Journal of Universal Computer Science, vol. 28, no. 6 (2022), 620-647
submitted: 8/11/2021, accepted: 22/3/2022, appeared: 28/6/2022

Towards an Open Ontology for Renewable Resource Management in Smart Self-Sustainable Human Settlements

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Abstract: This paper proposes an open ontology for self-sustainable human settlements in an effort to set the common language for modelling self-sustainable systems and address the issues regarding heterogeneity of physical devices, protocols, software components, data and message formats and other relevant factors, which proved to be unavoidable in implementations of smart systems in the domain of self-sustainability, smart homes, Internet of things, smart energy management systems, demand side systems, and related areas of research and engineering. Although the existing body of research is showing significant results in related, specialized research areas, currently there is no common formal language available which would bring the diversity of such research efforts under a single umbrella and thus enhance and integrate such efforts, which is often pointed out by the researchers in related fields. This paper discuses self-sustainable systems and associated areas, argues the need for the ontology development, presents its scope, development methodology, domain's architecture and metamodel, and finally the proposed ontology itself, implemented in an open OWL format.

Keywords: self-sustainability, metamodeling, ontology, sustainable development, renewable resources, Internet of things, human settlements
Categories: H.4, I.6, J.7, K.4, M.4
DOI: 10.3897/jucs.77793

1 Introduction

The term 'self-sustainability' is hereafter referred to as a property of a system in the specific context of the system's resource management and autonomy capabilities: a system is considered 'self-sustainable' for the observed resource, if it is able to produce, store and consume such resource exclusively within its own boundaries, without involving any external sources, and within the observed time frame. Such a system presumes that accumulated demands for a specific resource can be met with resource quantities produced within the system's boundaries in every given moment in the observed time frame. Resources in this context include, but are not limited to,

electricity, food, water, heat, gas, biomass, and "anything that we can obtain from the environment to meet our need and wants." [Miller and Spoolman, 2011]
For a self-sustainability supporting framework to become functional in the real world, there is an inevitable requirement for considering existing technologies needed for the implementation of the infrastructure comprised of heterogeneous elements such as underlying hardware, operational systems, data formats, communication protocols, transmission mediums, software components, etc. The feasibility of the implementation would increase if such heterogeneity issues would be addressed explicitly. By offering a unique formal language which would encompass naming and definitions of relevant entities, their types, properties and mutual interrelationships that exist in the self-sustainable systems' domain, not only those issues would be addressed in the formal manner, but also the research field of self-sustainability could yield efficient cooperation between researchers and produce complementary research results. This paper proposes an ontology which would implement such formal knowledge structure, called the "SSSHS ontology", abbreviated from the "smart self-sustainable human settlements".

Being a formal knowledge structure, the SSSHS ontology could be used both by people (scientific and/or engineering communities) and by software agents, both in the domain of real-world implementations and in the simulated environments.

More generalized advantages of developing an ontology for the self-sustainable systems would be the following [Noy et al., 2001]:

- The ontology would enable reuse of the knowledge from a self-sustainability domain;
- The ontology would make explicit specifications of self-sustainability domain knowledge;
- The ontology would enable sharing of common understanding of the structure of information among people (and/or software agents);
- The ontology would enable separating operational knowledge from the do- main knowledge;
- The ontology would enable the domain knowledge analysis.

Being an interdisciplinary field, the ontology proposed in this paper would facilitate interoperability between models developed by the modelers working in different fields, a consistent software design, and reduced costs in software analysis and design phases, being a concrete source of semantic information.

The rest of the paper is structured as follows: in section 2, motivation and need for developing an ontology in the domain of self-sustainable systems is further elaborated. Section 3 presents an overview of existing work in related areas. In section 4, the core research material is presented, including the ontology development methodology, knowledge elicitation methods and the process of ontology development details organized into subsections. Starting with the knowledge elicitation process, the work advances with defining the scope of the ontology, identification of relevant concepts, metamodeling the domain of self-sustainable systems by using UML graphic language, defining properties and mutual relationships, building the basic axioms, towards implementing the SSSHS ontology by using OWL language and re-use and integration of existing ontologies into the SSSHS ontology. Section 5 gives an overview of some of the object properties within the SSSHS ontology that define the mutual relationships between objects. Section 6 argues the ontology consistency, its inferential potential, and presents two possible use-case scenarios for the initial ontology validation. The paper concludes with discussion on the applicability of the developed ontology, its future potential and further research plans within section 7.

2 Motivation and Research Questions

Although the field of explicit self-sustainability research is relatively young, there are several related areas that provide similar and complementary research efforts offering technologies, methods and techniques needed for the future real- world implementation of the self-sustainability framework in human settlements. These areas of research include the Internet of Things (IoT) [Atzori et al., 2010], Environmental Internet of Things (EIoT) [Hart and Martinez, 2015], smart cities [Caragliu et al., 2011], smart residential buildings [Schatten, 2014], smart grids including techniques such as load shifting [Logenthiran and Srinivasan, 2012, Logenthiran et al., 2014], and similar, describing various models of mutually interconnected devices which are dynamically networking, communicating, negotiating, collaborating, making decisions, etc., in order to establish a smart infrastructure which is able to provide the residents with higher degrees of comfort and efficiency in the resource management context. However, the heterogeneous nature of these devices represent one of the key issues in developing and implementing such infrastructures.

