS		-	x	x	x	x	Partly	x
PRIMES		-	x	x	x	x	x	-
ProdRisk		x	x	-			-	x
RAMSES		x	x	Partialy			Partly	-
RETScreen	-	-	x	x			-	x
SimREN		-	x	x			Partly	-
SIVAEL		-	x	Partialy			-	-
STREAM		x	x	x			Partly	-
TRNSYS	-	x	x	x			-	x
UniSyD3.0		-	x	Partialy	x	Partialy	-	x
WASP		x	x	-			-	x
WILMAR Planning Tool		x	x	Partialy			Partly	-
TRACE	-	-	x	x	x	x	x	-
Urban Network Analysis	x	-	-	-	-	-	x	
CitySim	x	x	x	x	x	x	-	-
Energis	x	-	-	x	-	x	-	x
Beacon	-		x	x	x	x	x	-
CO2ST	-		x	x	x	x	-	x
IRM	-	-	x	x	x	x	x	
GRIP	-		x	x	x	x	x	-
Urban Strategy	x	-	x	x	-	-	x	-
ArcGIS/CityEngine	x		x	x	x	x	x	x
Scenario 360,	x	-	x	x	x	x	x	x
TERMIS	x		x	x	-	-	x	x
UrbanSim	x	-	x	x	-	-	x	-
OSeMOSYS	x		x	x	x	x	-	x
Landexplorer/Galileo	x		x	x	-	-	x	-
Energiestadt	-		x	x	x	x	x	x
Envision Tomorrow	-		x	x	x	x	x	-
INDEX and Cool Spots	-		x	x	x	x	x	-
Development Pattern Approach	-		x	x	x	x	x	-
SynCity	x	x	x	x	x	x	-	x

Table 2.6: Energy planning related tools (compilation partialy based on [CLML10])

CHAPTER 3

Modeling Urban energy systems

This section defines the methodology that is based on semantic modeling and integration. The Methodology ensures the flexibility to integrate a variety of heterogeneous data sources and models that do not necessarily use the same level-of-detail of data. The main idea behind the methodology is to allow the integration of divers modeling approaches with different demands on data availability. Thus, it is possible to model complex urban systems that use existing data, and given the modularity of the approach it is possible to update certain parts of the system, when better data become available.

3.1 Design principles

The principles taken into consideration for the methodology development are described below. They are aligned with the necessary conditions in urban energy planning.

- **Keeping the development of the system permanently open to change**: given the data (un-)certainty, (un-)availability in different cities, this design principle allows to extend the system to cope with data avail-ability problems. This principle is important to consider given the findings in the previous chapter, regarding the necessary conditions in urban energy planning support software. One of the requirements is "System viability through robustness against data availability problems".
  Accordingly, having a system which is permanently open and ready to change ensures its ability to adapt to the environment where it is being used. Having mechanisms that explleicitly formalize how the change process is done makes it a viable system [Bee81].

  Figure 3.1 illustrates the planner /stakeholder- related causal chain behind the design principle of keeping the system open to change. It is noted that the planning support system is required to answers the questions of different stakeholders in the

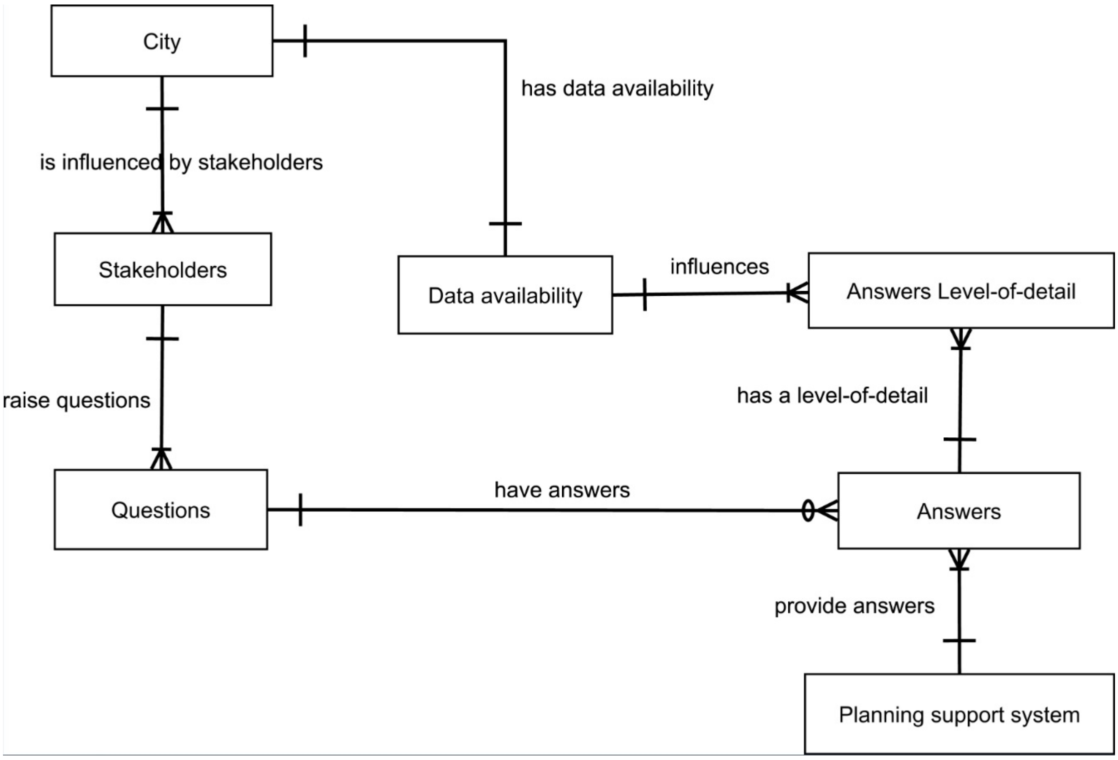


Figure 3.1: Planning support systems within the data availability context in cities [Cov13].

city, which vary from a city to another. Besides each answer, the planning support system provides, has a level-of-detail (accuracy) conditioned by data availability.

- **Linking the domain concepts to the initial requirements**: as the system is meant to be permanently extendible, this design principle allows the traceability of how the system fulfills the initial requirements.
  Ontologies are becoming more common in the domain of requirement engineering, given their semantic richness. A more comprehensive review of the use of ontologies in requirement engineering has been achieved by [DVB+14]. Specific examples of requirement engineering based on domain ontologies include the work of [SL10]. Breitman and Sampaio do Prado Leite described how ontologies can be a deliverable in the requirement engineering process [BSdPL03]. In the same direction, Bossche et al have described an ontology based software engineering process (including requirements engineering) [BRM+07]. Similar approaches include the work of Kossmann et al. [KWOG08] and Lee and Gandhi [LG05].
  The target decision support system is large and supposed to gradually grow to answer more questions, regarding measures to be implemented. Thus, it is important to be able to trace the origin of the answers that are implemented in the system.

- **Including the notion of level-of-detail of data**: this design principle allows

the integration of data that have different level-of-detail. It is motivated by the data availability problems at the level of cities.
As already mentioned, different cities have different data sets and data availability [OPS+13]. Thus, in order to allow a better transparency about the answers the system is offering, the notion of level-of-detail is included. It shall be easy to trace what input data are used, what calculation methodologies have been implemented, and what is level-of-detail of the final answer. This concept helps the integration of answers, of the same level-of-detail.

- **Integrating different computation models**: this design principle allows the integration of existing computation models and the re-use existing data sets, in order to save development efforts. As shown in Figure 3.1, the answers that the system gives depend on what stakeholders are involved, which in their turn depend on which city the system is applied. Thus, there is a high level of uncertainty concerning the expected answers. This design principle, integrating (re-using, adapting) different computation models, allows saving development effort. It is possible to develop a fixed system, which elements can work with each other and even optimized for that purpose. However, the instability of the requirements of the system is a threat to this. Therefore, it is more appropriate to develop a system that is highly modular, where re-usable computation models can be rapidly integrated with the rest of the system, depending on the specific requirements of the city.

- **Tracking the interactions between different components and data properties**: This concept is necessary to enable consistent operations among the different computation models that are used. This design principle allows the formalization of interactions and it is used by computation models to understand their mutual-interactions. Rather than adopting other classic modeling approaches to capture the behavior of the components of the system, the choice has been made to only capture the necessary interactions between components that are triggered by the integrated computation models. Classic approaches such as agent-based modeling [Ehr08] require a better understanding on data availability to model a generic behavior of the components. This is not feasible in the case of the system within the scope of this research because the data that are necessary for operating it are not always available in all cities.

  This design principle (tracking the interactions between different model components and data properties) ensures a high level of interoperability (L4: Pragmatic), with a potential to go to higher levels (as explained in the conclusion chapter). Different levels of interoperability are shown in Table 3.1 [WTW09].

- **Decoupling the interface of the system from the actual computation models that prepare all the data beforehand**: this principle allows designing different interfaces that present the data according to the need of the users. Fur-

Level of interoperability	Information defined	Content defined
L6: Conceptual	Assumptions, constraints, etc.	Documented conceptual model
L5: Dynamic	Effect of data	Effect of information exchanged
L4: Pragmatic	Use of data	Context of information exchanged
L3: Semantic	Meaning of data	Content of information exchanged
L2: Syntactic	Structured data	Format of information exchanged
L1: Technical	Bits and bytes	Symbols of information exchanged
L0: None	-	-

Table 3.1: Levels of conceptual interoperability model [WTW09]

thermore, given the large amount of data that are involved in the computations at a city level, this saves time during the actual use of the system.
As discussed in the previous chapter, urban energy planning processes require the participation of stakeholders [MLKK09] [Eur10]. Typically, this participation happens in workshops or forums where participants try different scenarios. Knowing that calculations at the level of the city require the processing of large datasets, the response time of the planning support system would take too long if the interface is coupled to the calculations.
Furthermore, the system is to be used in different cities by different urban energy planners that do not necessarily want to use it in the same workflow. Accordingly, decoupling the interface of the system from the computation models allows more flexibility in designing more customized interfaces that suit to the needs of the specific context where the system is used.

3.2 Ontologies

The proposed methodology in this this research, to develop urban energy planning support systems, is based on the use of an ontology as a core of the whole system. Therefore, this section gives an overview about ontologies: their origin, definitions, formalization, and reasoning.

3.2.1 Origin of ontologies

In the history of design of intelligent systems, it has been proven that knowledge is an important component [Obi07]. Obikto argues as well that in many cases the

quality of knowledge is more important than the quality of algorithms in solving a task [Obi07]. Thus, it is necessary to (i) capture knowledge, (ii) process it, (iii) reuse it, (iv) and communicate it, in order to a have a truly intelligent system [Obi07]. Accordingly ontologies, supporting all these tasks, are needed. According to Giaretta and Guarino [GG95], the use of ontologies and the increasing interest in defining the term “ontology” has increased especially after the ARPA knowledge sharing initiative [Gru93, GGP93, Gua95, Mus92].
Earlier than the existence of intelligent systems, the term Ontology has referred to a branch in philosophy [GG95], dealing with the organization of reality i.e. explaining and sorting concepts of existence. According to Aristotle, Ontology is the science of being [GG95], thus, describing what being is, or features that compose the being. The philosophical origin of ontologies intersects with the current use of ontologies in intelligent systems and knowledge bases. Definitions of the different specific types of ontologies are provided in the next section, thus clarifying their use within the scope of this thesis.

3.2.2 Definitions of ontologies

Several definitions of the term ontology exist and dedicated articles in related literature have been dedicated to clarify this term such as the work of Giaretta and Guarino [GG95]. A comprehensive overview is given about the use of the term ontology, as shown in Figure 3.2 [GG95]. However, Obitko [Obi07] reduces this list of possible interpretations to only three definitions: (i) a philosophy discipline, (ii) an explicit specification of conceptualization, and (iii) a body of knowledge.

1. Ontology as a philosophical discipline
2. Ontology as a an informal conceptual system
3. Ontology as a formal semantic account
4. Ontology as a specification of a “conceptualization”
5. Ontology as a representation of a conceptual system via a logical theory
    5.1 characterized by specific formal properties
    5.2 characterized only by its specific purposes
6. Ontology as the vocabulary used by a logical theory
7. Ontology as a (meta-level) specification of a logical theory

Figure 3.2: Sample interpretations of the term “ontology” [GG95].

The first definition of ontology, as a philosophy discipline, is as described before has earlier origins. It is rather a general definition of explaining the existence and the being. This definition has a different scope that the one that is addressed by this dissertation. Concerning the definition of ontologies as an explicit specification of conceptualization [GOS09], [GGP93], [Gru93], it is closer to the scope being addressed in this research. In this sense, an ontology represents a formal description of a domain. It is describes a given domain in terms of what concepts it comprises and how they are inter-related. The description of the domain does not necessarily have to be complete [GG95], therefore, it is rather representing a restriction of the concepts of a domain that are relevant to the scope of a given purpose. Therefore, ontologies, according to this definition, can be used as a communication medium for sharing the vocabulary of a domain. Users (including software agents) of these ontologies commit to them and share the same vocabulary for communicating about the represented domain. The explicit specification of conceptualization of a domain is necessary to build a body of knowledge of it. Concerning the definition of ontologies as a body of knowledge, it considers them as a description of a given domain knowledge, using a shared vocabulary (specification of conceptualization), which has been described in the above paragraph. Thus, an ontology as a body of knowledge is not only a taxonomy (i.e. a classification of concepts in hierarchical way) but it also contains the actual domain knowledge that is within its scope.
The scope of the thesis mainly considers the second definition of ontology (explicit specification of conceptualization), since an ontology is developed to define the concepts and vocabulary in urban energy systems. Furthermore, when validating the ontology (explicit specification of conceptualization of urban energy system), actual domain knowledge is integrated and it becomes as a body of knowledge that answers a given set of questions. Thus, both meanings of ontology (ii and iii) are used in this thesis.
Here the term ontology is used to refer to its meaning as an explicit specification of conceptualization. When the term ontology is used in a different way in this text, then this is explicitly stated.

3.2.3 Formalizing an ontology

As ontologies are intended to be used and processed through programs as system of conditions and equations, the explicit specification of conceptualization is required to be formally represented using an adequate language. Figure 3.3 illustrates the levels of expressivity in an ontology description, where expressivity is increasing from left to right [Obi07]. A formal description is considered to be an ontology when it has at least one formal is-a relationship defined, as shown in Figure 3.3.

The different families of knowledge representation (languages to build ontologies) include frame-based models, semantic networks, conceptual graphs, common logic, and description logic. Frame-based models, already proposed in the seventies [Min75], are simple representations of knowledge: a frame represents a concept or an object and each frame is linked to slots, which represent its attributes [LM01]. An example of using frame-based models is Open Knowledge Base Connectivity (OKBC), which provides an API to access knowledge representation systems [CFF+98]. The frame-based models are

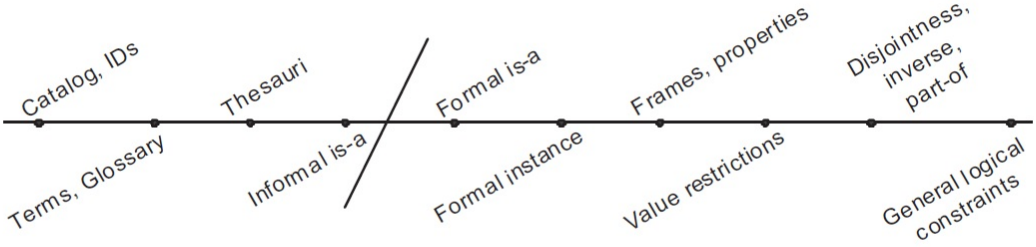


Figure 3.3: Levels of expressivity in ontology description [Obi07]

close to an earlier type of knowledge representation called semantic networks [Woo75]. Semantic networks are formalized in graphs, where each vertex describes a "meaning" (i.e. concept), while edges represent relationships between them. Examples of relationships include: synonym (same as), antonym (opposite of), meronym (part of), or holonym (has part). An example of semantic networks include WorNnet, a lexical database for English [Mil95], [MBF+90].

Based on semantic networks, another type of knowledge representation can be achieved using conceptual graphs [Sow99]. Knowledge is represented through: classes, relations, individuals and quantifiers. An example application of conceptual graphs was in improving the precision and recall of semantic search, where an algorithm can traverse the graphs to calculate the semantic similarity [ZZLY02]. Sowa argues that conceptual graphs are as expressive as the predicate logic [Sow99]. Description logics serve the purpose of knowledge representation by providing the logics to formally describe concepts and relations (roles of concepts) [BMNPS03].

Description Logics are based on predicate logic, in terms of semantics [Obi07]. However, syntactically, they are more practical in terms of both modeling purposes and their computational properties. Description Logics comprises two types of components: TBox and ABox. The TBox components are used to represent the terminology of concepts and their attributes. The ABox components represent the assertions about the individuals. Figure 3.4 shows Architecture of a knowledge representation system based on Description Logics [BMNPS03]. It highlights the importance of reasoning as a main component of the architecture of Description Logics-based systems. Reasoning is the ability of inferring and deriving facts that have not been explicitly expressed in the ontology. In fact, Description Logics have a focus on tractable reasoning [Obi07], and reasoners such as HermiT [SMH08], FACT++ [TH06], Racer [HM01], or TrOWL [TPR10]. A comprehensive review and comparison of different reasoners is elaborated by Dentler et al [DCTTDK11].

3.3 Overview of semantic modeling

There are many modeling approaches serving the purpose of capturing the components, behavior, and knowledge in complex urban systems in general. Here, semantic modeling

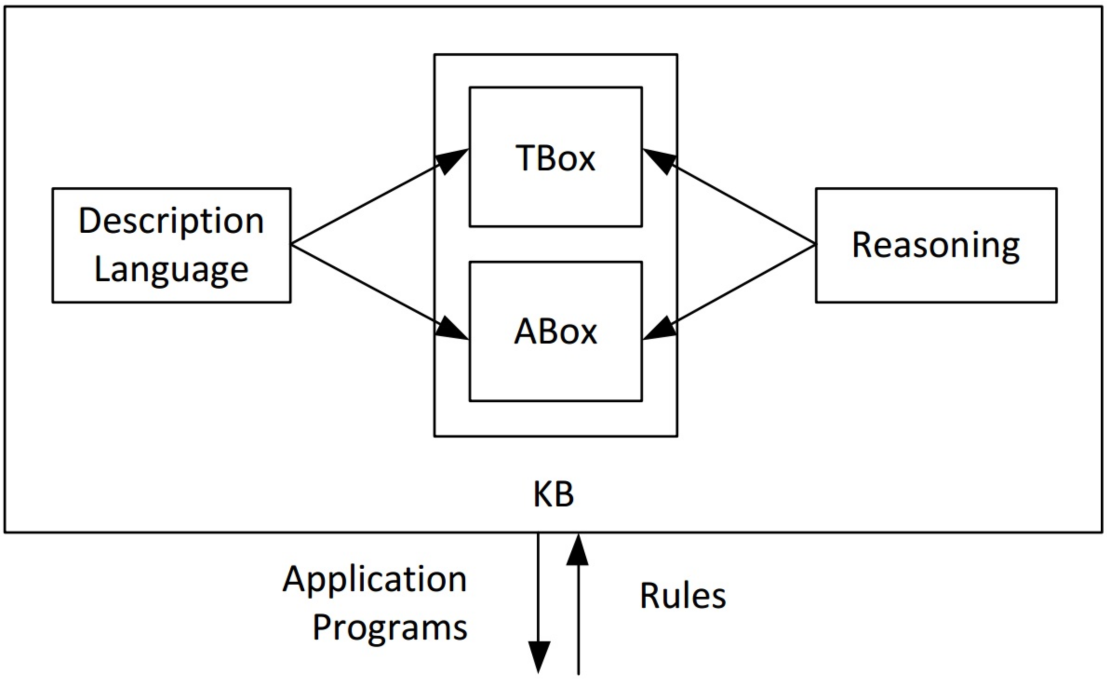


Figure 3.4: Architecture of a knowledge representation system based on Description Logics [BMNPS03]

is used, considering its expressiveness, which is required to "explain" such a large and complex system.
Semantic modeling is a formal description of the different concepts that exist about a given domain, their relationships, and their data properties. The formalization of these semantics is based on the use of ontologies, which are described in a formal language, such as web ontology language (OWL) [MVHo04].
Ontologies have the advantage of being semantically rich, i.e. easily understood by humans. At the same time, they are also computer process-able. Therefore, they are suitable for sharing knowledge and data over the web, as they are self-explanatory. Their use in complex urban systems in general (or urban energy systems in particular) is appropriate, given the large amount of data to be explained and shared across the different disciplines (by different people or software).
In the context of this thesis, ontologies were used to formalize a common vocabulary that describes an urban energy system (a complex urban system), explain its inter-relationships, and formalize opinions of stakeholders about it. Then, it is used as an integration platform of data that computation models process and output, to form a body of knowledge. Accordingly, it ensures the integration and consistency of data and their representation of the system as a whole rather than a group of datasets. Thus, the semantic model of a system is represented through an ontology, expressed in OWL [MVHo04]. Here, OWL DL has been used, allowing a maximum of expressiveness

while ensuring its computational completeness. OWL DL is more appropriate to be used in the specific context of this work by contrast to OWL Lite that does not offer enough expressiveness to model complex urban system, or OWL Full that does not have computational completeness.
Semantic models (ontologies) are not regarded as computer programs that process data and deliver some output. They are rather used to make sense of unorganized information [AH08]. Therefore, an application layer is still needed to perform computations if needed or to browse through the data and information they offer. An OWL ontology can be serialized in RDF [KC06] in a form of triples: subject, predicate, and object as shown in the explanatory example in Figure 3.5.

The ontology, as stated before does not perform computation itself but rather integrates data and allows reasoning to infer knowledge that has not been explicitly modeled and asserted. Figure 3.6shows a typical semantic web architecture and how a semantic model (ontology) can be used either by a user interface/application or queried via SPARQL [PSo08], or even via GeoSPARQL [BK11] a spatial-querying-enabled version of SPARQL. Ontologies can be serialized in RDF, which is an XML-based language. The XML layer [BPSM+98] provides a common syntax to semantic web data, where each node within the RDF graphs is exclusively referred to by a uniform resource identifier (URI) [MBLF05].

In general, ontologies are used according to a classic workflow. A semantic model is defined, which only describes the domain but does not include data about it yet. i.e. the ontology is defined as a an explicit specification of conceptualization rather than a body of knowledge. By analogy to classical databases, this model can be considered like a conceptual model but richer in terms of semantics and more expressive. Then, data sources (e.g. databases, spreadsheets, csv files, etc.) are identified then integrated using the semantic model, which defines relationships between data even if they come from different data sources. Once the data are integrated, they are deployed in dedicated database servers. Finally, the deployed data are accessible on the web via SPARQL endpoint, linked data browsers, or through web interfaces that are developed to interfaces in a more specific and customized manner.
It is to note that ontologies can be linked to each other to take advantage of other available data on the web. For example, an ontology-A that describes the demographics of countries and ontology-B that describes the agriculture of countries can be linked by stating that the concepts "country" are the same in both ontologies A and B. The outcome would be that both agriculture and demographics information are integrated.
In the next section, based on semantic modeling and semantic web technologies, an approach to model an urban energy planning support system is described.

3.4 The Urban energy system modeling methodology

The methodology described in this section is based on semantic modeling. The choice of semantic modeling and semantic web technologies in general to solve this problem (of modeling an urban energy system) is due to the flexibility it offers and its richness

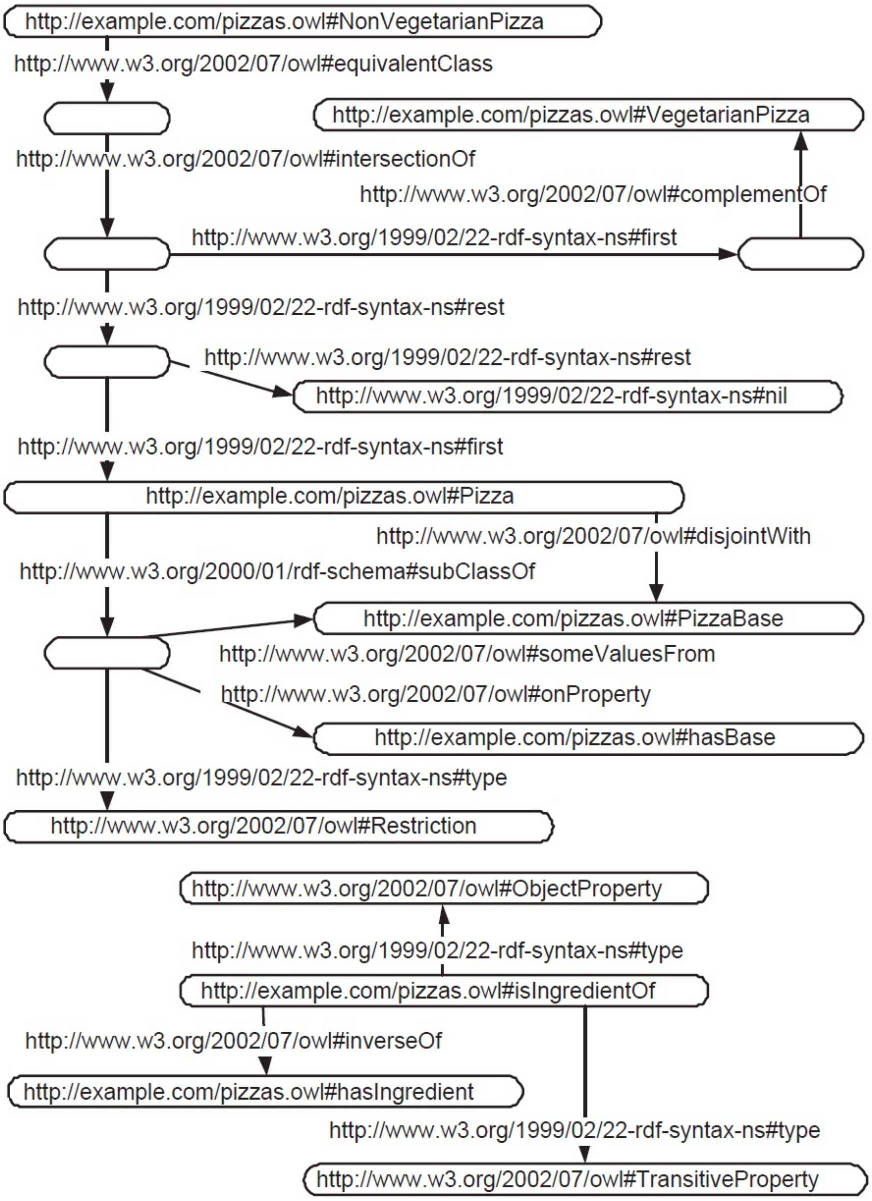


Figure 3.5: Sample OWL ontology expressed in RDF triples [Obi07]

in terms of expressiveness of concepts, besides their interoperability advantages. These main features are necessary especially when modeling a large system that requires the collaboration of a large number of domain experts and requires the use of different methodologies to develop software applications that are specific to each domain and integrating them ensuring their functioning as a system.

The general scope of this thesis is to support urban energy planners in developing

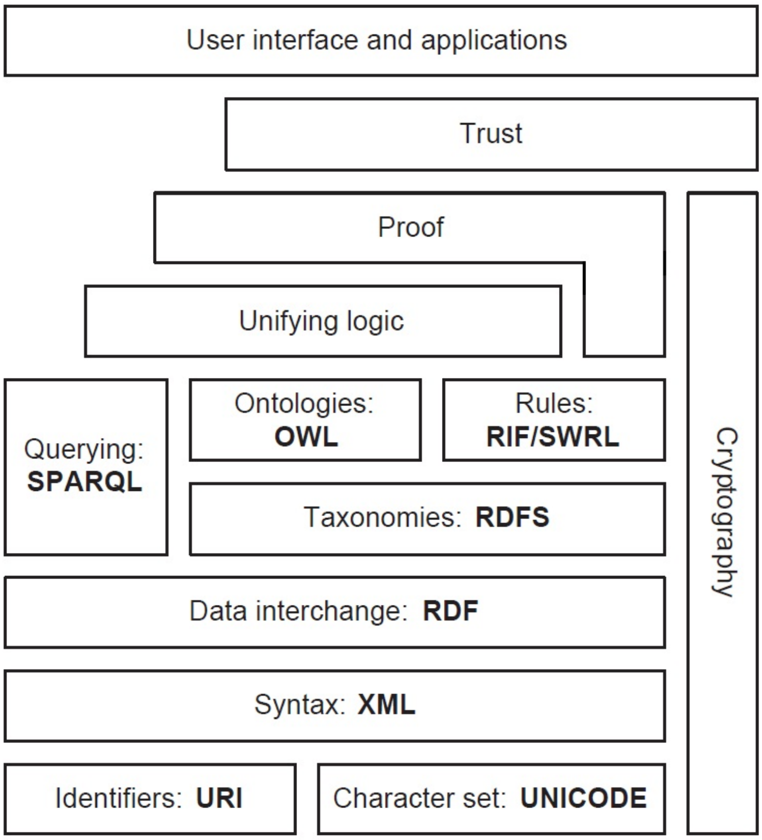


Figure 3.6: Semantic web architecture in layers [Obi07]

sustainable energy action plans i.e. the choice of adequate measures to implement at the level of the city, with the purpose of reducing CO_2 emissions. This general scope is described, in the research questions in Chapter 1. To locate the general scope within the SEAP process time line, its purpose is to provide support during the planning phase, as shown in Figure 3.7.

The proposed approach is an iterative process (as shown in Figure 3.8) that breaks down the modeling of complex urban systems into graspable parts, in terms of the required effort and the target modeling domain. Each iteration leads to the integration, or update, of a module of the whole urban energy system model. Therefore, the urban energy system is gradually growing and including more and more functionality. It is important to mention that by the end of each iteration, a working urban energy planning support system model is delivered.
The choice of a modular methodology is due to the fact that modeling a decision support system for urban energy planning is an open ended task addressing certain purposes. Urban energy planners can always come up with new decisions - and purposes - for which they require support. This requires modeling more elements and relations of the urban

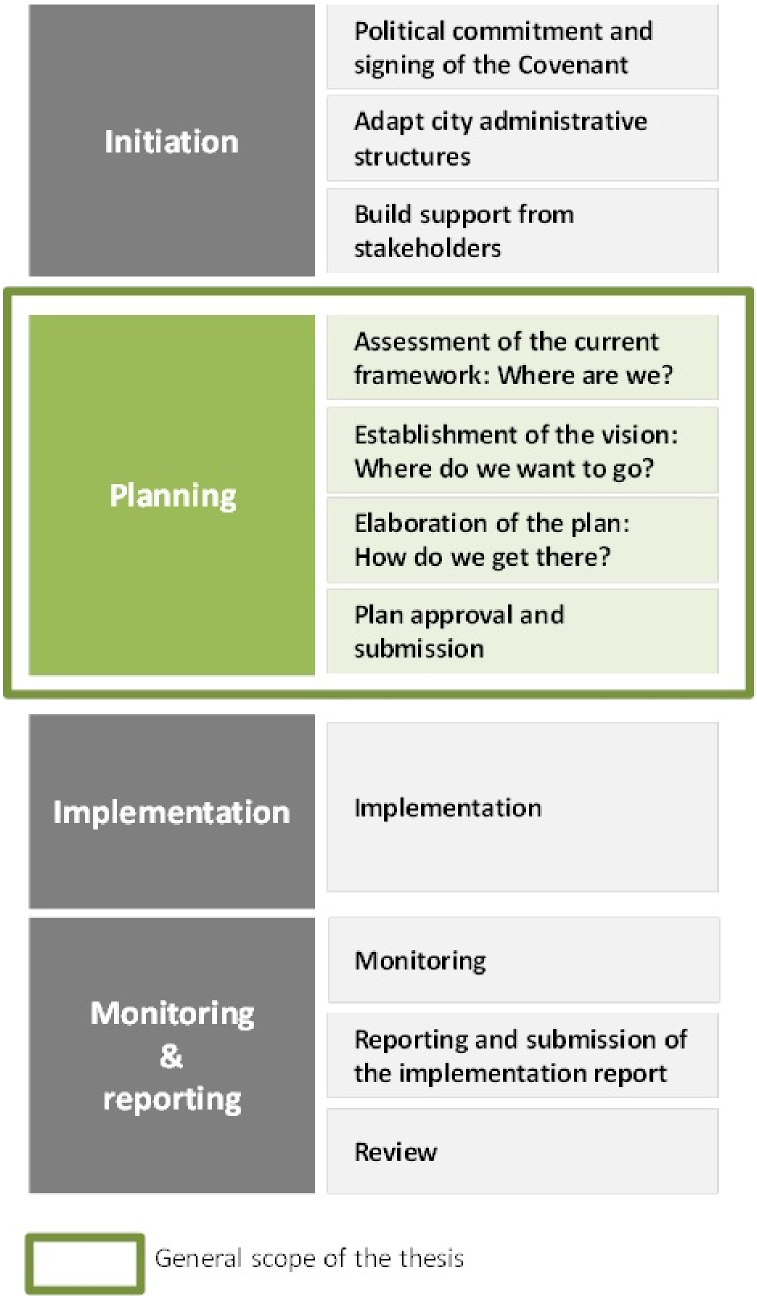


Figure 3.7: General scope of the thesis within the context of the SEAP process [Eur10]

energy system. For example, if the decision-support system provides support to the planners concerning installing PV systems, wind turbines, and refurbishing buildings, there are no need to model heat supply through ground water. However, ground water is necessary to model if the planners need support concerning the decision of ground-water-

based heat storage, for example. Therefore, a decision support system in urban energy planning can grow in correlation with the measures it implements (decisions it supports planners with).
The choice of a modular methodology is also due to the fact that the decision support system is intended to be used in different cities with different needs and data availability. Therefore, it must provide some flexibility (modularity). As explained in Chapter 1, data unavailability threatens the use of the system [OPS+13]. Therefore, modularizing the system (as well as its development methodology) offers the flexibility to change and adapt modules of the system instead of redeveloping the whole system from scratch.
This phase is aligned with the urban energy planning processes nature: both the generic one [MDG13] and the SEAP process [Eur10] that is a more concrete implementation of the generic one, with more implementation guidelines.

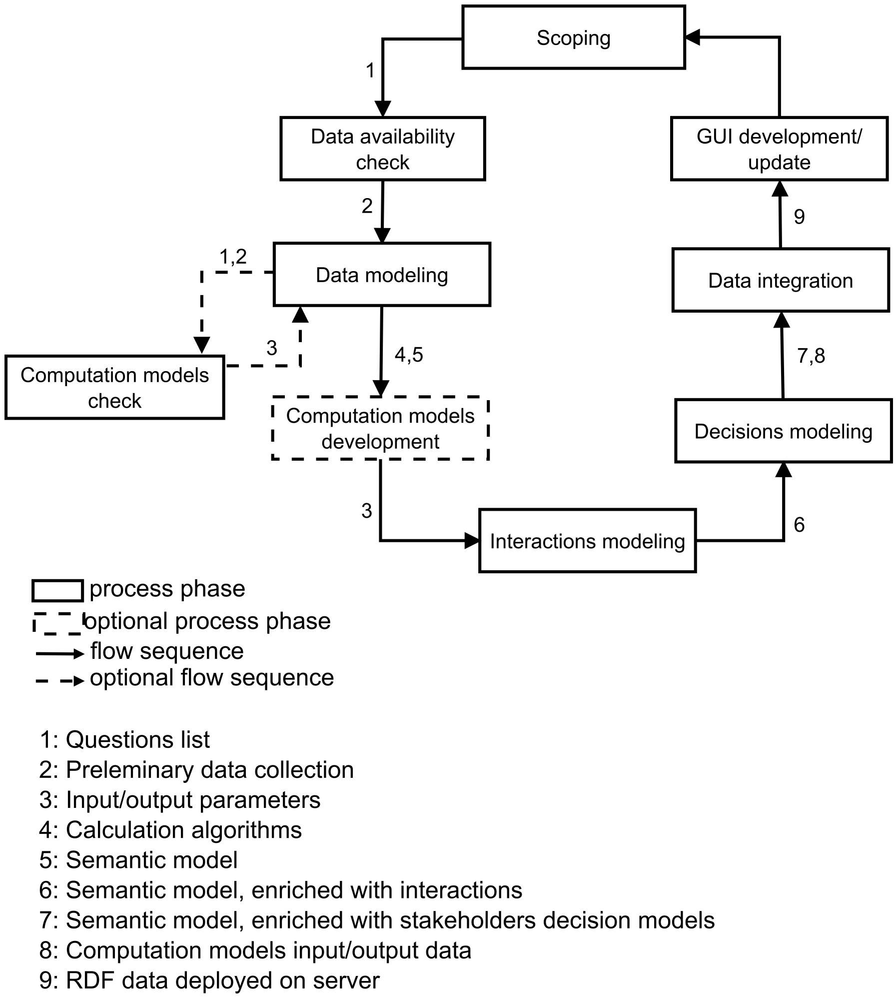


Figure 3.8: The Modeling methodology overview.

3.4.1 A Defining the scope of the system

The scoping phase is part of the iterative process shown in Figure 3.8, meaning that the scope and the functionality of the system are dynamic. This concept is derived from agile software development processes [Mar03]. The motivation behind adopting agile software development concepts are due to the expected changes to adapt the system to cope with different data availability in cities. Beck et al argue that changes costs are lower through the development process, when adopting an agile process [BBVB+01] (Figure 3.9).

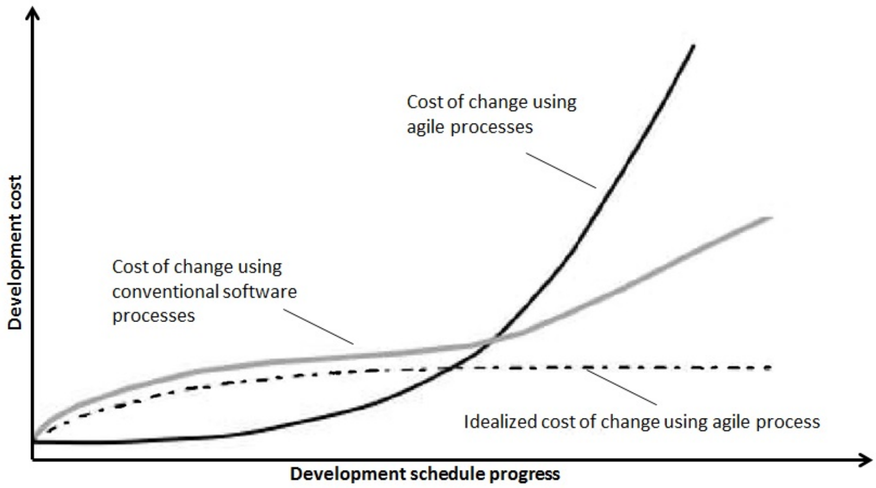


Figure 3.9: Development cost in conventional and agile processes [BBVB+01].

The objective of this phase is to define or re-adjust the scope of the decision support software, in terms of the measures it provides support for. Each measure is further detailed to define its number of perspectives, which is defined by the number of actors that are affected by the potential application of the measure [OPS+13]. The granularity of an iteration within this phase is measure-based i.e. the activities of this phase can be iteratively conducted measure by measure. The activities of the scoping phase are listed below, as shown in Figure 3.10, are explained below.

- **A1 Define the measure to be implemented:** In this activity, the measures to include in the system are defined. Typically, each iteration leads to the integration of a new measure that the system supports planners with. Each measure is a specific action or decision that has the goal (and ability) to reduce CO_2 emissions, such as in stalling PV systems or refurbishing buildings. A more comprehensive list of measures is shown in Table 2.2.
  Input: this activity does not require specific input. The measures to be implemented in the system are formulated by energy planners, as users of the systems. A measure that has been already been integrated in the system could be again reconsidered in the case an update of the system is required. An update of a

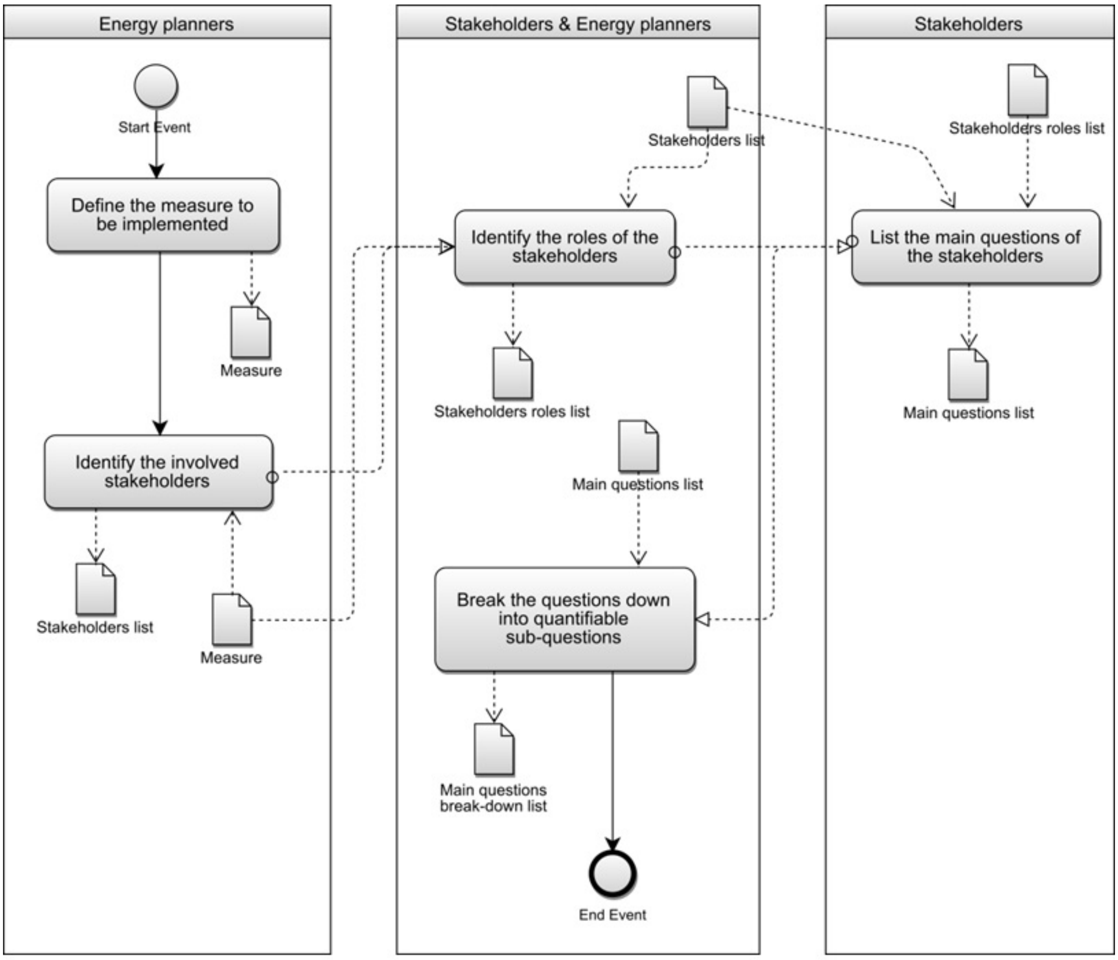


Figure 3.10: The scoping phase process model.

measure occurs if new stakeholders are involved or if the same ones have different questions.
Output: The output of this activity is a measure to be implemented. As stated above, a list of measures that can be the output of the activity is shown in Table 2.2.
Actors: The actors participating in this activity are urban energy planners i.e. the users of the system having the duty to implement measures to achieve the targets of the energy strategy for a given city.

- **A2 Identify the involved stakeholders:** In this activity, the stakeholders involved in measure implementation as defined in activity A1 are identified. Stakeholders are defined as any persons or organizations who are involved in the imple-

mentation or with activities or interests being affected by the measure. Stakeholders eventually contribute in the final decision to accept or reject the implementation of a measure. For example, for the measure install solar PV systems, one of the stakeholders is the building owner. The building owner is qualified as a stakeholder given the fact that a financial investment is required.
Input: activity A1 is a prerequisite-activity; therefore, the input of this activity is a measure.
Output: the output of this activity is a list of stakeholders that are involved in the input measure.
Actors: the actors that define the stakeholders are urban energy planners i.e. the users of the system that have the duty to implement measures to achieve the targets of the energy strategy for a given city. According to the specific context of each city, stakeholders might vary and be different. Therefore, it is necessary that the urban (energy) planners are involved.

- **A3 Identify the roles of the stakeholders:** in this activity the roles of the stakeholders (output in A2) within the context of the implementation of the measure (output in A1) are identified. This activity defines how the stakeholders' activities or interests are being affected so that it comforts the conduction of the next activity.
Input: activity A2 is a prerequisite-activity; therefore, the input of this activity is the list of stakeholder and the measure in question.
Output: the output of this activity is a list of roles of stakeholders that are involved in the input measure.
Actors: the actors that identify the roles of the stakeholders are the urban energy planners i.e. the users of the system that duty to implement measures to achieve the targets of the energy strategy for a given city.

- **A4 List the main questions of the stakeholders:** in this activity the main questions, which stakeholders would raise for their acceptance or rejection of a given measure, are listed. At this stage the questions do not necessarily have to be quantifiable. The main purpose in this activity is to prepare the next activity, quantifiable questions, which answers, together answer the parent questions defined within this activity.
Input: activity A3 is a prerequisite-activity; therefore, the input of this activity is the list of stakeholders and the measure in question.
Output: the output of this activity is a list of roles of stakeholders that are involved in the input measure.
Actors: the actors that participate in this activity are the stakeholders that are involved in the measure.

- **A5 Break the questions down into quantifiable sub-questions:** the aim of this activity is to break-down the questions that are formulated in the previous phase

into quantifiable questions. This means that each question from activity A4 is split into a set of sub-questions that require concrete, quantifiable answers. Therefore, answering the sub-questions answer the main questions that are formulated by the stakeholder.
Input: activity A4 is a prerequisite-activity; therefore, the input of this activity is the list of the main questions that are formulated by the stakeholders.
Output: the output of this activity is a list of sub-questions to the input main questions of stakeholders, formulated in activity A4.
Actors: the actors that participate in this activity are the energy planners together with the stakeholders. The role of the energy planners is to make sure that the sub-questions are quantifiable and that they are not composed questions that still require more than one answer.
It is to note that this phase is applicable in both integrating a new measure and updating an existing one. The scoping phase leads to the formalization of the main competency questions [FLGPJ97] of the ontology. Therefore, it defines the scope of the ontology-based decision support system for urban energy planning. The competency questions of the ontology, are also integrated within the ontology to keep track of the initial requirements, the way they were formulated by the stakeholders, and the urban energy planners, which are the eventual users of the system. As shown in Figure 3.10, the final output of the scoping phase (and activity A5) is the main questions break-down list. This list also represents the competency questions of the ontology.
Accordingly, this phase leads to the formalization of the first concepts of the ontology. These concepts are shown in Figure 3.11. To hierarchize the non-domain concepts, a Scenario Concept and a Data Integration Concept have been created. The Scenario Concept class comprises the concepts that take part of defining the settings of a scenario, such as what questions are addressed. The Data Integration Concept class comprises concepts that contribute in keeping the consistency of the ontology, ensure the integration of data and the behavior of the modeled urban energy system as a whole rather than a collection of datasets. The Question Concept is a sub-class of both the Scenario Configuration Concept and the Data Integration Concept because it serves two different purposes. The Questions Concept is a subclass of the Scenario Configuration Concept since it is necessary to define what questions are being answered within a given scenario. On the other hand, the Question Concept is a sub-class of the Data Integration Concept because it establishes a link between the initial requirements of the users of the system and the answers it provides. These concepts are further explained and detailed especially in the next two chapters.
The Question Concept has two sub-classes Question Properties and Question. The Question Properties class serves the purpose to contain the classes that are part of the range of the Question object properties. Thus, any modeled question has three object properties ranging in the classes, Measure, Actor, and Question. This implies that any question corresponds to a measure, has an interested actor, and

might have a parent question.

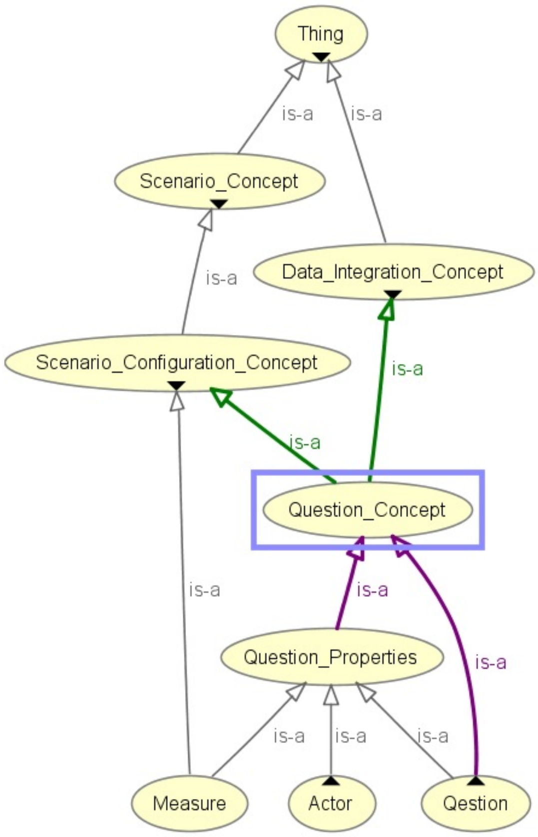


Figure 3.11: Ontology part: Question Concept.

3.4.2 B Data availability check

The goal of this phase is to gain knowledge about the data availability, its level-of-detail, and the opportunity to re-use existing ontologies. As discussed in Chapter 2, data availability varies from a city to another. Therefore, it plays a role in re-defining and adjusting the scope of the system [OLP+14]. Batty argues that confronting data to the model is part of the modeling process [Bat09]. Therefore, the data availability check is included as one of the phases in the proposed methodology to modeling and developing the target decision support system for urban energy planning.

This phase is conducted in a non-formal way, depending on the context i.e. the structure of the city, in terms of its organization and its specific data sources. It is to recall that this phase is not necessarily leading to the final data collection, which is actually finished during the next phase (data modeling phase). Bertoldi et al. argue that the data collection tas is difficult [BCMdR10]. Based on the review of several projects of elaborating CO_2 emission inventories (such as the project Energy Planning for Sustainable

Communities [EC10]), energy experts admitted that data collection in an acceptable accuracy level is difficult. Table 3.2 shows examples of different data-types in relation to the difficulty of collecting them, in the city of Illnau-Effretikon in Switzerland. It is to note that the figures in this table are more likely to be different in different cities, as discussed in the previous chapter.
There exist two categories of data that are collected during this phase: (i) data defining the current situation, (ii) and data to compute the outcome of scenarios that change the current situation. The data defining the current situation are referred to in different literatures as baseline emission inventory data, such as the guidebooks for developing sustainable energy action plans [Eur10], [SKMS14]. This data serves the purpose in defining an energy inventory of the city, stating the energy flows in the city, their sectorial distribution, and their CO_2 emission factors [Eur10]. This data collection also helps the energy planners in identifying which sectors of energy consumption have the best potential and best impact on CO_2 emission reduction [SKMS14].
It is to note that it is possible to collect CO_2 emission data according to different standards. A possible way is to use a Life Cycle Assessment (LCA) based method, where CO_2emissions are accounted through the whole life time [Gui02]. E.g. in LCA based method the CO_2 emissions of a fuel include the ones caused by burning the fuel, besides the CO_2 emissions caused by its production, transportation, etc. Another possible method was developed by the Intergovernmental Panel on Climate Change (IPCC). It was used in this research. It is a simpler method, since it considers only the CO_2 emissions that occur in the location where energy is consumed [EBM$^+$06]. An example of the estimation of CO_2 emissions according to the IPCC method is shown in Figure 3.12. It illustrates a decision tree of which exact figures of fuels carbon content to use when estimating the CO_2 emissions of combustion of fuels by road vehicles [EBM$^+$06]

Concerning the second type of data, measure-oriented data, they are used to calculate the impact of a given measure on the emission inventory of the city. For instance, the available roof areas for installing solar PV systems belong to the category of measure-oriented data. This information is necessary to assess the impact of a measure in terms of the production of renewable energy. However, this information does not take part of the activity of defining the emission inventory of the city.

Parts of the ontology related to the CO_2 emission inventory are also modeled in this phase. Figure 3.13 shows the main concepts that constitute the emission inventory and put it in the context of a whole urban energy system (i.e. the rest of the ontology). An Emission Inventory Concept is a Scenario Concept, meaning that it contains concepts that contribute in constructing a current situation of a city. The concepts that fall under the Emission Inventory Concept are as the following:

- Emission Inventory: a concept that represent the situation of a city in terms of its energy consumption and distribution over the sectors where it is consumed.

- Emission Inventory Property: a concept that helps reading and understanding the ontology by classifying the concepts that have Emission Inventory as a domain concept.

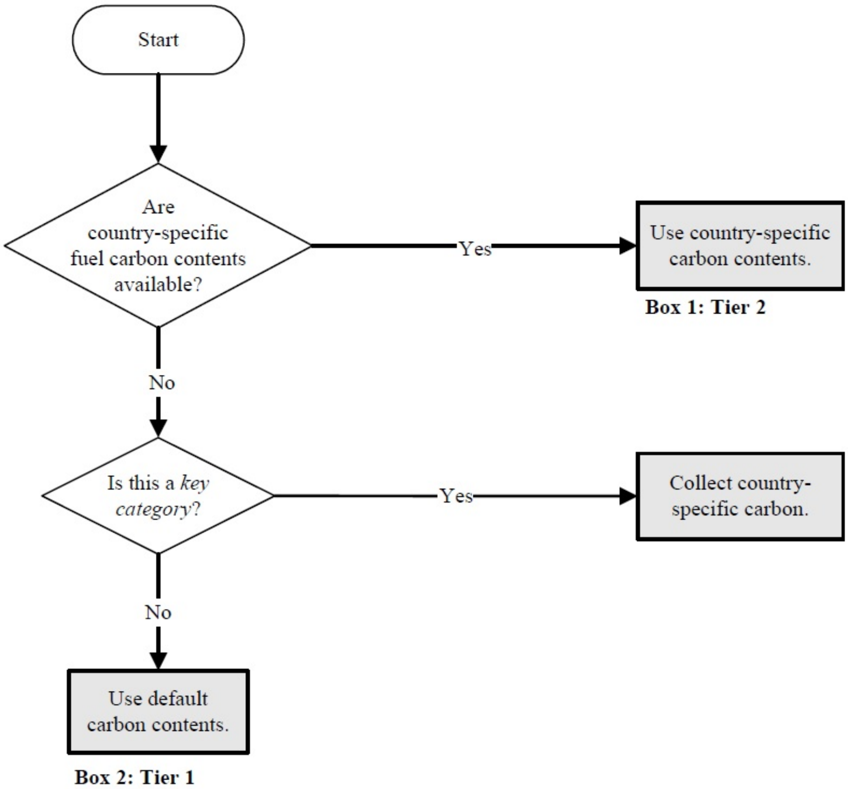


Figure 3.12: Decision tree for CO_2 emissions from fuel combustion in road vehicles [EBM+06].

- Emission Inventory Entry: a concept that represents the actual entries (rows) within an emission inventory. Thus, it behaves like a sub-component of the emission inventory i.e. a collection of Emission Inventory Entry instances makes are related to an Emission Inventory instance and all together represent an emission inventory of a city in a given time.

- Emission Inventory Entry Property: a concept that helps reading and understanding the ontology by classifying the concepts that have Emission Inventory Entry as a domain concept.

- Scenario Snapshot: it describes the time and space settings of a given scenario i.e. which year it represents and which city it describes

- Energy Carrier: this concept as its name indicates represent energy carriers. Examples of instances include diesel, petrol, natural gas, hydro power, etc. This concept is also a domain concept as in the next phase, as it is an energy concept and it also belongs to the properties of energy supply technologies, as shown in Figure 3.14.

Sector	**Data type**	**Difficulty of Data collection**
Transport	Number of public transport passengers per year	1
	Kilometers of biking ways.	1
	Kilometers of pedestrians streets/ Kilometers of municipal roads and streets.	1
	Number of vehicles passing fixed point per year/month (set a representative street/ point).	2
	Total energy consumption in public administration fleets.	1
	Total energy consumption of renewable fuels in public fleets.	1
	Percentage of population living within 400 m of a bus service	3
	Average Kilometers of traffic jams.	2
	Tons of Fossil fuels and biofuels sold in representative selected gas stations.	1
Buildings	Percentage of households with energetic label A/B/C.	2
	Total energy consumption of public buildings.	1
	Total surface of solar collectors.	3
	Total electricity consumption of households.	2
	Total gas consumption of households.	2
Local Energy Production	Electricity produced by local installations.	2
Involvement of the private sector	Number of companies involved in energy services, energy efficiency and renewable energies business.	2
Citizens involvement	Number of citizens attending to energy efficiency/renewable energies events.	1
Green Public Procurement	Establish an indicator for each category and compare with the typical value before implementing GPP. For example compare $kgCO_2/kWh$ of green electricity with the previous value. Use the data collected from all purchases to produce a single indicator.	2

Table 3.2: Data collection difficulty examples (adapted from [Eur10])[a]

[a]* 1-EASY, 2-MEDIUM, 3-DIFFICULT

- Energy Consumption Sector: this concept represents the sectors into which the energy consumption of a city is broken-down. Examples of energy consumption sectors include heating for residential buildings, the power consumption by public transportation vehicles, etc. An energy flow diagram is show in Figure 3.15, representing the different fuels that flow in the city of Vienna and how they are broken down into different sectors and energy use types.

It is to note that at this stage, it is already possible to identify similar ontologies or concepts to be linked to. For example, the concept Energy Carrier is already defined in DBpedia [BLK+09] and referred to with the URI `http://dbpedia.org/page/Energy_carrier`. Figure 3.16 shows a screenshot of the energy carrier concept from DBpedia. This part is optional depending on the purpose of the ontology. Data quality and consistency have to be checked if the ontology is to be used for computational purposes, as it is the case in this research.

In conclusion, the data availability check phase not only contributes in collecting data but also helps in understanding and refining the scope of the system. It is to note that this phase is carried every time the system is to be used in a different city. This is due

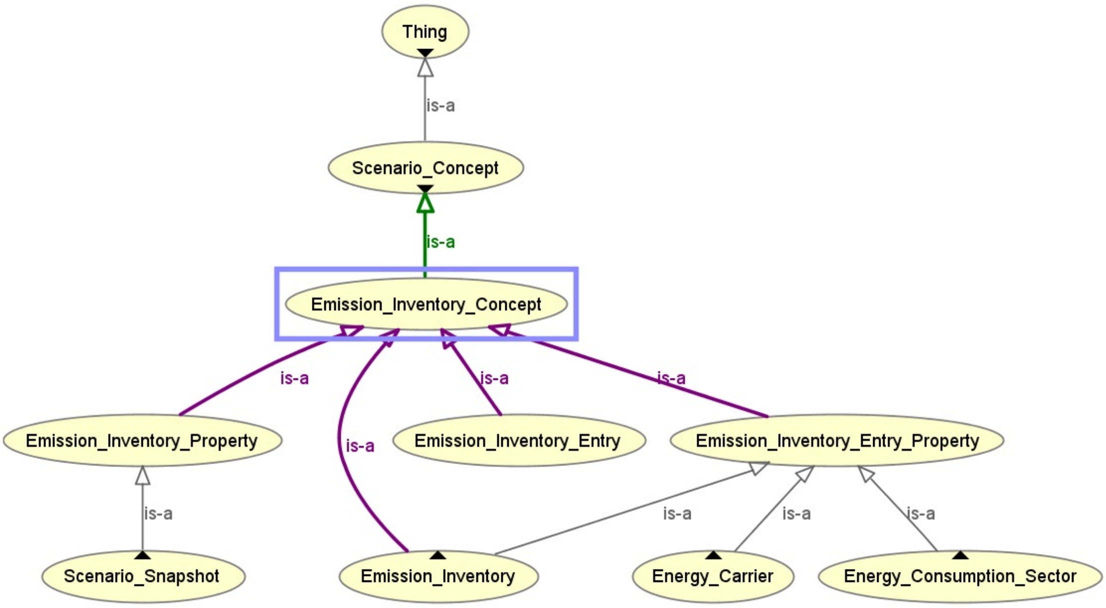


Figure 3.13: Ontology detail: Emission Inventory Concept.

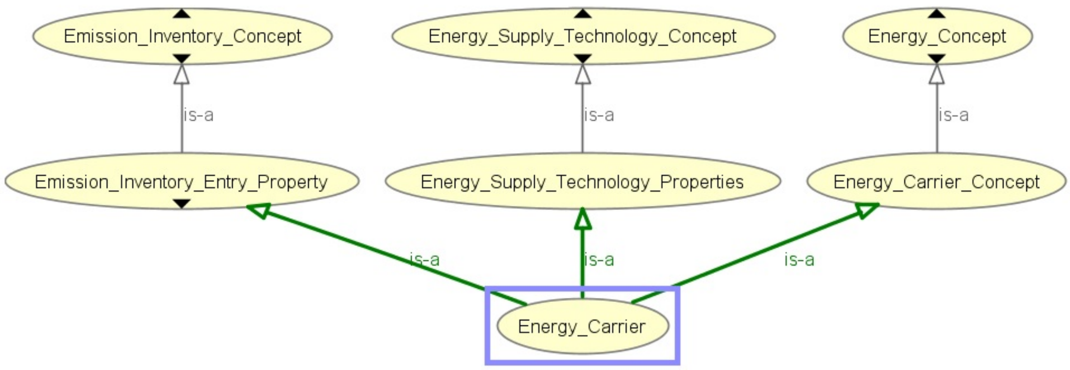


Figure 3.14: Ontology detail: Energy Carrier concept.

to the fact that it is expected that the data availability varies from a city to another [OLP+14]. It is to recall that the ontology-based decision support system for urban energy planning that is developed includes upgrade (adaptation) mechanisms. The data availability check phase is part of these upgrade mechanisms since it revises the feasibility of answering the questions that were defined in the scoping phase.
The next phase, data modeling / computation models check, is conditioned by the outcome of the data availability. It is possible to model only as much as the level of

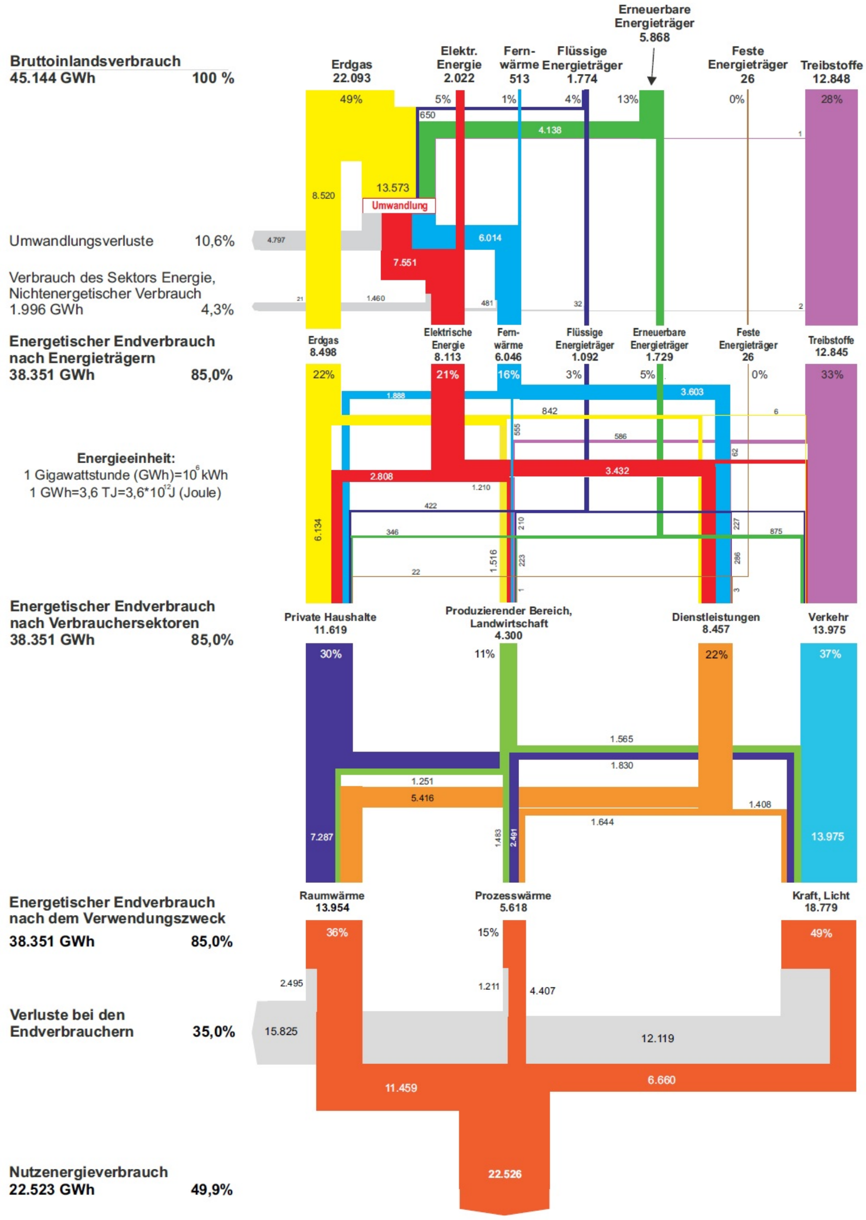


Figure 3.15: Energy consumption and flow in the city of Vienna [Sta10].

detail of existing data allows. The more detailed data are available, the more accurate computation models can be developed. As shown in Figure 3.17, on the other hand, the less details are available the larger the scope of the system becomes [Jan00]. According to Jank [Jan00] there is a difference between operative and strategic planning and the supporting systems they require, in terms of level of detail. Strategic planning focuses

About: Energy carrier

An Entity of Type : Thing, from Named Graph : http://dbpedia.org, within Data Space : dbpedia.org

An energy carrier is a substance (energy form) or sometimes a phenomenon (energy system) that contains energy that can be later converted to other forms such as mechanical work or heat or to operate chemical or physical processes. Such carriers include springs, electrical batteries, capacitors, pressurized air, dammed water, hydrogen, petroleum, coal, wood, and natural gas. An energy carrier does not produce energy; it simply contains energy imbued by another system.

Property	Value
dbpedia-owl:abstract	An energy carrier is a substance (energy form) or sometimes a phenomenon (energy system) that contains energy that can be later converted to other forms such as mechanical work or heat or to operate chemical or physical processes. Such carriers include springs, electrical batteries, capacitors, pressurized air, dammed water, hydrogen, petroleum, coal, wood, and natural gas. An energy carrier does not produce energy; it simply contains energy imbued by another system.
dbpedia-owl:thumbnail	http://commons.wikimedia.org/wiki/Special:FilePath/Different_energy_forms_(EC).png?width=300
dbpedia-owl:wikiPageExternalLink	http://ourenergyfutures.org/page-cid-7.html#Energy_Carriers http://www.eagle.ca/~gcowan/Paper_for_11th_CHC.html http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=22366 http://www.euronuclear.org/info/encyclopedia/e/energy-carrier.htm
dbpedia-owl:wikiPageID	827528 (xsd:integer)
dbpedia-owl:wikiPageRevisionID	577575398 (xsd:integer)
dbpprop:hasPhotoCollection	http://wifo5-03.informatik.uni-mannheim.de/flickrwrappr/photos/Energy_carrier
dcterms:subject	category:Hydrogen_production category:Energy_storage category:Thermodynamics category:Energetics
rdfs:comment	An energy carrier is a substance (energy form) or sometimes a phenomenon (energy system) that contains energy that can be later converted to other forms such as mechanical work or heat or to operate chemical or physical processes. Such carriers include springs, electrical batteries, capacitors, pressurized air, dammed water, hydrogen, petroleum, coal, wood, and natural gas. An energy carrier does not produce energy; it simply contains energy imbued by another system.
rdfs:label	Energy carrier
owl:sameAs	http://fr.dbpedia.org/resource/Vecteur_énergétique http://de.dbpedia.org/resource/Energieträger http://wikidata.dbpedia.org/resource/Q568469 http://es.dbpedia.org/resource/Vector_energético http://it.dbpedia.org/resource/Vettore_energetico http://nl.dbpedia.org/resource/Energiedrager_(techniek) http://wikidata.org/entity/Q568469 fbase:Energy carrier http://ca.dbpedia.org/resource/Vector_energètic http://no.dbpedia.org/resource/Energibærer http://sv.dbpedia.org/resource/Energibärare
prov:wasDerivedFrom	http://en.wikipedia.org/wiki/Energy_carrier?oldid=577575398
foaf:depiction	http://commons.wikimedia.org/wiki/Special:FilePath/Different_energy_forms_(EC).png
foaf:isPrimaryTopicOf	http://en.wikipedia.org/wiki/Energy_carrier
is dbpedia-owl:wikiPageRedirects of	dbpedia:Energyware dbpedia:ISO_13600
is owl:sameAs of	http://fr.dbpedia.org/resource/Vecteur_énergétique http://de.dbpedia.org/resource/Energieträger http://wikidata.dbpedia.org/resource/Q568469 http://es.dbpedia.org/resource/Vector_energético http://it.dbpedia.org/resource/Vettore_energetico http://nl.dbpedia.org/resource/Energiedrager_(techniek) http://ca.dbpedia.org/resource/Vector_energètic http://no.dbpedia.org/resource/Energibærer http://sv.dbpedia.org/resource/Energibärare
is foaf:primaryTopic of	http://en.wikipedia.org/wiki/Energy_carrier

Figure 3.16: Energy Carrier concept entry in DBpedia [DBp13].

on long term and comprehensive problem solving. It is currently a tool for structuring territories and developing regions [TAH07]. On the other hand, operational planning has a shorter time horizon and it is more concerned about the implementation details of the planned solutions.

The objective of the data modeling phase is to formalize the semantics of the urban energy system, which scope is defined in the scoping phase, given the data availability situation investigated in the data availability check phase. The main outcome of the data modeling phase is to develop an ontology that formalizes the semantics of urban energy systems. The modeling in this phase requires the participation of (i) the respective

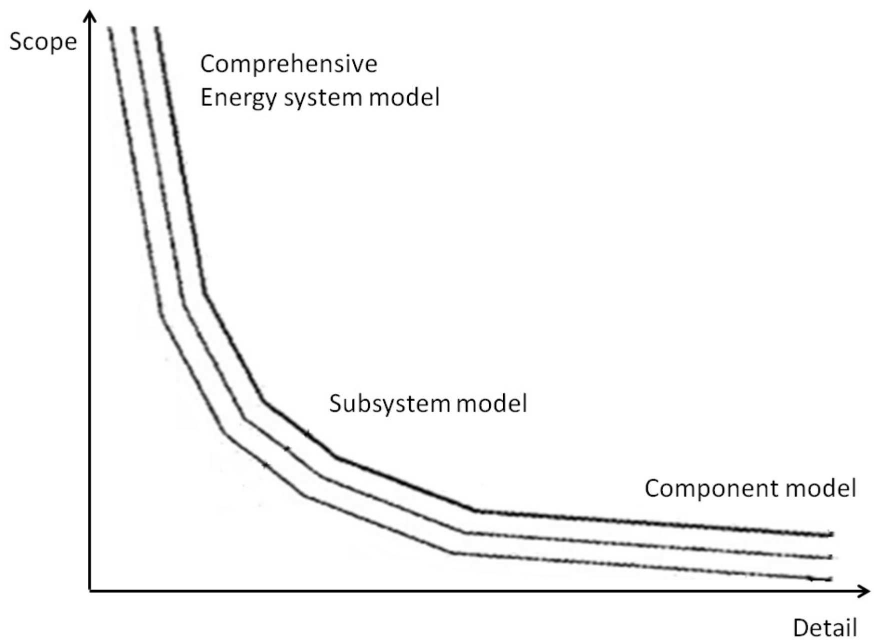


Figure 3.17: Scope and detail of models [Jan00].

stakeholders that formulated the questions in the scoping phase (ii) any actor that play the role of data provider, and (iii) domain experts that have the expertise to define calculation methods or suggest existing tools that answers the questions that are the output of activity A5. The activities of the Data modeling/Computation models check phase are listed below, as shown in Figure 3.18.

- **C1 Define expected answers:** In this activity, a list of indicators that the stakeholders are interested in is defined. The indicators represent answers to the question break-down in activity A5. The level of detail of these answers depends on the level of detail of the available data. This activity works as a validation and final agreement on the expected requirements and competency questions that the system addresses [FLGPJ97]. This is a necessary activity because at this stage there is a better overview on the data availability of the city. An ideal flow of this activity results into a one-to-one answer to question. Alternatively, it could be the case that the energy planners and stakeholders realize given the data availability of the city that some questions are to be discarded or replaced. It is to note that this activity might lead to a repetition of the scoping phase, to redefine the scope and the expected answers.
  Input: the input that is required in this activity is the main questions break-down list defined in activity A5.
  Output: The output of this activity is the list of answers that the system provides. These answers are considered as indicators of the urban energy system from the

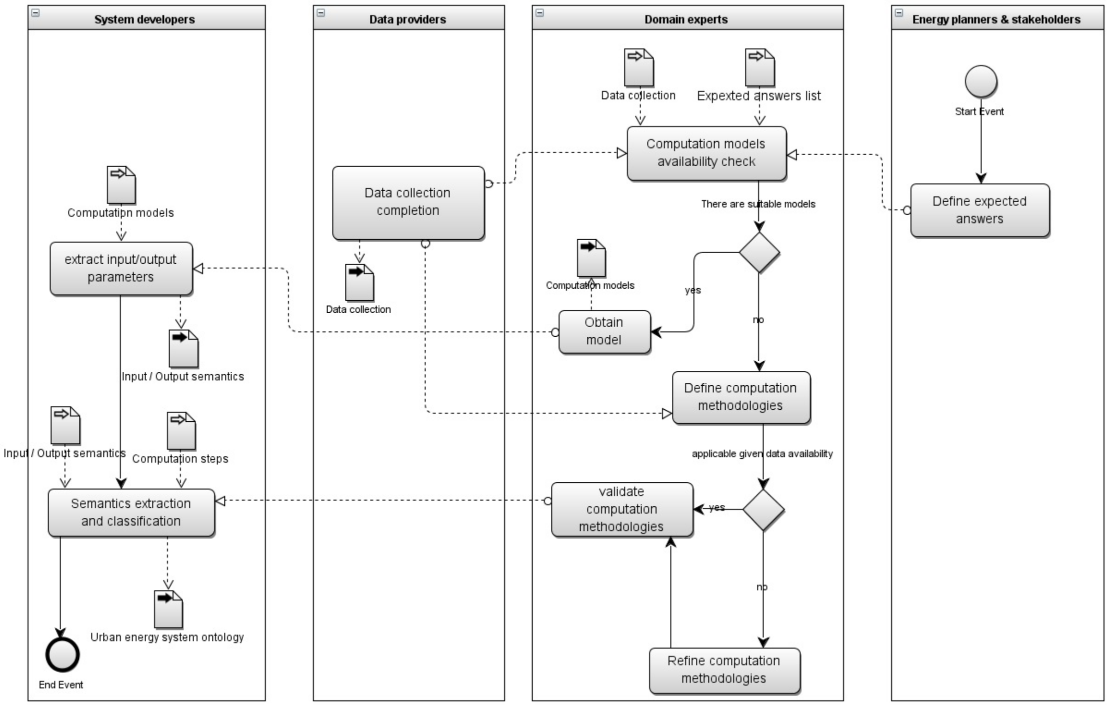


Figure 3.18: The data modeling/computation model availability check phase process model.

different perspectives of the stakeholders. Changing the urban energy system i.e. developing different scenarios of it, results in an update of these indicators. Therefore, changes of the urban energy system are accompanied with a change of the indicators that show how the interests of the stakeholders are affected.
Actors: the actors that participate in this activity are the energy planners together with the stakeholders. The role of the energy planners is to present the data availability situation of the city to the stakeholders. Then a review of the main questions break-down list is performed, based on the data availability of the city.

- **C2 Data collection completion:** the goal of this activity is to complete the data collection that has been initiated in the previous phase (data availability check). The motivation behind splitting the data collection into two phases is that because it is a long process [BCMdR10]. Therefore, splitting the process over two phases allows to avoid the bottleneck that could be caused by the data collection. It is to recall that the type of system being developed in this research belong to the strategic planning support category [Jan00]. This category of planning support system does not require high levels of detail of data but especially a large variety of data that cover a larger number of disciplines [Jan00].
Input: the required input in this activity is not formal. The domain experts have

a poor understanding of the available data and cannot develop computation models. Therefore, the domain experts wait for data to know what computation models they could develop. On the other hand, data providers ask for a template of data parameters that they are expected to deliver, as it has been the case for example in projects of developing energy strategies for the cities of Vienna and Linz [The11]. Therefore, a deadlock situation may occur.
Output: the output of this activity is the complete data collection: datasets, databases, files, maps, etc.
Actors: the actors that provide the data are the data providers i.e. municipalities, energy agencies, public transport agencies, etc. The data providers depend on what data are to be provided and also on the city. The energy planners also participate in this activity by moderating the communication between the domain experts and the data providers.

- **C3 Computation models availability check:** The aim of this activity is to find out if there are any computation models that can be-reused, before investing effort to develop new ones. In this activity, every answer is checked with the respective domain experts that discuss the existence of computation models that can provide results. The existence of computation models means not only that they are available and accessible but also usable given the data availability of the city. For example, the existence of a simulation model for energy demand in the city that requires detailed geometric data of each building cannot be used in most cases. Therefore, not only models should exist but also be operational given the level of detail of the available data.
Input: the input of this activity is the data collection and the expected answers list.
Output: the output of the activity is the list of re-usable computation models.
Actors: the actors that participate in this activity are the domain experts. Depending on the answer for which computation models are to be checked, domain experts are designated by the energy planners. For example, an expected answer such us "electricity production of buildings" requires electric systems experts. Thus the actors in this phase are teams of multi-domain experts.

- **C4 Define/refine computation methodologies:** the aim of this activity is to define and understand computation methods to reach the expected answers to the questions of the stakeholders, formulated in the scoping phase. It consists in writing the logic steps in plain text, which will be the basis of the semantics extraction in the next activity. For example, to reach the answer "investment net present value", it is required to go through a certain number of steps. These steps are simplified in this example as shown in Figure 3.19.

  Input: this activity takes as input the expected answers that are defined in activity C1 as well as the data collection that results from activity C2.

Get a **building** for which the answer is to be computed

Get **total PV investment cost** required by the **building owner**

Get **Subsidies percentage** on PV investment

defined by the **funding scheme** of the **city administration**

Compute **PV funding** amount

Get **annual gains on electricity feed-in** to the grid

Get **annual savings on electricity demand**

Get **discount rate**

Get the **investment horizon**

Compute **investment net present value**

Figure 3.19: The PV investment net present value computation logic steps.

Output: this activity outputs the logic steps of reaching each answer. Therefore, for each answer there is a document with the logic steps in plain text that will be used later on by the system developers to implement them as computation models.
Actors: the actors that define the logic steps of calculating each answer are their corresponding domain experts.

- **C5 Validate computation methodologies:** the goal of this activity is to make sure that the computation models data demand is aligned with the reality of data availability. Thus, the data parameters that are contained in the logic steps are checked against the data collection. If there are missing data from the data collection, a request to the data providers shall be triggered. If the data do not exist, the domain experts have to refine their computation models. In the case that there are no alternatives to compute the answers in different ways, a repetition of the scoping phase is necessary.
  Input: the required input of this activity involves the documents containing the logic steps to compute each answer as well as the data collection.
  Output: the output of this activity is the list of validated re-usable computation models. This means that these models are usable and there are enough data in the city to configure them.
  Actors: the actors that validate computation models, considering data availability, are the corresponding domain experts that defined them beforehand.

- **C6 Semantics extraction and classification:** This activity aims to formalize the multiple domain concepts of the ontology that integrates all the data that are needed to answer the questions that have been previously listed. Moreover, the captured domain concepts are integrated with the rest of the scenario and data integration concepts that are shown in Figure 3.11, 3.13, 3.14. The ontology keeps a permanent link to the requirements of the users of the system (through the Question Concept and Actor Concept) as well as to the calculation methods that have been adopted to provide the expected functionality. This integration of users' requirements with the rest of the system is important in order to allow a better transparency of how results are reached, in the context of a large system where customization is permanently required to deal with data availability.
  Based on a reference methodology of ontology development [FLGPJ97], the semantics extraction and classification is achieved based on logical steps that the domain experts define in activity C4. The keywords within each logic step are highlighted, then classified into their respective categories: classes, object properties, or data properties. Alternatively, in the case of reusing existing computation models, their input and output data parameters are considered as the necessary semantics to be modeled. The reused models are to be considered as black-boxes.
  At the end of this activity, all the semantics describing an urban energy system, which considers the computation models within the scope, are captured. This means that the urban energy system gradually grows, as more computation models are being integrated. The need of integrating more computation models is controlled by the number of questions that the stakeholders are interested in, in the scoping phase. Therefore, the richness of the semantics and the expressiveness of the ontology that represents the modeled urban energy system are correlated to the number and the nature of the questions of the stakeholders that are defined in the scoping phase.
  The extracted semantics are integrated with the rest of the modeled concept that have been captured in previous activities and phases. Thus, the ontology of the urban energy system at this activity comprises semantics that are extracted from: the stakeholders list, questions list, questions break-down list, answers list, calculation methods, calculation algorithms, and computation models.
  Input: the input of this activity includes the logic steps of the computation models (defined by the domain experts) and the computation models to be reused (if there are any), including their input/output data parameters.
  Output: the output of this activity is an ontology that represents an urban energy system. The ontology comprises concepts that are related to urban energy system and integrate them within their context of users' requirements (why they have been modeled), the calculation methods that contribute in calculating some of their data properties (how non-existing data has been created), the computation models that implement the calculation methods (which specific computation models are used).
  Actors: the actors in this phase are the system developers, assisted by the domain experts if necessary. It is to note that "system developers" in this text refers to all

the roles of analyst, architect, developer, and tester.

As stated before, the ontology integrates the initial users' requirements (i.e. stakeholders' questions) with the answers that it provides. This integration is shown in Figure 3.20. The Question Concept refers to the questions that the stakeholders raise as well as their break-down. Therefore, every question can be related to a parent question vial the object property hasParentQuestion. Every question has context measure where it is relevant, and an actor that raises the question. Concerning how the questions are related to the rest of the ontology, it is managed by the relationship answersQuestion:

```
<owl:ObjectProperty rdf:ID=" answersQuestion ">
<rdfs:domain rdf:resource="#Answer_LOD" />
<rdfs:range rdf:resource="#Question" >
</owl:ObjectProperty>
```

The level-of-detail (LOD) of an answer is defined by the calculation method it uses. Therefore, a question can have more than one answer, depending on its level-of-detail. The Answer LOD concept represents answers to the questions and allows the flexibility to answer the same questions using different calculation methods. For example if a part of a city (e.g. a district) has more detailed data, more detailed answers (instances of the Answer LOD class) can be integrated with the rest of the ontology.
Computation models that produce the end results (instances of the Answer LOD class) are also kept track of and integrated within the ontology. An instance of the Calculation Implementation class is related to a computation model through the object property usesCalculationModel, and a calculation method through the object property implementsCalculationMethod.

It is to note that the Answer Concept is a scenario configuration concept, as shown in Figure 3.21. It is hierarchized as part of configuring a scenario because answers selections and their level of detail happen while configuring the system for its actual use to energy planning support. While Answer LOD concept is the class that comprises instances of single answers to the questions of stakeholders, the Answer Bundle concept comprises sets of Answer LOD instances, which are of interest to the same stakeholder.

Besides the domain concepts, the ontology also includes data integration concepts, shown in Figure 3.22. The goal of integrating these concepts with the rest of the ontology is to ease updating the ontology since data availability varies in different cities. For example, if there is not enough data to use a given computation models, it becomes transparent (using the integration concepts part of the ontology) how the given model is linked to the rest of the ontology and which data it contributed to generate. The data integration concepts include the following:

- **Calculation Method:** contains instances that describe the calculation methods that take part in the computation of answers (instances of the Answer LOD class). The main data properties of this class include:

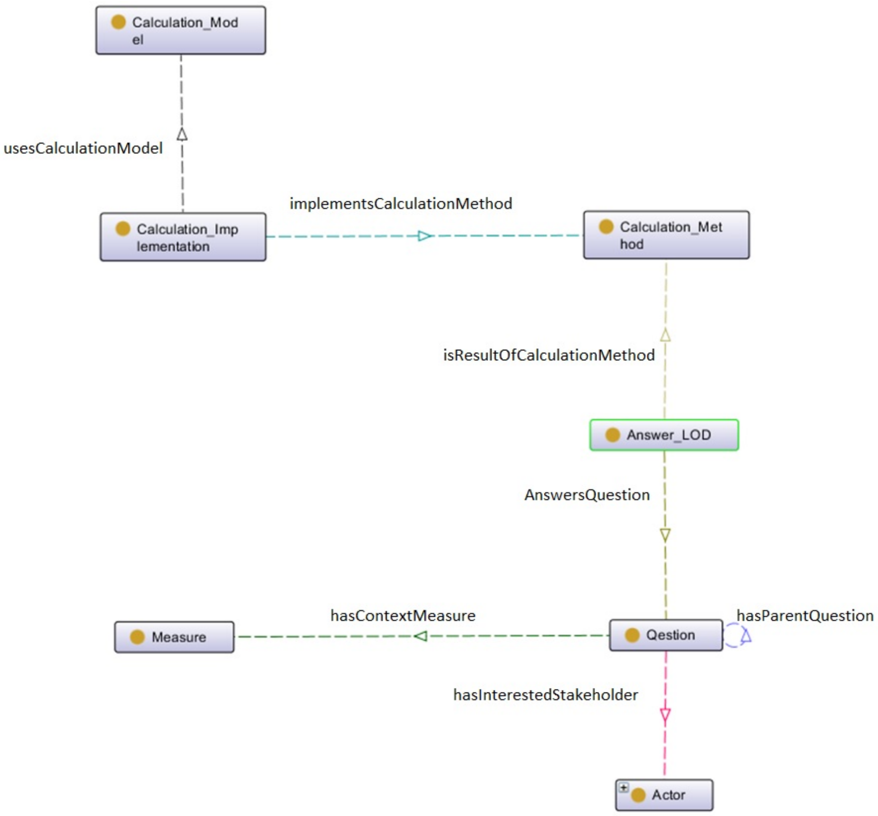


Figure 3.20: Ontology detail: integration of the initial requirements with the answers.

<owl:DatatypeProperty rdf:ID=" hasCalculationMethodDescription">
<rdfs:domain rdf:resource="#Calculation$_M ethod"/ >$
$< rdfs : rangerdf : resource = "xsd; string"/ >$
$< /owl : DatatypeProperty >$

$< owl : DatatypePropertyrdf : ID = "requiresMinimumTimeLOD" >$
$< rdfs : domainrdf : resource = "\#Calculation_M ethod"/ >$
$< rdfs : rangerdf : resource = "xsd; string"/ >$
$< /owl : DatatypeProperty >$

$< owl : DatatypePropertyrdf : ID = "requiresMinimumSpaceLOD" >$
$< rdfs : domainrdf : resource = "\#Calculation_M ethod"/ >$
$< rdfs : rangerdf : resource = "xsd; string"/ >$
$< /owl : DatatypeProperty >$

$< owl : DatatypePropertyrdf : ID = "requiresMinimumTechnologyLOD" >$

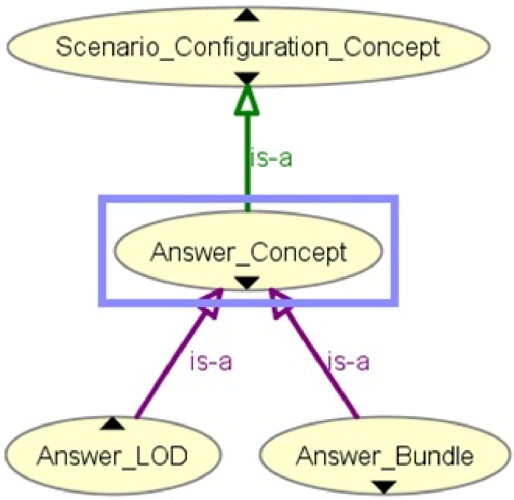


Figure 3.21: Ontology detail: Answer Concept.

$$< rdfs : domainrdf : resource = "\#Calculation_Method"/ >$$
$$< rdfs : rangerdf : resource = "xsd; string"/ >$$
$$< /owl : DatatypeProperty >$$

Every calculation method is bounded to a description and three levels of detail that describe the minimum requirement of the method in terms of the granularity of space, time, and technology.