A group of authors noted that "the subsystems defined in smart home environment are often heterogeneous in nature and developed in isolation" [Perumal et al., 2008]. Similar limits would be reached in implementing smart self-sustainable dwellings or neighbourhoods by using technologies such as solar grids, wind turbines, batteries, inverters, chargers, various consuming devices, etc., with communication protocols, data formats and other standards that are often proprietary to each vendor which consequently makes for the equipment in the systems difficult or even completely impossible to communicate with each other in their default configurations.

In their efforts to implement a home energy management system, a group of authors have recognised that "multiple communication technologies and myriads of heterogeneous data formats and device-specific protocols dominate home area networks", as well as that "there needs to be a flexible and extensible system design that not only inter-work heterogeneous devices but also allows easy inclusion of future smart appliances and meter/control devices" [Li et al., 2011].

The current stage of self-sustainability and related research in the context of resource management in human settlements provides an adequate time frame in which the domain ontology should be developed. Such an ontology would provide systematization and order in the research field by developing a common language of the domain, should enable sharing, reuse and data processing more efficiently, and set the guidelines for resolving interoperability issues between heterogeneous components more clearly, especially in the context of using the ontology by intelligent software agents. These guidelines would provide a common ground on which to build models, simulations and applications, facilitating both the unambiguous human-to-human communication, and, at the same time, reasoning about the domain knowledge in a formal, machine-readable processes. The development of ontology includes not only the domain-specific vocabulary, but also the relationships between concepts, and the rules (axioms) that govern or explain such concepts. The ontology proposed in this paper in the domain of self-sustainable systems would remain open both for further development and the integration with other relating engineering ontologies for a more holistic coverage of the domain.

As such, the ontology within this research would answer the following research questions:

1. What interoperability issues could be addressed with the development of ontology for the self-sustainability domain?
2. Which existing ontologies could be re-used for the development of the ontology for self-sustainability domain?
3. Which concepts are of most importance in developing an ontology for the self-sustainability domain?
4. What are the application areas of ontology in the self-sustainability domain?

3 Related Work

Self-sustainability as defined in this paper has only recently induced explicit research efforts in forms of modelling and simulations of human settlements which directly facilitate such property [Tomičić and Schatten, 2015, Tomičić and Schatten, 2016, Tomicic and Schatten, 2016]. Authors have demonstrated that a software framework based on the multi-agent modelling paradigm has the ability to model and simulate self-sustainable human settlements, and the ability to prolong the self-sustainability period of such settlements by using dedicated mechanisms working together across multiple dwelling units, sharing a common top-level goal [Tomičić and Schatten, 2016].

Other explicit self-sustainability references include the work on the Self-Sustainability in Peer-to-Peer Swarming Systems [Menasché et al., 2010] and the terms “self-sufficiency”, “self-containment”, all related to some form of a system’s autonomy across various fields of research. A group of authors researching a photovoltaic self-consumption in buildings have defined the self-sufficiency as “the degree to which the on-site generation is sufficient to fill the energy needs of the building” [Luthander et al., 2015]. This self-sufficiency degree is illustrated via the following formula:

$$\text{Self-Sufficiency} = \frac{A+B}{C+A+B} \quad (1)$$

where A stands for photovoltaic system-to-load, B for storage-to-load, and C for grid-to-load [e Silva and Hendrick, 2016]. In complement to the self-sustainability described by authors in [Tomičić and Schatten, 2015, Tomičić and Schatten, 2016, Tomicic and Schatten, 2016], where the self-sustainability is modeled as a binary property, the presented formula clearly illustrates the degree to which the system is self-sustainable in respect to the resources used from outside the system itself.

The Semantic Sensor Network (SSN) ontology [W3C, 2017] describes sensors, actuators, procedures, features of interests, observed properties, and other enti- ties used for possible representations of smart environments. SSN also includes a core ontology called SOSA (Sensor, Observation, Sample, and Actuator) for its basic classes and properties. As described on the Semantic Sensor Network Ontology website, SSN and SOSA are able to support applications and use cases such as "satellite imagery, large-scale scientific monitoring, industrial and house- hold infrastructures, social sensing, citizen science, observation-driven ontology engineering, and the Web of Things".

SmartEnv [Alirezaie et al., 2018] is another ontology proposed for the use within smart environments. Authors proposed the use of the Ontology Design Pattern paradigm regarding the modular nature of their proposal, with their modules inspired by the previously described Semantic Sensor Network. Interesting notions within this ontology include the spatial and temporal aspects.