- **Calculation implementation:** contains instances that are used to match calculation methods with computation models, offering the flexibility to use different computation models that require the same level of detail. A case where this can be needed is if a computation model is to be upgraded to a better performance one.

- **Computation Model:** is a software application that is used for the purpose of calculating answers (instance of the Answer LOD class).

- **Question concept:** is the same concept that has been described before, as a sub-class of the scenario configuration concept. The question concept has two parent classes as it plays roles in both of them. As a data integration concept, the question concept is required to maintain traceability between the initial users' requirements (what the stakeholders are interested in knowing) and what data the ontology is gradually integrating to fulfill them.

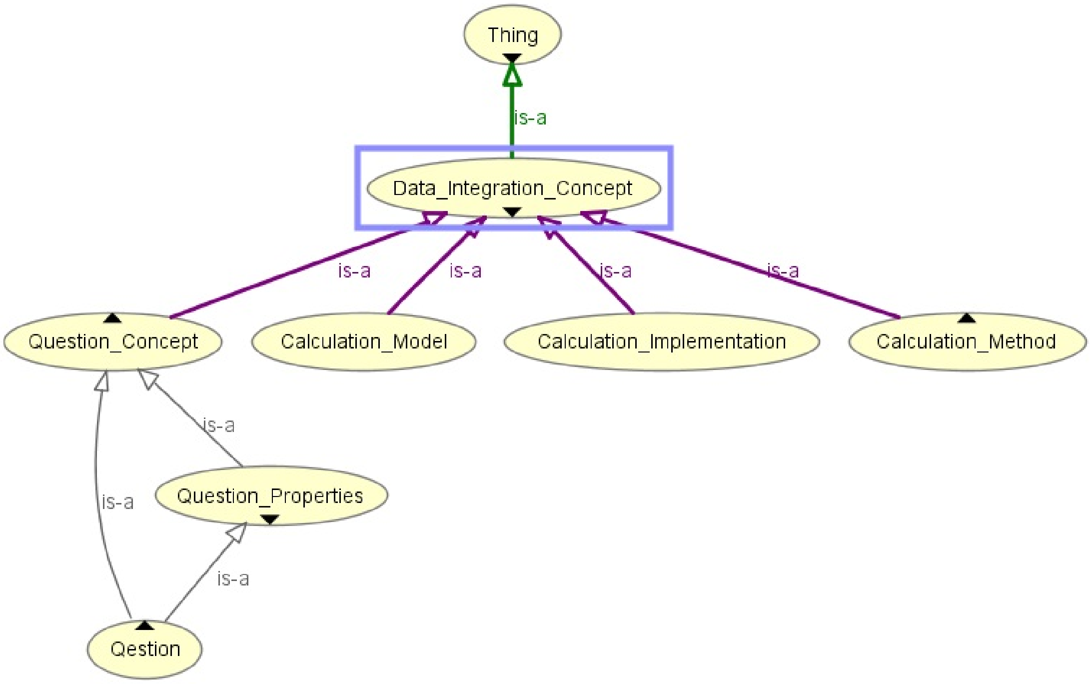


Figure 3.22: Ontology detail: Data Integration Concept.

It is to note that the data integration concepts described above are the ones that are captured until the data modeling phase. More data integration concepts are captured and integrated (within the ontology) in the coming phases.

3.4.3 D Computation models development

The goal of this phase is to develop computation models to reach the answers (instances of the "Answer LOD" class), or any intermediary data that contribute in reaching them. The computation models represent an implementation of the calculation methods that are described by the domain experts, as an output of activity C4 (example in Figure 3.19). This phase is optional because it is needed only in the case that no existing calculation models are found. There exist several software development methodologies that can be used in this phase if it is to be taken independently from the rest of the phases. Such methodologies include the Rational Unified Process (RUP), which is rigorous in addressing all the activities around software development, including requirements management, business modeling, analysis/design, implementation, testing, and development [Kru04]. This process is more suitable for larger projects (in software development) than developing the target computation models in the specific case of this research. The simplified version of RUP, is the open Unified Process (OpenUP). It is a lighter weight process compared to RUP but still addresses all the disciplines around software development [Bal07], ensuring both discipline and agility at the same time [KM06]. A more comprehensive review and discussion of more agile software development processes has been performed by DybÃě and DingsÃÿyr [DD08].

The large variety of existing processes do address software development in a systemic approach, however, they are not necessary to use in the specific context of this phase. The required development effort as a process is minor since some of the activities are already addressed in previous phases. For example the business analysis and requirement engineering related activities are conducted in the scoping phase, then in the data modeling phase. Reusing an existing dedicated software development process will require either the adaptation of that process, which is outside the scope of this research, or repeating unnecessary activities, creating an overhead or even inconsistencies.

The proposed process to develop the required computation models in this research is show in Figure 3.23. It is based on the solution increment development activity of the OpenUP software development process [Bal07]. In this phase, only the implementation aspect of the computation models is addressed. This phase does not lead to the implementation of the whole target planning support system. Only single computation models development is within the scope of this phase, provided that the calculation methods they are based on are captured beforehand (in the data modeling phase). The activities that this phase comprises are as the following.

- **D 1 Define test cases:** the test cases represent the testing scenarios of the computation models. They describe the expected (successful) behavior of the computation models
  Input: the required input for this activity include the data collection and the calculation methods that describe the logic steps of the expected behavior of the computation models.
  Output: the output of this activity is the description of the test cases.
  Actors: this activity is conducted by the domain experts.

- **D 2 Define specific test data:** the data that are required to run the test cases are defined in this activity.
  Input: the required input for this activity include the data collection and the test cases that are defined in activity D1.
  Output: the output of this activity is the test data collection.
  Actors: this activity is conducted by the domain experts.

- **D 3 Design solution:** in this activity, the design of the computation model is defined i.e. how they are internally organized in terms of functions, classes, libraries to be used, or any other aspects related to the architecture of the computation model to be developed. Different approaches might be used to develop the solution; therefore, this activity does not restrict the developers to any specific practices.
  Input: the required input of this activity involves the documents containing the logic steps to compute each answer.
  Output: the output of this activity is the design of the computation model. No

specific format is required, as the modeling approaches might differ.
Actors: this activity is conducted by the system developers.

- **D 4 Implement developers' tests:** in this activity, developers' test cases are defined. They represent the testing scenarios of the computation models from the developers' perspective. They describe the expected (successful) behavior of the computation models.
  Input: the input of this activity is the solution design from activity D4, if available/applicable.
  Output: the output of this activity is the collection of developers test.
  Actors: this activity is conducted by the system developers.

- **D 5 Implement solution:** in this activity, the solution is developed, implementing the calculation methods that are defined beforehand, during the data modeling phase (activity C4). The choice of the programming language or tools depends on the developers.
  Input: the required input of this activity involves the documents containing the logic steps to compute each answer.
  Output: the output of this activity is the implementation of the solution.
  Actors: this activity is conducted by the system developers.

- **D 6 Run developer test:** in this activity, the solution is tested against the predefined developers' tests. The main goal of this activity is to test the operational functioning of the computation models rather than the logic they implement, which is tested in later activities.
  Input: the required input of this activity is the implementation of the solution as well as the developer test cases.
  Output: the output of this activity is the developers test log.
  Actors: this activity is conducted by the system developers.

- **D 7 Integrate and create build:** in this activity, in case the model is created incrementaly (depending on the size of the model), the increment is integrated with the rest of the computation model. Then, a working version of the computation modelis created, evenif it is still under construction.
  Input: the required input of this activity is the implementation of the solution.
  Output: the output of this activity is an implementation increment i.e. a working software that can be used in the next activity in a different environment than the developers'.
  Actors: this activity is conducted by the system developers.

- **D 8 verify test implementation:** the developed solution is verified and tested within this activity. This time, unlike in activity D6, the logic behavior of the computation model is verified. The computation models are checked against the test cases that are defined by the domain experts. This is considered as the final verification of the computation models.

Input: the required input of this activity is the implementation of the solution as well as the test data that are prepared by the domain experts.
Output: the output of this activity is the test log that results in running the computation models with the prepared data collection.
Actors: this activity is conducted by the system developers together with the domain experts.

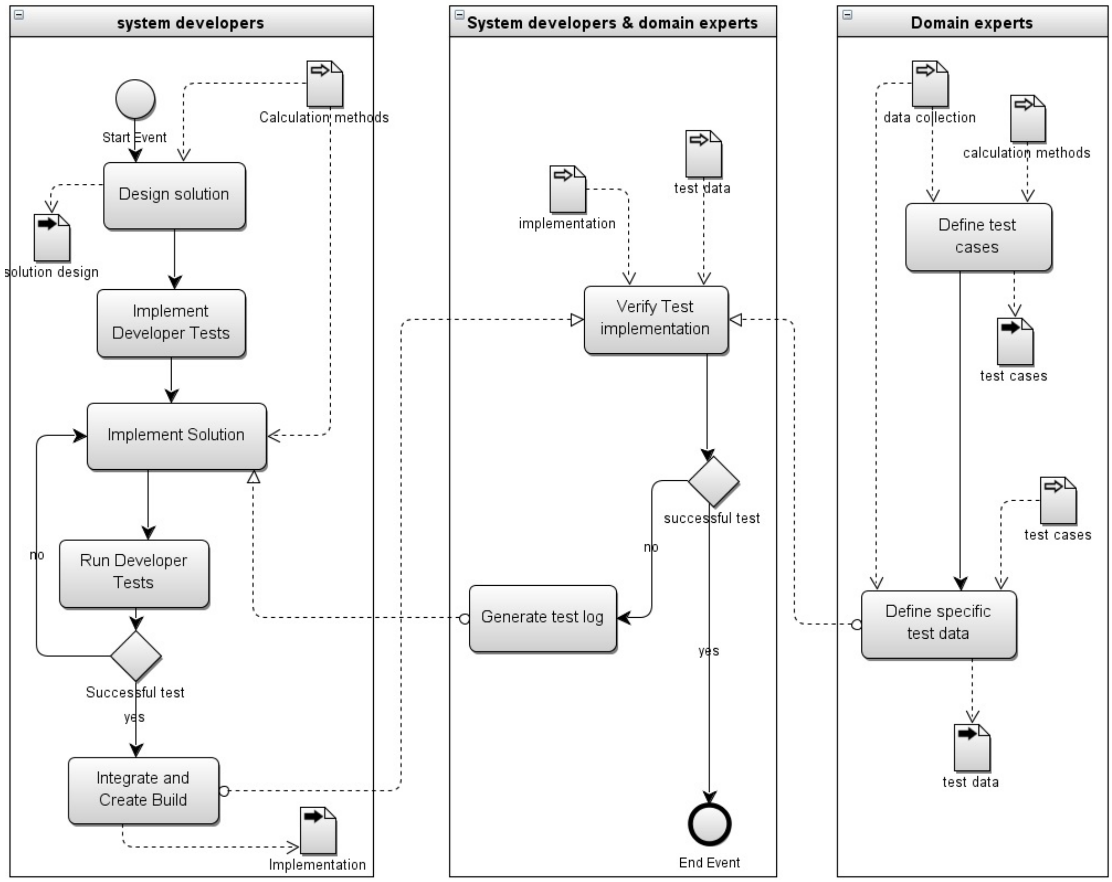


Figure 3.23: Computation models development process model.

It is to be recalled that the developed computation models contribute to create data that did not exist before to be integrated within the ontology. The computation models that are developed are not dynamically used, within the scope of this research. They are developed to create new data: synthesize existing data, and/or calculating the answers that the stakeholders need to make their decisions. Therefore, the computation models are not to be considered as an application layer that uses the ontology (as a knowledge base) of the urban energy system. At this stage the data management of the computation models is locally processed. Each computation model has its own data management

system. Any data transaction, at this stage, is completely decoupled from the ontology. Moreover, the computation models are not supposed, within the scope of this research, to communicate with the ontology.
The data of these different computation models are integrated within the ontology, later on the data integration phase (phase G). The choice of decoupling the data management systems from the integration ontology allows more flexibility because it imposes no restrictions on the computation models to be integrated. This gives a larger variety of choice in terms of integrating existing computation models.

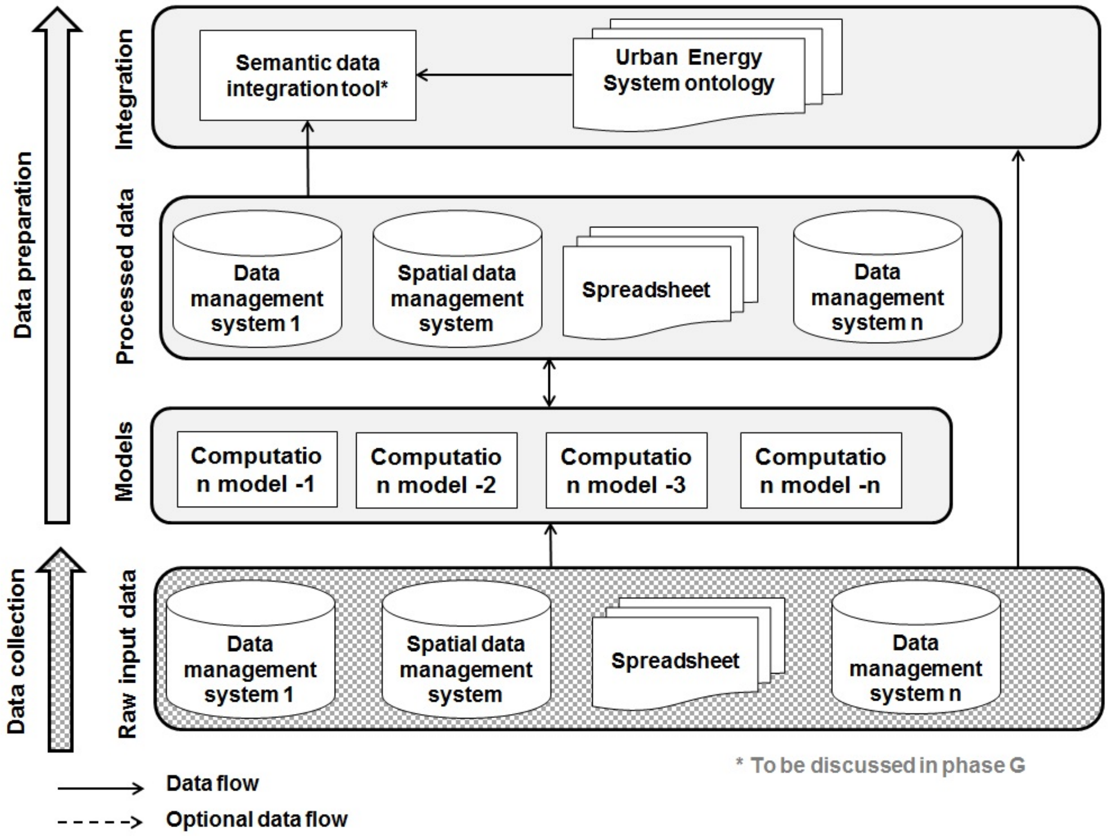


Figure 3.24: Computation models role in the data processing flow.

At the computation models development phase, the data are not yet integrated within the ontology to form an urban energy system knowledge base. Figure 3.24 shows the role of the computation models in the data processing flow and their relation to the urban energy system ontology. The data processing flow goes in three stages (i) data collection, (ii) data preparation, and (iii) data use (which is discussed in phase H: data use). In the data collection stage, raw input data physically exist in different data management systems. The data management systems are not necessarily integrated or aware of the existence of each other. The types of the data management systems range from

spreadsheets, to relational databases or spatial databases. At the data collection stage, data are physically stored in adequate data management systems; however, querying these data does not provide answers to the questions that have been set in the scoping phase. Thus, in the next stage, data preparation, adequate computation models are used in order to synthesize or perform calculations on the raw data so that they become useful. The data become useful once the questions of the stakeholders (i.e. the competency questions of the system), from the scoping phase can be answered.
The computation models access the data management systems where raw input data are stored, process them, and store the synthesized/calculated data in appropriate data management systems. Each computation model can use its own data management system. The integration of data is not an issue at this stage. Data are integrated, using the ontology in later phases.

3.4.4 E Interactions modeling

The objective of this phase is to keep the different computation models integrated, by capturing which data parameters influence which others. In other words, it adds a part to the ontology so that it is aware about how every computation model influences the data parameters (which are accessed by all the other models). Thus, not only concepts of the urban energy system are kept within the ontology but also computation models that are used to calculate their actual data are preserved, as shown in Figure 3.26. Computation models that are used to synthesize/calculate data are part of the urban energy system ontology, because they can be used to trace the dynamics of the urban energy system in terms of influences. Therefore, any other interactions between the components of the urban energy system that are not triggered by the computation models are simply ignored. Thus, it is the accuracy of the computation models that are used that define the interactions that are modeled within the urban energy system.
The execution of this phase consists of three steps, as shown in Figure 3.25. First, the output and input data parameters of the computation models are listed. Then, interactions are captured at the level of computation models i.e. which input influence which output parameters within the same model. Then, finally, the multi-model influences are captured. An interaction is set to be any relationship where an output parameter being used as an input parameter in a different model. The activities in this phase are explained as the following.

- **E1 Define the input/output of the computation models:** In this activity, it is formalized what data input or output are managed by the computation models. Therefore all the computation models are listed, including the reused existing models (if there are any). For each computation model, it is listed what data input and output are used.
  Input: the required input of this activity is the collection of computation models that are used. Ideally, what is needed is the input and output parameters of the computation models, if the domain experts have optionally performed this task beforehand.

Output: the output of this activity is the list of input and output parameters of all computation models.
Actors: this activity is conducted by the system developers. The participation of the domain experts is optional in case existing computation models are re-used that only domain experts are knowledgeable about.

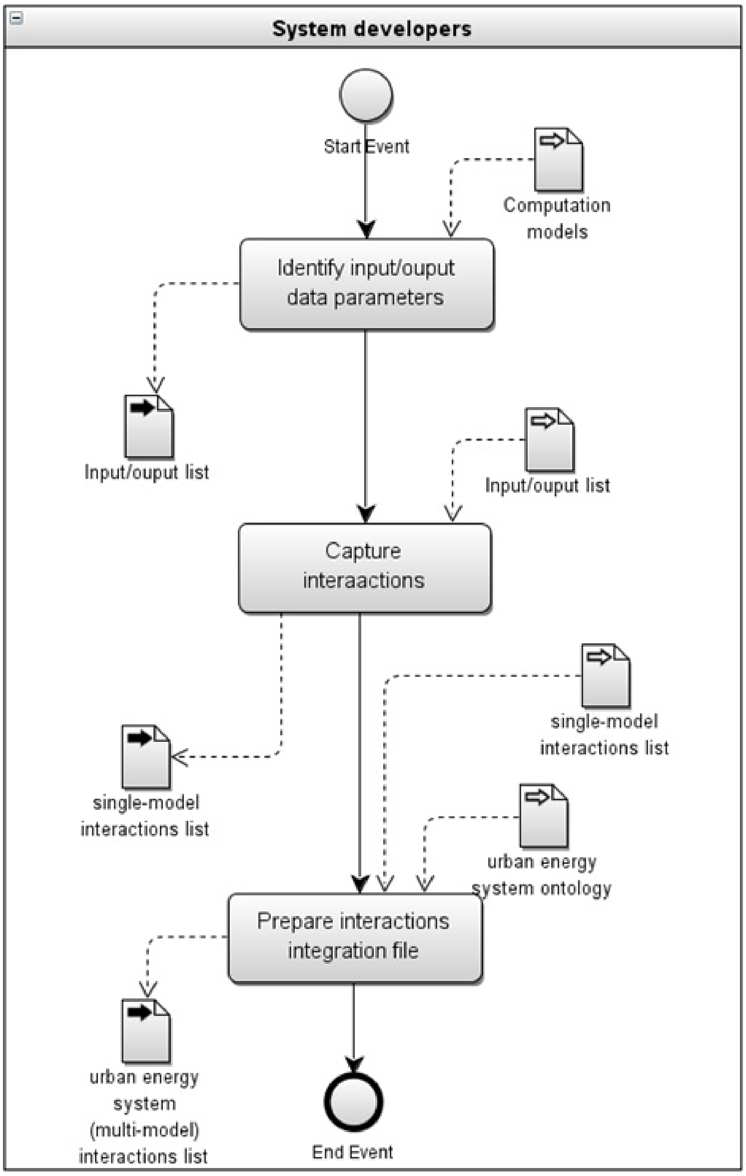


Figure 3.25: Interactions modeling process model.

- **E2 Capture interactions:** in this activity, it is identified which data parameters

have impacts on others within each computation model. These interactions represent the dynamics of the urban energy systems that are triggered by each computation model that has been used to create it, the template according to which these interactions are capture is shown in below under the output point.
Input: the required input of this activity is the input/output list that is defined in activity E1.
Output: the output of this activity is the list of input and output parameters. Each entry within this list is comprised of:

  - a computation model identifier (referring to a unique computation model)
  - an input parameter of the computation model that influences other data parameters.
  - the component (concept) that is described by input data parameter as a data property, within the urban energy system ontology
  - an output parameter that is influenced by the input parameter
  - the component (concept) that is described by the output data parameter as a data property, within the urban energy system ontology

  Actors: this activity is conducted by the system developers.

- **E3 Integrate interactions within the ontology:** in this activity, it is identified which computation models have an impact on which other computation models. Therefore, It is to capture data parameters that have an impact on others across different computation models. These interactions are captured according to the model in Figure 3.27. A script to automate this activity might be developed, since all data that it requires are formalized and computer process-able.
  Input: the required input of this activity is: the single-model interactions list from activity E2 and the ontology of the urban energy system.
  Output: the output of this activity is the list of all potential interactions that can happen in the whole urban energy system ontology. Each input or output parameter is referred to by its Uniform Resource Identifier (URI).
  Actors: this activity is conducted by the system developers.

In the interaction modeling phase, more data integration concepts are added to the urban energy system ontology, which were previously discussed in Figure 3.22. The added concepts ensure that the ontology is integrated with the computation models that contribute in the creation of the knowledge it contains. Moreover, these added concepts contribute in the explanation of the dynamics that happen within the urban energy system, from the perspective of the computation models.

There are three data integration concepts that are added to the urban energy system ontology in this phase. They ensure capturing the interactions between the data parameters of the ontology. These concepts are described as the following:

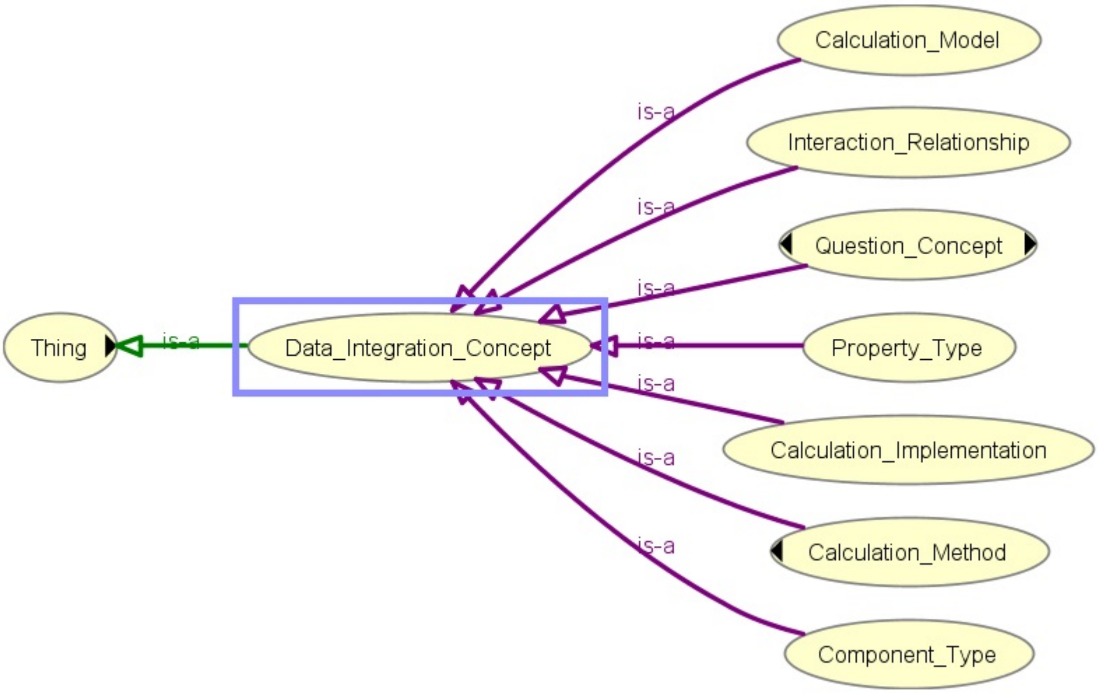


Figure 3.26: Ontology detail: considered data integration concepts.

- Interaction Relationship: this concept defines the existence of a relationship between two data parameters within the ontology that is triggered by a given computation model.

- Property Type: this concept represents data parameters that take part in an interaction relationship. This can be either an input or an output data parameter, within a computation model. Each instance of this class is referred to by its URI, formalized beforehand in the urban energy system ontology.

- Component Type: this concept represents components (instances of concepts within the urban energy system ontology) that take part in an interaction relationship. These components can be involved either as an affecting or affected components, within a computation model. Each instance of this class is referred to by its URI, formalized beforehand in the urban energy system ontology

The dynamics within the ontology are modeled according to the interaction mechanisms shown in Figure 3.27. Data properties together with the classes they belong to form an interaction relationship. Furthermore, an interaction relationship happens (potentially happens) within a computation model. A computation model can have more than one implementation. Each implementation can use a different calculation method that require different data in terms of level-of-detail By the end of this phase, the urban

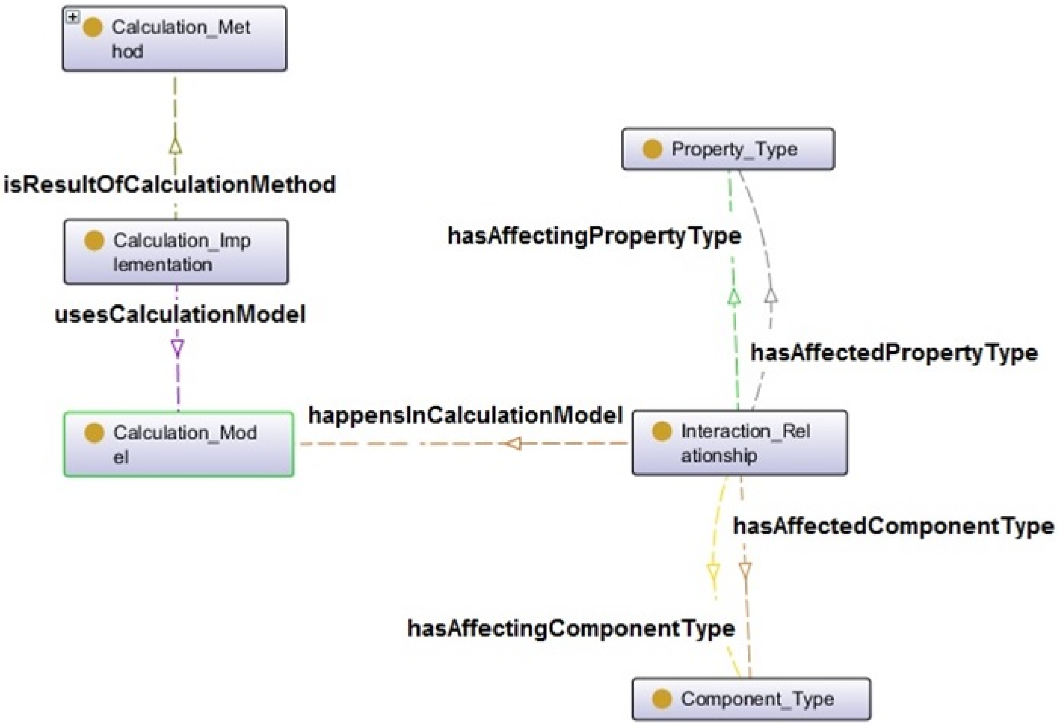


Figure 3.27: Ontology detail: Interactions mechanisms.

energy system ontology not only includes the domain concepts that describe it but also integrates concepts that explain it dynamics. In the next phase, more concepts are integrated within the urban energy system ontology so that it is aware of the opinion of the stakeholders that are involved.

3.4.5 F Decision modeling

The goal of this phase is to capture the knowledge of the different stakeholders (decision makers) concerning their interpretations of the different answers, to their questions raised in the scoping phase. Modeling the decision of (multidisciplinary) stakeholders summarizes the results of the calculations and makes their interpretations commonly understood among the multi-disciplinary teams. For instance, the meaning of a “peak electricity feed-in power” is understood mainly by electricity experts. Therefore, assigning a simple interpretation to values of this answer as “good” or “bad” makes it understandable by everyone. Having a common understanding of the output of the system is beneficial when negotiating energy plans in multi-disciplinary teams [OPS+13]. Modeling stakeholders’ knowledge about how to interpret the answers allows summarizing and simplifying the output so that it is more user-friendly i.e. instead of showing the exact figures

about each given building, they are classified as having high or medium potential from the stakeholders' perspectives. Eventually, the stakeholders accept (or reject) the implementation of a measure because of a given input information for their decisions. This input information is simply composed of answers to the questions they raise in the scoping phase.
The decision modeling phase gradually integrates the interpretations of the stakeholders into the urban energy system ontology. Figure 3.28 shows that in each cycle (for a given measure) a new set of decisions is integrated, in four increments. (i) Decisions of single stakeholders are modeled as if there is only one measure to be implemented and also as if there are no other stakeholders involved. (ii) Mutual decision are modeled from the perspective of all the stakeholders together, considering each other interests, but assuming that there is only one measure to implement. (iii) Decisions of single stakeholders are modeled as if there are no other stakeholders involved but considering that they could implement more than one measure. (iv) Mutual decision are modeled from the perspective of all the stakeholders together, considering each other interests and considering that they could implement more than one measure. The description of this process is explained below, in terms of detailed activities, input, output, and participating actors.

- **F1 identify value ranges:** the aim of this activity is to define ranges of values where the same judgment of a given stakeholder would apply. This is done because it is not possible to assign an interpretation to every single value.
  It is to recall that in the scoping phase, each answer (indicator) corresponds to one stakeholder (or stakeholder type, in the case of a building owner stakeholder type i.e. assuming that all instances from the same stakeholder type react the same way to the same information). Therefore, an interpretation range is related to one answer. If the same indicator is needed by more than one stakeholder, they are conceptually modeled as different indicators. Thus, each stakeholder makes a pass over the answers that have been indicated as required during the data modeling phase. Then, only the most important ones (from the perspective of the stakeholders) are selected for modeling values ranges. The selection of important indicators is motivated by seeking for simplifying negotiations between stakeholders.
  Input: the required input of this activity is expected answers list.
  Output: the output of this activity is a list containing for each answer ranges of values that the stakeholders would interpret the same way. This means that any two different values within the same range are to be interpreted the same way by the stakeholders.
  Actors: this activity is conducted by the stakeholders together with the energy planners as moderators.

- **F2 Define single-stakeholder & single-measure perspective interpretations:** the aim of this activity is to assign interpretations to the value ranges that are defined in the previous activity (activity F1). This interpretation represents the

opinion of the stakeholder about the potential implementation of a given measure, in a specific location. Each range is assigned an interpretation of "very good", "good", or "bad" (location) from the perspectives of each stakeholder.
Input: the required input of this activity is the answers' value ranges from the previous activity (activity F1).
Output: the output of this activity is the list of single-stakeholder & single-measure interpretations to the value ranges defined in the activity F1.
Actors: this activity is conducted by the stakeholders together with the energy planners as moderators.

- **F3 Upgrade ontology: Add single-stakeholder & single-measure (SSSM) perspective interpretations inference rules:** the aim of this activity is to upgrade the urban energy system ontology so that it becomes aware of the stakeholders' opinions (single-stakeholder & single-measure) regarding the data it contains. Therefore, classes are added to the ontology, including adequate inference rules.
  Input: the required input of this activity is the list of single-stakeholder & single-measure interpretations to the value ranges defined in the activity F1.
  Output: the output of this activity is an increment of the urban energy system ontology that includes:
  - The urban energy system concepts, object and data properties
  - Data integration concepts
  - Scenario configurations concepts
  - Stakeholders interpretations of the potential implementation of measures: SSSM

  Actors: this activity is conducted by the system developers.

- **F4 Define multiple-stakeholder & single-measure perspective interpretations:** the aim of this activity is to combine the interpretations of single stakeholders about single measures into a common agreement interpretation. Therefore, each location would be classified as "very good", "good", or "bad" from all the stakeholders together, in terms of its potential for the implementation of a given measure.
  Input: the required input of this activity is the list of single-stakeholder & single-measure interpretations to the value ranges defined in the activity F1.
  Output: the output of this activity is the list of multiple-stakeholder & single-measure interpretations to the value ranges defined in activity F2.
  Actors: this activity is conducted by the stakeholders together with the energy planners as moderators.

- **F5 Upgrade ontology: Add multiple-stakeholder & single-measure perspective interpretations (MSSM) perspective interpretations inference rules:** the aim of this activity is to upgrade the urban energy system ontology so that it becomes aware of the stakeholders' opinions (multiple-stakeholder & single-measure) regarding the data it contains. Therefore, classes are added to the ontology, including adequate inference rules.
  Input: the required input of this activity is the list of multiple-stakeholder & single-measure interpretations to the value ranges defined in activity F2.
  Output: the output of this activity is an increment of the urban energy system ontology that includes:
  - The urban energy system concepts, object and data properties
  - Data integration concepts
  - Scenario configurations concepts
  - Stakeholders interpretations of the potential implementation of measures: SSSM, MSSM

  Actors: this activity is conducted by the system developers.

- **F6 Define single-stakeholder & multiple-measure perspective interpretations:** the aim of this activity is to combine the interpretations of a given stakeholder about multiple measures. The interpretation of each stakeholder about a given measure considers the possibility that there are other measures that could be implemented as well. For example, a location that was very good in terms of the potential implementation of a measure A, and that generate benefit X, is not anymore "very good" once a measure B, requires less investment and generates a benefit that is greater than X.
  Input: the required input of this activity is the list of single-stakeholder & single-measure interpretations to the value ranges defined in the activity F1.
  Output: the output of this activity is the list of single-stakeholder & multiple-measure interpretations to the value ranges defined in activity F2, for all the measures within the scope of the system (incrementally defined in the scoping phase).
  Actors: this activity is conducted by the stakeholders together with the energy planners as moderators.

- **F7 Upgrade ontology: Add single-stakeholder & multiple-measure perspective interpretations (SSMM) perspective interpretations inference rules:** the aim of this activity is to upgrade the urban energy system ontology so that it becomes aware of the stakeholders' opinions (single-stakeholder & multiple-measure) regarding the data it contains. Therefore, classes are added to the ontology, including adequate inference rules.

Input: the required input of this activity is the list of single-stakeholder & multiple-measure interpretations to the value ranges defined in activity F2, for all the measures within the scope of the system (incrementally defined in the scoping phase).
Output: the output of this activity is an increment of the urban energy system ontology that includes:

- The urban energy system concepts, object and data properties
- Data integration concepts
- Scenario configurations concepts
- Stakeholders interpretations of the potential implementation of measures: SSSM, MSSM, SSMM

Actors: this activity is conducted by the system developers.

- **F8 Define multiple-stakeholder & multiple-measure perspective interpretations:** the aim of this activity is to combine the interpretations of single stakeholders about multiple measures into a common agreement interpretation. Therefore, each location would be classified as "very good", "good", or "bad" from all the stakeholders together, in terms of its potential for the implementation of a given measure, considering that other measure could be implemented as well, competing about the same resources.
Input: the required input of this activity is the list of single-stakeholder & multiple-measure interpretations to the value ranges defined in activity F2, for all the measures within the scope of the system (incrementally defined in the scoping phase).
Output: the output of this activity is the list of multiple-stakeholder & multiple-measure interpretations.
Actors: this activity is conducted by the stakeholders together with the energy planners as moderators.

- **F9 Upgrade ontology: Add multiple-stakeholder & multiple-measure perspective interpretations (SSMM) perspective interpretations inference rules:** the aim of this activity is to upgrade the urban energy system ontology so that it becomes aware of the stakeholdersâĂŹ opinions (multiple-stakeholder & multiple-measure) regarding the data it contains. Therefore, classes are added to the ontology, including adequate inference rules.
Input: the required input of this activity is the list of multiple-stakeholder & multiple-measure interpretations.
Output: the output of this activity is an increment of the urban energy system ontology that includes:

  - The urban energy system concepts, object and data properties

– Data integration concepts
– Scenario configurations concepts
– Stakeholders interpretations of the potential implementation of measures: SSSM, MSSM, SSMM, MSMM

Actors: this activity is conducted by the system developers.

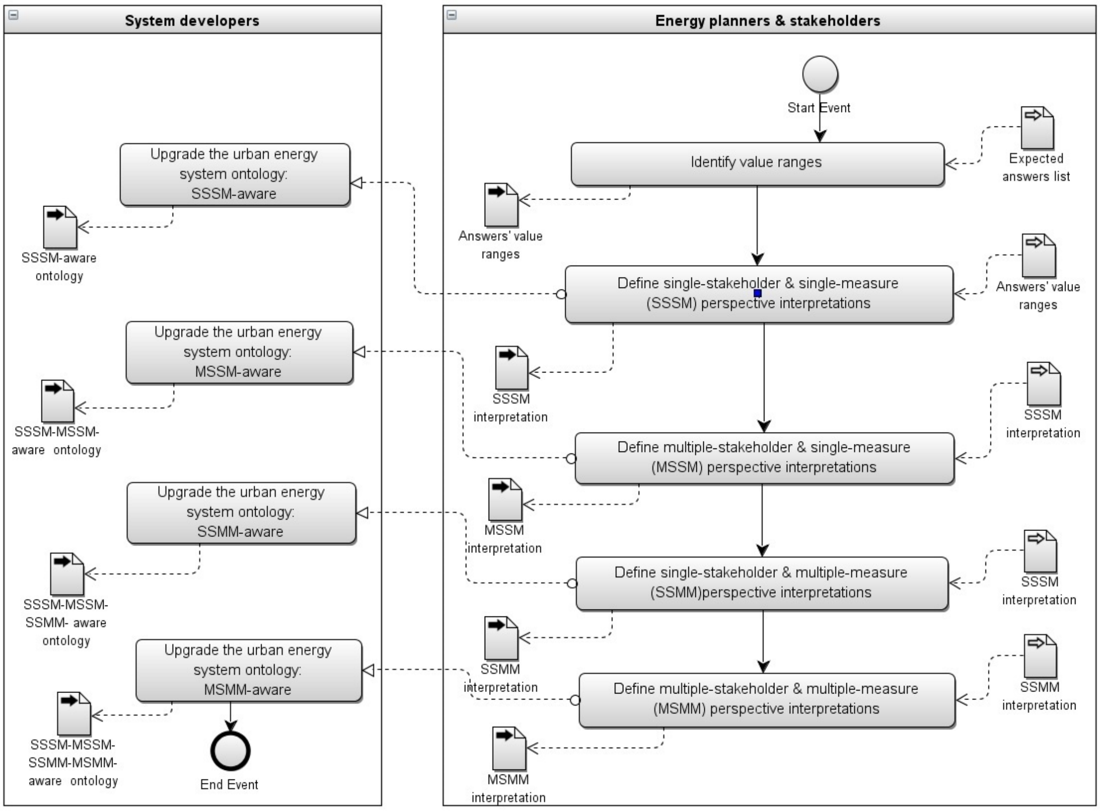


Figure 3.28: Decision modeling process model.

The Main concepts to support the decision modeling phase are shown in Figure 3.29. A Decision Concept is created as the parent class that comprises all the decision making concepts. The Decision Summary Classes concept clusters four different types of classes that are aligned with the decision modeling process described above: (i) Single Perspective Single Measure Based Decision Class: clustering classes where inference rules are defined to classify instances (locations) as “very good”, “good”, or “bad”. The perspective is from a single stakeholder, not considering the others and considering only one measure. (ii) Multiple Perspective Single Measure Based Decision Class: clustering classes where inference rules are defined to classify instances (locations) as “very good”, “good”, or “bad”. The perspective is from all stakeholders together, and it considers only one measure. (iii) Single Perspective Multiple Measure Based Decision Class: clustering classes where inference rules are defined to classify instances (locations) as "very good", "good", or "bad". The perspective is from a single stakeholder, not considering the others but considering all the other potential measures in which the stakeholder takes part. (iv) Multiple Perspective Multiple Measure Based Decision Class: clustering classes where inference rules are defined to classify instances (locations) as "very good", "good", or "bad". The perspective is from all stakeholders together, and it considers all measures (within the scope of the system) that can potentially be implemented.

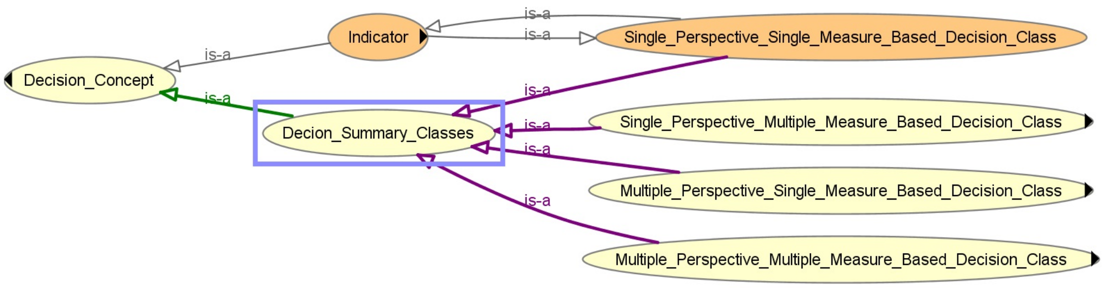


Figure 3.29: Ontology detail: Decision concepts.

By the end of this phase, the modeling part of the urban energy system ontology is completed. The ontology describes an urban energy system in terms of concepts it includes together with their object and data properties. Furthermore, dynamics within this urban energy system are captured and integrated within the same ontology, as data integration concepts. The dynamics within the urban energy system are derived from the data parameters interactions that are triggered by the computation models that are used to calculate answers (to the questions defined in the scoping phase). Finally, the ontology includes the opinions (potential decisions) of the different stakeholders. These opinions represent an abstract interpretation of the answers that the system offers. These interpretations are further processed so that common opinions (potential agreement on decisions) are modeled as well.
At this stage, the term ontology has been referring to the definition of ontologies as an explicit specification of conceptualization [GGP93]. Therefore, it does not contain any data, information or knowledge. In the next phase, the ontology is used as a basis to integrate data from different sources so that it can be used for decision support in urban energy planning.

3.4.6 G Data integration

The goal of this phase is to integrate the output of the different developed /re-used models, with other data sources, within the context of an urban energy system (i.e. creating an instance of an urban energy system). It is to recall that both the data and the models to be integrated are heterogeneous. The models are the results of different modeling approaches, from different natures and do not necessarily share the same data stores or format. The main problem addressed in this phase is to make the data that has been collected or calculated obey to the schema and logics defined in the urban energy system ontology. It is to recall that the data collection process at this stage is completed. Data have been collected in the data availability check phase, as well as in the data modeling phase, to complete the missing parts or to drop the data that are not usable. Furthermore, the computation models are used to process the collected data and produce answers to the questions of the stakeholders. Thus, all the required data to create an instance of an urban energy system is achieved. On the other hand, the urban energy system ontology gradually developed through the different phase, represents the logics of the urban energy system. Therefore, using the created ontology to integrate the collected and calculated data creates an instance of the urban energy system that can be used for decision support in urban energy planning.

Considering the scarcity of data at the level of cities, efforts to publish public data and make them interoperable are ongoing to deal with this data unavailability. Such initiatives include the open government data (OGD) of the USA and UK [DLE+11] or the linked open government data (LOGD) concept [BL09], [SOBL+12] that aims to establish links between open government data and make them integrated. A concrete pilot study has been performed in the UK (the Office of Public Sector Information) to implement LOGD to link data from several sectors [ADS+07]. Other approaches are based on semantic streaming, which uses ontologies and semantic web technologies to integrate data from heterogeneous sources. Such approach include the semantic streaming platform developed by Wetz et al. [bi1], based on using open linked widgets [TWD+14]. Other approaches are based on converting data from relational databases to a web browsing friendly format i.e. Resource Description Framework (RDF) [KC06]. There are tools performing these conversion operations, such as the D2R server [BC06]. There also exists a language R2RML [DSC12] for defining mappings that are customized from relational databases to RDF datasets.

The most adequate existing solution to the data integration problem addressed in this cases is a semi-automatic data integration tool called Karma [KSA+12]. This tool offers a graphical user interface to load data from different data sources format, including spreadsheets, csv files, spatial databases, relational databases, etc. Then an ontology that describes the data to be integrated is loaded as well as a basis for mapping semantic types between the loaded data sources and the domain ontology. Once the semantic mapping is finished, it is possible to generate source models, RDF data in our case. This tool has been used in different use cases of large data integration and publishing to the linked data cloud, such as the data of the Smithsonian American Art Museum [SKY+14], [SKY+13].

The adopted data integration flow using Karma tool is shown in Figure 3.30. Considering Karma as a black box tool, it takes as input the data to be integrated (from various data sources) as well as the urban energy system ontology that contains the semantic types that have been modeled in the previous phases. As an output of the tool, the data are integrated and published as RDF data. The only operation that is required to be performed within Karma is to map the semantic types of the data sources to those defined in the urban energy system ontology.

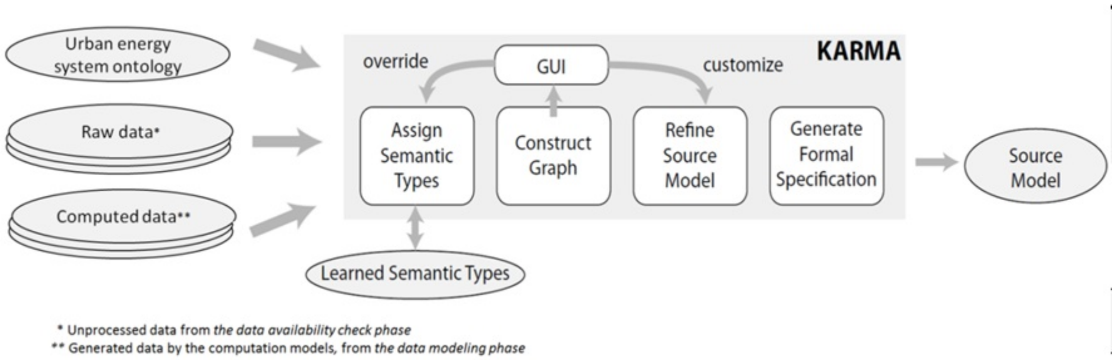


Figure 3.30: Karma tool data integration process [KSA+12].

As in this phase Karma data integration tool is used, its data integration process is adopted as well. The Karma data integration tool is integrated within the presented architecture in Figure 3.24, in the data modeling phase. The data collection, preparation, and integration flow architecture is show in Figure 3.31. Data are collected from the sources (e.g. municipalities, local authorities), then the collected data are processed by the developed/reused computation models to complete the data needs and to answer the questions of the stakeholders (formulated in the scoping phase), the Karma data integration tool is used to integrate all these data. Karma integration tool takes as input the urban energy system ontology as well. The data integration phase results in producing a source model as RDF.

By the end of the data integration phase, RDF data are generated representing integrated and semantically rich data. These data can be already used for supporting the decision making in urban energy planning support. The possible ways of using these data is further explained in the next phase.

3.4.7 H Data use

The goal of this phase is to use the RDF data that have been produced in the previous phase, to support the decision making in urban energy planning. As discussed in Chapter 2 (Urban energy planning support), different cities have different structures, involved stakeholders, and planning practices. Therefore, the focus in this phase is on presenting the possible ways of using the RDF data and exploiting them in a way that is independent from the specific conditions of cities. Hence, no specific data use process is presented, as it is out of the scope of this research.
It is to recall that the data calculations and the interface that the users access (for planning support) are designed decoupled. This means that the data computed beforehand, using the computation models (developed in the computation models development phase) are not recalculated. The dynamic recalculation of these data involve processing large datasets, which require more time than what can be tolerated while using the system. The

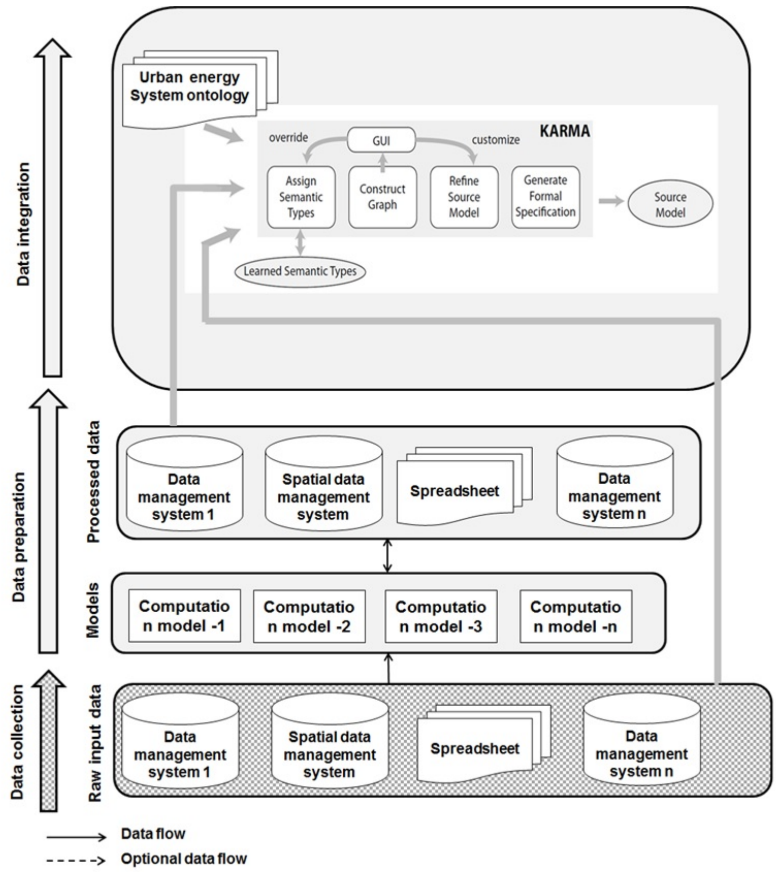


Figure 3.31: Data collection, preparation, and integration flow architecture.

typical use of a such system is in workshops that involve a variety of stakeholders besides the energy planners [Eur10]. Such workshops to develop energy strategies together with stakeholders have been organized in previous related work, such as the case of the projects Smart City Wien, Amstetten, or Linz [The11].

As any other type of data, RDF data (generated in the previous phase) can be exploited in different ways [BHBL09]. The semantic web technologies offer different tools, APIs, and methods to interact with RDF data. The most common ways to interact with RDF data include, linked data browsers, search engines, and domain-specific applications [BHBL09], and querying endpoints.

Linked data browsers are used the same way as web browsers. They allow users to navigate from an HTML page to another, following the hypertext links that represent RDF resources. These browsers display for each subject a number of predicates with their objects, where some of these predicates and objects are themselves hypertext links. Following their hypertext links lead to pages where they are considered as a subject and they have their own predicates and objects. Such linked browsers include, Tabulator [BLHL+08], [BLCC+06], Disco Hyperdata browser [BG07], or Marbles

[BB08]. Querying endpoints, known as SPARQL [PSo08] endpoints are an effective way for interacting with RDF data. SPARQL is to RDF data and data stores what SQL is to classic databases. Therefore, SPARQL endpoints give the opportunity to query RDF data over the web using a dedicated language. SPARQL endpoints are both manually accessible for more advanced users that want to interact with RDF datasets. Furthermore, they are considered as services of RDF stores that offer the possibility to remotely query them, by applications.
RDF data can also be processed through domain applications. Such applications offer a graphical user interface to the users, to which the data storage technologies are not transparent. These domain applications can be customized to be used for one specific use case of consuming RDF data. Alternatively, the applications can be more generic and give mechanisms of filtering, merging different data. The later type of applications mainly include mashup applications, which can be used by non-domain experts to customize what data to view from several data sources [KTP09]. Such applications include the proposed platform of Wetz et al. [bi1] which uses linked widgets [TWD+14], [TDW+13], each offering pre-built functionality that are linked to each other so that together they deliver the information of interest to the user. Deri Pipes [LPPTM08] is another example of mashup tools that do not require any programming skills to mashup different data sources to produce customized information. Deri Pipes was inspired from Yahoo! Pipes that deliver almost the same functionality with the difference that Yahoo! Pipes did not handle RDF data [Pru07]. A more comprehensive list of mashups tools has been described by Koschmider et al [KTP09], which addresses more general tools and details their functionality. In this phase, Data use, no specific way of consuming the RDF data is specified, in terms of data flow. This is due to the fact that cities might have different processes. However, the data use ways in figure are suggested. After the data integration phase both raw data and computed data are integrated using Karma tool, using the developed urban energy system ontology. The RDF data are then deployed in a server (e.g. Virtuoso Server [EM09], Sesame [BKVH02], or Jena SDB, which are the most popular ones [BS08]) that allow to link data to the linked open data cloud, if it is to be used by other users than the urban energy planners. Alternatively the server hosting the RDF data can be accessed in three different ways: using linked data browsers, a SPARQL endpoint (offered by most of RDF server), or a customized web client application.

3.5 Summary

The main goal of this chapter was to describe the generic methodology to develop an ontology-based decision support system in urban energy planning. The proposed methodology is an iterative process where the ontology is gradually built. The ontology comprises urban energy planning domain concepts, as well as other concepts that facilitates the data integration and the development of scenarios. Furthermore, the ontology includes concepts and inference rules that “emulate” the potential decisions and negotiations of decisions of the involved stakeholders in the planning process, concerning the potential implementation of given sets of measures. On the other hand, computation models are

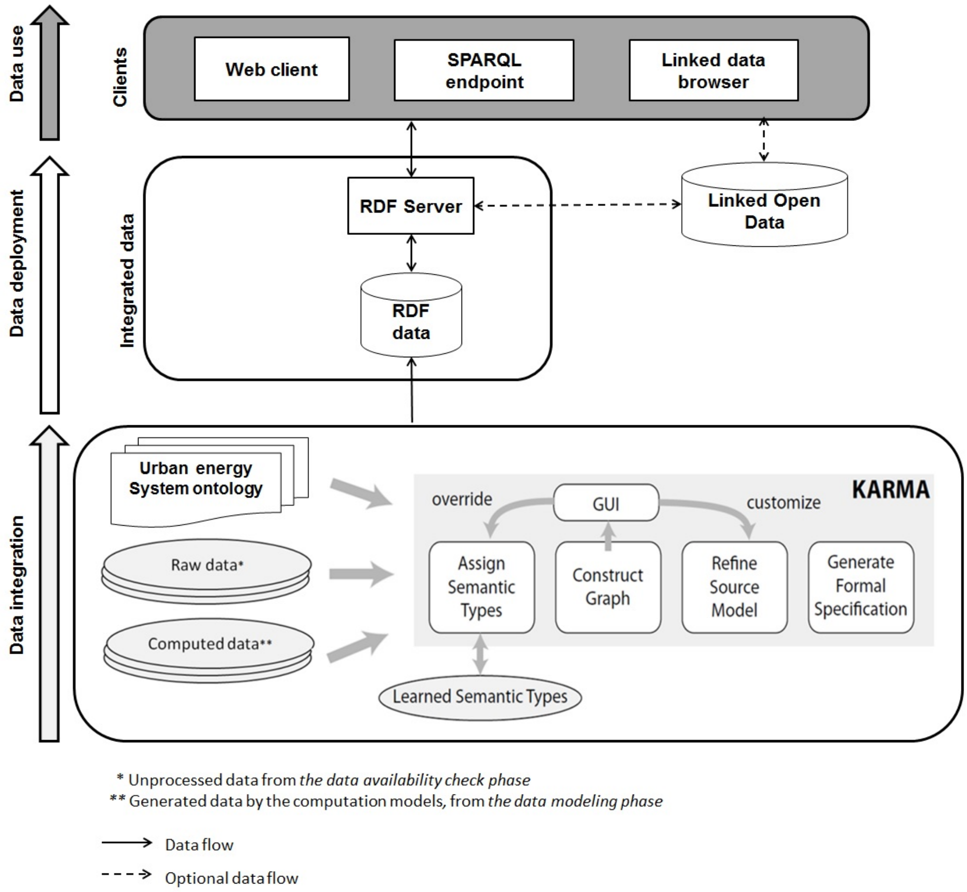


Figure 3.32: Data integration, deployment and use flow.

developed or re-used to calculate missing data that are required by the stakeholders. Then, the developed ontology is used to integrate the computed data (by the computation models) and the raw data that are collected at the beginning of the process. Once the data are integrated (using an existing data integration tool), the data are deployed in RDF format in an adequate server so that it can be consumed. The different ways the data can be used are web client applications, SPARQL endpoints, or linked data browsers, noting that it is also possible to link the RDF data to the linked data cloud, to be exploited by other users that were not initially considered but to whom the urban energy planning data might be useful.

The methodology is a generic one, in terms of measures that it could integrate, stakeholders that could be involved, or the city for which energy strategies are to be developed. In the next chapters, it is illustrated how this methodology can be used to develop a decision support system for energy planning that includes, first, solar PV planning, then, integrated solar PV with building refurbishment planning. These uses cases have different ranges of data availability and cover two aspects of urban energy planning i.e. decentralized renewable energy production and energy demand reduction (energy efficiency). The two measures consider both electric energy and thermal energy. Concerning the application of the measures, it considers a district of the city of Vienna with about 1200 buildings.

CHAPTER 4

Building-integrated solar PV planning support modeling

The goal of this chapter is to apply the methodology described in the previous chapter to develop an ontology-based decision support system for energy planning. This can be considered as a use case of the methodology (described in the previous chapter), which also serves as a validation for the proposed methodology.
This chapter is structured according to the main phases of the urban energy system modeling methodology, discussed in the previous chapter. This allows a better mapping between the theoretical methodology and its practical application. In the first section, an introduction to the use case is presented. Then, the scope of the system, in terms of building-integrated solar PV planning is defined. Then, data availability check concerning this measure is performed, within a the a district in the city of Vienna. Afterwards, the data modeling phase is discussed, in terms of parts of the ontology that are modeled. Then, computation models that are necessary to develop, providing the functionality defined in the scoping phase, are discussed. Then, interactions that represent the dynamics within the urban energy system (which are triggered by the computation models) are captured and integrated within the ontology. Afterwards, the potential decisions that the stakeholders involved in building-integrated solar PV planning are modeled and integrated within the ontology as inference rules. The collected data and the calculated data, using the computation models are then integrated in an RDF format, using an existing data integration tool, which takes the ontology as a basis for semantic mapping between the different data sources. Finally, a sample data use is presented with the results of the system.

4.1 Introduction

The goal of this section is to describe the use case: Building-integrated solar PV planning support modeling, and the motivation behind the choice of this specific use case.

4.1.1 Motivation

In order to meet its ambitious targets for climate and energy, the European Union defined the climate and energy package, which is a group of binding legislations [Eur12]. The targets that the European Union aims to reach (known as the 20-20-20 targets) by 2020 are as the following: The climate and energy package is a set of binding legislation which aims to ensure the European Union meets its ambitious climate and energy targets for 2020.

- Reducing greenhouse gas emissions by 20%, compared to the recorded levels in 1990.
- Raising the production (and consumption) of energy from renewable resources so that it supplies 20% of the energy demand.
- Improving the energy efficiency by 20%.

Integrating solar PV systems in buildings contributes in both producing energy from renewable resources (solar energy) and reduces the amount of CO_2 emissions, since it eventually substitutes another fossil fuel energy source. Therefore, this use case Building-integrated solar PV planning support modeling, helps addressing two of the 20-20-20 targets (which have been recently, since November 2014, updated in the same order to 40-27-27 targets by 2030), by providing support to urban energy planners to know where it is the best to invest, in terms of solar PV installations. Many local and national governments across Europe subsidize this measure (i.e. installing building-integrated solar PV systems). Therefore, building owners that are willing to install solar PV systems are financially supported in several ways, such as low interest loans, incentive feed-in tariffs, and direct contributions to finance a share of investment costs.
The city of Vienna, where the application of this use case takes place, provides subsidies for this measure [Aus]. Therefore, making informed decisions about planning this measure in a long term horizon would allow a better distribution of the budget, or even develop more customized funding schemes that are adapted to the reality.

4.1.2 Use case description

The goal of this use case is to assist urban energy planners to choose the best locations where to install building-integrated solar PV systems. The assessment of the suitability of the locations considers the different perspectives of the involved stakeholders in this measure. For example, a good location for installing solar PV systems is not only where the building owner is satisfied, but also where the grid operator has no objections.
The application of this use case takes place in the 4th district of Vienna , taking into

account 1200 buildings. The choice of this specific district is due to the important number of buildings it contains, yet still a graspable size of debugging or validating the results by manually retracing the results of the system.
At this stage, as long as the scoping phase has not been performed, the only specifications of the system that need to be addressed are the necessary conditions in urban energy planning support systems that were discussed in Chapter 2. These necessary conditions are as the following:

- Supporting the perspectives of different actors
- Shared understanding and quantifiable impact of decisions
- Measures integration and resources negotiation
- System viability through robustness against data availability problems

As the scoping of the system is also part of the methodology, the description of the use case is gradually building through that phase. Hence, the same use case (building-integrated solar PV systems planning) might be different in different cities. What completes the description of the use case is what stakeholders are involved, what questions they raise, and in which levels-of-detail data exist.

4.2 Scoping

The scope of the system is defined through the sequence of the activities that are defined in the scoping phase. The measure to be implemented, building-integrated solar PV, is described. Stakeholders that are involved are identified, as well as their roles in the planning process. Their main questions are listed, and then they are broken down to quantifiable sub-questions.

4.2.1 Define the measure to be implemented

The measure to be implemented, as stated above is building-integrated solar PV. This measure refers to the action of installing PV systems in buildings. The measure is not restricted only to PV installations on horizontal surfaces. It also includes vertical surfaces as well, provided that data exist about their solar potential. The measure only applies to buildings i.e. it does not include installing PV systems in any type of wasteland.

4.2.2 Identify the involved stakeholders

Installing building-integrated solar PV systems involves stakeholders, whose interests or activities are impacted. The identified stakeholders in the city of Vienna are as the following:

- Building owners: individuals or organizations that own buildings and have the legal rights to make modifications on them.

- City administration: The local authorities of the city of Vienna
- Grid operator: The organization that manages the infrastructure of the electric grid
- Electric energy suppliers: companies providing electricity (selling electricity) to end users

4.2.3 Identify the roles of the stakeholders

The roles of the stakeholders identified above are as the following:

- Building owners: the building owners are supposed to make the investment if they are willing to install solar PV systems on their buildings. Therefore, their role as a stakeholder is important, as they are the ones that make or do not make the investment to implement the measure.
- City administration: The city administration is considered as a stakeholder in this measure as they provide subsidies for building owners that are willing to install solar PV systems.
- Grid operator: as the responsible entity for the infrastructure and the normal operation of the electric grid, the grid operator is considered as a stakeholder. Their roles is to make sure that the potential implementation of the measure does not affect the noral functioning of the grid.
- Electric energy suppliers: installing solar PV systems means that there is an excess in electricity production that has to be reduced somewhere else. Therefore, the electricity market is affected by this measure, therefore, the interests of the electricity suppliers. Their role is to make sure that there is a stable electricity supply.
  However, the implication of this stakeholder is left out of the scope of this work, as the electricity market requires more detailed simulation tools to provide useful information. It is to recall that the type of systems being developed in this work fall in the comprehensive energy system models, which require lower levels-of-detail of data but address more domains [Jan00].

4.2.4 List the main questions of the stakeholders

The stakeholders that have been identified raise questions regarding the installation of solar PV systems. The questions that are raised identify concerns they might have regarding the potential implementation of the measure. These questions have been identified while interacting (informally) with stakeholders in Smart City projects, in which the Austrian Institute of Technology (AIT) took part of. These projects concerned the cities of Vienna, Linz, Amstetten in Austria [The11], and Nanchang in China. The main questions of the stakeholders involved in building-integrated solar PV installation are the following:

- Building owner: does it pay off to install PV on my building?
- City administration: where is it the best for the city, in terms of environmental impact, to subsidize PV installations?
- Grid operator: Will the installation of PV systems have an impact on the transformers within the low voltage grid?

4.2.5 Break the questions down into quantifiable sub-questions

The main questions are broken down to more concrete questions that together provide enough information to the stakeholders to make their decisions. These questions will represent the main competency questions of the ontology, and therefore the target ontology based system. The question breakdown, raised by the involved stakeholders in building-integrated solar PV, is as the following:

- Building owner: CQ 1 does it pay off to install PV on my building?
  - CQ1.1 What is the net present value of my investment?
  - CQ1.2 What is my investment Break-even duration?
  - CQ1.3 How much investment costs are required?
- City administration: CQ2 where is it the best for the city, in terms of environmental impact, to subsidize PV installations?
  - CQ2.1 How much subsidies are to be paid to PV installations?
  - CQ2.2 How much electricity is produced from subsidized PV installation?
  - CQ2.3 How much CO_2 emissions are saved with subsidized PV installations?
  - CQ2.4 What is the CO_2-emissions-saved-equivalent in terms of carbon sequestering by trees?
- Grid operator: CQ 3 Will the installation of PV systems have an impact on the transformers within the low voltage grid?
  - CQ3.1 What transformers are overloaded because of PV installations?
  - CQ3.2 What is the peak feed-in power at the transformers?
  - CQ3.3 How long does the overload occur?
  - CQ3.4 What is the electricity feed in quantity?
  - CQ3.5 How much is the direct use of the generated electricity?

The question breakdown defines the theoretical scope of the system. However, this theoretical scope might be unfeasible in case there are not enough data to answer all the questions. The next phase, data availability check, helps obtaining data to be analyzed by domain experts so that they know how far in detail they can go in answering or not answering the questions.

4.3 Data availability check

In this phase, the data are collected from the different available data sources in a non-formal way. The data that have been collected were provided by the city administration of Vienna, publicly accessible data sources (e.g. Statistik Austria), and technical reports or scientific papers.
The data requests are characterized by being broad at the beginning of the process, as no software tool exists (yet) to be configured with a fixed set of data parameters. The process is inverted in this case i.e. data are collected and then the system is developed to provide as much functionality as possible with the existing data. A sample data request form that has been used in this work for data collection purposes is shown in Figure 4.1.

Required Data for Smart City Decision Support Tool		
Categories		
Demographic data	necessary data	additional data (desirable)
Energy supply		
Building		
Transport		
Renewable Energy		
Emissions		
Demographic data		
Inhabitants (EW)	[-]	
Population development	[±% / a]	
Energy consumption increase	[±% / a]	
Waste (combustible)	[T / a]	
Energy (energy flow diagram)		
Gross consumption (energy, which is imported into the viewing limit)		
Natural gas	10790	[GWh / a]
(Import) electrical energy	970	[GWh / a]
(Import) district heating	0	[GWh / a]
Liquid fuels (fossil)	355	[GWh / a]
(Import) renewable energy sources (incl. Combustible waste)	700	[GWh / a]
solid fuels (fossil)	21240	[GWh / a]
Fuels	1300	[GWh / a]
Final energy consumption by energy source (after conversion)		
Natural gas	5305	[GWh / a]
electrical energy	4645	[GWh / a]
District heating	1390	[GWh / a]
Liquid fuels (fossil)	355	[GWh / a]
renewable energy sources, incl. combustible waste	310	[GWh / a]
solid fuels (fossil)	1920	[GWh / a]
Fuels	1300	[GWh / a]
Final energy consumption by sectors of consumption AND fuels		

in [GWh / a]	households	Industry	Services + Business	Transport
Natural gas	450	4580	265	10
electrical energy	260	3690	665	30
District heating	580	270	540	0
Liquid fuels (fossil)	30	295	30	0
renewable energy sources (Incl. Brennb. Waste)	20	270	20	0
solid fuels (fossil)	0	1920	0	0
Fuels (gasoline, diesel, biofuels)	0	0	0	1300

juid fuels (fossil)	renewable energy sources (Incl. Brennb. Waste)	solid fuels (fossil)	Fuels (gasoline, diesel, biofuels)
30	20	0	0
295	270	1920	0
30	20	0	0
0	0	0	1300

Figure 4.1: Sample data request form.

The data availability check was a phase where interactions with data providers were built to obtain as much data as possible. The data requests forms were oriented in a way such that the data providers are oriented to understand what category of data are of interest rather than asking for specific datasets.
The data that have been obtained from the city administration of Vienna included GIS-based data of buildings, buildings properties, and the solar potential cadaster of the

Vienna, indicating the potential of solar radiations in horizontal surfaces in the city, as shown in Figure 4.2. The solar potential cadaster represents the main data, on which the computation models development phase was based.
The Solar potential cadaster was constructed using LIDAR [Ren00] based technologies, described in Chapter 1. A high resolution database (in terms of the fine granularity of pixels to which data are assigned) has been constructed based on that technology, in 2007. The database indicates which areas within the city have what annual solar radiation. The following parameters have been considered in defining the annual solar radiations on surfaces:

- The orientation of the roof surface
- The inclination of the roof surface
- The shading of the roof surfaces caused by vegetation, buildings or even the terrain objects causing remote shadowing.
- An 18-year average of local global radiation in Vienna

Thus, the solar cadaster of the city of Vienna used in this work contains the usable surface areas of the buildings (roofs) and the solar radiation categories they belong to. The categories that have been considered is more than 1100 kWh per square-meter per year, more than 900 kWh per square-meter per year, or other potential that is less than 900 kWh, which was considered to be ignored (i.e. having not economically sufficient potential).

Figure 4.2: Solar potential cadaster of Vienna [Mag13].

Other main sources of data include the energy flow diagram of the city of Vienna, provided by Statistik Austria. An illustration of that diagram is show in Figure 3.15. The energy flows included the different types of fuels used in Vienna, including the imports of heat and electricity. The use of energy is also broken down into different sectors, easing the establishment of an emission inventory, as suggested by the SEAP process [Eur10]. Another set of data that was important to make the necessary calculations was the load profiles of the buildings. As there was no available measurements per building to know the exact electricity demand, typical load profiles have been used. The load profiles that have been collected are 15-minute based that show the electricity demand of a predefined set of types of buildings, over a whole year. Thus, for each type of buildings there are 35040 recordings.

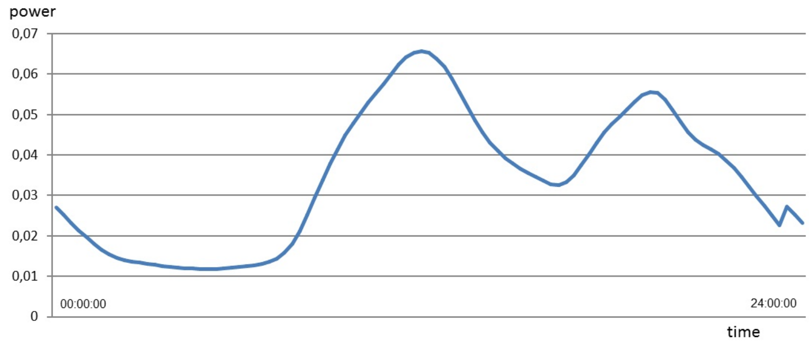


Figure 4.3: Sample electricity load profile of a residential building type in a day in January [EC12].

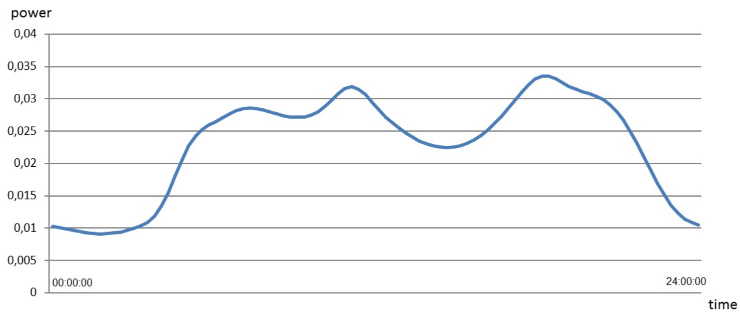


Figure 4.4: Sample electricity load profile of a residential building type in a day in July [EC12].

Other technical data that are related to PV technologies, such as efficiencies were found in technical reports or obtained from domain experts, such as [KS10], [SK10].

4.4 Data modeling/Computation models check

In this phase, customized calculation methods with respect to the data availability were developed together with domain experts from the Austrian Institute of Technology, namely

Mattias Stifter, Johannes Kathan, and Serdar Kadam as electric systems and technologies experts, Branislav Iglar as a financial expert and Florian Judex as a mathematician. The calculation methods were used as a basis for semantics extraction and classification, as explained before in the previous chapter.

4.4.1 Define expected answers

The expected answers were defined as a confirmation that the questions defined in the scoping phase are to be considered as competency questions of the system. The answers that the system provides are listed in Table 4.1.

Question	Answer
Q1.1	A1.1 PV Net present value
Q1.2	A1.2 PV Investment Break Even duration
Q1.3	A1.3 PV Investment Cost
Q2.1	A2.1 PV Funding cost
Q2.2	A2.2 PV subsidized electricity Production
Q2.3	A2.3 PV-saved CO_2 Emissions
Q2.4	A2.4 PV number Of CO_2 equivalent Trees
Q3.1	A3.1 PV Transformer overload Status
Q3.2	A3.2 PV Electricity feed-in peak power
Q3.3	A3.3 PV Transformer overload Duration
Q3.4	A3.4 PV Electricity feed in Quantity
Q3.5	A3.5 PV direct use of generated electricity

Table 4.1: Building-integrated PV related answers list

4.4.2 Computation models availability check

There exists computation models that can be used to answer some of the questions defined in Table 4.1. However, these tools and computation models require higher levels of detail of data. Such tools include EnergyPlus [CLW+01] or HOMER [AKK10]. A more comprehensive list of energy calculation and simulation tools are defined by Connolly et al. [CLML10]. These tools require more data than available in the city of Vienna, as most of them perform simulations at a building-level. Others that require less data do not provide the answers that the system is required to provide e.g. Urban Strategy [BSL+09].

Accordingly, customized (with regard to the data availability situation) computation models were necessary to develop.

4.4.3 Define/refine computation methodologies

The calculation methods descriptions that are adopted for each answer are listed below. The calculation algorithms are also captured during this activity and kept as a basis for the next phase (computation models development). Furthermore, the corresponding time, space, and technology LODs of the calculation methods is shown in Table 4.2.

- **CM 1.1**: based on discounted cash flow (DCF) analysis. The outflows only consider the investment costs. All the maintenance costs are ignored. The DCF analysis is carried over a time span of 25 years, which represent the lifetime of a PV installation, under its conventional operation conditions. It could drop to 20% less efficiency after 25 years. The DCF consider the inflation rate and the national fixed deposit rate.

- **CM 1.2**: based on DCF analysis. The outflows only consider the investment costs. All the maintenance costs are ignored. The DCF analysis is carried over a time span of 25 years, which represent the lifetime of a PV installation, under its conventional operation conditions. It could drop to 20% less efficiency after 25 years. The DCF consider the inflation rate and the national fixed deposit rate"

- **CM 1.3**: based on the estimation of the costs that are directly proportional to the nominal power of the installation. Two different intervals of nominal power are used:]0-5kWp[and $[5kWp, +\infty)$

- **CM 2.1**: based on the size of the PV system in terms of nominal power and total investment cost related to the system

- **CM 2.2**: based on annual electricity generation values of each PV system, associated to a building

- **CM 2.3**: based on the deduction of the equivalent CO_2 emissions produced to generate the electricity using a standard gas power plant technology (efficiency of 59%)

- **CM 2.4**: based on EPA method [EPA14] counting 25.6 trees, growing for 10 years, being able to sequester 1 t-CO_2 emissions.

- **CM 3.1**: based on the analysis of 15-min demand and generation profiles of the buildings that belong to the same low voltage grid. Transformer is flagged "overloaded" when the peak feed-in power is higher or equal to 70% (as a coincidence factor/diversity factor) of the capacity of the transformer. This calculation method was based on an existing methodology [AHC04], [ASHC01], which solves the problem that all the buildings of the same type are assigned the same load profile type. This methodology creates the required diversity in terms of buildings load profiles that is closer to reality.

- **CM 3.2**: based on analysis of demand and generation profiles of the buildings that belong to the same low voltage grid. The feed-in peak power is taken as the highest generation value when subtracting the demand profile from the generation profile of low voltage grid.

- **CM 3.3**: based on analysis of demand and generation profiles of the buildings that belong to the same low voltage grid. It is the sums of 15 minute intervals when peak feed-in power is higher or equal to 70% (as a coincidence factor/diversity factor) of the capacity of the transformer.

- **CM 3.4**: based on analysis of demand and generation profiles of the buildings that belong to the same low voltage grid. The feed-in quantity is the sum of generation values that are higher than the demand values in each 15 min.

- **CM 3.5** based the analysis of demand and generation profiles of each specific building in a given standard year. The direct use is taken as the ratio between the matched generation over the total generation.

An example of a more detailed description of these calculation methods is shown in Figure 4.5. It shows the sequence of steps that are necessary to conduct in order to reach the answer Annual electricity production (answer A2.2).

Calculation method	**Answer**	**Level-of-detail**		
		Time	**Space**	**Technology**
CM 1.1	A 1.1	Annual	Building	-
CM 1.3	A 1.3	Annual	Building	-
CM 1.3	A 1.3	-	Building	PV system
CM 2.1	A 2.1	-	Building	PV system
CM 2.2	A 2.2	Annual	Building	PV system
CM 2.3	A 2.3	Annual	Building	PV system Gas power plant
CM 2.4	A 2.4	Annual	Building	-
CM 3.1	A 3.1	15min-standard demand 1h-real generation	Building	Transformer PV system
CM 3.2	A 3.2	15min-standard demand 1h-real generation	Building	Transformer PV system
CM 3.3	A 3.3	15min-standard demand 1h-real generation	Building	Transformer PV system
CM 3.4	A 3.4	15min-standard demand 1h-real generation	Building	Transformer PV system
CM 3.5	A 3.5	15min-standard demand 1h-real generation	Building	PV system

Table 4.2: Building-integrated PV related calculation methods list

It is to be noted that only the main calculation methods of the expected answers are recorded. However, there are other intermediary calculations that are necessary but they are not recorded, as the stakeholders are only interested in obtaining a general idea on the calculation methods. Other intermediary calculation methods are also kept but separately in other documents that are associated to the development process of the system.

Intermediary answer: Annual electricity production of PV systems
Calculation method
Get Building
Get roof surfaces of building
Get the average annual solar radiation of surfaces exposed to radiations higher than 900 kWh
Get the average annual solar radiation of surfaces exposed to radiations higher than 1100 kWh
Get the protection status of the block/building
Get the PV technical feasibility status of the building
Get the ratio of the PV array to roof surface area
Calculate electricity production on roofs
Get roof surface area (>900 kWh and > 1100kWh)
Get PV installation type (medium, high, low)
Get PV installation nominal power
Get PV installation Self Consumption Ratio
Get PV Inclination Impact Factor
Multiply roof surface area by the factors above

Figure 4.5: Sample intermediary calculation method.

4.4.4 Semantics extraction and classification

The semantics extraction and classification phase leads to capturing domain concepts, related to components of the urban energy system that are related to building integrated solar PV planning. Accordingly, all the concepts, object properties, and data properties that are necessary to know about (by computation models, or by different domain experts, or stakeholders) are formalized in this phase.

The ontology is organized in three different categories of concepts: (i) domain concepts, grouping concepts that are related to building integrated solar PV and urban energy systems. (ii) Data integration concepts, grouping concepts that keep the requirements of the stakeholders involved in building integrated solar PV linked to their answers, making the adopted calculation methods transparent. Furthermore, it groups the concepts, which are necessary to formalize the interactions that happen within the urban energy system, caused by the computation models that perform the necessary calculations to reach the required answers (A1.1; A1.2; A1.3; A2.1; A2.2; A2.3; A2.4; A3.1; A3.2; A3.3; A3.4; A3.5). (iii) Scenario configuration answers, containing concepts regarding establishing an emission inventory [Eur10], as well as all the decisions classes and other concepts that the urban energy planners choose to include (or not include) when using the system, through a customized interface. An overview of these concepts is shown in Figure 4.6. A more detailed description of the building integrated solar PV concepts modeling is explained below.

Figure 4.6: Ontology detail: the main concepts.

As stated in the previous chapter, the semantic extraction is based on the calculation steps that are developed by the domain experts, such as the one shown in Figure 4.5. The key words in each calculation step are highlighted. The key words might refer to a concept, a data property, or object property.

Extracted building-integrated solar PV concepts

Concepts are characterized by being non quantifiable by themselves. They appear in calculation steps as objects that still need data properties so that they are described. For example "Building" or "Location" are concepts because they still need data properties to be described.
The calculation steps that have been outlined add to the ontology concepts that are related building-integrated solar PV. It is to note that all concepts that have the suffix

"Property" have been added for a better organization of the ontology: they contain the concepts that are related to the concepts followed by the suffix "Property". The main goal of this modeling decision is to make the ontology class hierarchy self-explanatory in terms of the relationships between the classes, with no need to browse the object properties of the ontology. The main concepts that have been captured are as described below:

- Energy Supply Installation Concept: A building-integrated solar PV installation is considered as an Energy Supply Installation concept. The choice of modeling it as an instance of the more general concept (Energy Supply Installation) is due to the fact that the ontology will include more energy supply installation types in the future. Figure 4.7, shows how the "energy supply installation" concept linked to the rest of the ontology. An energy supply installation is modeled also as a sub-class of the class Solar Area Property, meaning that a Solar Area concept has an Energy Supply Installation as an object property.

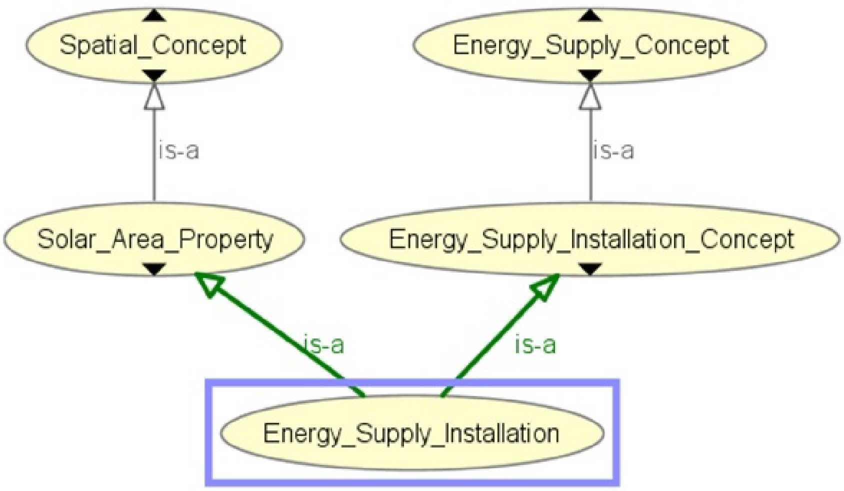


Figure 4.7: Ontology detail: Energy Supply Installation Concept.

- Solar Area (area exposed to gain solar energy): A solar area represents surfaces of locations that have a certain solar radiation exposure potential. In the case of Vienna, there are data only about horizontal surfaces (roofs of buildings). However, the concept Solar Area might stand for horizontal or vertical surfaces. This concept can be regarded as bundling the data properties of the solar potential cadaster and integrate it (the solar potential cadaster) in the context of an urban energy system. Figure 4.8 shows the related concepts to the Solar Area concept. It is both a geo-referenced spatial concept and an energy property of locations.

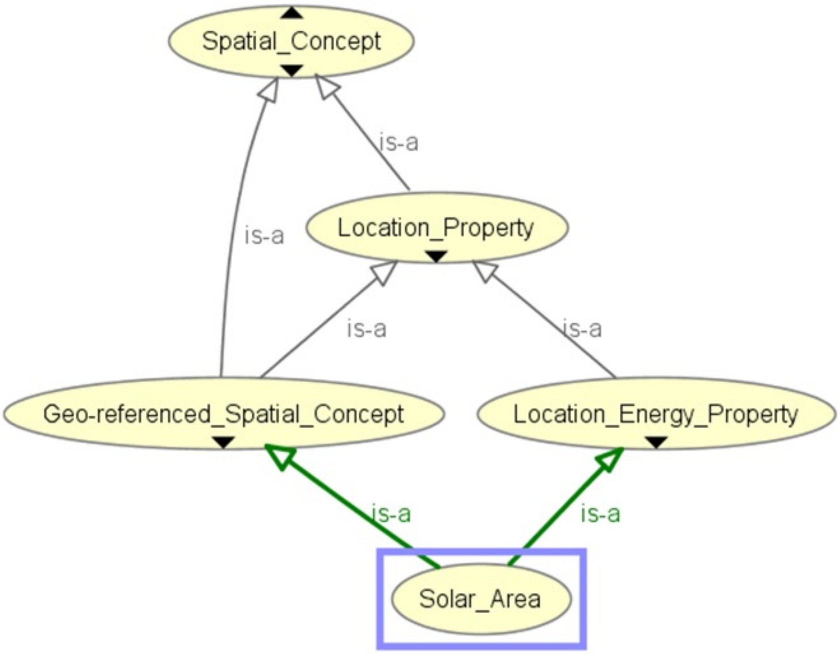


Figure 4.8: Ontology detail: Solar Area Concept.

- Energy Supply Technology Concept: As described before, the Energy Supply Installation concept does not specify the type of the energy installation. Therefore, the Energy Supply Technology concept comes as a property of energy supply installations, bundling the details related to the technology used, such efficiencies or used fuels. Figure 4.9shows the related concepts to the Energy Supply Technology Concept.

- Electricity Grid Concept: The electricity grid concept is required because the impact of installing solar PV on the infrastructure is necessary to compute. The infrastructure within the scope of interest is composed of the transformers of the low voltage grid. A low voltage grid in this case is composed of a given number of buildings that consume electricity, building integrated solar PV installations, and transformers.
  Ideally, the electricity produced is consumed within the low voltage grid (by other buildings that belong to the same low voltage grid). In other cases, the produced electricity is not all consumed within the low voltage grid. Therefore, the electricity flows to the medium voltage grid through the transformer. The power flow through the transformer has to be below a certain value that characterizes it, else the transformer is overloaded, which is a non-desirable situation.
  Figure 4.10 shows the electricity grid concepts. The main concepts are transformer and electricity grid, together with its subclass low voltage grid.

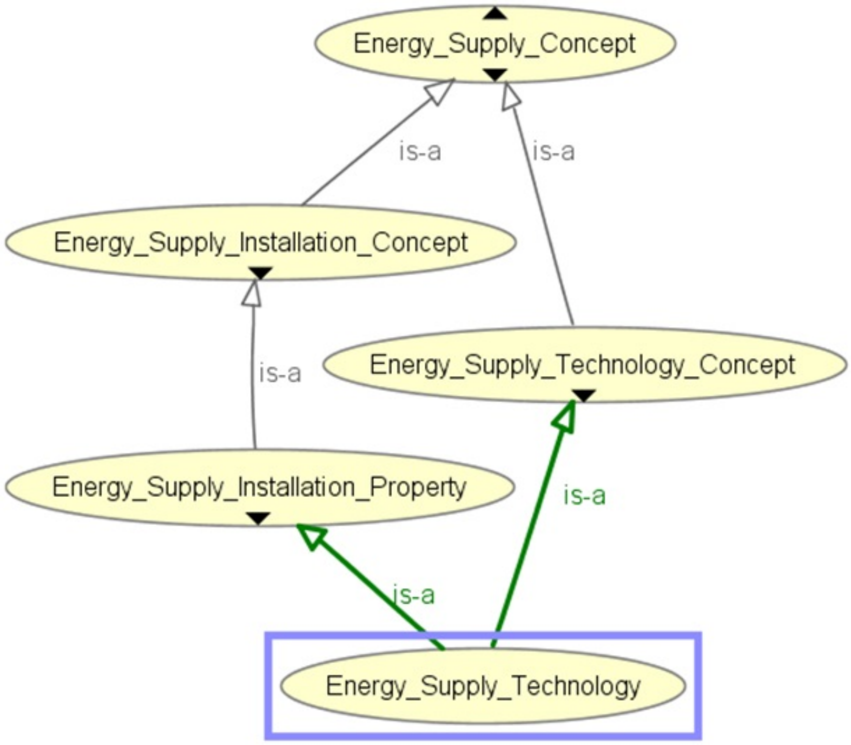


Figure 4.9: Ontology detail: Energy Supply Technology concept.

- Energy Profile Concept: this concept behaves as a time series data type. The computation models perform calculations that have a 15-minute time step over a whole year. Each energy profile instance bundles data of a time series of 35040 recordings. This concept is used as a property of different other concepts that require the description of energy demand or energy supply. Figure 4.11 shows the different concepts that require energy profiles including: solar areas (solar radiation profiles), locations (energy demand profiles), location use (standard demand profiles per building use [EC12]), energy supply installations (generation profiles), and low voltage grids (generation profiles, demand profiles, and matched load profiles [KS10]).

- Cost Concept: this concept comprises the necessary concepts for calculating the cost of the implementation of building integrated solar PV. Thus, funding scheme is a sub-concept of the cost concept, as shown in Figure 4.12. The funding scheme comprises bundles necessary data to compute the amount of subsidies to be paid by the city to the building owner. Thus, the concept actor is a funding property so that entities that receive or issue the funding are part of the system as well.

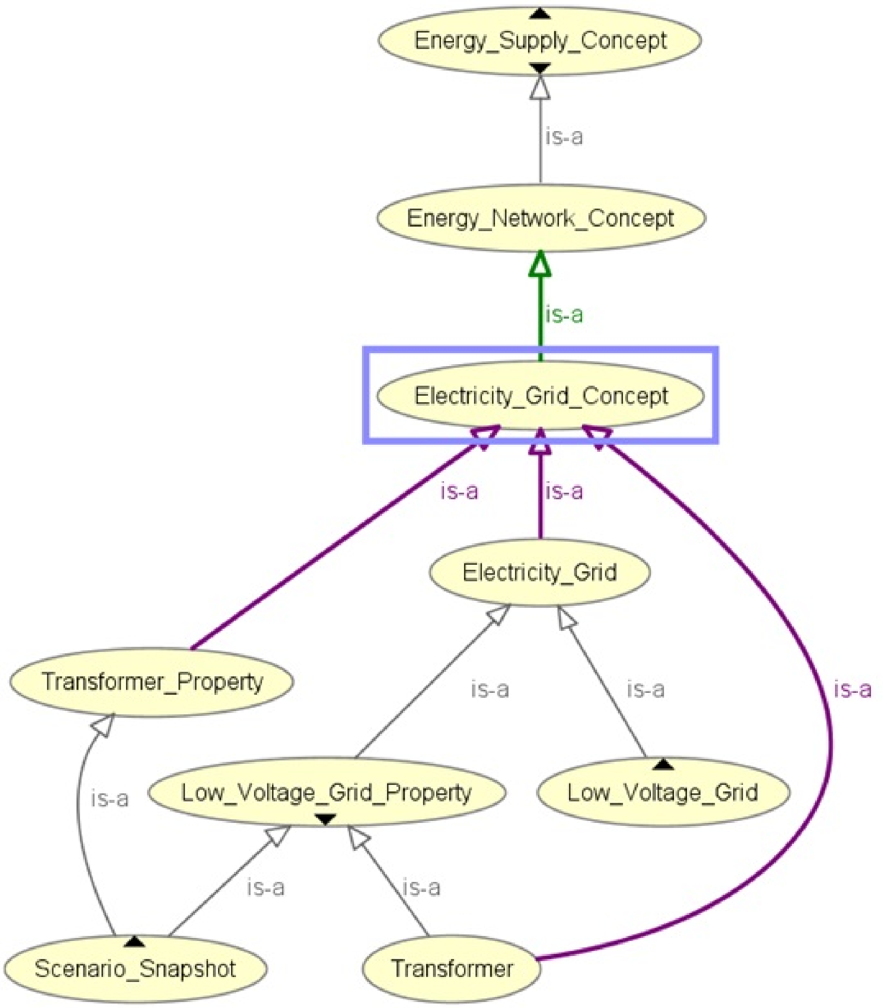


Figure 4.10: Ontology detail: Electricity Grid Concept.

Extracted object properties

object properties represent the relationships between two concepts i.e. one concept is a property of another. By analogy to classic databases, it is similar to the relationships that exist between two tables.

In the calculation steps, they are recognized in two ways: (i) when two concepts are written in the same step (line), implicating that a data property of a concept is needed to be reached through another concept. For example, in the step "Get surface area of the roof of building", the concept roof is related to the concept building. Therefore, an object property, which domain is building and range is roof would be "hasRoof". (ii) In a sequence of steps, a subsequent step might include concepts that are object properties of the previous one. For example, in Figure 4.5., the first step is "get building", the second

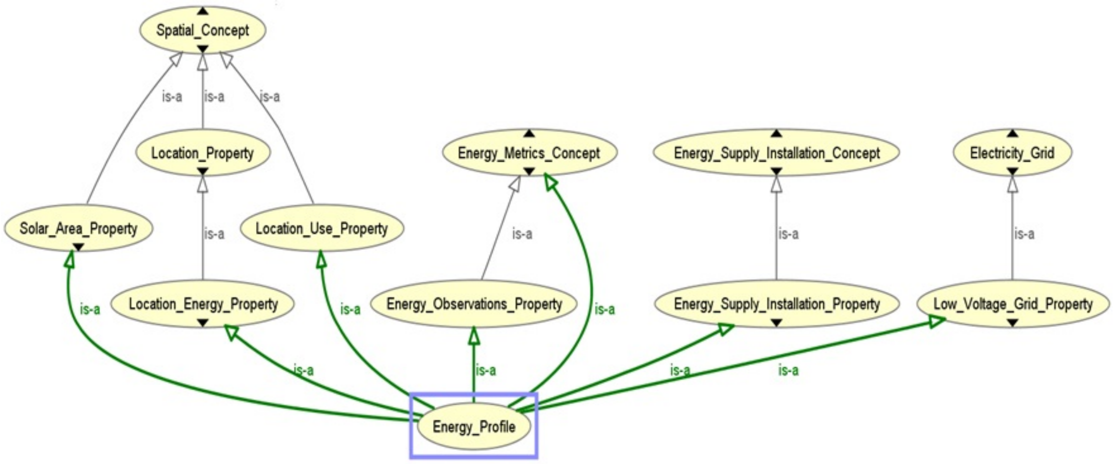


Figure 4.11: Ontology detail: Energy Profile Concept.

step is “get roof surfaces of building”, meaning that buildings have roof surfaces, which are considered as object properties of buildings.
As stated before, an adopted design principle is to add concepts with the suffix “Property” to concepts that are related to other concepts. Thus, the object properties of each concept are found under the construction <class name> <Property> class.
The main object properties in the ontology have been discussed above as sub-classes of concepts named <class name> <Property>. An overview of the modeled object properties, their domains, and ranges is shown in Figure 4.13.

Extracted data properties

Data properties represent the data parameters that describe instances of classes e.g. the surface area of a roof. The data properties are easy to capture as they represent any keyword within the calculation steps that is quantifiable.
The data properties that have been captured in this use case are shown in Figure 4.14. These data properties are used also by the computation models.

4.5 Computation models development

In this phase computation models are developed, implementing the calculation steps and methods that have been defined by the domain experts. The developed calculation models perform calculations to complete the data that are required by the stakeholders and urban energy planners. The computation models process raw data that have been collected from the different data sources, so that more data are created.
These calculation models are used in the data preparation phase. Therefore, the final use of the ontology-based planning support system does not invoke the use of these models. Once they perform the necessary calculations, they are disconnected from the

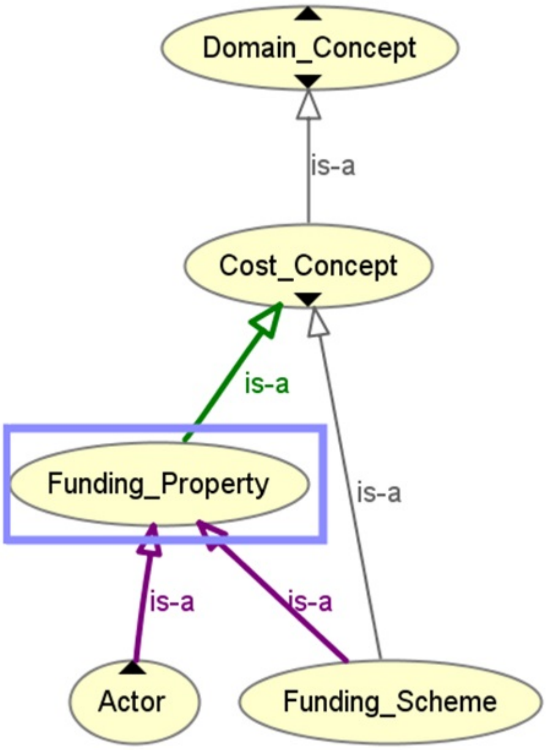


Figure 4.12: Ontology detail: Cost concepts.

final system, in terms of use. However, a link between the used computation models and the calculated data is maintained within the ontology, as part of the data integration concepts.
The choice of programming languages, data management systems, or technologies is not restricted by the methodology. In the case of the computation models required for the use case building-integrated solar PV, Java models have been developed (as listed in Table 4.3). As a database management system, a MySQL database [Sue02] has been used.

The developed computation models use data properties and produce/update other data properties, regarding installing building-integrated solar PV systems. These dynamics across data are considered to be the dynamics of the urban energy system, since the computation models aim to approach reality (in a low level of detail that is rather defined by the data availability in the city). These dynamics of the urban energy system are captured in the interaction modeling phase, as described below.

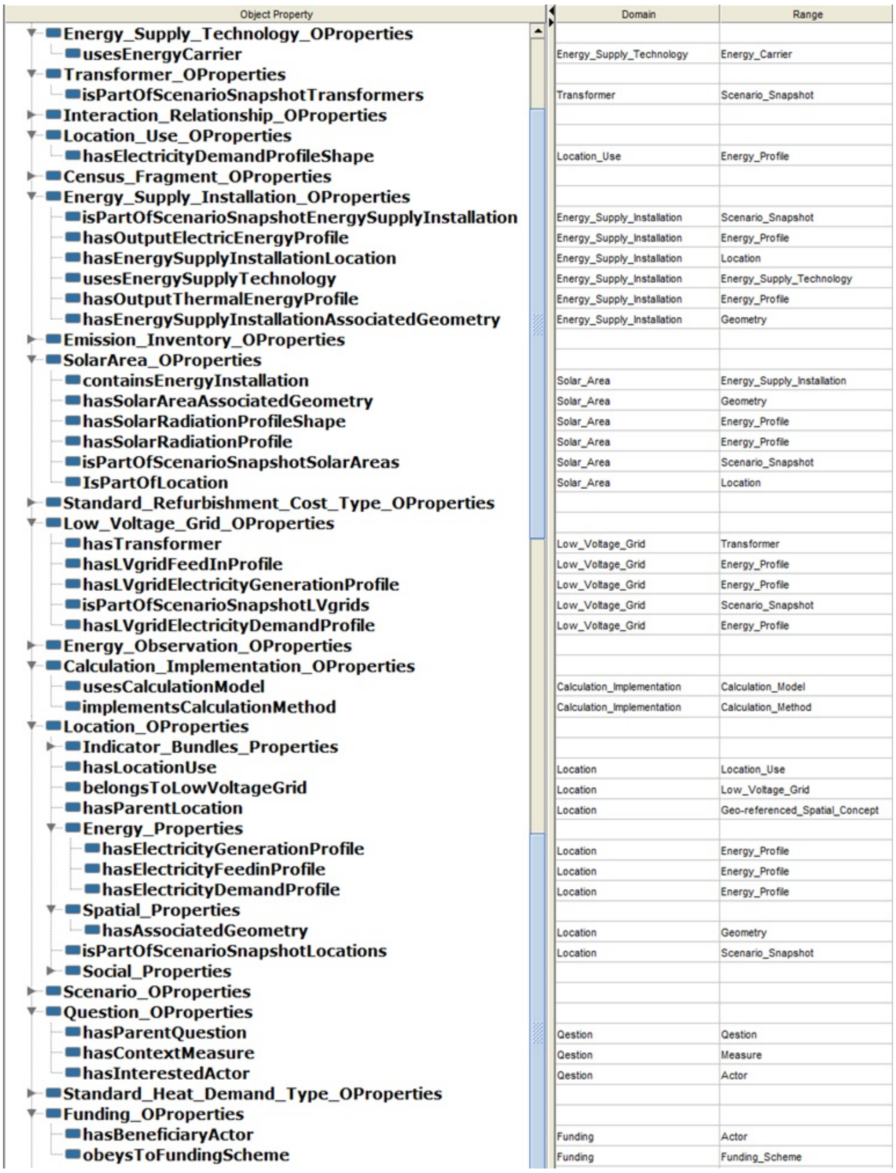


Figure 4.13: Building-integrated solar PV related object properties overview.

4.6 Interactions modeling

The interactions between different data properties (and objects) have been captured, and they depend on the computation models that have been developed shown in Table 4.3. Therefore, the interactions are coupled with computation models and using different computation models can cause non-similar interactions. Figure 4.15 shows that an interaction involves one affecting property and one affected property, which results in one affecting component and one affected component (i.e. the components which properties

Figure 4.14: Building-integrated solar PV related data properties overview.

are involved in the interaction). An interaction is also depending on one computation model. About a hundred interactions have been captured in this current case.

Computation Model ID	Computation Model
PV_1	Building annual electricity demand
PV_2	Building demand profiles generation
PV_3	Solar areas radiation profiles generation
PV_4	PV installations electricity generation profiles generation
PV_5	low voltage groups construction
PV_6	low voltage groups demand profiles generation
PV_7	low voltage groups electricity generation profiles generation
PV_8	low voltage groups feed-In profiles generation
PV_9	Low voltage groups overload status calculation
PV_10	low voltage groups overload duration and frequency
PV_11	low voltage groups feed-in quantity
PV_12	Building electricity generation quantity
PV_13	Electricity supply installation nominal power and price
PV_14	Update installation price and investment cost
PV_15	Buildings feed-In profiles generation
PV_16	Buildings direct use and feed In quantity
PV_17	Buildings self-coverage and direct use ratios
PV_18	PV Return on Investment calculation
PV_19	City investment calculation
PV_20	CO_2 savings and CO_2-Tree-Equivalent Calculation
PV_21	Voronoi GIS function for low voltage groups random generation

Table 4.3: Building-integrated solar PV related computation models

The interactions that were captured will also be integrated with the rest of the data under as data integration concepts. The comprehensive model that explains an interaction relationship is illustrated in Figure 4.16. Every interaction happens between two components (i.e. two instances of a class) an affecting component and an affected component. The interaction between two components happen because of a change in a data parameter in the affecting component (i.e. a data property of an instance of a class) and results in a change in a data parameter of the affected parameter. This model is used to integrate these data with the rest of the ontology in the data integration phase.

4.7 Decision modeling

A selection of indicators that stakeholders mainly use to make their decisions has been established, as described in Table 4.4. Then the stakeholders associate an interpretation (in natural language) to value ranges, which define how satisfied they are with the situation. Table 4.4 lists the value ranges and their associated interpretations from the single perspectives of all the involved stakeholders in building-integrated solar PV

Interaction ID	ModelID	Property URI	Component URI
1	PV_1	coPlan#hasLocationUseElectricityDemandIndex	coPlan#Location_Use
		coPlan#hasLocationElectricityDemand	coPlan#Location
2	PV_1	coPlan#hasLocationGFA	coPlan#Location
		coPlan#hasLocationElectricityDemand	coPlan#Location
3	PV_2	coPlan#hasLocationElectricityDemand	coPlan#Location
		coPlan#hasElectricityDemandProfile	coPlan#Location
4	PV_2	coPlan#hasElectricityDemandProfileShape	coPlan#Location_Use
		coPlan#hasElectricityDemandProfile	coPlan#Location
5	PV_3	coPlan#ReceivesSolarRadiation	coPlan#Solar_Area
		coPlan#hasSolarRadiationProfile	coPlan#Solar_Area
6	PV_3	coPlan#hasSolarAreaSurface	coPlan#Solar_Area
		coPlan#hasSolarRadiationProfile	coPlan#Solar_Area
7	PV_3	coPlan#hasSolarRadiationProfileShape	coPlan#Solar_Area
		coPlan#hasSolarRadiationProfile	coPlan#Solar_Area
8	PV_4	coPlan#hasSolarRadiationProfile	coPlan#Solar_Area
		coPlan#hasOutputElectricEnergyProfile	coPlan#Energy_Supply_Installation
9	PV_4	coPlan#hasSystemElectricEnergyConversionEfficiency	coPlan#Energy_Supply_Technology
		coPlan#hasOutputElectricEnergyProfile	coPlan#Energy_Supply_Installation
10	PV_4	coPlan#hasSolarRadiationProfile	coPlan#Solar_Area
		coPlan#hasEnergySupplyInstallationNominalPower	coPlan#Energy_Supply_Installation
11	PV_4	coPlan#hasSystemElectricEnergyConversionEfficiency	coPlan#Energy_Supply_Technology
		coPlan#hasEnergySupplyInstallationNominalPower	coPlan#Energy_Supply_Installation
12	PV_5	coPlan#hasGeometryID	coPlan#Geometry
		coPlan#belongsToLowVoltageGrid	coPlan#Location
13	PV_5	coPlan#hasOutputElectricEnergyProfile	coPlan#Energy_Supply_Installation
		coPlan#belongsToLowVoltageGrid	coPlan#Location

affecting component/property

affected component/property

Figure 4.15: Sample building integrated solar PV related interactions.

planning.
It is to note that the figures of the value ranges are subjectively chosen and can be customized once specific stakeholders are defined.

Stakeholder	Indicator	Value range	Interpretation
Building owner	Net present value	]€10000,€25000]	Good
		]€25000,$(+\infty)$[	Very good
City administration	CO_2-equivalent Trees	]200,350]	Good
		]350, $(+\infty)$[	Very good
Grid operator	Transformer overload	yes	Not allowed
		no	Allowed
	Direct use of generation	]80%,90%]	Good
		]90%, 100%[	Very good

Table 4.4: Building-integrated PV related value ranges interpretations

After capturing the single perspectives interpretations, an aggregated interpretation from all the perspectives together is established. Priority has been given to the grid operator, in case the measure involves changes in the grid (i.e. transformers overloaded).

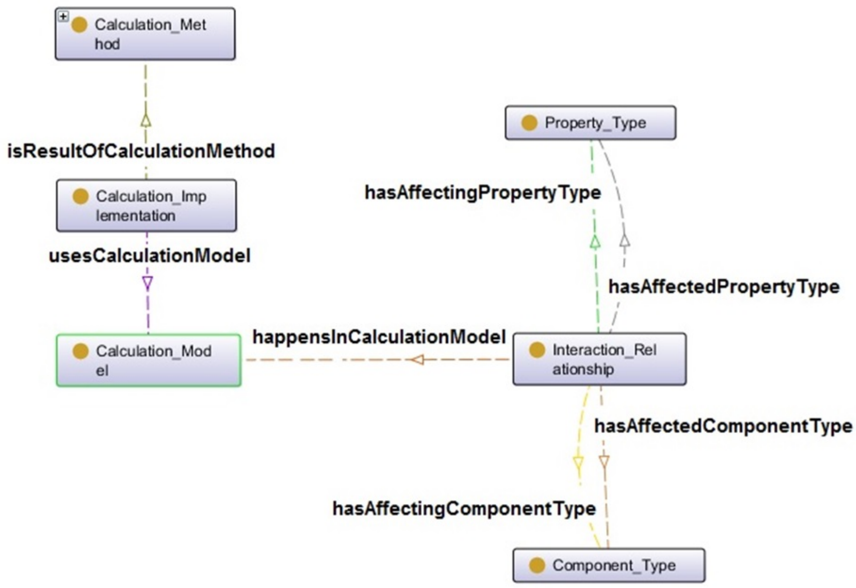


Figure 4.16: Interactions model.

The second priority was given to the building owner, as the investment is initiated by this stakeholder. Finally, the city administration is given the lowest priority. The Multi-perspective aggregated interpretations are shown in Table 4.5.

Stakeholders interpretations			**Aggregated Interpretation**
City Administration	**Building Owner**	**Grid Operator**	
Very Good	Very Good	Very Good	Very Good
Very Good	Very Good	Good	
Good	Very Good	Very Good	
Good	Very Good	Good	
Very Good	Good	Very Good	Good
Very Good	Good	Good	
Good	Good	Very Good	
Good	Good	Good	
Very Good	Very Good	Not Allowed	Bad
Good	Good	Not Allowed	
Good	Very Good	Not Allowed	
Very Good	Good	Not Allowed	

Table 4.5: Multi-perspective-aggregated interpretation

4.7.1 Implementation of the decision modeling

Each location (building) has associated information, which answers the questions of the stakeholders (building owner, grid operator, and city administration). These answers are grouped by stakeholder in a class that is called Answer Bundle. Therefore, each location in this case has three different associated answer bundles (one answer bundle for each stakeholder), as shown in Figure 4.17.

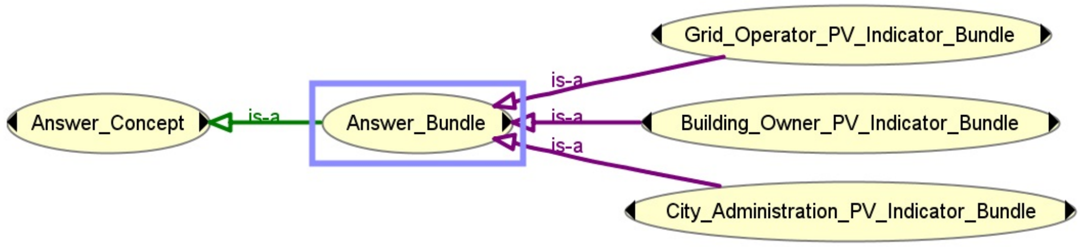


Figure 4.17: Building-integrated solar PV related answer bundles.

Thus instances of the class Answer Bundle contain enough data so that they are flagged as being “very good”, “good”, or “bad” form the perspective of the stakeholders. For example *Building Owner PV Indicator Bundle* class comprises answers to all the questions that the building owner (as a stakeholder) formulated in the scoping phase, as shown in Figure 4.18.

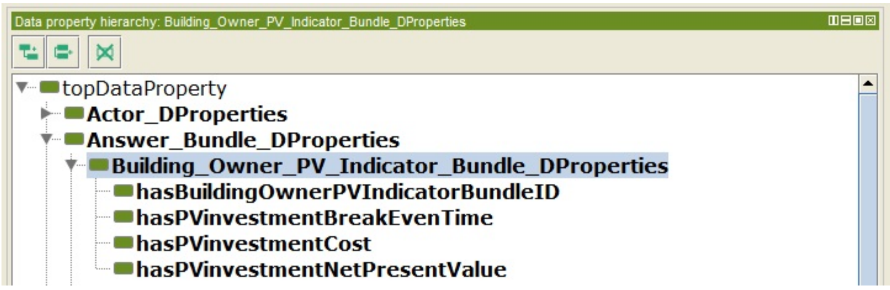


Figure 4.18: Building-integrated solar PV related answer bundles.

Based on the values of these data properties inference rules are developed to classify these indicator in different classes: very good potential, good potential, or no potential at all in the case that installing solar PV systems would require changes in the infrastructure (i.e. increasing the capacity of the low voltage grid transformer). Therefore, other classes are created, as shown in Figure 4.19, representing logic classes where instances of the Answer Bundle class will be inferred as being part of based on the logics in Table 4.4.

An example of the implementation of these logics within the ontology is show in Figure 4.20. It represents the necessary conditions so that an instance of the Answer Bundle class is inferred as a *Building Owner Good Potential PV Indicator*. Therefore, an

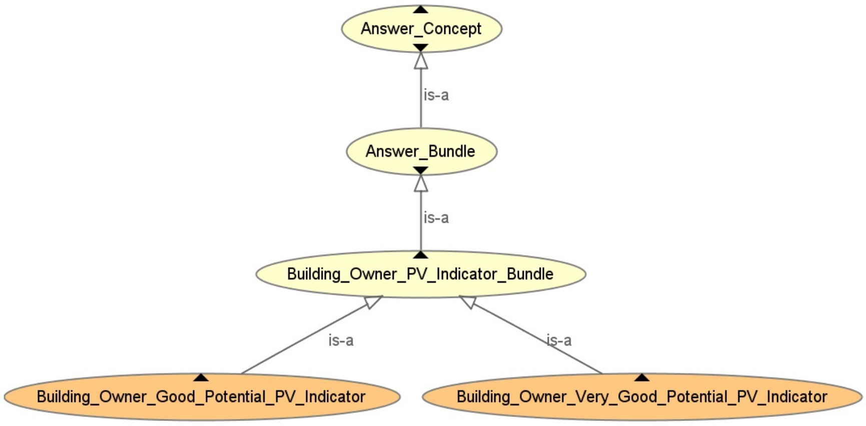


Figure 4.19: Sub-classes of the building owner PV indicator bundle.

implementation of classification of locations from single perspectives of stakeholders is achieved, regarding the measure building-integrated solar PV.

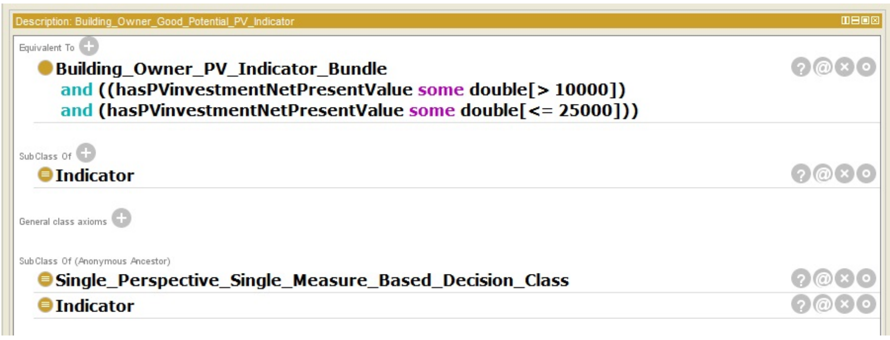


Figure 4.20: Necessary conditions of the class Building Owner Good Potential PV Indicator.

Concerning the assessment of locations from the perspectives of all the stakeholders together, it is based on the single perspective assessments. As described in Table 4.5, combinations of single perspective assessments result in a common assessment from all the perspectives together. Therefore, the indicators that inferred for each location are used. For example, a location is inferred to be “very good” for all stakeholders in four cases. One of which is if it is very good for all of them. This is implemented within the ontology as a class “PV Very Good Potential Location MPSM” with necessary conditions as shown in Figure 4.21.

By the end of this phase the development of the ontology is complete. The ontology represents an urban energy system within the scope of building integrated solar PV i.e. containing all concepts that belong to this domain and making calculations about it. Moreover, the ontology includes concepts that are related to the integration of the

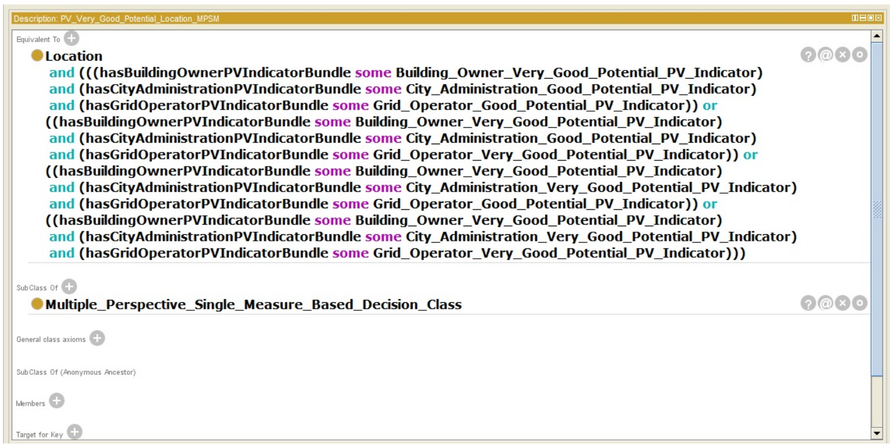


Figure 4.21: Necessary conditions for the class PV VeryGood Potential Location MPSM.

computation models that were developed and how they influence the urban energy system, in terms of interactions (that are considered to be the dynamics within the urban energy system). Finally, the ontology includes the knowledge of the stakeholders in terms of how they interpret their interests if building-integrated solar PV is to be implemented. So far the ontology is considered as an explicit specification of conceptualization [GGP93]. The ontology does not integrate data yet. In the next phase, the ontology is used to integrate the different data that have been collected or generated, using the developed computation models.

4.8 Data integration

The aim of the semantic integration of data is to use output of the different developed models [OLGG+14] (in Table 4.3), within the context of a system. These models are the results of different modeling approaches, from different natures and do not necessarily share the same data stores or format.
An existing data integration tool (Karma [KSA+12] has been used to integrate the data that has been generated and the data that has been collected. The semantic integration is based on the urban energy system ontology that has been developed through the previous phases. Thus, a mapping between the data parameter names within the data sources and the modeled semantics in the urban energy system ontology is established. Figure 4.22 shows an example of the mapping process flow. A table called locations has been uploaded in Karma from a MySQL database, then the data parameters names within this table are mapped with the ontology (which has been uploaded to Karma, as an input).

After all links are established, between the semantics of the ontology and the data parameters names of the data sources, data are integrated and uploaded in a specific file format that is more appropriate to semantically rich data. The specific format is in a Resource Description Framework (RDF) [KC06], an XML based format that combine

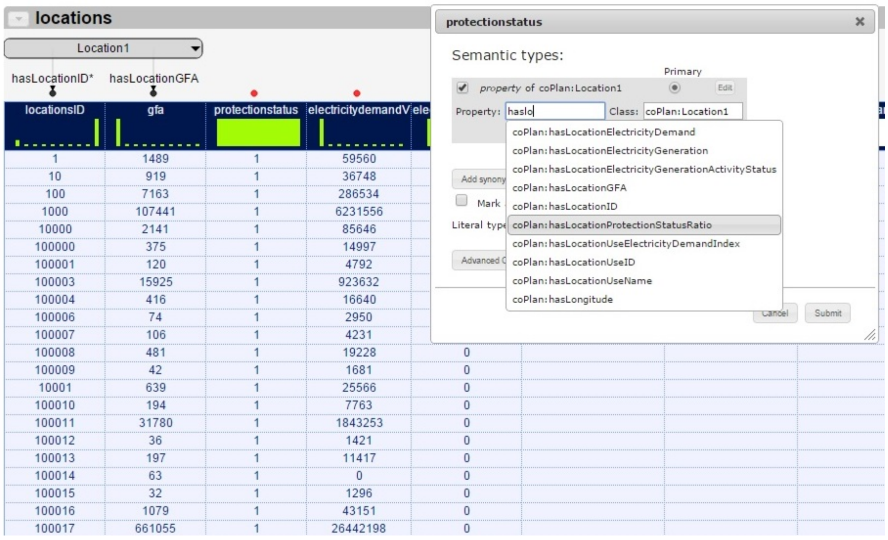


Figure 4.22: Data integration process flow using Karma [KSA+12].

data with its meta-data that describes its semantics, relationships, and therefore puts it in the context of the whole semantic model.
Thus the output of Karma, and the data integration phase, is an RDF file. The RDF data represent a knowledge base that embeds answers to the questions raised by the stakeholders in the scoping phase. All the semantics are preserved when using this type of data representation (RDF) i.e. descriptions of concepts, object properties, data properties, the dynamics of the urban energy system, the models that were used, etc. By the end of the data integration phase, the data, information, and knowledge that are needed in the planning building-integrated solar PV systems in the city are ready. Applications and browsing/querying systems can be used by urban energy planners.

4.9 Data use

There are different possible ways to use and interact with the integrated data. Once available in RDF format, the data can be deployed in an RDF repository, such as Virtuoso server [Ope14], giving the possibility to use the data in three ways (three client types), as shown in . Figure 3.32.
First, it is possible to query the data. They are available on the web and can be queried using a dedicated language, SPARQL [PSo08], that has a specific syntax and that offers a similar functionality as SQL.
The second possibility to use the RDF data is though linked data browsers. Such browsers, e.g. Tabulator [BLCC+06] are used to navigate through linked data, not requiring any programming knowledge.
Finally, it is possible to develop a web client that interacts with the integrated data, as it

was the case in this work. It is a JavaScript based interface, using google maps to display geo-referenced data. The interface has the goal to implement the process the planners want to adopt i.e. how to present the integrated data and under which workflow.
Here, an interface has been developed as shown in Figure 4.23. The interface displays locations according to their potential for containing PV systems. The classification of the buildings is done from the single perspectives of each involved stakeholder, then from the perspective of all of them together. The goal of this workflow is to choose the buildings that are most suitable for installing solar PV systems. More detailed information is also available about each building, which includes the answers to all the questions raised by the stakeholders.
In fact, the aim of this phase is rather to show an example of a possible way of using the system rather than proposing a process of how to use the system. This use case (building-integrated solar PV) is a proof of concept of the methodology that was described in the previous chapter. It is specific to the city of Vienna. Therefore, as stated in the design principles in chapter 3, the viability of the system requires that it can be customized to be used in different cities. The use of data (data flow, stakeholders to participate, interfaces, etc.) is part of this customization. A generic process of using these data is discussed in the Chapter 6 as future work and further development.

4.10 Summary

The final results of using the ontology-based system are about classifying buildings in terms of their suitability to install building-integrated PV. Thus, based on indicators at each single building level, buildings are classified according to their suitability for solar PV from single stakeholders perspectives. Then, the classification is aggregated to a common suitability from all the perspectives together.
The starting point and the basis of all the classifications are the indicators that are related to buildings. They show details (information that stakeholders are interested in) about buildings from different perspectives. The indicators represent answers to the questions that have been elaborated during the scoping phase. Table 4.6 shows indicators that are obtained at a single building level.

Figure 4.24 shows the number of buildings that are classified as very good, good, or bad from each single perspective. It is to note that all the buildings are geo-referenced and these data are included within the ontology. Therefore, it is also possible to display the buildings on a geo-referenced context (map).

It is also possible to obtain more abstract data about each building i.e. the classification of buildings in terms of their suitability for solar PV from all the perspectives together, as shown in Figure 4.25.
The presentation of data in an aggregated manner as quality indicators allows the different stakeholders to have a common discussion ground, where all their interests are considered. This is an effective way of planning at a city level, where it is not to possible to discuss the details about each single building. In brief, the proposed solution allows the aggregation

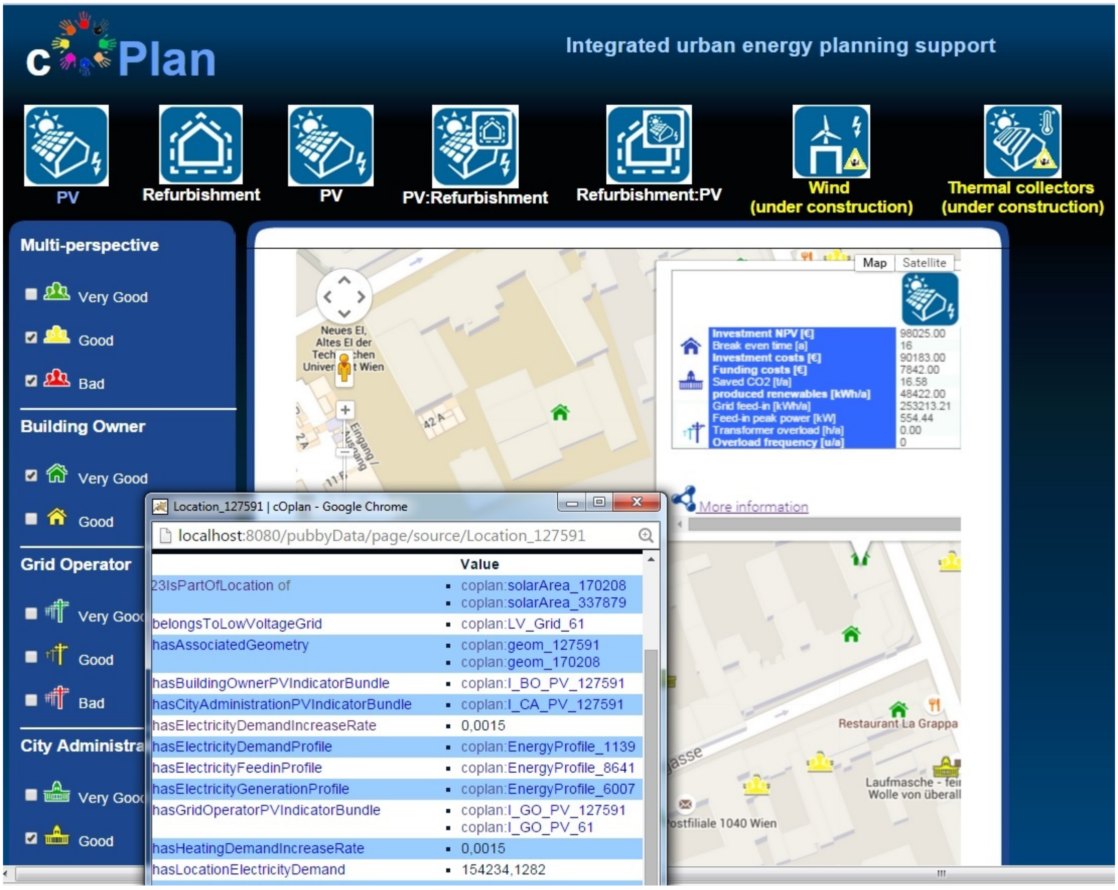


Figure 4.23: Building-integrated solar PV planning support sample interface.

of buildings' assessment to a high level of abstraction, while it is still possible to "zoom-in" and obtain more detailed data about each single building.

The proposed solution can be compared to a similar purpose tool (a previous related work), which has been previously developed at the Austrian Institute of Technology. The developed tool in the context of Smart City projects [The11] is an excel based tool that integrates measures to reduce CO_2 emissions in the city of Vienna. Therefore, its input is a set of quantities to a pre-defined set of measures and its output is the impact on the city in terms of four indicators (renewable energy productions, CO_2 emissions, energy efficiency, and modal split, which related to mobility).
The implementation of building-integrated solar PV in the excel-based tool does not consider the city as geo-referenced context, does not consider the specific buildings potentials, nor does it consider the electric grid infrastructure. The excel-based tool considers the city as a sum of square meters of potential roofs to install solar PV systems, regardless of where they are located. Moreover, these square meters of roofs with solar PV potential are not broken down at the level of buildings. The input (number of square

Perspective	Indicator	
Grid operator	Electricity Feed-in Quantity [kWh]	100,465
	Electricity Feed-in Peak Power [kW]	419
	Overload Duration [h]	0
	Overload Status (yes/no)	no
	Direct Use Of Generated Electricity [%]	90%
Building owner	Net Present Value [€]	73,425
	Investment Break-Even Time [a]	16
	Investment Cost[€]	67,551
City administration	PV Funding cost[€]	5,874
	Subsidized PV electricity Production [kWh]	36,260
	PV saved CO_2 Emissions [t-CO_2]	12
	Number Of CO_2 equivalent Trees	318

Table 4.6: Sample single building indicators

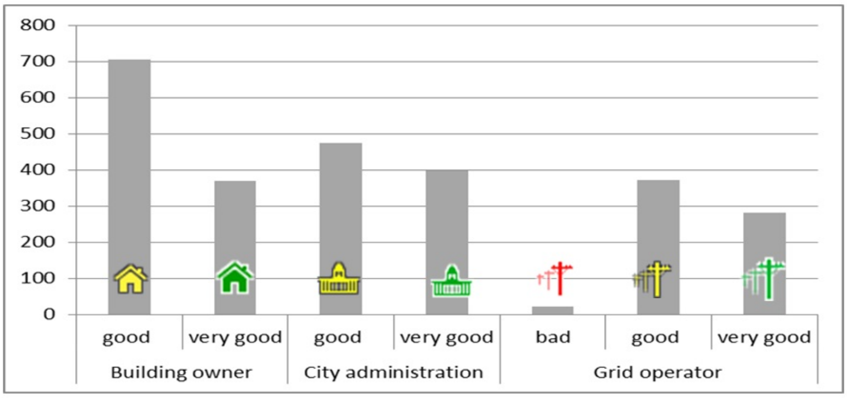


Figure 4.24: Single perspectives buildings PV suitability classification.

meters of roofs) is a city-related figure where there is no notion of buildings, or space in general. Finally, the electric grid infrastructure was out of the scope of the tool i.e. the potential roofs to install solar PV did not consider the fact that the grid operator as a stakeholder could oppose to this "potential". On the other hand, the purpose of this tool was to integrate as many measures as possible, aligning with the description of comprehensive tools, privileging scope (number of measures) than the level of detail the scope is being addressed in [Jan00].
Concerning the proposed solution in this thesis, it fulfills the main characteristics of urban energy planning support systems. (i) The calculations are presented from different perspectives and present different results that are relevant to each specific stakeholder. (ii) The output is aggregated to a simple level of understanding that does not require domain expertise in any field. Then the results are even more aggregated to a level of abstraction

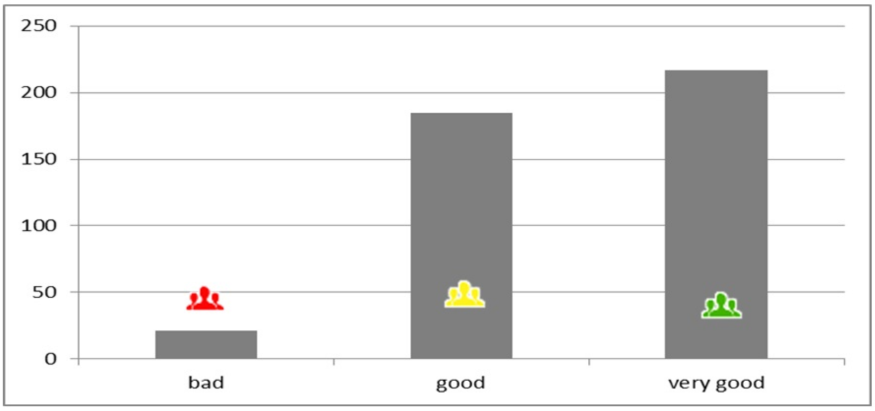


Figure 4.25: Multiple perspectives buildings PV suitability classification.

that represents the common interpretation of all stakeholders. (iii) Interactions between different computations have been captured, and then the ontology is used to integrate data from different computation models. These allow the integration and consistency of results (data). (iv) This approach gives the flexibility to calculate one answer in more than one level of detail, in case of data unavailability, or better data availability. Mechanisms are formalized and integrated within the ontology that ensures the possibility to plug other computation models to the system.

CHAPTER 5

Building refurbishment planning support modeling

The goal of this chapter is to apply the methodology described in the previous chapter to develop an ontology-based decision support system for energy planning. This can be considered as another use case of the methodology, besides the one described in the previous chapter, which also serves as a validation for the proposed methodology.
This chapter is structured according to the main phases of the urban energy system modeling methodology, discussed in Chapter 3. This allows a better mapping between the theoretical methodology and its practical application. In the first section, an introduction to the use case is presented. Then, the scope of the system, in terms of building refurbishment planning is defined. Then, data availability check concerning this measure is performed, within the same district as the previous use case (addressing the same 1200 buildings in the city of Vienna). Afterwards, the data modeling phase is discussed, in terms of parts of the ontology that are modeled. Then, computation models that are necessary to develop, providing the functionality defined in the scoping phase, are discussed. Then, interactions that represent the dynamics within the urban energy system (which are triggered by the computation models) are captured and integrated within the ontology. Afterwards, the potential decisions that the stakeholders involved in building refurbishment planning are modeled and integrated within the ontology as inference rules. The collected data and the calculated data, using the computation models are then integrated in an RDF format, using an existing data integration tool, which takes the ontology as a basis for semantic mapping between the different data sources. Finally, a sample data use is presented with the results of the system.

5.1 Introduction

The goal of this section is to describe the use case: building refurbishment planning support modeling, and the motivation behind the choice of this specific use case.

5.1.1 Motivation

The motivation behind the choice of this specific use case is similar and complementary to the choice of the building-integrated solar PV use case. It is also targeting the reduction of CO_2 emissions that the European Union defined within the climate and energy package, which groups binding legislations [Eur12]. These targets are known as the 20-20-20 targets i.e. targeting to reach 20% reduction of CO_2 emissions, 20% energy efficiency, and 20% renewable energy production, as detailed in the previous chapter.
Refurbishing buildings i.e. improving then to reach a better thermal insulation, contributes in both improving their energy efficiency (therefore the global energy efficiency of the city) and reduces the amount of CO_2 emissions, since it eventually consumes less energy than before. Therefore, this use case Building refurbishment planning support modeling, helps addressing two of the 20-20-20 targets, by providing support to urban energy planners to know where it is the best to invest, in terms of building refurbishment. Many local and national governments across Europe subsidize this measure (i.e. refurbishing building). Therefore, building owners that are willing to refurbish their buildings are financially supported in several ways, such as low interest loans and direct contributions to finance a share of investment costs.
The city of Vienna, where the application of this use case takes place, provides subsidies for this measure [Wieb]. Therefore, making informed decisions about planning this measure in a long term horizon would allow a better distribution of the budget, or even develop more customized funding schemes that are adapted to the reality.

5.1.2 Use case description

The goal of this use case is to assist urban energy planners to choose the best locations to refurbish. The assessment of the suitability of the locations considers the different perspectives of the involved stakeholders in this measure. For example, a good location to refurbish is not only where the building owner is satisfied, but also where the city administration, as a funding organization has the best outcome in terms of reduction of CO_2 emissions.
The application of this use case takes place in the 4th district of Vienna, of 1200 buildings in the (as used before in Chapter 4). The choice of this specific district is due to the important number of buildings it contains, yet still a graspable size of debugging or validating the results by manually retracing the results of the system.
At this stage, as long as the scoping phase has not been performed, the only specifications of the system that need to be addressed are the necessary conditions in urban energy planning support systems that were discussed in Chapter 2. These necessary conditions are as the following:

- Supporting the perspectives of different actors
- Shared understanding and quantifiable impact of decisions
- Measures integration and resources negotiation
- System viability through robustness against data availability problems

As the scoping of the system is also part of the methodology, the description of the use case is gradually building through that phase. Hence, the same use case (building refurbishment planning) might be different in different cities. What completes the description of the use case is what stakeholders are involved, what questions they raise, and in which levels-of-detail data exist.

5.2 Scoping

The scope of the system, in terms of this use case, is defined through the sequence of the activities that are defined in the scoping phase. The measure to be implemented, building refurbishment, is described. Stakeholders that are involved are identified, as well as their roles in the planning process. Their main questions are listed, and then they are broken down to quantifiable sub-questions.

5.2.1 Measure to be implemented

The measure to be implemented, as stated above is building refurbishment. The measure applies to existing buildings that are qualified for improving their thermal insulation. The thermal insulation improvement in this case refers to the improvement of the building envelope i.e. roofs, slabs, walls, and windows.

5.2.2 Involved stakeholders

Refurbishing buildings involves stakeholders, whose interests or activities are impacted. The identified stakeholders in the city of Vienna are as the following:

- Building owners: individuals or organizations that own buildings and have the legal rights to make modifications on them.
- City administration: The local authorities of the city of Vienna

5.2.3 Rroles of the stakeholders

The roles of the stakeholders identified above are as the following:

- Building owners: the building owners are supposed to make the investment if they are willing to refurbish their buildings. Therefore, their role as a stakeholder is important, as they are the ones that make or do not make the investment to implement the measure.

- City administration: The city administration is considered as a stakeholder in this measure as they provide subsidies for building owners that are willing to refurbish their buildings.

5.2.4 Main questions of the stakeholders

The stakeholders that have been identified raise questions regarding the impact of building refurbishment. The questions that are raised identify concerns they might have regarding the potential implementation of the measure. These questions have been identified while interacting (informally) with stakeholders in Smart City projects, in which the Austrian Institute of Technology (AIT) took part of. These projects concerned the cities of Vienna, Linz, Amstetten in Austria [The11], and Nanchang in China. The main questions that the stakeholders that are involved in building-integrated solar PV installation are as the following:

- Building owner: does it pay off to refurbish my building?
- City administration: where is it the best for the city, in terms of environmental impact, to subsidize building refurbishment?

5.2.5 Questions breakdown into quantifiable sub-questions

The main questions are broken down to more concrete questions that together provide enough information to the stakeholders to make their decisions. These questions will represent the main competency questions of the ontology, and therefore the target ontology based system. These competency questions add up to the ones formulated in the previous use case. Thus, the competency questions become richer and include other measures. The question breakdown, raised by the involved stakeholders in building refurbishment, is as the following:

- Building owner: CQ 4 does it pay off to refurbish my building?
  - CQ4.1 What is the net present value of my investment?
  - CQ4.2 What is my investment Break-even duration?
  - CQ4.3 How much investment costs are required?
- City administration: CQ5 where is it the best for the city, in terms of environmental impact, to subsidize building refurbishment?
  - CQ5.1 How much subsidies are to be paid to refurbish buildings?
  - CQ5.2 How much energy is saved by subsidizing building refurbishment?
  - CQ5.3 How much CO_2 emissions are saved by subsidizing building refurbishment?
  - CQ5.4 What is the CO_2 emission-saving-equivalent in terms of carbon sequestering by trees?

The question breakdown defines the theoretical scope of the system. However, this theoretical scope might be unfeasible in case there are not enough data to answer all the questions. The next phase, data availability check, helps obtaining data to be analyzed by domain experts so that they know how far in detail they can go in answering or not answering the questions.

5.3 Data availability check

As in the previous use case, the data have been collected from the different available data sources in a non-formal way. Data have been provided by the city administration of Vienna, or collected from publicly accessible data sources (e.g. Statistik Austria), guidelines (such as the Guideline of energy savings & calculation of energy indicators [OIB12]), and technical reports or scientific papers. It is to recall that the data requests are characterized by being broad at the beginning of the process, as no software tool exists (yet) to be configured with a fixed set of data parameters. The process is inverted in this case i.e. data are collected and then the system is developed to provide as much functionality as possible with the existing data.
The data that have been obtained from the city administration of Vienna included GIS-based data of buildings, buildings properties. The GIS data included information about the census (a group of adjacent buildings) the buildings belong to.
Important data that is required to calculate the heating demand, refurbishment needs, costs, and other measure-related answers include ages of buildings, heating technologies (used fuels) of buildings, building use, building type (number of dwellings), etc. These elements would allow making the necessary basic calculations, [BCCT11]. However, these required data did not exist at the level of single buildings. Data existed about the distribution of square meters within censuses in the city, in terms of building age classes, heating fuel types, and building topology types, as shown in Table 5.1. Thus, for each census, it is said how many square meters of the contained floor space falls in each of the categories in Table 5.1.

The official statistics do not provide data on energy consumption for heating (neither on a building nor on a census-district level) thus proxy data (on census-district level) have been applied to estimate heating demand. This has been carried out by taking data on building size (number of flats), building use (residential vs. non-residential) and building age (age classes) related to wall insulation and heating efficiency. To estimate energy consumption energy demand factors from the European project Tabula [TAB12] have been taken. Tabula gives typical heat demand of buildings at the level of Austria (and other countries) based on building topologies and age classes. A sample overview of the interface of the web tool Tabula offers to access data about different building topologies and countries is shown in Figure 5.1

Heat demand values of building typologies, based also on their construction period, have been obtained from Tabula. The used heat demand values are shown in Table 5.2.

Other data collected from scientific sources include the work from Siegel [Sie12] that defined characteristic length (lc) values corresponding to building topologies in Austria

Heating fuel types	Oil
	Coal
	Gas
	Power
	District heating
	Renewables
Age class	Built earlier than 1919
	Built earlier than 1944
	Built earlier than 1960
	Built earlier than 1980
	Built earlier than 1990
	Built later than 1991
Topology types	building 1-2 flats
	building 2-10 flats
	building more than 11 flats
	mixed and non-residential buildings

Table 5.1: Building refurbishment related data collection at census-district level

Topology types	**Age class**					
	<1919	**<1944**	**<1960**	**<1980**	**<1990**	**>1991**
Building 1-2 flats	240	285	270	212,5	145	100
Building 2-10 flats	198	225,5	231	167,75	121	84,15
Building 11+ flats	180	205	210	152,5	110	76,5
mixed and non-residential buildings	150	180	180	150	80	75

Table 5.2: Heat demand [kWh/m2/a] of buildings according to building type and age class [TAB12].

and Vienna as well. The lc values defines length by width ratio and other physical properties of buildings associated to this value [OCOL90]. The lc values that have been collected are shown in Table 5.3.

Topology types	**lc value**
Building 1-2 flats	1,5
Building 2-10 flats	2
Building 11+ flats	3
mixed and non_residential buildings	3

Table 5.3: Used lc values [Sie12].

Other main sources of data include the energy flow diagram of the city of Vienna, provided by Statistik Austria. These data have been already integrated within the

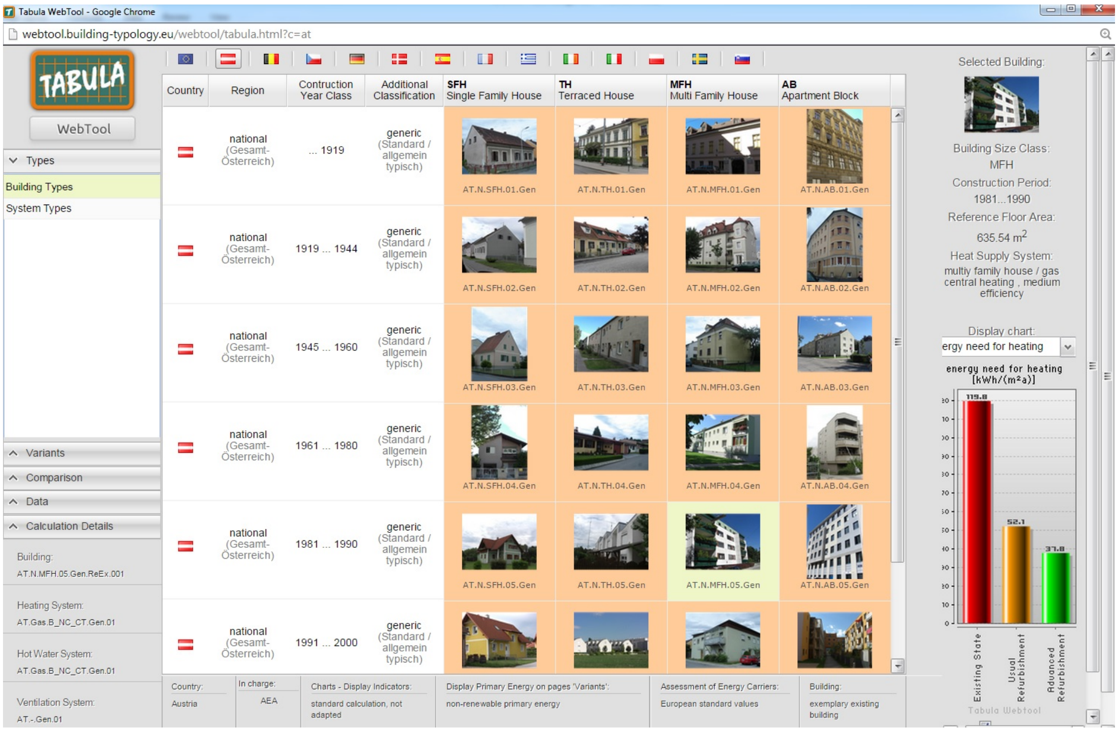


Figure 5.1: Sample Tabula web too interface to access heat demand values in Austria [TAB12].

ontology in the previous use case, together with other data. It is to recall that this use case: building refurbishment builds on top of the previous one building-integrated solar PV. The final result is an integrated building refurbishment and building-integrated solar PV planning support system.

5.4 Data modeling/Computation models check

In this phase, an existing excel-based computation model developed at the Austrian Institute of Technology (developed by Wolfgang Loibl) was re-used. This model calculates heat demands of census districts based on using the floor-space breakdown of each census district: heating fuel type, age class, and topology of buildings. Further development was necessary to extend the developed model so that it answers the questions defined in the scoping phase. Calculation methods with respect to the data availability were developed together with domain experts from the Austrian Institute of Technology, namely Georg Siegel, as architect and building technologies expert, Sebastian Möller as energy and energy economics expert, and Branislav Iglar, as a financial expert.

5.4.1 Expected answers

The expected answers were defined as a confirmation that the defined questions in the scoping phase are to be considered as competency questions of the system. The answers that the system provides are listed in Table 5.4.
It is to note that the answers in this use case are not related to buildings but to census districts (groups of buildings). The level-of-detail of data that was collected did not allow computing building-level answers.

Question	Answer
Q4.1	A4.1 Refurbishment investment Net present value
Q4.2	A4.2 Refurbishment Investment Break Even duration
Q4.3	A4.3 Refurbishment investment Cost
Q5.1	A5.1 Refurbishment Funding Cost
Q5.2	A5.2 Refurbishment energy savings
Q5.3	AA5.3 Refurbishment CO_2 Emissions savings
Q5.4	A5.4 Refurbishment CO_2 equivalent Trees savings

Table 5.4: Building refurbishment related answers list.

As stated above, an excel based computation model has been used as a basis for the development of other models as an extension of its functionality so that it calculates the answers shown in Table 5.4. Other models such as EnergyPlus [CLW+01] to calculate more accurate results cannot be used, given the low level-of-detail of available data.
The existing computation model has been developed to prepare data to be displayed in a GIS-based interface. The information that has been prepared and synthesized concerns a heat demand and CO_2 emission map for a district in the city of Vienna.

5.4.2 Define/refine computation methodologies

The calculation methods descriptions that are adopted for each answer are listed below. The calculation algorithms are also captured during this activity and kept as a basis for the next phase (computation models development). Furthermore, the corresponding time, space, and technology LODs of the calculation methods is shown in Table **??**.

- CM 4.1 Net present value on refurbishment investment calculation based on discounted cash flow (DCF) analysis. The outflows only consider the investment costs. All the maintenance costs are ignored. The DCF analysis is carried over a time span of 40 years, which represent the lifetime of a building insulation. The DCF considers a scenario of an annual increase of 1% of the prices of all fuels, and a loan of 1% flat rate over 20 years as stated in the residential construction and renovation Law -WWFSG 1989 [Lan13].

- CM 4.2 The break-even period on refurbishment investment calculation is based on discounted cash flow analysis. The outflows only consider the investment costs. All the maintenance costs are ignored. The DCF analysis is carried over a time span of 40 years, which represent the lifetime of a building insulation. The DCF considers a scenario of an annual increase of 1% of the prices of all fuels, and a loan of 1% flat rate over 20 years.

- CM 4.3 The building owner Investment costs on refurbishment calculation is based on deducing the funds of the Viennese regional government according to the regulations for housing promotion and retrofitting WWFSG1989 [Lan13] i.e. Minimum (€50/m2 or 20% investment). A loan over 20 years with a flat rate of 1% is also considered. It is to note that an assumption (based on the experience of domain experts) is made: the refurbishment costs linearly decreases from €400/m2 to €200/m2 when the heated floor space area is between 0-5000m2 then from 5000m2 on the cost stabilizes in €200/m2. The heated space floor area is considered to be 80% GFA in residential buildings and 85% GFA in non-residential buildings.

- CM 5.1 The refurbishment funding cost calculation is based on the Viennese regional government regulations for housing promotion and retrofitting WWFSG1989 [Lan13]. Minimum (€50/m2 or 20% investment) is granted. The loan costs at privileged tariffs are not considered as costs on the city administration side.

- CM 5.2 The subsidized refurbishment energy savings calculation is based on applying the minimum requirement for heat demand to qualify for a grant from the city administration. i.e. 1.15 times the heat demand of a low energy consumption building, which is equal to 17x(1+2,5/lc Value), as defined in the regulations for housing promotion and retrofitting WWFSG1989 [Lan13].

- CM 5.3 The refurbishment saved CO_2 emissions calculation is based on deducting the amount of CO_2 emissions of the saved energy per census fragment. It is to note that each census fragment is identified by the share of buildings referring to heating fuel type, building size, building age, and building use.

- CM 5.4 Refurbishment Equivalent number of trees for sequestering the same amount of CO_2 calculation based on EPA method [EPA14] counting 25.6 trees, growing for 10 years, being able to sequester 1 t- CO_2 emissions.

It is to note that only the main calculation methods of the expected answers are recorded. However, there are other intermediary calculations that are necessary but they are not recorded, as the stakeholders are only interested in obtaining a general idea on the calculation methods. Other intermediary calculation methods are also kept but separately in other documents that are associated to the development process of the system.

Calculation method	Answer	Level-of-detail		
		Time	Space	Technology
Q 4.1	A 4.1	Annual	Census fragment	Abstract heating technology
Q 4.2	A 4.2	annual	Census fragment	Abstract heating technology
Q 4.3	A 4.3	annual	Census fragment	-
Q 5.1	A 5.1	annual	Census fragment	-
Q 5.2	A 5.2	annual	Census fragment	Abstract heating technology
Q 5.3	A 5.3	annual	Census fragment	Abstract heating technology
Q 5.4	A 5.4	annual	Census fragment	Abstract heating technology

Table 5.5: Building refurbishment related calculation methods list.

5.4.3 Semantics extraction and classification

The semantics extraction and classification phase leads to capturing domain concepts, related to components of the urban energy system that are related to building refurbishment planning. Accordingly, all the concepts, object properties, and data properties that are necessary to know about (by computation models, or by different domain experts, or stakeholders) are formalized in this phase. All the semantics that are captured within this phase are integrated with the others that have been captured in the previous use case (building-integrated solar PV). No separate ontology is developed in this phase. Therefore, the ontology keeps the structure that has been described in the previous chapters i.e. three different categories of concepts: (i) domain concepts, grouping concepts that are related to building refurbishment, building integrated solar PV and urban energy systems. (ii) Data integration concepts, grouping concepts that keep the requirements of the stakeholders involved in the two use cases (building refurbishment and building-integrated solar PV) linked to their answers, making the adopted calculation methods transparent. Furthermore, it groups the concepts, which are necessary to formalize the interactions that happen within the urban energy system, caused by the computation models that perform the necessary calculations to reach the required answers (A1.1; A1.2; A1.3; A2.1; A2.2; A2.3; A2.4; A3.1; A3.2; A3.3; A3.4; A3.5; A 4.1; A 4.2; A 4.3; A 5.1; A 5.2; A 5.3; A 5.4). (iii) Scenario configuration answers, containing concepts regarding establishing an emission inventory [Eur10], as well as all the decisions classes and other concepts that the urban energy planners choose to include (or not include) when using the system, through a customized interface. As stated in the previous chapter, the semantic extraction is based on the calculation steps that are developed by the domain experts. The key words

in each calculation step are highlighted. The key words might refer to a concept, a data property, or object property.
It is to note that in this use case an existing spreadsheet-based model is reused. Furthermore, the calculated answers are calculated as a census-level, unlike the previous use case, where answers were calculated at the level of each single building. This is due to the data unavailability to perform such calculations at a building level.

Extracted building refurbishment concepts

As, stated before, concepts are characterized by being non quantifiable by themselves. They appear in calculation steps as objects that still need data properties so that they are described. The calculation steps that have been outlined by domain experts, in order to calculate the building refurbishment related answers (A 4.1; A 4.2; A 4.3; A 5.1; A 5.2; A 5.3; A 5.4) are used as a basis. These calculation steps resulted in the fact that the answers can be matched only at a census level. Therefore, a new spatial concept is added to the ontology i.e. Census. At this stage all concepts that are added are classified within the domain concepts category, besides the answer bundles that are related to the new measure (building refurbishment) in the scenario configuration concept category. The following concepts have been captured.

- Census district concept: A census district is a group of buildings (adjacent to each other), which is the finest spatial granularity (level-of-detail) in the building refurbishment use case. All answers are attached to instances of this class. It is also spatially represented (geo-referenced) in this use case by a point.

- Census fragment concept: this represents a fragment or part of a census district that has a given gross floor area of buildings that are contained within this census district, without a reference to their exact location. This concept is not geo-referenced. It is a conceptual spatial split of a census district, in abstraction of the exact location of the resulting fragment of census district.
  The census fragments are homogeneous parts of a census district, defined as shown in Figure 5.2, by the percentages regarding building type, age class , building use (referred to in the data collection as building topology), the heating source type (i.e. the fuel that is used by the heating technology in the census fragment), and its parent census.

- Census sized fragments: describe the building structure of the census fragments according to the building size class distribution (gross floor area) i.e. more than 5000 m2 or less than 5000 m2 per building. This class is complementary to the Census Fragment class that does not include the notion of size of buildings, which is necessary for calculating the costs of buildings refurbishment, only available in combination with information on the buildings' sizes (as explained in the calculation method CM 4.3. The census sized fragments are further defined, as shown in Figure 5.3, by their building age type distribution, building type (referred to in the data

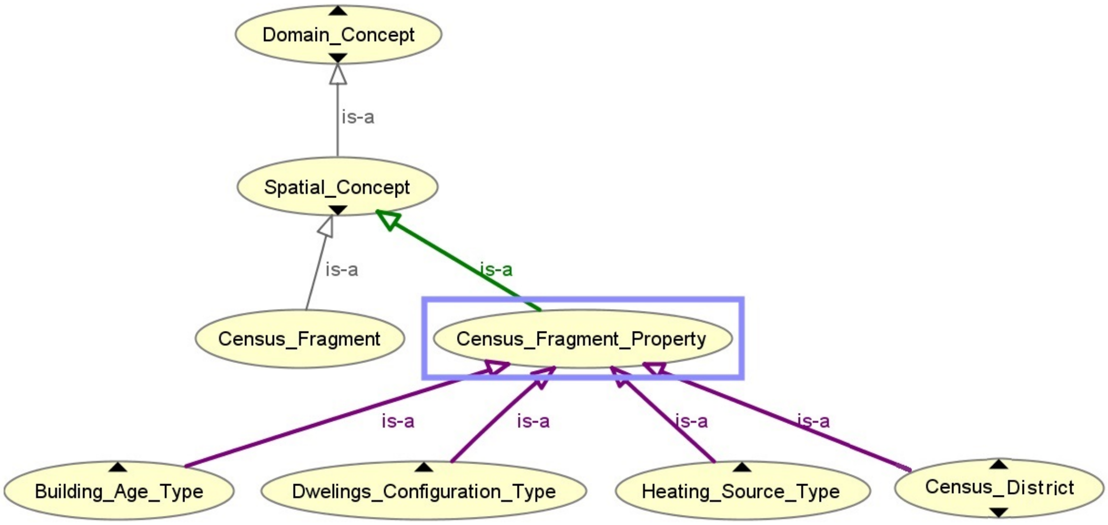


Figure 5.2: Ontology detail: census fragment concept.

collection as building topology), and the heating source type (i.e. the fuel that is used by the heating technology in the census fragment), and its parent census district.

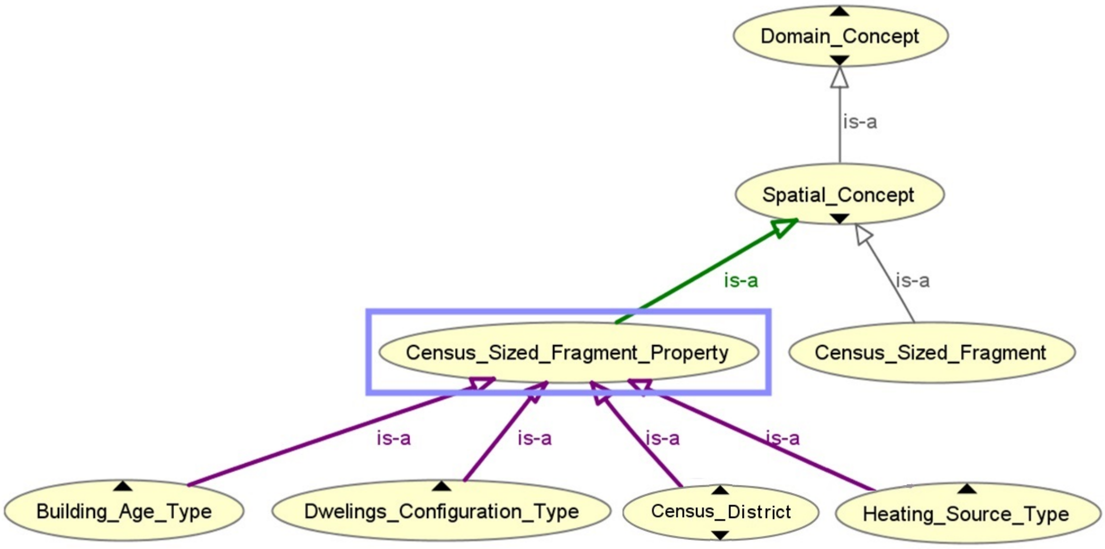


Figure 5.3: Ontology detail: census sized fragment concept.

- Energy Demand Concept: This concept is to represent more complex energy demand types that require more than just a value. It is not restrictive for heat demand. It can also stand for electricity demand (however, in the previous use case, electricity demand was modeled in a different way, which was an annual value as a data property of a building). The subclasses of the energy demand concept are shown in Figure 5.4 . The sub-classes are standard heat demand type and its “auxiliary class” standard heat demand type which groups its object properties.

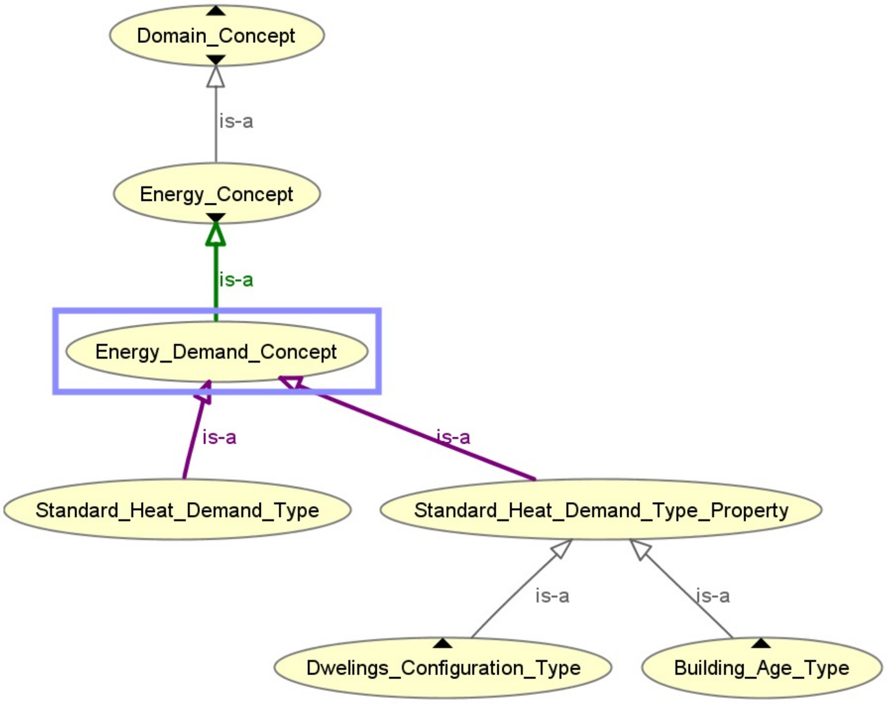


Figure 5.4: Ontology detail: energy demand concept.

- Standard Heat Demand Type Concept: this concept models the link between, on the one hand, building age classes and their topologies and on the other hand their heat demand. Therefore, the standard heat demand type property concept includes the subclasses Building type and Building Age Type.

- Building Type Concept: this concept refers to the topologies of buildings that define a certain number of their properties, such as those shown in Tables 5.2 and 5.3. The Building type concept is related to other concepts as an object property that defines them, such as Census Fragment, Census Sized Fragment, Standard refurbishment Cost Type, or Standard Heat Demand Type, as shown in Figure 5.5.

These concepts are integrated within the ontology that has been developed for the previous use case: building-integrated solar PV. Therefore, there are shared concepts between the two use cases. The ontology that represents an urban energy system becomes richer, as more use cases (measures) are integrated.

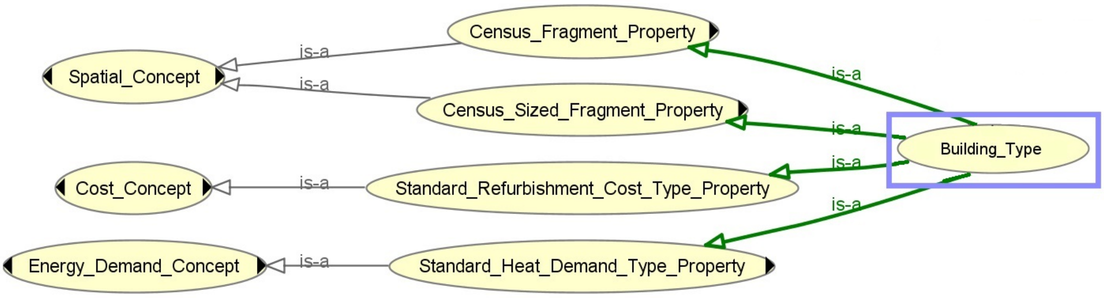
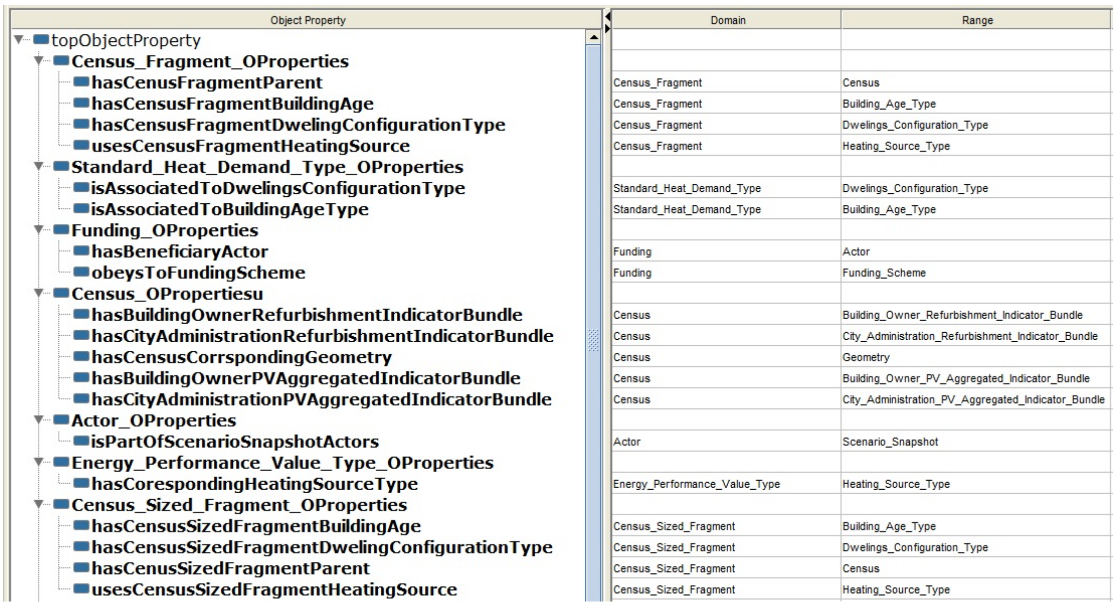


Figure 5.5: Ontology detail: building type.

Extracted object properties

Object properties represent the relationships between two concepts i.e. one concept is a property of another. By analogy to classic databases, it is similar to the relationships that exist between two tables.
As stated before, an adopted design principle is to add concepts with the suffix “Property” to concepts that are related to other concepts. Thus, the object properties of each concept are found under the construction <class name> <Property> class.
The main object properties in the ontology have been discussed above as sub-classes of concepts named <class name> <Property>. An overview of the modeled object properties, their domains, and ranges is shown in Figure 5.6.



Object Property	Domain	Range
topObjectProperty		
Census_Fragment_OProperties		
hasCenusFragmentParent	Census_Fragment	Census
hasCensusFragmentBuildingAge	Census_Fragment	Building_Age_Type
hasCensusFragmentDwelingConfigurationType	Census_Fragment	Dwelings_Configuration_Type
usesCensusFragmentHeatingSource	Census_Fragment	Heating_Source_Type
Standard_Heat_Demand_Type_OProperties		
isAssociatedToDwelingsConfigurationType	Standard_Heat_Demand_Type	Dwelings_Configuration_Type
isAssociatedToBuildingAgeType	Standard_Heat_Demand_Type	Building_Age_Type
Funding_OProperties		
hasBeneficiaryActor	Funding	Actor
obeysToFundingScheme	Funding	Funding_Scheme
Census_OPropertiesu		
hasBuildingOwnerRefurbishmentIndicatorBundle	Census	Building_Owner_Refurbishment_Indicator_Bundle
hasCityAdministrationRefurbishmentIndicatorBundle	Census	City_Administration_Refurbishment_Indicator_Bundle
hasCensusCorrspondingGeometry	Census	Geometry
hasBuildingOwnerPVAggregatedIndicatorBundle	Census	Building_Owner_PV_Aggregated_Indicator_Bundle
hasCityAdministrationPVAggregatedIndicatorBundle	Census	City_Administration_PV_Aggregated_Indicator_Bundle
Actor_OProperties		
isPartOfScenarioSnapshotActors	Actor	Scenario_Snapshot
Energy_Performance_Value_Type_OProperties		
hasCorespondingHeatingSourceType	Energy_Performance_Value_Type	Heating_Source_Type
Census_Sized_Fragment_OProperties		
hasCensusSizedFragmentBuildingAge	Census_Sized_Fragment	Building_Age_Type
hasCensusSizedFragmentDwelingConfigurationType	Census_Sized_Fragment	Dwelings_Configuration_Type
hasCenusSizedFragmentParent	Census_Sized_Fragment	Census
usesCensusSizedFragmentHeatingSource	Census_Sized_Fragment	Heating_Source_Type

Figure 5.6: Building refurbishment related object properties overview.

Extracted data properties

Data properties represent the data parameters that describe instances of classes e.g. the surface area of a roof. The data properties are easy to capture as they represent any keyword within the calculation steps that is quantifiable.
The data properties that have been captured in this use case are shown in Figure 5.7. These data properties are used also by the computation models.

5.5 Computation models development

In this phase computation models are developed, implementing the calculation steps and methods that have been defined by the domain experts and extending the existing spreadsheet-based tool that is re-used as a basis.
It is to recall that these calculation models are used in the data preparation phase. Therefore, the final use of the ontology-based planning support system does not invoke the use of these models. Once they perform the necessary calculations, they are disconnected from the final system, in terms of use. However, a link between the used computation models and the calculated data is maintained within the ontology, as part of the data integration concepts.
The level-of-detail of available data for building refurbishment was not as high as the one for building-integrated solar PV. Therefore, no advanced tools or technologies were needed in this case. Most of the calculations are based on simple operations that are offered in each basic spreadsheet tool. Furthermore, the existing tool that was reused in this case is spreadsheet-based. Therefore the choice to develop the computation models in this case was Excel spreadsheets.

Table 5.6 lists the computation models that have been developed. In this context, a computation model refers to a spreadsheet. The computation models have been developed to prepare the data to be integrated according to the semantics of the urban energy system ontology. No data management system was necessary to use, as the data integration tool that is used (in a later phase) takes spreadsheets as a valid input.

The developed computation models use data properties and produce/update other data properties, simulating in a low level-of-detail what happens when refurbishing buildings. The computation models, listed in Table 5.6, trigger some dynamics in the urban energy system. These dynamics are captured in the next phase.

5.6 Interactions modeling

The interactions between different data properties (and objects) have been captured, and they depend on the computation models that have been developed shown in Table 5.6. Other interactions that are important are the ones with the previous use case (building-integrated solar PV). Any interactions that update data properties used as input in the models of the previous use case must be considered.

Figure 5.7: Building refurbishment related data properties overview.

Data that has been calculated in the previous use case was already integrated. Therefore, to keep data consistency, the interactions between the computation models have to be captured as well.

Figure 5.8 shows the interactions that are triggered by the computation models (spreadsheets) that have been developed for calculating different required data, related to the

Computation Model ID	Computation Model
BR_1	Census Fragments Heat Demand
BR_2	Refurbished Census Fragments Heat Demand
BR_3	Refurbished Census Fragments Heat Savings
BR_4	Refurbished Census Fragments CO_2 Savings
BR_5	Refurbished Census Fragments CO_2 Equivalent Trees Savings
BR_6	Refurbished Census Fragments Fgee Values
BR_7	Census Fragment Average Buildings GFA
BR_8	Census Fragment Refurbishment Total Cost
BR_9	Census Fragment Refurbishment Funding Cost
BR_10	Refurbishment Investment Net Present Value
BR_12	Refurbishment Investment Break-Even Time
BR_13	Refurbishment Investment Cost
BR_14	Refurbishment Investment Net Present Value Per GFA
BR_15	City administration refurbishment indicators calculations: funding Cost, Energy Savings, CO_2EmissionsSavings, tree equivalent

Table 5.6: Building refurbishment related computation models.

impact of refurbishing buildings.

Interactions define relationships between affected components (element in the urban energy system) and the affecting ones, in terms of the data properties that cause them and the computation model that triggers them.

A total number of 167 interactions have been detected, including those triggered by building-integrated solar PV computation models. Concerning the impact of the building refurbishment computation models on those of build-integrated solar PV, no interactions have been detected. The output data properties of the building refurbishment computation models were checked if they are shared as input data properties in the building-integrated solar PV computation models. As the building refurbishment involves data that are more related to thermal energy while building-integrated solar PV models rather deal with electric energy, no interactions have been detected. Therefore no interaction-protocols were necessary to be modeled.

The interactions that were captured will also be integrated with the rest of the data under as data integration concepts. This is also achieved during the data integration phase.

5.7 Decision modeling

The indicators used by building owners and the city administration (as stakeholders) to make their decisions are described in Table 5.7. The stakeholders associate an interpretation (quality indicators in natural language) to values, which define how

Interaction ID	ModelID	Property URI	Component URI
		coPlan#hasCensusFragmentGFA	coPlan#CensusFragment
117	BR_1	coPlan#hasCensusFragmentsHeatDemand	coPlan#CensusFragment
		coPlan#hasStandardHeatDemandPerGFA	coPlan#StandardHeatDemand
118	BR_1	coPlan#hasCensusFragmentsHeatDemand	coPlan#CensusFragment
		coPlan#hasCensusFragmentGFA	coPlan#CensusFragment
119	BR_2	coPlan#hasRefurbishedCensusFragmentsHeatDemand	coPlan#CensusFragment
		coPlan#hasDwelingConfigurationTypeLCvalue	coPlan#DwelingConfigurationType
120	BR_2	coPlan#hasRefurbishedCensusFragmentsHeatDemand	coPlan#CensusFragment
		coPlan#hasDwelingConfigurationTypeName	coPlan#DwelingConfigurationType
121	BR_2	coPlan#hasRefurbishedCensusFragmentsHeatDemand	coPlan#CensusFragment
		coPlan#minmumTargetOfRefurbishmentHeatDemand	coPlan#FundingScheme
122	BR_2	coPlan#hasRefurbishedCensusFragmentsHeatDemand	coPlan#CensusFragment
		coPlan#hasRefurbishedCensusFragmentsHeatDemand	coPlan#CensusFragment
123	BR_3	coPlan#hasRefurbishedCensusFragmentsHeatSavings	coPlan#CensusFragment
		coPlan#hasCensusFragmentsHeatDemand	coPlan#CensusFragment
124	BR_3	coPlan#hasRefurbishedCensusFragmentsHeatSavings	coPlan#CensusFragment
		coPlan#hasRefurbishedCensusFragmentsHeatSavings	coPlan#CensusFragment
125	BR_4	coPlan#hasRefurbishedCensusFragmentsCO2Savings	coPlan#CensusFragment
		coPlan#hasHeatingSourceTypeCO2Emissions	coPlan#HeatingSourceType
126	BR_4	coPlan#hasRefurbishedCensusFragmentsCO2Savings	coPlan#CensusFragment
		coPlan#hasRefurbishedCensusFragmentsCO2Savings	coPlan#CensusFragment
127	BR_5	coPlan#hasRefurbishedCensusFragmentsCO2Equivalent	coPlan#CensusFragment
		coPlan#hasEnergyPerformanceParameterValue	coPlan#EnergyPerformanceValueType
128	BR_6	coPlan#hasRefurbishedCensusFragmentsFgeeValue	coPlan#CensusFragment
		coPlan#hasDwelingConfigurationTypeLCvalue	coPlan#DwelingConfigurationType
129	BR_6	coPlan#hasRefurbishedCensusFragmentsFgeeValue	coPlan#CensusFragment
		coPlan#hasLocationGFA	coPlan#Location
130	BR_7	coPlan#hasCensusFragmentAverageBuildingsGFA	coPlan#CensusSizedFragment

affecting component/property
affected component/property

Figure 5.8: Sample building refurbishment related interactions.

satisfied they are if building refurbishment in a given census district has to be made. It is to note that the stakeholder "building owner" in this use case is a conceptual one that refers to all the building owners within the census district. Table 5.7 lists the value ranges and their associated interpretations from the single perspectives of the building owners and the city administration regarding building refurbishment. The figures of the value ranges are subjectively chosen and can be customized once specific stakeholders are defined.

After capturing the single perspectives interpretations, an aggregated interpretation from all the perspectives together is established. Priority has been given to the building owner, as the investment is initiated by this stakeholder. Then, the city administration is given the second priority, because the success of the implementation of building

Stakeholder	Indicator	Value range	Interpretation
Building owner	Net present value [€/m2]	[60,90[	Good
		]90,+∞[	Very good
Cityadministration	CO_2-reduction cost [€/t-CO_2]	] 815, 855]	Good
		]0, 815]	Very good

Table 5.7: Building refurbishment related value ranges interpretations.

refurbishment mainly depend on the building owner. The city administration can only subsidize this measure but cannot initiate it or force it. The resulting multi-perspective aggregated interpretations are shown in Table 5.8.

Stakeholders interpretations		**Aggregated Interpretation**
Building Owner	**City Administration**	
Very Good	Very Good	Very Good
Good	Very Good	
Good	Very Good	Good
Good	Good	

Table 5.8: Multi-perspective-aggregated interpretation.

5.7.1 Implementation of the decision modeling

Each census district (group of buildings) has associated information, which answers the questions of the stakeholders (building owners and city administration). These answers are grouped by stakeholder in a class that is called Answer Bundle. Therefore, each census district in this case has two different associated answer bundles (one answer bundle for each stakeholder). As explained before, the adopted methodology (to develop this decision support system for urban energy planning) is incremental. Therefore, the indicators of the building refurbishment are integrated within the same ontology and add up to the answer bundles that were modeled in the previous use case, as shown in Figure 5.9.

Thus instances of the class Answer Bundle contain enough data so that census districts are flagged as being “very good” or “good” form the perspective of the building owners and the city administration. The answer bundles *Building Owner Refurbishment Indicator Bundle* and *City Administration Refurbishment Indicator Bundle* respectively comprise answers to all the questions that the building owners and the city administration (as a stakeholders) formulated in the scoping phase, as shown in Figure 5.10.

Based on the values of these data properties inference rules are developed to classify these indicators in different classes: very good potential or good potential. Therefore, other classes are created, as shown in Figure 5.11, representing logic classes where

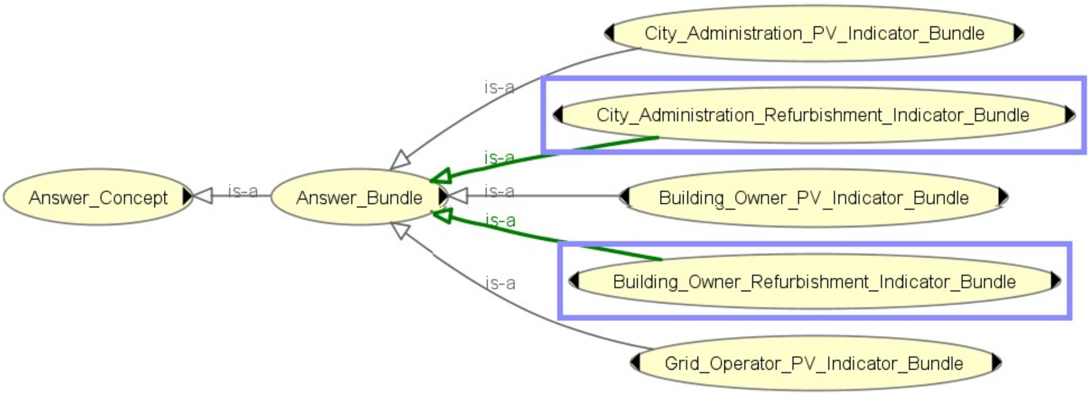


Figure 5.9: Building-integrated solar PV and building refurbishment related answer bundles.

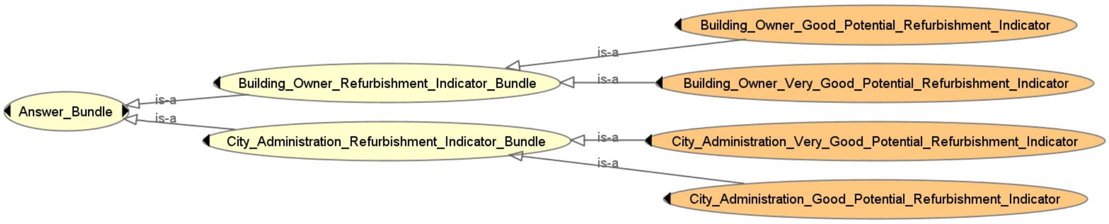


Figure 5.10: Building refurbishment related answer bundles.

instances of the Answer Bundle class will be inferred as being part of, based on the logics in Table 5.7.

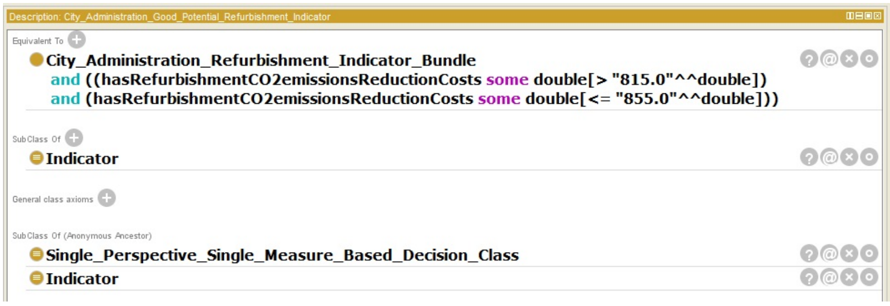


Figure 5.11: Sub-classes of the building owner PV indicator bundle.

An example of the implementation of these logics within the ontology is show in Figure 5.12. It represents the necessary conditions so that an instance of the Answer Bundle class is inferred as a *City Administration Good Potential Refurbishment Indicator*. Therefore, an implementation of the classification of census districts from single perspectives of stakeholders is achieved, regarding the measure building refurbishment.

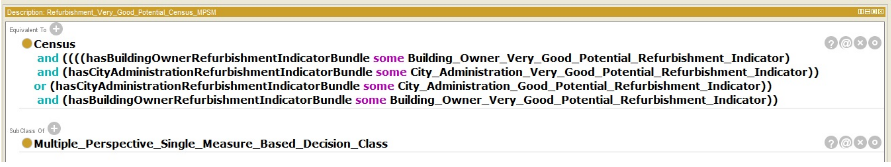


Figure 5.12: Necessary conditions of the class City Administration Good Potential Refurbishment Indicator.

Concerning the assessment of locations from the perspectives of all the stakeholders together, it is based on the single perspective assessments. As described in Table 5.8, combinations of single perspective assessments result in a common assessment from all the perspectives together. Therefore, the indicators that are inferred for each location are used. For example, a census district is inferred to be "very good" for all stakeholders in two cases: if it is very good for all of them or if it is very good for the building owner and good for the city administration. This is implemented within the ontology as a class "Refurbishment Very Good Potential Census MPSM" (MPSM refers to multi perspective singe measure) with necessary conditions as shown in Figure 5.13.

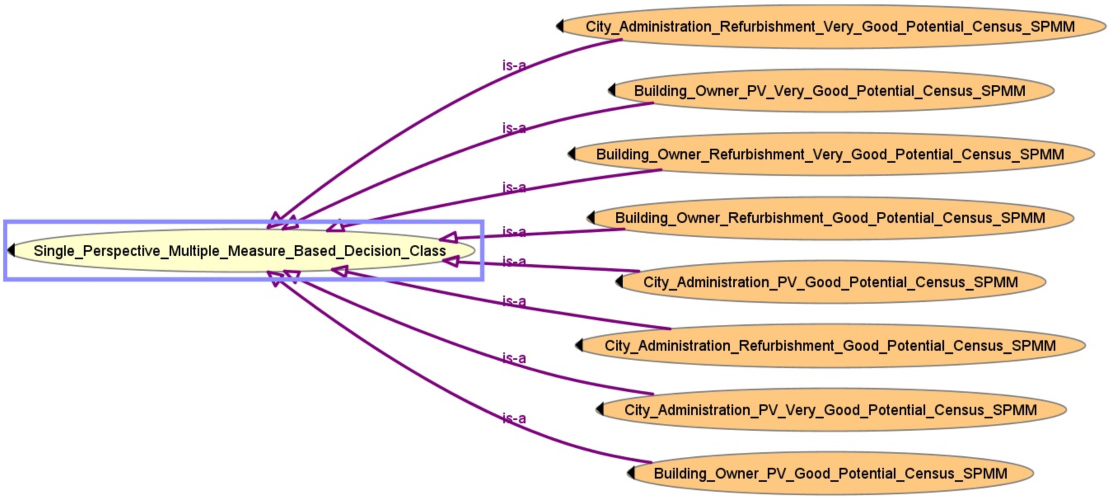


Figure 5.13: Necessary conditions for the class Refurbishment Very Good Potential Census MPSM.

So far, the decisions that have been modeled were related to single perspectives i.e. stakeholders were considering that they have two silos of measures that are not integrated. Each stakeholder has an interpretation of on measure as if it is the only option. Then stakeholders make an interpretation all together on one measure, again, as if it is the only available option.

5.7.2 Multi use case integration of the decision modeling

The interpretations of the stakeholders that were single-measure oriented are integrated. This means that every stakeholder have an interpretation of the outcome of a measure, being aware also of the outcome of the other measure. For example, if the building owner has very good potential to invest in both solar PV and building refurbishment, the choice will be defined by the one that has the highest return on investment.
The building integrated solar PV measure was achieved at a building-level, while the building refurbishment measure was achieved only at a census district level. Therefore, answers that are calculated for building refurbishment cannot be broken down to a building level. However, it is possible to partially aggregate the answers of the building integrated solar PV measure and bring them to a census district level.
The aggregation of answers to a census-district level can be achieved only regarding indicators of the building owners and the city administration. The answers of the grid operator are not aggregate-able since the locations of the transformers (therefore, low voltage grids) significantly impact the results i.e. unlike the other cases it is not sufficient to sum results of single buildings that belong to the same census district.
Therefore two more answer bundles are added to encapsulate the aggregated data of building-integrated solar PV calculations (to a census-district level). The answer bundles concern the answers required by the building owners and the city administration. It is to note that information regarding the third stakeholder (the grid operator) is lost and it is not possible to include it, given this level-of-detail. The data properties of these answer bundles are illustrated in Figure 5.14.

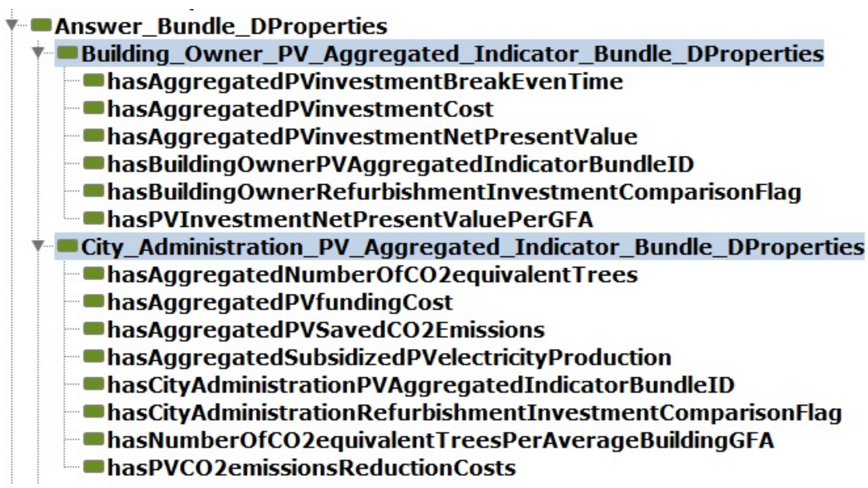


Figure 5.14: Data properties of census-district level aggregated building-integrated solar PV calculations.

Now it is possible to compare results of the two measures since they belong to the same spatial level-of-detail, which is census-district level in this case. Therefore, more decision classes are added i.e. single perspective multiple measure (SPMM) decision classes, as shown in Figure 5.15.

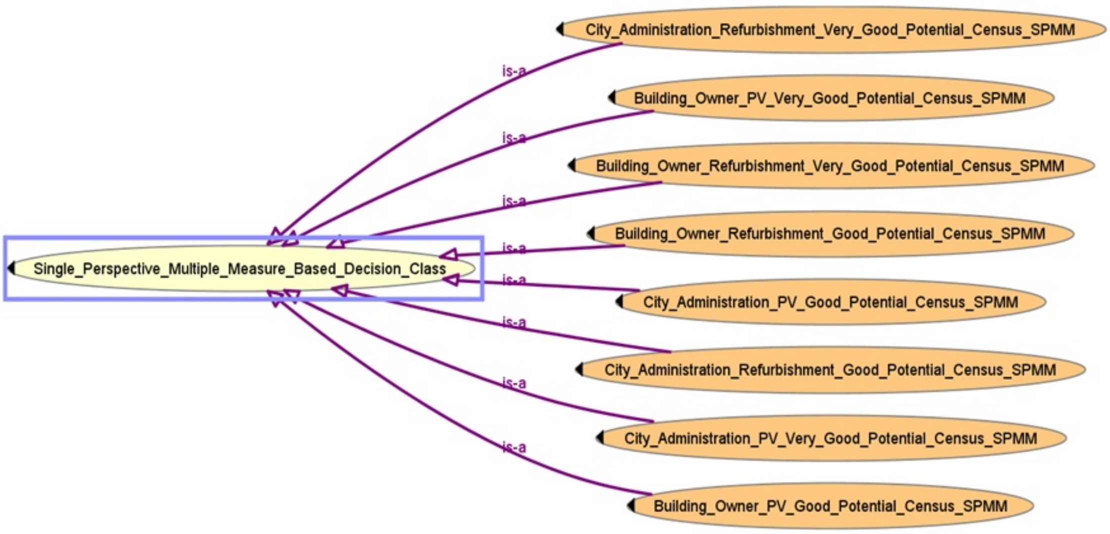


Figure 5.15: Sub-classes of the single perspective multiple measure-based decision class.

The basis for assessing the better measure (building-integrated solar PV or building refurbishment) from single perspectives is based on two values. Concerning the building owner, the better option (measure to implement) is the one that has the better return on investment value per square meter. The return on investment is calculated per square meter since there are data only available at a census-district level. Concerning the city administration, the better option is the one that requires less investment to save more CO_2 emissions.
Based on the above logic, a good or very good (considering that there are two measures as options) census district for a stakeholder is one that is good or very good (considering the single measure in question) and also qualifies as a better option (measure to invest in), knowing that there is another competing measure. An example implementation of such rule is shown in Figure 5.16, concerning how to classify census districts that are very good from the perspective of the building owner, being aware that there are two options (building-integrated solar PV and building refurbishment).

The last type of modeled decisions classes is the multi-perspective and multi-measure aware decision class. These classes classify census districts as very good or good for building-integrated solar or PV and building refurbishment, as an agreed interpretation of all stakeholders together (building owners and city administration, in this case). Furthermore, this classification considers that both options (building-integrated solar PV and building refurbishment) are available. This classification is performed according to the logic shown in Table 5.9.

The implementation of the logics of classifying census districts as very good or good for the two measures leads to the creation of the fourth and last type of decisions summary

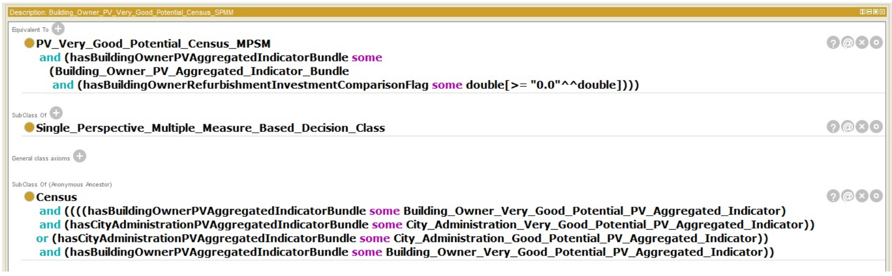


Figure 5.16: Necessary conditions for the class Building Owner Very Good Potential Census SPMM.

Measure	**Stakeholders interpretations Single-perspective Multi-measure**		**Aggregated Interpretation**
	Building Owner	**City Administration**	
Building-integrated solar PV	Very Good	Very Good	Very Good
	Good	Very Good	
	Good	Very Good	Good
	Good	Good	
Building refurbishment	Very Good	Very Good	Very Good
	Good	Very Good	
	Good	Very Good	Good
	Good	Good	

Table 5.9: Multi-perspective multi-measure interpretation.

classes, as shown in Figure 5.17. An example of necessary conditions of a very good census district, multi-perspective and multi-measure aware decision class concerning building refurbishment is shown in Figure 5.18.

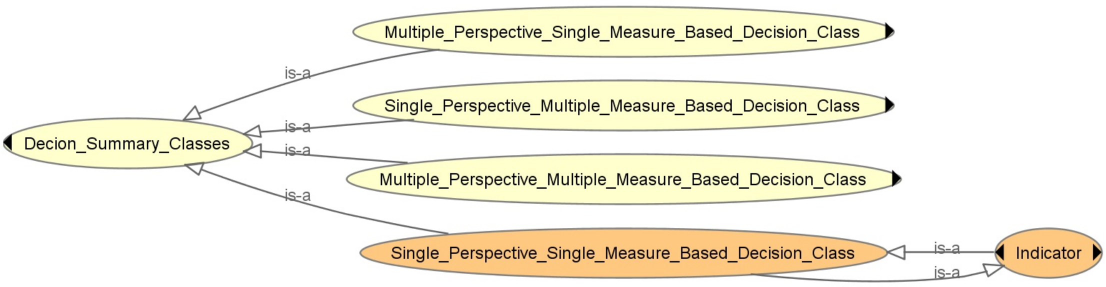


Figure 5.17: Decision summary classes.

By the end of this phase the development of the ontology is complete. The ontology represents an urban energy system within the scope of building refurbishment and

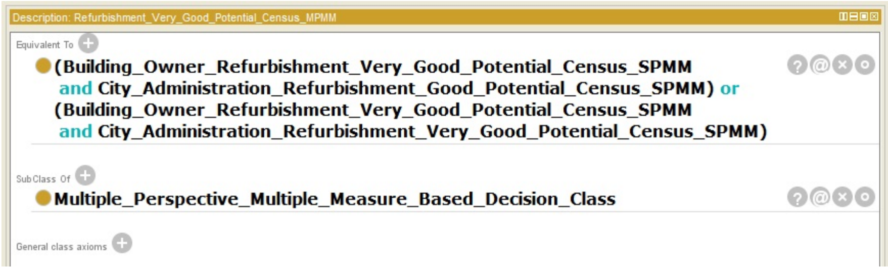


Figure 5.18: Necessary conditions for the class Refurbishment Very Good Potential Census MPMM.

building integrated solar PV i.e. containing all concepts that belong to these domains and making their related calculations. Moreover, the ontology includes concepts that are related to the integration of the computation models that were developed and how they influence the urban energy system, in terms of interactions (that are considered to be the dynamics within the urban energy system). Finally, the ontology includes the knowledge of the stakeholders in terms of how they interpret their interests if building refurbishment and/or building-integrated solar PV are to be implemented.
So far the ontology is considered as an explicit specification of conceptualization [GGP93]. The ontology does not integrate the actual data yet. In the data integration phase, the ontology is used to integrate the different data that have been collected or generated, using the developed computation models. This is achieved using an existing tool, Karma [KSA+12], exactly the same way as described in the previous use case.

5.8 Data use

As mentioned in the previous chapter, the prepared RDF data can be used in several different ways to support the urban energy planning process. The focus of this work is rather to show one possible way than to develop a standard way of using these data. In fact, the choice of using an ontology based system is to provide flexibility in using the integrated data so that it can be customized according to the specific case where it is used.
In this use case, the interface that has been developed for building integrated solar PV was extended so that it provides access to all of the new decision classes. The developed interface, as shown in Figure 5.19, displays locations according to their suitability:

- From the perspective of the building owner for integrating solar PV systems.
- From the perspective of the city administration for integrating solar PV systems.
- From the perspective of the Grid operator for performing building refurbishment.
- From the perspective of the building owner for performing building refurbishment.

- From the perspective of the city administration for performing building refurbishment.

- From all the perspective together regarding both measures as integrated options

- From all the perspective together regarding both measures as independent options

The integration of the measures building refurbishment and building-integrated solar PV required aggregating (to census-district level) the data that were calculated at a building-level. Therefore, the interface includes building integrated solar PV data at both levels. However, some data are lost in the aggregation process, namely the grid operator perspective, which requires the exact locations of buildings.

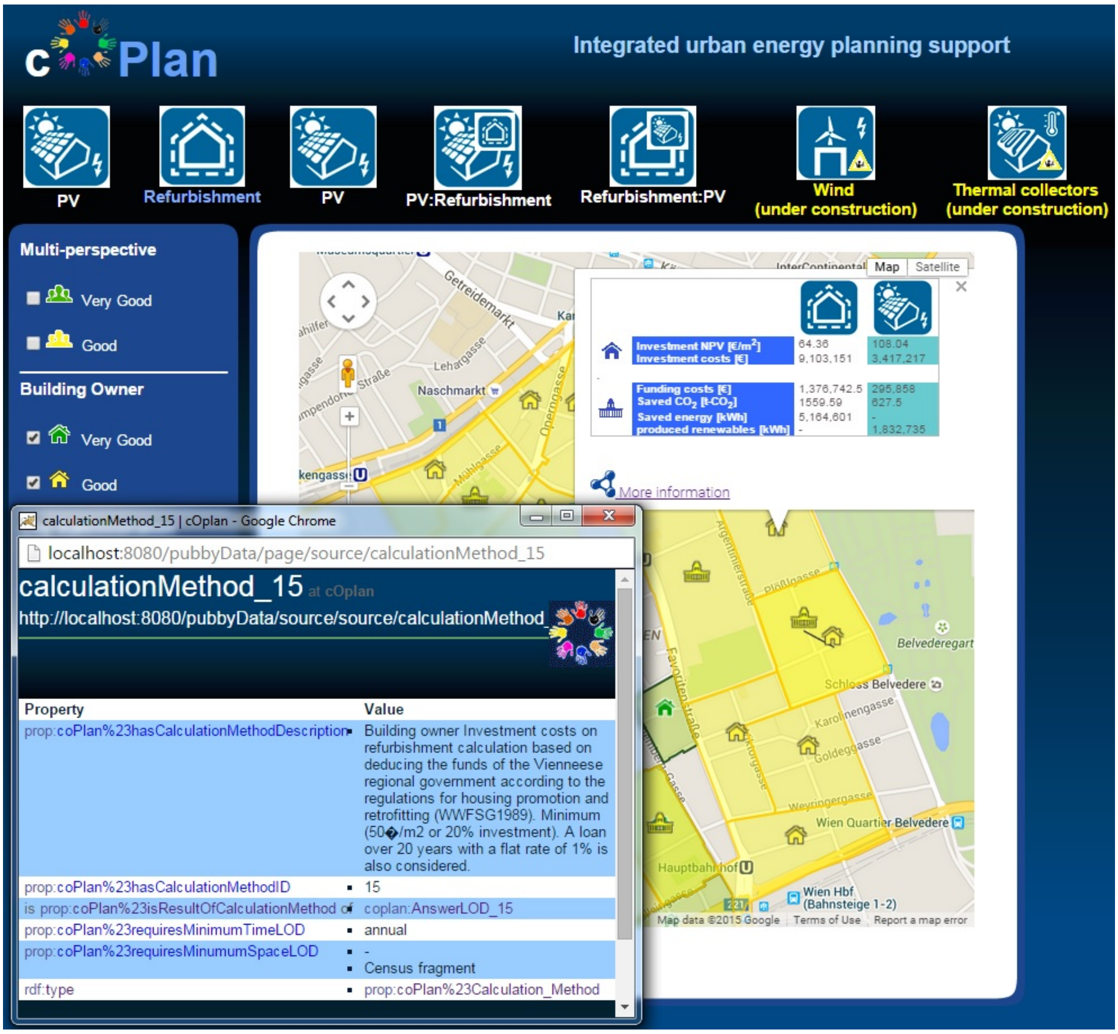


Figure 5.19: Integrated urban energy planning support sample interface.

5.9 Summary

The final results of using the ontology-based system are about classifying buildings in terms of their suitability to install PV and/or to refurbish. Thus, based on indicators at each single building level or census district level (for building refurbishment), buildings or census districts are classified according to their suitability from single stakeholdersâĂŹ perspectives. Then, the classification is aggregated to a common suitability from all the perspectives together.
Furthermore, the classification of census districts (the level at which measures integration was possible) considers the mutual influences of the measures, as options. This means that the modeling considers not only that the stakeholder has one option (one measure) but also other options that impact the decision making process. For example, a census district might be classified as having a good potential for building refurbishment. However, if building-integrated solar PV is to be considered too, it may have a better return on investment and make this census district not good anymore, as better options are possible. The different classifications that the system offers for the integrated measures (solar PV and building refurbishment) are shown in Figure 5.20. It is important to recall that this integration was possible only at the census-district level, since no breakdown from census district to building was possible for the building refurbishment measure, because of the low level of detail of the available data.

The proposed solution can be compared to a similar purpose tool (a previous related work), which has been previously developed at the Austrian Institute of Technology. The developed tool in the context of Smart City projects [The11] is an excel based tool that integrates measures to reduce CO_2 emissions in the city of Vienna. Therefore, its input is a set of quantities to a pre-defined set of measures and its output is the impact on the city in terms of four indicators (renewable energy productions, CO_2 emissions, energy efficiency, and modal split, which related to mobility).
The implementation of building refurbishment in the excel-based tool does not considers the city as having a data property of a given number of square meters of gross floor area that has the potential to be refurbished. To calculate the heating and CO_2 emissions savings, city-level percentages of building age classes and used heating technologies have been applied. Concerning the costs of refurbishment, they were out of the scope of that tool and therefore no decision making elements are given to the building owners to evaluate this measure from this specific perspective. As stated before, the purpose of this tool was to integrate as many measures as possible, aligning with the description of comprehensive tools [Jan00] rather privileging the scope (number of measures) than the level of detail.
Concerning the proposed solution in this thesis, it fulfills the main characteristics of urban energy planning support systems. (i) The calculations are presented from different perspectives and present different results that are relevant to each specific stakeholder. (ii) The output is aggregated to a simple level of understanding that does not require domain expertise in any field. Then the results are even more aggregated to a level of abstraction that represents the common interpretation of all stakeholders. (iii) Interactions between

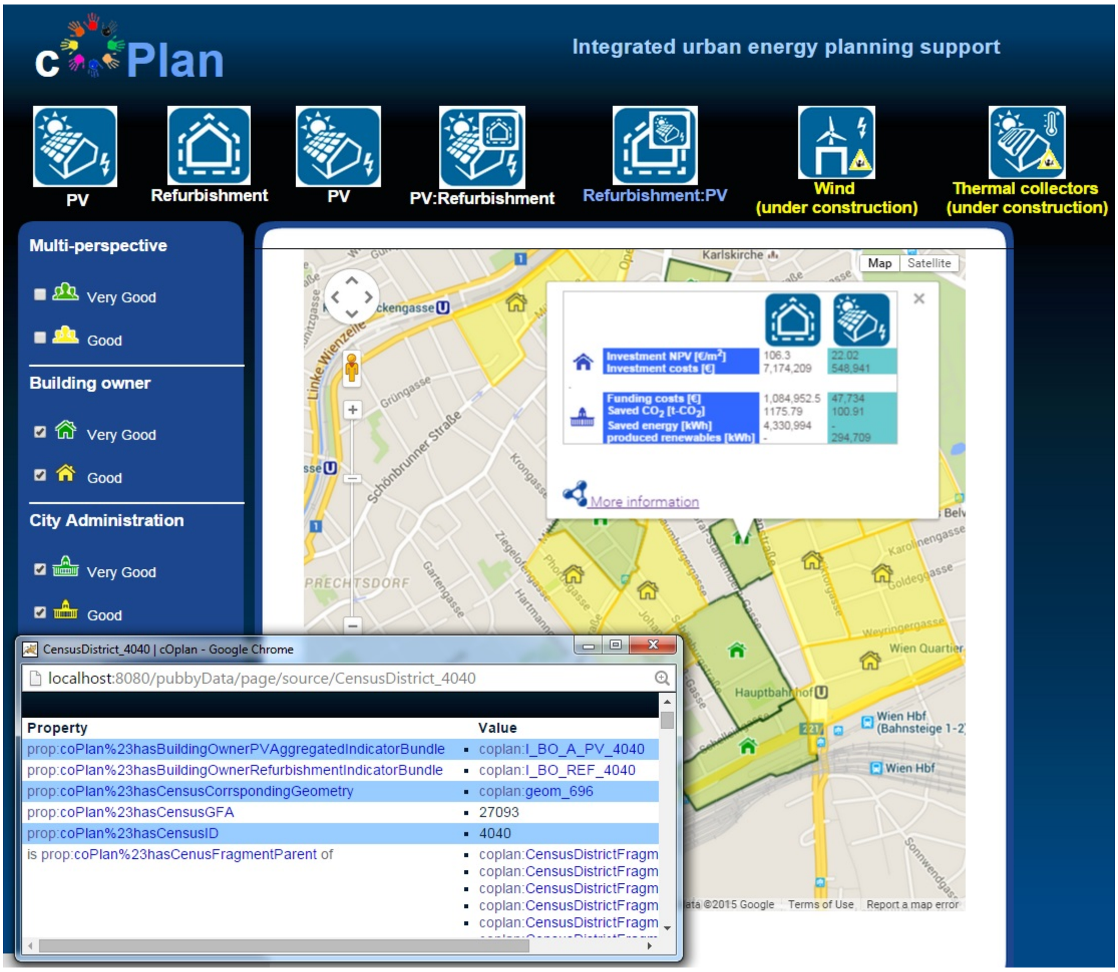


Figure 5.20: Integrated measures sample interface.

different computations have been captured, and then the ontology is used to integrate data from different model and measures. These allow the integration of results (data) and their consistency. (iv) This approach gives the flexibility to calculate one answer in more than one level of detail, in case of data unavailability, or better data availability. Mechanisms are formalized and integrated within the ontology that ensures the possibility to plug other computation models to the system. Furthermore, the approach allowed integrating two measures with different levels-of-detail: building-integrated solar PV at a building level and building refurbishment at census district level. Thus, the approach offers the flexibility to combine more detailed calculation with rather basic ones, regardless of the modeling approach or the technologies.

CHAPTER 6

Discussion & Conclusion

The proposed work in this dissertation mainly addresses modeling a large complex system, for urban energy planning support purposes. Developing a "master decision support system" is not feasible simply because the problem space is non-finite because of the differences in data availability in cities, the changing requirements of the stakeholders, or in general the changing environment where the decision-support is required.
The solution that this dissertation is based on assumes that the development of these systems is a continuous process. It always requires (i) updates to deal with the change in data availability and requirements and (ii) extensions to gradually include as much functionality as possible from a non-finite problem space.
Accordingly an incremental development methodology is proposed as a solution, where integration mechanisms, used computation models involved stakeholders, and their requirements are part of the system. This offers a transparency of the dynamics of the system and ensures the tractability of the requirements with regards to how they are fulfilled. The methodology was applied to develop an ontology-based decision support system for building-integrated solar PV. The same methodology was applied again, as a second use case, to extend the developed system to include building refurbishment planning support. The resulting system has been applied in a district of 1200 buildings in the city of Vienna.
The developed system has also been tested in a ̈real-worldënvironment to evaluate its usability and applicability, within a workshop that involved the Department of Energy Planning of the city of Vienna [Wiea].
The next sections discuss how the developed energy planning support system fulfill the "real-world" needs (in the city of Vienna). Later, it is explained how the results of this work address the research questions that have been initially formulated. Then, it is discussed how the resulting methodology and system fulfill the necessary conditions in urban energy planning support, which resulted from the analysis of urban energy planning processes, in Chapter 2. Then, it is explained how the research framework rigor

was addressed. Finally, the main topics that suit the best for further development are pointed out.

6.1 Reality check of the developed system

A workshop has been organized to assess the usability and applicability of the developed system with real users. Within the workshop, there has been a representation from the Department of Energy Planning in the city of Vienna (MA20) as well as from the Sustainable Building and Cities business unit from the Austrian Institute of Technology (AIT).
the Department of Energy Planning in the city of Vienna plays an important role in the energy planning process as a stakeholder that participate in the elaboration and promotion of energy strategies in the city. More specifically, the main tasks that MA20 performs are as the following [Wiea]:

- Coordination and development of energy-related concepts, among others, the Municipal Energy Efficiency Program (also known as the StÃďdtisches Energieeffizienz-Programm (SEP)).
- Control and monitoring of the achievement of the objectives of the existing energy management concepts and recommendation of relevant measures.
- Management of the funds of the Province of Vienna to promote renewable generation capacity and design of the reference-off funding guidelines.
- Participation in the design and provision of other energy-related subsidies.
- Energy Economic appraisal of projects in administrative procedures.
- Development of pilot projects for promotion of new energy technologies.
- Participation in projects to raise awareness concerning the improvement of energy efficiency (energy consulting).
- Energy data and reports.
- Research in the field of energy.

In the workshop, the MA 20 has been represented by Stefan Geier from the office of energy planning. Stefan Geier is involved in several initiatives of smart integrated energy planning. Furthermore, he works in the field of spatial data harmonization. Stefan Geier is also the spokesman of MA20 regarding ViennaGIS [dSW], a geographic information system of the City of Vienna that provides a comprehensive and sustainable spatial data and geo-services infrastructure.

Regarding the AIT, it has been represented by Wolfgang Loibl a senior scientist and leader of the sustainable cities research group at the Energy Department. Wolfgang

loibl is involved in research and projects to develop integrated concepts and long-term strategies to ensure a sustainable energy supply for cities, including Vienna (namely in Liesing, one of the districts of the city). Moreover, he is leading a work package of developing an integrated urban energy planning support tool in the European project Transform (involving the cities of Vienna, Amsterdam, Copenhagen, Genoa, Hamburg, and Lyon)[tra].
A complementary workshop has been organized, as a solution to the conflicting time availability of all the participants. The complementary workshop involved experts from the AIT represented by Daiva Walangitang, Andreas Frohner, and Branislav Iglar. They are respectively experts in urban planning, energy systems & simulation, and finance. Further more these participants have all been managers of smart-city projects, where it has been required to develop energy strategies that state which measures have to been taken in order to reach desirable energy efficiency and CO2 emissions targets. The concerned cities were Nanchang (in China), Vienna, and Amstetten (in Austria).

Two questionnaires have been distributed. The first questionnaire aimed to reach an understanding of the current situation in terms of the data collection process, data quality, clarity of the identity of the decision makers, and existing planning support tools. The second questionnaire aimed to assess the usability and applicability of the developed energy planing support system. The assessment included both the functionality and the user-interface of the system. A copy of the filled questionnaires is found in appendix A.

6.1.1 Overview of the energy-planning-related decision making in Vienna

The energy-planning-related decision making in Vienna is characterized by the multitude of the decision makers and the changing (improving) data availability and quality, in the absence of adequate supporting tools.
The decision making process involves a large number of stakeholders, depending on the measures to be implemented. Furthermore, the city of Vienna attempts to have an integrated urban planning with energy planning. Thus, the decision making process is organized in a participatory approach that lets all of the stakeholders have their opinions considered.
Concerning the data availability and quality in the city, they are both improving through time. For example, while in this work data about the solar potential of buildings was available only on horizontal surfaces (roofs), in the near future, more data will appear concerning vertical surfaces (facades). There is also a clarity on what data is available and what other needs to be collected. Moreover, it is clear who is responsible for data acquisition in the city.
The city of Vienna has committed to a an Open Government Data initiative. The available open data are regularly updated and enriched. Furthermore, there is a will to go toward Open Government Linked Data, as an integrated and "handy" solution to the deployment of data.

Regarding the support of the energy planning (decision making) process, no specific tools are currently being used. The planning process is supported by simple calculations that are based on averages but that give better (or comparable) results to tools that need detailed unavailable input data and which are compensated by making assumptions.

6.1.2 System usage worflow

The worflow under which the system has been used (in the workshop) comprises seven activities, as shown in figure6.1. The workflow begins by presenting the status-quo of the city, then the involved stakeholders and potential measures to (potentially) implement in the city. The worflow continues by selecting a measure in a given spatial level-of-detail (building or census district) and filtering locations according to their suitability for a that measure, and a given stakeholder(s). Then, details about each location can be browsed through, ending up by selecting a set of locations, to which a given measure is applied. The workflow ends by assessing the impact on the city, caused by the implementation of a selected measure in the selected locations.

In the city status-quo presentation activity, the system displays information about the city. The users are free to browse through the presented linked data. The system has initially integrated data that have been required by the developed computation models, to answer the specific questions of the different stakeholders. The users of the system are able to access all these data, as well as other ontologies that are available on the web, to which links have been established. For example, the users can also browse to data about Vienna that are available in DBPedia, as shown in figure6.2.

In the stakeholders presentation activity, data are shown about all the involved stakeholders regarding building-integrated solar PV and building refurbishment. The data include the questions they raise as well as their break-down into quantifiable questions that the system provides answers for.

In the measures presentation activity, data are shown about all the offered measure by the system (PV and building refurbishment). The measures are described in details concerning what they mean and to what the apply. These data aim to achieve a common understanding about the measures.
Once a measure is selected, the users filter locations that are suitable for its potential implementation. The filters that are used are stakeholder-oriented. They filter locations that are very good or good from their single perspectives or alternatively those that are very good or good as common agreement that considers all their perspectives. A sample view of the filtering activity is shown in Figure 6.3.

Locations can be selected to view detailed data. The data includes the impact of the potential implementation of the available measures, in a sort of simplified "benchmark-view". The simplified view displays specific answers to the different stakeholders that are involved in the implementation of the measure. More data can be browsed through as well in a linked data environment. This enables, optionally, the verification of the used calculation methods or other general data that are related to a given location, which

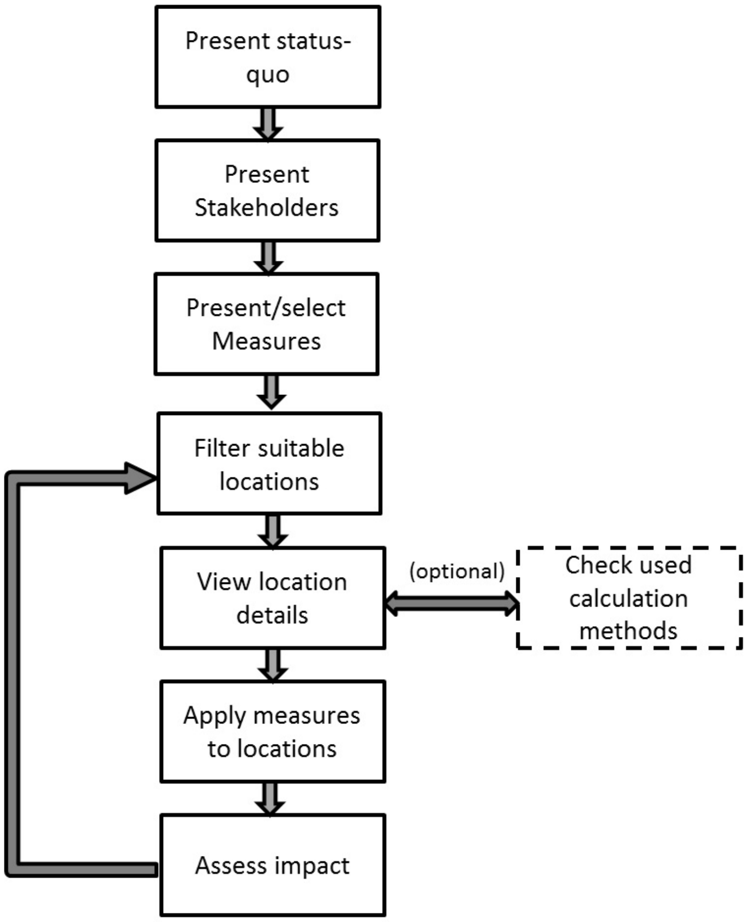


Figure 6.1: Worflow of system usage.

can be linked to the linked open data cloud (for example as it has been the case for the Vienna University of Technology entry).
The locations that are agreed upon are then selected (double-clicked on) to apply a measure. The selection of the locations is based on the discussion of the displayed data in the previous activity. Finally, once the selection of locations is finished, as shown in Figure 6.4, an assessment of the scenario (of applying a given measure to the locations) is performed regarding its impact on the city in terms of CO2 emissions reduction,renewable energy production, energy efficiency, and associated costs (per stakeholder). A sample view of this assessment is shown in Figure 6.5.

6.1.3 System assessment and adjustment

The assessment of the developed energy planning support system has been captured through a questionnaire and open discussions while using the system during the work-

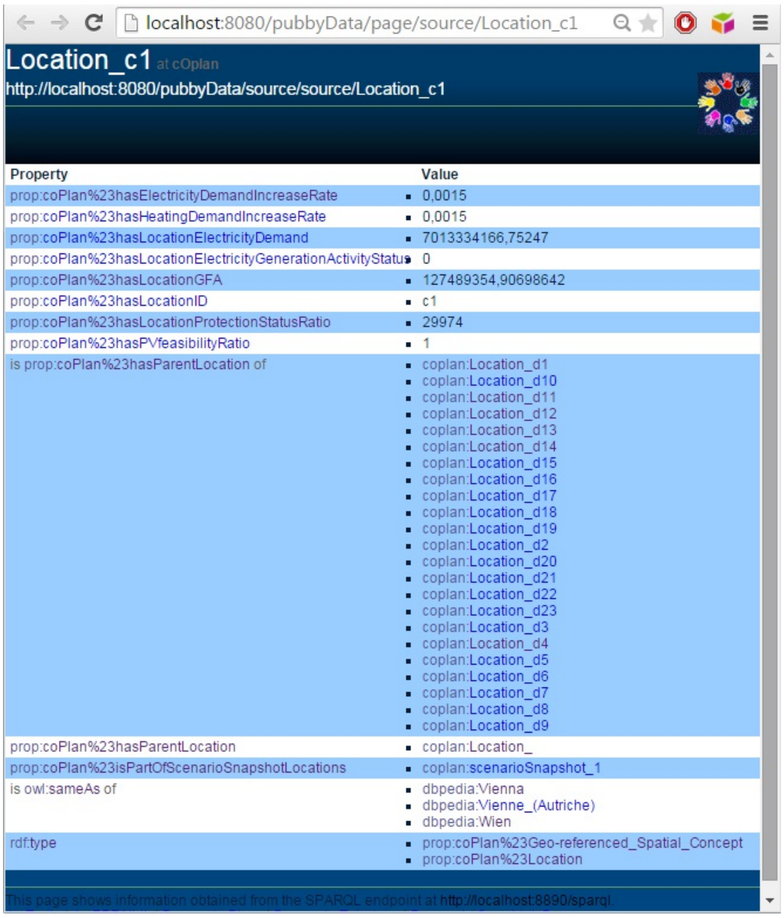


Figure 6.2: Status-quo sample view.

shop. The assessment addressed both the functionality of the system as well as its user-friendliness. The system has been satisfactory, in terms of both functionality and user-friendliness. However, the level-of-detail of data (which are currently available in Vienna and embedded in the system) have been seen as a limiting factor to the usability of the system, as it is.

The functionality of the system has been assigned scores that ranged between good and average (in a scale of: poor, below, average, good, very good). The functionality aspects that has been assessed are: the presentation of city data, scenario setting, allocating measures, determining impact, answering specific questions of stakeholders, and measures library.
The strengths of the system in terms of functionality have been summarized as two points. First, the integration of data allows to browse through the status-quo of the city in a linked data environment. This gives a richer data environment that answers questions

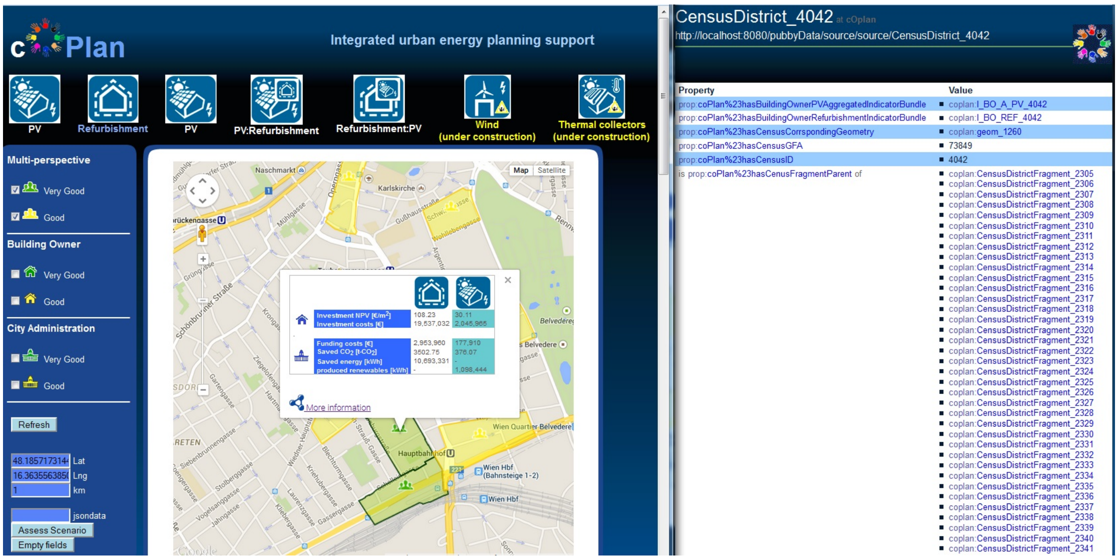


Figure 6.3: Filtering activity sample view.

of stakeholders that are needed during discussions. Second, the integration of measures allows to assess which one is more suitable from different stakeholders' perspectives. This saves time when stakeholders discuss the suitability of locations for measures, as the system discards (using filters) the locations that have no potential from different perspectives and considering both of the measures (PV and building refurbishment).
The weaknesses of the system in terms of the functionality it offers are related to the level-of-detail of the integrated data. The building refurbishment measure is offered only at a the level of census districts (groups of buildings). This means that all the answers that the system offers are related to census districts rather than buildings. Therefore, a census district is suggested as a good location (for building refurbishment) in fact if in average the buildings it comprises are good. Thus, it might be the case that a location within a census district that is not suitable for the application of building refurbishment but marked as being so. This problem is due to the scarcity of data regarding building refurbishment in Vienna, as described in in Chapter 5.

The user-friendliness of the system has been assigned scores that ranged between very good and average (in a scale of: poor, below, average, good, very good). The user-friendliness aspects that has been assessed are: the general look and feel, flow of steps, ease of use, ease of understanding of output, speed, and the traceability of the origin of result.
The strengths of the system in terms of its user-friendliness have been summarized as being a visual tool, which displays summarized data that does not require domain experts to understand. The interface of the system is simplified to the extent that it includes (in its initial state) only measures, stakeholders filters, and a map that displays

Figure 6.4: Sample-workshop scenario: a selection of locations for PV implementation.

locations, reacting to the filtering process. When more details are needed while using the system, it is possible to switch to the linked data view where links can be intuitively browsed through and obtaining more detailed information. As all data are linked, using an ontology that describes the whole system, the origin of (and logic behind) every piece of information is traceable.

The weaknesses of the system in terms of the user-friendliness are related to the visibility of the impact of measures on the city. Applying a measure in one district (of 1200 buildings) does not show a visible (visually noticeable) impact on the indicators: CO2 emission reduction, energy efficiency, and renewable energy production. A noticeable impact on the indicators requires the application of measures on more buildings, while the system integrates data regarding only around 1200 buildings (one district) in Vienna.

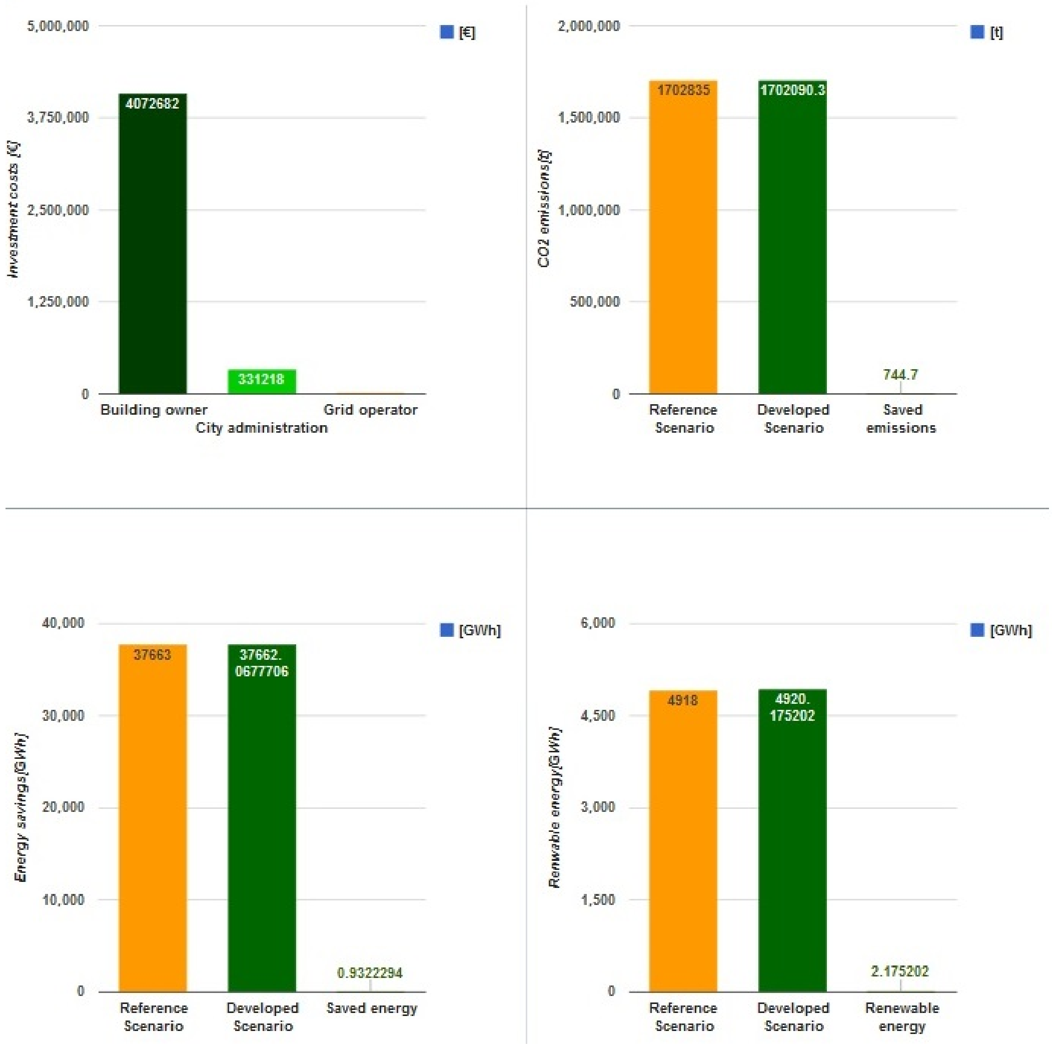


Figure 6.5: Sample workshop-scenario assessment.

Regarding the expectations of the participants against the actual **output of the tool**, it was satisfactory. The assessment of the energy strategies outputs a set of indicators that addresses the needs of the planners (and stakeholders). It helps assessing the scenario from a global perspective. During the workshop, it was always possible to provide the participants with the information they required in more details (at a level of each location). It was also traceable how the information that have been required is calculated.

Regarding the expectations of the participants against the actual **behavior of the tool**, it was satisfactory regarding the solar PV-related functionality and less satisfactory regarding the building refurbishment-related functionality. The participants expected

associated information of building refurbishment at the level of each building. However, due to poor data availability, the tool integrates at the moment only census-district-level information about building refurbishment.
Regarding the expectations of the participants against the **concept of the tool**, it was very satisfactory. A special attention has been given to two facts: the integration of data with the Linked Open Data cloud, and the plurality of perspectives (stakeholders) that the tool considers. the integration of the data with the Linked Open Data cloud enriches the data environment and offers a wider range of data that can be accessed through the tool. The plurality of perspectives that tool considers helps the negotiation process between the different stakeholders. The tool represents a solid integrated reference for negotiation that eases the understanding of the mutual interests and conflicts of the stakeholders.

Overall, the improvements that the system required (as it resulted from the assessment workshop) are either related to the interface or to data availability. An updated version of the interface has been developed to address the flaws that have been pointed out in the assessment workshop. However, regarding the data availability-related flaws, no improvements could be currently achieved, because so far no higher level-of-detail data (i.e. building-level instead of census district-level) exist regarding building refurbishment. In fact, one of the main features of the work that has been discussed in this thesis is to provide the flexibility to integrate data with both low and high levels-of-detail under one system. The flexibility allows also to replace data that has a low level-of-detail with better data, once they become available. Mechanisms of achieving this have been discussed in the previous chapters.

6.2 Research questions

In this section, the results of the research work are discussed against their fulfillment to the research questions that have been stated in Chapter 1.
RQ: Is it possible to develop an ontology of an urban energy system to support decision making i.e. the choice of adequate measures in the process of developing a sustainable energy master plan?
The main research question above reflects the goal of this dissertation, which is to support urban (energy) planners in choosing measures that help reducing CO_2 emissions at the level of the city. This has been achieved by describing an ontology based methodology, then, applied in developing an ontology-based decision support system in urban energy planning. The developed system supports building-integrated solar PV and building refurbishment.

- **RQ1**: How can a geo-referenced urban energy system be represented within an ontology?
  Classic approaches of dealing with geo-referenced data are related to geographical information systems (GIS). As today, classic GIS-related technologies offer more advanced geo-spatial features to perform advanced spatial operations. However,

the semantic web technologies offer enough functionality to deal with the problem addressed within the scope of this work. More advanced geo-spatial focus of ontologies have been addressed in a project related to open linked spatial data [SLHA12]. In this work, as described in the methodology section, modeling is performed according to the needs that are arising from the use cases (measures to be integrated). Two use cases have been implemented that required spatial data. Therefore, the urban energy system that has been modeled is geo-referenced and it is put within its spatial dimension. Furthermore, a notion of spatial level-of-detail has been included. The spatial level-of-detail notion provides the flexibility to integrate geo-referenced concepts that are not from the same granularity. For example, concepts that are related to buildings can still be integrated with concepts that are related to census districts, communal districts, or cities.

Ontologies offer richness at the level of their expressiveness of concepts. Therefore, in a domain (geo-referenced urban energy systems), where there is a large variety of concepts that need to be put in relation with their spatial dimension, ontologies are semantically rich and clarify (formalize) the complexity of this domain. There exist semantic web technologies that allow managing geo-data, such as Virtuoso Server [Ope14], which has been used in this work. Such technologies allow the indexing of geo-spatial data as well as the fundamental features that spatial databases offer, such spatial joins. The developed use cases did not require such advanced features to be performed from the semantic web technologies side. However, in the data preparation phase and some computation models required advanced features, such as the construction of the low voltage groups, in the building integrated solar PV use case.

The ontology (or semantic web technologies in general) does not offer all the required spatial functionality but the adopted methodology (in Chapter 1) makes the ontology integrate data that heterogeneous computation models generate. These heterogeneous models also include spatial ones, such as the one described in chapter 5, (PV21 for generating low voltage groups).

Accordingly, ontologies can be used to represent geo-referenced urban energy systems. In some cases, they cannot be used to perform all the advanced geo-spatial functions (or in general calculations that require an application layer); however, the methodology section describes how different computation models can be integrated to perform the necessary tasks that ontologies do not perform.

- **RQ2**: How can an urban energy system ontology be used in urban energy-related decision support?
  Urban energy planning support is a discipline that demands the integration of large, multi-domain datasets. The decision making at the level cities requires adopting a systemic (holistic) approach, paying attention to several elements that are not necessarily directly related to the decision making context. Different stakeholders have interests that are impacted by the future implementation of the strategic decisions, which are adopted during the planning phase. Furthermore, the involved

disciplines in urban energy planning are numerous and different but require to be considered as a system. Finally, urban energy planning support needs data, so that informed decisions (or in other cases framed assumptions) are made. These required data do not always exist in the desired level-of-detail or exist in different levels-of-detail, depending on the decision (measure) to be supported. This short overview of the context and needs of urban energy-related decision support explains the choice of developing an ontology for that purpose.

Ontologies are semantically rich and can be used to explain complex concepts, putting them in their global context. As urban energy systems involve a variety of domains, which experts do not have the same understanding about, using an urban energy system ontology helps achieving a common understanding about concepts. It helps formalizing and integrating the knowledge of different experts or stakeholders that might use the same semantics to describe different concepts. Therefore, communication between the domain experts, stakeholders, and urban energy planners is improved by having a common understanding of the whole system, modeled as an urban energy system ontology. This concludes that a first use of the urban energy system ontology is a communication basis between the different experts that provide knowledge in urban energy-related decision support. Stakeholders, with interests being potentially impacted by the decision making process, are to be considered. The urban energy system ontology includes these stakeholders as part of the system. This is important in the decision support process as the stakeholders are in fact the actual decision makers, because eventually at the implementation phase they have the last word. These stakeholders might have different or conflicting interest that need to be understood. Again, the offered semantic richness in ontologies allows to formalize this required knowledge. The urban energy system ontology integrates the potential decisions of the stakeholders concerning scenarios of strategies. Furthermore, the decisions of the single stakeholders are raised to another level of abstraction, which are common decisions i.e. locations are not only classified in terms of their suitability for a measure from single perspective but also from the perspective of all stakeholders. It is to note that the decisions of the stakeholders are systemic in the sense that they are aware of the different options (measures) that they have and also aware of the interests of each other.

The urban energy system ontology is used in urban energy-related decision support also in the classic sense of providing quantifiable information, evaluating the impact of the decisions. The ontology has a set of competency questions that are raised during the urban energy planning support process. These competency questions are answered by the ontology as a quantitative support to the urban energy planning process. The urban energy system ontology goes together with the methodology described in Chapter 3. It offers extension mechanisms so that, if necessary, more questions that are raised during the energy planning process can be integrated. This has been demonstrated through the integration of building refurbishment related questions with building-integrated solar PV.

The urban energy system ontology integrates data from heterogeneous sources that can be queried, supporting the energy planning process. The ontology integrates data from the data collection phase together with calculated data (by different computation models). The data integration, in here, means that data are put within the context of other data. The urban energy system ontology allows browsing and querying an integrated system rather than a collection of datasets. The data are presented in abstraction of how they were calculated or collected. However, this information is still preserved within the ontology, first to ease the upgrade of the ontology in the future, if better data appear; second, to make the decision making support process transparent in terms of the quality of data it offers.

- **RQ3**: What mechanisms need to be integrated within the urban energy system ontology so that it copes with the variety of data availability, requirements, and use?
  The developed urban energy system ontology (and the ontology-based decision support system for urban energy planning are generic). They are supposed to be used in different contexts of data availability (and levels-of-detail) and be customized to meet the changing requirements or stakeholders in these contexts.
  The proposed urban energy system ontology is modular, allowing its extension to include more measures. The urban energy system ontology together with its modeling methodology (described in Chapter 3) respectively offer and describe extension mechanisms. An example of extension of the urban energy system ontology was to upgrade it from considering building-integrated solar PV planning support to merge it with building refurbishment planning support. Thus, the most basic form of upgrade mechanisms is the development methodology that is described in Chapter 3. It shows how to grow the system to include more measures and so that it answers more questions, which are related to urban energy planning.
  The urban energy system ontology includes a data integration part (under the Data Integration Concepts), which explains the dynamics within the system. This part of the ontology formalizes which elements of the urban energy system influence which others. The influence is modeled by formalizing which data property of an affecting component causes an impact (if data property changes) on another data property of an affected component. Therefore, it is known which data properties within the system are changing if others change. These influences of data properties on each other are considered to be the dynamics within the system and they are directly derived from the computation models that are used (It is to recall that the ontology does not perform the calculations but rather integrates their results). Thus, the used computation models are also put in relationship with these dynamics, because the existence of the latter is conditioned by the existence of the computation model. This is considered as a mechanism to cope with the changing data availability, requirements and use. It allows replacing a computation model (or more) with a more appropriate one to the context of use. When this needs to be achieved, it is transparent to the system developers what dynamics are not valid anymore, which

other computation models are impacted, and what answers need to be recalculated. There is a formalized relationship (integrated in the urban energy system ontology) between the domain concepts and data integration concepts. Therefore, domain concepts can be traced to which measure they belong, stakeholders that involved in the measure, questions they raise, computation models that calculate their answers, calculation methods that have used to answer the questions, and the levels-of-detail that the calculation methods require.

- **RQ4**: What software architecture is needed to implement an ontology based tool for decision support in urban energy planning?
  The urban energy system ontology represents the core of decision support system. It comprises all the data, information, and knowledge that is required for the decision support process. It is to recall again that the ontology does not make calculations by itself. It rather integrates data from several sources, including data that are generated by computation models. Thus the ontology behaves as a middleware between the users (urban energy planners and stakeholders) from the one hand, and developers of specific computation models and data providers on the other hand.
  The urban energy system ontology integrates data from computation models (and data sources) in abstraction of their internal architecture. The ontology offers the necessary semantics to perform a semantic mapping between the ontology and the data parameters of the multiple sources. Thus, computation models are used to perform the necessary calculations but their results are stored as regular datasets. Therefore, the modeling approach or the internal architecture of these computation models are not important in this case. Once the semantic mapping is achieved, the ontology becomes a knowledge body integrating and ensuring the consistency of heterogeneous data, from different sources and computation models.
  In the specific case of this work, an existing data integration tool has been used [KSA+12]. It was used to perform the semantic mapping and generate the data source in RDF, so that the transition from the data collection and preparation phases toward the data use phase is achieved.
  There are several ways to use the data once they are in an RDF format, deployed in a web-based server. These data can be queried using a specific querying language (SPARQL). Another option is to use linked data browsers to navigate through these data. These data can also be linked to the cloud linked open data. Finally, a web client that addresses the specific needs of the users can be developed, as it was the case in this work. The web client behaves as an interface to the integrated data. Serving the data integrated and ready to use, in abstraction of computation models or data collections contribute in the flexibility of using the system. The interface of the system does not trigger any computation model; only local simple calculations can made. The interface has access to all the data that are required to support the urban energy planning process, but it is not bound to a single process. Decoupling the presentation layer from the required core data for the

planning support process gives flexibility to the users in choosing how to conduct their specific urban energy planning processes.

6.3 Urban energy planning support conditions

Necessary conditions in urban energy planning support have been derived (in Chapter 2). These conditions are based on the analysis of an urban energy planning process that is widely spread in the world, more than 6000 users (cities and municipalities). The proposed solution i.e. the urban energy system ontology and its accompanying development methodology fulfill these conditions.

- Supporting the perspectives of different actors (stakeholders): the decision making process must involve all the stakeholders that have potentially affected interests and provide them with specific information, from their different perspectives.
  This condition has been addressed through the modeling of a system that answers questions from the perspectives of the involved stakeholders. Sets of answers from the perspectives of the stakeholders are available regarding each measure. Different stakeholders are provided with specific information that addresses their concerns. In the implemented use cases (building-integrated solar PV and building refurbishment), sets of answers are available from the perspectives of the building owners, the electric grid operator, and the city administration.

- Common understanding and quantifiable impact of decisions: the assessment of the impact of energy strategies must be quantifiable. The output results must be aggregated to a level of abstraction that is understandable by all the different actors (i.e. stakeholders and planners).
  Concerning the quantifiable impact of decisions, the urban energy system ontology comprises sets of competency questions. These competency questions result from the scoping phase, where a breakdown (of the competency questions) is performed to make sure that all questions are broken-down to a level where quantifiable answers can be provided.
  In the implemented use cases, the ontology offers quantifiable answers at the level of each building (in the case of building-integrated solar PV) and at the level of each census district (in the case of building refurbishment).
  Concerning the common understanding of the impact of the decisions, it has been addressed in the decision modeling phase. Interpretations in natural language from the perspective of each stakeholder are assigned to the quantifiable answers. For example, the building owner does not have to know the meaning of "transformer overload duration". An interpretation from the grid operator is assigned to value ranges of answers as good or bad. Then, the building owner (or any other stakeholders or participant in the planning process) understands the meaning of the value without necessarily having any knowledge in electric systems.
  Furthermore, the interpretations from single perspectives are aggregated to a higher level of abstraction. A common interpretation (from all the involved perspectives)

about locations is defined. This eases the urban energy planning process, by filtering the locations that have good potential from all perspectives and that no one would be opposing to.

- Measures integration and resources negotiation: the assessment of the impact of energy strategies must consider the inter-dependencies between different elements and calculations.
  This condition has been addressed in two different aspects. The first aspect is that the ontology includes interactions mechanisms that represent the dynamics of the system. The second aspect is that the system includes decisions of the stakeholder not only about single silos of measures but also decisions that involve them together. The dynamics within the urban energy system are modeled and integrated within the ontology. Therefore, it is transparent which elements influence which others. This helps in the integration process. Of course, interaction protocols are still needed to handle interactions or automate them. This is further discussed in the future work section. The ontology offers integrated (in terms of measures as well) decisions. Locations are assessed (very good, or good) from single stakeholder perspectives for each measure, given that the stakeholder knows also about the possibility of implementing a different measure. For example, the system would flag a location as good for solar PV from the perspective of the building owner, only if it has a better return on investment compared to building refurbishment. Finally, for each measure, locations are assessed from the perspectives of all of the stakeholders together , taking into consideration the mutual competition of measures.

- System viability through robustness against data availability problems: The system must be flexible to be used within different conditions of data availability and levels of detail.
  This condition has been addressed by the development methodology, described in Chapter 3, which is considered as part of the contribution of this research. It allows the flexibility in calculating each single answer in more than one level of detail, using different calculation models e.g. if more detailed data are available about a given share of the city, more detailed models can be used for these, while the rest is calculated using more general models that do not require detailed datasets. Furthermore, mechanisms of integrating multiple levels of detail data are formalized and integrated within the ontology.
  In this work, the developed system combined building-integrated solar PV calculations that were performed at the level of single buildings (15-min time step over a whole year) with more basic calculations at a census-district level (group of buildings). This demonstrates the ability of the methodology to cope with low level-of-detail data availability, while still using higher levels-of-detail where it is possible.

6.4 Research framework rigor

The presented results of this thesis have been conducted within the Design Science framework [HMPR04]. An overview of the fulfillment of this research to the guidelines of the Design Science is explained below.

- Design as an Artifact: Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation The main result of this research is an ontology-based decision support system for urban energy planning. This system is based on an urban energy system ontology as well as methodology to develop such a system. The artifact is viable as it can be re-created, updated or, extended using the methodology that accompanies the system. This has been demonstrated through the incremental development of the system to support building-integrated solar PV planning, then its integration with building refurbishment.

- Problem Relevance: The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
  The problem addressed in this research resulted from a real world need to supporting the development of energy strategies (sustainable energy action plans). As explained in Chapter 2, there are more than 6000 cities and municipalities that officially manifested their interest in developing urban energy strategies to sustain their environment. A computerized support for developing these energy strategies is necessary given the large size of the city, the data it requires, and the complexity of the city as a system.

- Design Evaluation: The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
  The evaluation of the design is achieved through the implementation of the proposed methodology in two use cases. The two use cases have been applied to a district of 1200 buildings in the city of Vienna. Then, the functionality of the system was evaluated against its fulfillment of the conditions of urban energy planning support, as described in the previous section. Furthermore, a comparison between the resulting system and an existing similar scope tool has been performed. Finally, the resulting design artifact (an ontology-based urban energy planning support system) has been tested together with real users, i.e the Department of Energy Planning in the city of Vienna as well as the Sustainable Building and Cities business unit from the Austrian Institute of Technology.

- Research Contributions: Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies. The contribution of this research includes the development methodology that is based on gradually constructing an urban energy system ontology to serve as a core for a decision support system. Different phases within this methodology are described in terms of activities they require, actors that participate, as well as their input and output. The methodology has been applied twice and its applications contribute as well in its clarification so that it can be re-used.

- Research Rigor: Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
  Concerning the construction of the system, it obeyed to a rigorous methodology with formal steps. The methodology itself was based on an analysis of existing urban energy planning processes and their needs that must be addressed. The construction of the system involved the development and integration of several computation models (from different domains) that are verified by their respective domain experts. The ontology that integrates all the data as an urban energy system was verified against its fulfillment of the competency questions that are aligned with the results of the scoping phase (stakeholders stating which questions they want answers for). Regarding the rigor of the evaluation, it is emphasized through the application of the methodology to include two use cases that cover different domains, require different nature of computation models to be integrated, and finally have different levels of-detail of available data.

- Design as a Search Process: The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
  The nature of the problem addressed in this research makes the search process obey to the generate and test incremental development pattern [HMPR04] that this guideline suggests. Developing a "master decision support systems" that implements all the possible decisions is not feasible, since the problem space in this case is infinite. Therefore, one of the adopted design principles of the search process was to develop an open system, which incrementally grows and at the end of each iteration evaluate and adjust it.

- Communication of Research: Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.
  In terms of the final result of the research, the ontology-based decision support systems models multiple domains, requiring different expertise, however, the output of the system is aggregated to a level of abstraction that everyone understands. In fact, the developed system is intended to be used by users that are not domain experts. Furthermore, even domain experts as users of the system, cannot eventually be experts in all the modeled fields. The development methodology of the system is explained in a such way that it is understood by a target audience in the fields of:

urban planning, (geographical) information systems development, environmental planning, and energy planning.
Concerning the communication of the results of this research, other than this dissertation, presentations/publications also have been made in targeting different domains. The domains included information systems and technologies [OLP+14], cyber physical systems modeling [OPS+13], cybernetics and systems research [OLGG+14], [OLGG+15], processes and product modeling [OLA+14], building physics and energy [OLFT15a], and environmental informatics [OLFT15b], [OLFT14].

6.5 Future work

The presented work in this dissertation includes an incremental methodology to develop ontology-based decision support systems, as well as its application in the integration of building-integrated solar PV with building refurbishment. Based on these artifacts, further development and extension could be achieved.
The first building blocks of a more comprehensive decision support system in urban energy planning have been defined in this work. The goal is to incrementally include more measures that the system can provide support for. Two different measures have been implemented that cover decentralized electricity generation and heat demand reduction. Therefore, similar measures within the same topics could be integrated with building-integrated solar PV and building refurbishment. Further measures that can be integrated with the actual system include:

- Building-integrated wind turbine: It is very similar to the first use case. Most of the concepts that apply to solar PV also apply to wind turbines. They influence the grid (low voltage grid) the same way and they involve the same stakeholders, most probably asking the same questions. The implementation of this measure requires data about the wind potential at the level of roofs of buildings.

- In-city power hydro-storage: This measure concerns the construction of hydro storage facilities where it is possible and where there is an excess of decentralized electricity generation. Some of the data demands of this measure have been covered in the use case of building-integrated solar PV, including the demand and generation profiles of the buildings. Data regarding costs, and possible locations for such storage are required.

- Efficient lighting in buildings: the data and computation models demands of this measure have been covered in the building-integrated solar PV as well. The urban energy system ontology includes concepts and data that describe the behavior of buildings in terms of energy demand. Introducing efficient lighting as an extra measure requires minor development effort to change the electricity demand profiles of buildings.

- Solar thermal collectors: the implementation of this measure is similar to the one of solar PV. They both require solar data and energy demand profiles at the level of buildings. Standard heat demand profiles per building use are also available as it was the case for electricity demand. Computation models that have been developed for building integrated solar PV could be re-used and adapted to solar thermal collectors.

The list above includes measures that are easier to include based on the existing system. However, other measures can be integrated as well, as described in the methodology section in Chapter 3.
The developed ontology includes data integration concepts that model the dynamics of the urban energy system. These dynamics helps understanding the behavior of the system when integrating new computation models or updating existing ones. So far, this is done manually, using customized scripts to detect interactions between different models when "plugging" them to the rest of the system. The link between the data contained in the urban energy system ontology and the computation models that contributed in calculating some these data is not dynamic. Future work in this topic includes making this link dynamic between the urban energy system ontology and the computation models. Currently, the urban energy system ontology behaves as a data integration platform. It is possible to equip it with an application layer so that together they behave as a computation model integration platform (adopting the same principles in co-simulation platforms, but in this case dealing with low-level-of-detail calculations compared to simulations). This potential application layer, to upgrade the ontology, has already all the necessary information that formalize the interactions between different models in terms of their data properties. The remaining work is to automate these interactions, through the definition of interaction protocols that regulate the communications between the integrated computation models.
Future work to enrich the ontology is to include urban planners as explicit stakeholders in the process. This means that the ontology would also include a set of questions (with their answers) that address the specific concerns of urban planners, if solar PV or building refurbishment are to be implemented in a given location(s). The importance of urban planners as explicit stakeholders would be clearer if other measures are to be included, such as hydro-storage, where the built environment is more significantly impacted.
The data use process could be further developed to include a tool box to offer a generic customizable interface to the users. A similar approach to the ones described in the methodology section (data use phase) in chapter 3 could be adopted. It is to recall that the ontology includes all the data, information, or knowledge that is required by the users. The interface does not invoke any computation models to perform complex operations, which are done during the data preparation phase. A customizable interface is feasible in this case because the problem space is finite. The quantity of answers and information that the system is supposed to provide users with is known. Combinations of possible flows of information can be modeled as a basis for this customizable interface.

APPENDIX A

Tool Assessment Questionnaires

The content of this appendix represents the filled questionnaires concerning the assessment of the developed urban energy planning support system. The questionnaires below are sorted according to the participants of the workshop in the following order: Stefan Geier (SG), Wolfgang Loibl (WL), Daiva Walangitang (DW), Andreas Frohner (AF), and Branislav Iglar (BI).

Decision Support Tool Questionnaire :
General context

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1. Context: current state of your city To which degree is determined/How would you rate:						
1	Is energy planning a priority for your city?				X	
2	Are the city energy targets defined?				X	
3	Are the city energy targets being tracked?		X			
4	Are the relevant energy measures being developed?		X			
5	Is the stakeholder landscape mapped? (coordination of the city wide flow of information, who are the data owners, etc..)			X		
6	Are the relevant sources of information identified?			X		
7	Are there potential sources of information untargeted?		X			
Open ended questions (please write your comments:						
8	Who are the relevant decision makers?					
9	Which energy measures have to be implemented?	Integrated urban and energy planning				
10	What are the current restrictions and barriers to informed decision making?	intransparency				

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
2. Commitment to collecting/publishing data.						
1	The clarity on what data is available and what data needs to be collected.			X		
2	The clarity on who is responsible for data acquisition in your city.				X	
3	The quality and resolution (level of detail) of available data/information.		X			
4	Regularity of update/enriched the Open Government Data.				X	
5	The presence of atempts/initiatives toward Open Government Linked Data.				X	

In case existing decision support tools are currently being used:

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
3. Creation: running scenarios, analyzing and making actionable plans.						
1	Who is implementing the available information in the tool?					
2	Who is responsible for the running of the tool?					
3	Who is defining and designing the measures?					
4	What needs to be installed to run the tool?					

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
4. Callibration: reviewing and maintaining accuracy of the DST.						
1	Who is keeping the data up to date?					
2	Who is providing additional data?					
3	Who ensures the continuous flow of new information?					
4	What needs to be installed to update the measures in the tool?					

Figure A.1: Assessment workshop questionnaire-General context-SG

c Plan

Decision Support Tool Questionnaire:
Tool & Testing Session

		Poor	Below	Average	Good	Very Good	Not Applicable
1. Functionality **Please indicate your experience with the following steps in the DST in terms of clarity and applicability:**		1	2	3	4	5	na
1	Presentation of City Data			●			
2	Set Scenarios			●			
3	Allocate Measures		●				
4	Determine Impact		●				
5	Answring specific questions of different stakeholders				●		
6	Measure Library			●			
a	Solar PV- Building level						
b	Solar PV- Census district level						
c	Building refurbishment						
d	Integrated Building Refurbishment with PV						
e	Integrated PV with Building Refurbishment						
7	Comments						

		Poor	Below	Average	Good	Very Good	Not Applicable
2. Userfriendliness **Please indicate your experience the DST in terms of clarity and applicability:**		1	2	3	4	5	na
1	General Look & Feel			●			
2	Flow of the Steps				●		
3	Ease of Use			●			
4	Ease of understanfing of output			●			
5	Speed			●			
6	Traceability of the origin of results (used input, calculation methods, etc)				●		
7	Comments						

		Poor	Below	Average	Good	Very Good	Not Applicable
3. About the Session **Please indicate your experience with the testing session:**		1	2	3	4	5	na
1	I rate the content of the session				●		
2	I rate the amount of 'hands- on' experience as			●			
3	I would recommend this tool within my network as being...			●			
Open ended questions (please write your comments):							
4	How would you see this tool support your daily work/tasks?	/					
5	What support would you need in order to be able to use this tool in your city?	/					

4. Other comments	
What is the general impression you got of the Decision Support Environment (DSE) prototype?	expert tool
How would you use it 'as is'?	
Which functionalities would you like to see integrated in a further developed version of the DSE prototype?	filter options
Do you see any barriers for you / your organisation using the tool ? (e.g. Data availability, operational responsibilities, knowledge on measures)	data quality / card level of focus

Figure A.2: Assessment workshop questionnaire-Tool & testing session-SG

c Plan

Decision Support Tool Questionnaire :
General context

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1. Context: current state of your city To which degree is determined/How would you rate:						
1	Is energy planning a priority for your city?				X	
2	Are the city energy targets defined?				X	
3	Are the city energy targets being tracked?			X		
4	Are the relevant energy measures being developed?		X			
5	Is the stakeholder landscape mapped? (coordination of the city wide flow of information, who are the data owners, etc..)			X		
6	Are the relevant sources of information identified?			X		
7	Are there potential sources of information untargeted?		X			
Open ended questions (please write your comments:						
8	Who are the relevant decision makers?	so many!				
9	Which energy measures have to be implemented?	wide variety; District heating, retrofitting, PV				
10	What are the current restrictions and barriers to informed decision making?	ownership, building age, quality				

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
2. Commitment to collecting/publishing data.						
1	The clarity on what data is available and what data needs to be collected.				X	
2	The clarity on who is responsible for data acquisition in your city.		X			
3	The quality and resolution (level of detail) of available data/information.		X			
4	Regularity of update/enriched the Open Government Data.	X				
5	The presence of atempts/initiatives toward Open Government Linked Data.			X		

In case existing decision support tools are currently being used:

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
3. Creation: running scenarios, analyzing and making actionable plans.						
1	Who is implementing the available information in the tool?	X				
2	Who is responsible for the running of the tool?	X				
3	Who is defining and designing the measures?	X				
4	What needs to be installed to run the tool?	X				

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
4. Callibration: reviewing and maintaining accuracy of the DST.						
1	Who is keeping the data up to date?	X				
2	Who is providing additional data?	X				
3	Who ensures the continuous flow of new information?	X				
4	What needs to be installed to update the measures in the tool?	X				

Figure A.3: Assessment workshop questionnaire-General context-WL

c Plan

Decision Support Tool Questionnaire:
Tool & Testing Session

		Poor	Below	Average	Good	Very Good	Not Applicable
1. Functionality **Please indicate your experience with the following steps in the DST in terms of clarity and applicability:**		1	2	3	4	5	na
1	Presentation of City Data				X		
2	Set Scenarios			X			
3	Allocate Measures					X	
4	Determine Impact				X		
5	Answring specific questions of different stakeholders				X		
6	Measure Library			X			
a	Solar PV- Building level					X	
b	Solar PV- Census district level					X	
c	Building refurbishment			X			
d	Integrated Building Refurbishment with PV			X			
e	Integrated PV with Building Refurbishment			X			
7	Comments						

		Poor	Below	Average	Good	Very Good	Not Applicable
2. Userfriendliness **Please indicate your experience the DST in terms of clarity and applicability:**		1	2	3	4	5	na
1	General Look & Feel				X		
2	Flow of the Steps				X		
3	Ease of Use					X	
4	Ease of understanfing of output					X	
5	Speed			X	X	X	
6	Traceability of the origin of results (used input, calculation methods, etc)						
7	Comments						

		Poor	Below	Average	Good	Very Good	Not Applicable
3. About the Session **Please indicate your experience with the testing session:**		1	2	3	4	5	na
1	I rate the content of the session				X		
2	I rate the amount of 'hands- on' experience as						
3	I would recommend this tool within my network as being…			X			
Open ended questions (please write your comments):							
4	How would you see this tool support your daily work/tasks?	would need data at building level					
5	What support would you need in order to be able to use this tool in your city?	→ data provision					

4. Other comments	
What is the general impression you got of the Decision Support Environment (DSE) prototype?	average
How would you use it 'as is'?	as a test. version
Which functionalities would you like to see integrated in a further developed version of the DSE prototype?	individual thresholds for icons!
Do you see any barriers for you / your organisation using the tool ? (e.g. Data availability, operational responsibilities, knowledge on measures)	~~spe~~ scepticism: low applicability

Figure A.4: Assessment workshop questionnaire-Tool & testing session-WL sprawl

c Plan — Decision Support Tool Questionnaire : General context

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1. Context: current state of your city						
To which degree is determined/How would you rate:						
1	Is energy planning a priority for your city?				✓	
2	Are the city energy targets defined?				✓	
3	Are the city energy targets being tracked?		✓			
4	Are the relevant energy measures being developed?				✓	
5	Is the stakeholder landscape mapped? (coordination of the city wide flow of information, who are the data owners, etc..)				✓	
6	Are the relevant sources of information identified?		✓			
7	Are there potential sources of information untargeted?	✓	✓			
Open ended questions (please write your comments:						
8	Who are the relevant decision makers?	Magistrate Director Mayor of Vienna, Wien Energie, other utilities				
9	Which energy measures have to be implemented?	Energie Efficiency – Refurbishment of old building stock, limiting urban sprawl				
10	What are the current restrictions and barriers to informed decision making?	old mindset 'silo' structures, fear of transformation, ignorance				

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
2. Commitment to collecting/publishing data.						
1	The clarity on what data is available and what data needs to be collected.		✓			
2	The clarity on who is responsible for data acquisition in your city.		✓			
3	The quality and resolution (level of detail) of available data/information.		✓			
4	Regularity of update/enriched the Open Government Data.		✓			
5	The presence of atempts/initiatives toward Open Government Linked Data.				✓	

In case existing decision support tools are currently being used:

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
3. Creation: running scenarios, analyzing and making actionable plans.						
1	Who is implementing the available information in the tool?	the tools are lacking				
2	Who is responsible for the running of the tool?					
3	Who is defining and designing the measures?					
4	What needs to be installed to run the tool?	Structural changes, an independent organization				

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
4. Callibration: reviewing and maintaining accuracy of the DST.						
1	Who is keeping the data up to date?	sectoral data √ monitoring				
2	Who is providing additional data?					
3	Who ensures the continuous flow of new information?	the is no cross-sectoral responsibility				
4	What needs to be installed to update the measures in the tool?					

Figure A.5: Assessment workshop questionnaire-General context-DW

c Plan

Decision Support Tool Questionnaire:
Tool & Testing Session

1. Functionality Please indicate your experience with the following steps in the DST in terms of clarity and applicability:		Poor 1	Below 2	Average 3	Good 4	Very Good 5	Not Applicable na
1	Presentation of City Data					✓	
2	Set Scenarios		✓				
3	Allocate Measures					✓	
4	Determine Impact					✓	
5	Answring specific questions of different stakeholders				✓		
6	Measure Library					✓	
a	Solar PV- Building level					✓	
b	Solar PV- Census district level					✓	Solar Cadastre
c	Building refurbishment				✓		
d	Integrated Building Refurbishment with PV				✓		
e	Integrated PV with Building Refurbishment				✓		
7	Comments						

2. Userfriendliness Please indicate your experience the DST in terms of clarity and applicability:		Poor 1	Below 2	Average 3	Good 4	Very Good 5	Not Applicable na
1	General Look & Feel					✓	
2	Flow of the Steps					✓	
3	Ease of Use					✓	
4	Ease of understanfing of output				✓		
5	Speed				~~✓~~	✓	
6	Traceability of the origin of results (used input, calculation methods, etc)				✓		
7	Comments	The definition of good / very good → Explained					

3. About the Session Please indicate your experience with the testing session:		Poor 1	Below 2	Average 3	Good 4	Very Good 5	Not Applicable na
1	I rate the content of the session					✓	
2	I rate the amount of 'hands- on' experience as					✓	
3	I would recommend this tool within my network as being...					✓	
Open ended questions (please write your comments):							
4	How would you see this tool support your daily work/tasks?	Providing very useful & complex information as basis for discussion / negotiation					
5	What support would you need in order to be able to use this tool in your city?	More in-depth training					

4. Other comments	
What is the general impression you got of the Decision Support Environment (DSE) prototype?	Very good, it is very helpful for tracking increasingly complex sources and constructs of information!
How would you use it 'as is'?	→ I would use it before meeting city stakeholders in order to prepare
Which functionalities would you like to see integrated in a further developed version of the DSE prototype?	myself with help of 'solid'
Do you see any barriers for you / your organisation using the tool ? (e.g. Data availability, operational responsibilities, knowledge on measures)	information for my points of argument.
Data availability on a 'level of planning'	

Figure A.6: Assessment workshop questionnaire-Tool & testing session-DW

c Plan

Decision Support Tool Questionnaire :
General context

	Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1. Context: current state of your city **To which degree is determined/How would you rate:**					
1 Is energy planning a priority for your city?				X	
2 Are the city energy targets defined?				X	
3 Are the city energy targets being tracked?			X		
4 Are the relevant energy measures being developed?		X			
5 Is the stakeholder landscape mapped? (coordination of the city wide flow of information, who are the data owners, etc..)		X			
6 Are the relevant sources of information identified?			X		
7 Are there potential sources of information untargeted?			X		
Open ended questions (please write your comments:					
8 Who are the relevant decision makers?	So many				
9 Which energy measures have to be implemented?					
10 What are the current restrictions and barriers to informed decision making?					

2. Commitment to collecting/publishing data.	Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1 The clarity on what data is available and what data needs to be collected.				X	
2 The clarity on who is responsible for data acquisition in your city.				X	
3 The quality and resolution (level of detail) of available data/information.				X	
4 Regularity of update/enriched the Open Government Data.			X		
5 The presence of atempts/initiatives toward Open Government Linked Data.			X		

In case existing decision support tools are currently being used:

3. Creation: running scenarios, analyzing and making actionable plans.	Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1 Who is implementing the available information in the tool?					
2 Who is responsible for the running of the tool?					
3 Who is defining and designing the measures?					
4 What needs to be installed to run the tool?					

4. Callibration: reviewing and maintaining accuracy of the DST.	Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1 Who is keeping the data up to date?					
2 Who is providing additional data?					
3 Who ensures the continuous flow of new information?					
4 What needs to be installed to update the measures in the tool?					

Figure A.7: Assessment workshop questionnaire-General context-AF

Decision Support Tool Questionnaire:
Tool & Testing Session

		Poor	Below	Average	Good	Very Good	Not Applicable
1. Functionality **Please indicate your experience with the following steps in the DST in terms of clarity and applicability:**		1	2	3	4	5	na
1	Presentation of City Data				X		
2	Set Scenarios			X			
3	Allocate Measures			X			
4	Determine Impact					X	
5	Answring specific questions of different stakeholders				X		
6	Measure Library			X			
a	Solar PV- Building level				X		
b	Solar PV- Census district level				X		
c	Building refurbishment			X			
d	Integrated Building Refurbishment with PV			X			
e	Integrated PV with Building Refurbishment			X			
7	Comments						

		Poor	Below	Average	Good	Very Good	Not Applicable
2. Userfriendliness **Please indicate your experience the DST in terms of clarity and applicability:**		1	2	3	4	5	na
1	General Look & Feel					X	
2	Flow of the Steps				X		
3	Ease of Use					X	
4	Ease of understanfing of output				X		
5	Speed			X			
6	Traceability of the origin of results (used input, calculation methods, etc)				X		
7	Comments						

		Poor	Below	Average	Good	Very Good	Not Applicable
3. About the Session **Please indicate your experience with the testing session:**		1	2	3	4	5	na
1	I rate the content of the session				X		
2	I rate the amount of 'hands- on' experience as			X			
3	I would recommend this tool within my network as being...			X			
Open ended questions (please write your comments):							
4	How would you see this tool support your daily work/tasks?	/					
5	What support would you need in order to be able to use this tool in your city?	/					

4. Other comments	
What is the general impression you got of the Decision Support Environment (DSE) prototype?	useful
How would you use it 'as is'?	testing
Which functionalities would you like to see integrated in a further developed version of the DSE prototype?	filters / thresholds
Do you see any barriers for you / your organisation using the tool ? (e.g. Data availability, operational responsibilities, knowledge on measures)	quality of input data

Figure A.8: Assessment workshop questionnaire-Tool & testing session-AF

Decision Support Tool Questionnaire :
General context

		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1. Context: current state of your city To which degree is determined/How would you rate:						
1	Is energy planning a priority for your city?				X	
2	Are the city energy targets defined?				X	
3	Are the city energy targets being tracked?		X			
4	Are the relevant energy measures being developed?			X		
5	Is the stakeholder landscape mapped? (coordination of the city wide flow of information, who are the data owners, etc..)				X	
6	Are the relevant sources of information identified?				X	
7	Are there potential sources of information untargeted?		X			

Open ended questions (please write your comments:

8	Who are the relevant decision makers?	urban planners, to set the conditions for energy planning
9	Which energy measures have to be implemented?	common urban and energy planning
10	What are the current restrictions and barriers to informed decision making?	availability of data

2. Commitment to collecting/publishing data.		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1	The clarity on what data is available and what data needs to be collected.			X		
2	The clarity on who is responsible for data acquisition in your city.		X			
3	The quality and resolution (level of detail) of available data/information.		X			
4	Regularity of update/enriched the Open Government Data.			X		
5	The presence of atempts/initiatives toward Open Government Linked Data.			X		

In case existing decision support tools are currently being used:

3. Creation: running scenarios, analyzing and making actionable plans.		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1	Who is implementing the available information in the tool?		X			
2	Who is responsible for the running of the tool?				X	
3	Who is defining and designing the measures?					
4	What needs to be installed to run the tool?		X			

4. Callibration: reviewing and maintaining accuracy of the DST.		Not at All 1	Somewhat 2	Neutral 3	Effectively 4	Completely 5
1	Who is keeping the data up to date?	X				
2	Who is providing additional data?	X				
3	Who ensures the continuous flow of new information?	X				
4	What needs to be installed to update the measures in the tool?	X				

Figure A.9: Assessment workshop questionnaire-General context-BI cPlan

Decision Support Tool Questionnaire:
Tool & Testing Session

		Poor	Below	Average	Good	Very Good	Not Applicable
1. Functionality **Please indicate your experience with the following steps in the DST in terms of clarity and applicability:**		1	2	3	4	5	na
1	Presentation of City Data				X		
2	Set Scenarios				X		
3	Allocate Measures					X	
4	Determine Impact				X		
5	Answring specific questions of different stakeholders					X	
6	Measure Library			X			
a	Solar PV- Building level					X	
b	Solar PV- Census district level					X	
c	Building refurbishment					X	
d	Integrated Building Refurbishment with PV					X	
e	Integrated PV with Building Refurbishment					X	
7	Comments						

		Poor	Below	Average	Good	Very Good	Not Applicable
2. Userfriendliness **Please indicate your experience the DST in terms of clarity and applicability:**		1	2	3	4	5	na
1	General Look & Feel				X		
2	Flow of the Steps				X		
3	Ease of Use					X	
4	Ease of understanfing of output					X	
5	Speed					X	
6	Traceability of the origin of results (used input, calculation methods, etc)				X		
7	Comments						

		Poor	Below	Average	Good	Very Good	Not Applicable
3. About the Session **Please indicate your experience with the testing session:**		1	2	3	4	5	na
1	I rate the content of the session				X		
2	I rate the amount of 'hands- on' experience as					X	
3	I would recommend this tool within my network as being…					X	
Open ended questions (please write your comments):							
4	How would you see this tool support your daily work/tasks?	development of scenarios					
5	What support would you need in order to be able to use this tool in your city?	availability of data					

4. Other comments	
What is the general impression you got of the Decision Support Environment (DSE) prototype?	support for the development of scenarios for a specific task
How would you use it 'as is'?	— // —
Which functionalities would you like to see integrated in a further developed version of the DSE prototype?	competition btw. PV and ST → decision making on building level
Do you see any barriers for you / your organisation using the tool ? (e.g. Data availability, operational responsibilities, knowledge on measures)	data availability

Figure A.10: Assessment workshop questionnaire-Tool & testing session-BI

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