In [Gruber et al., 1993], author defines an ontology as "the specification of conceptualizations, used to help programs and humans share knowledge". In [Fensel, 2001], author further describes that the term "formal" refers to the attribute of the ontology to be machine-readable, which is one of its key advantages and usefulness.

A group of authors note that an ontology "defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary" [Neches et al., 1991], but also that ontology includes "not only the terms that are explicitly defined in it, but also the knowledge that can be inferred from it." [Neches et al., 1991]

There are many other definitions of ontology, their relation to taxonomies, knowledge bases, ontology development processes, methodologies, languages, etc., and a good overview of the subject is presented in [Corcho et al., 2003]. Authors in this work also conclude that there is a "consensus among the ontology community and so there is not confusion about its usage. Different definitions provide different and complementary points of view of the same reality." [Corcho et al., 2003, p. 44]

Interoperability for smart home environment was researched by a group of authors [Perumal et al., 2008] for the heterogeneous elements which need to communicate and perform joint execution of tasks in such environments. Authors suggested an approach which include web technologies, more specifically, web services, by using Simple Object Access Protocol (SOAP), which provides data exchange mechanism and performance optimizations of smart home sub- systems. Authors also tackle a need for a "universal schema definition" towards "developing a generic abstraction tiers for managing sub-systems in smart home environment." [Perumal et al., 2008]. Interoperability has also been the subject of papers [Athanasopoulos et al., 2006] and [Widergren et al., 2007] with generic models which include basic connectivity, network and syntactic interoperability.

Smart metering deals with energy consumption awareness in users, which is claimed to reduce household energy usage consumption by 15% [Wood and New-borough, 2003]. Authors describing an energy aware smart home [Jahn et al., 2010] note that the "current solutions of smart metering are proprietary and generally not generic or flexible" and that "even an agreement on a common standard on smart metering technology, protocols etc. does not seem to be in sight.", stressing again the importance of interoperability issues in such implementations. There are several projects that tried to resolve these issues by using middleware frameworks, such as Hydra [Jahn et al., 2010], AMIGO [Ressel et al., 2006], SOCRADES [Kirkham et al., 2008], all integrating some form of networked embedded systems.

A group of authors [Wongpatikaseree et al., 2012] introduced context-aware infrastructure ontology for activity recognition in the smart home domain. The ontology model consists of a user's context such as location of the resident, posture, etc., and could be considered in the future developments of the SSSHS framework from the resources micromanagement perspective, as it might prove complementary to the existing infrastructure, as well as to the ontology proposed in this paper.

Another potentially complementary domain ontology was developed for construction concepts in urban infrastructure products by authors in [El-Diraby and Osman, 2011], and includes five main sectors: water, gas, electricity, telecommunication and wastewater. Authors used a top-down modeling approach for conceptualization of knowledge in civil infrastructure which is open and extensible, and available in the owl format. Implementing the infrastructure for local resource transfers would be an essential process in the physical implementation of the self-sustainable settlement.

SynCity is a "tool for the integrated modeling of urban energy systems." [Keirstead et al., 2010], and one of the key structure elements of this tool is the urban energy systems (UES) ontology. This ontology provides a description of the significant objects within an urban energy system, and is designed to be consistently referenced by both people and software entities, enabling a "common understanding of complex concepts". The UES ontology is comprised of five major object categories as follows: resources, processes, technologies, spaces and agents. When considering the existing SSSHS framework, the practical similarities between concepts are evident with "resources" ("materials that are consumed, produced and or interconverted including gas, electricity, and so on") and "processes" (authors of the UES ontology define it as technologies "that convert one set of resources into another set"), which can be partially related to SSSHS "consumers", entities which "consume" resources in order to provide certain functions to inhabitants or other systems.

Authors [Ahmad and Ahmad, 2016] had approached the issue of trust towards online providers by examining the credibility of the different sites in the domain of Renewable Energy providers. Authors argued and claimed that "using semantic and ontologies to measure the trust of online RE providers is crucial and useful." Although the paper is tackling the ontology approach in renewable resources domain, there is no formal representation of the ontology, nor are relationships among the concepts developed.

A domain ontology for wind energy was researched by authors [Küçük and Arslan, 2014] by presenting a semi-automatic ontology construction method using Wikipedia articles as input. The authors have published their ontology in OWL format is ready to be integrated with or into other ontologies; considering that wind energy systems could compose a vital part of the self-sustainable system, the domain ontology for wind energy could be fully complementary to this research by its integration into the SSSHS ontology.

A group of authors researched energy reduction in a smart home environment by using a framework which automatically controls the electronic devices [Cheong et al., 2011]. To that end, authors have developed an ontology that describe a smart home domain and a reasoning approach considering the contextual data of the residents and the devices. As presented in the paper, the ontology context and device concepts could be used as complementary classes considering the lower level of abstraction the authors have develop them in respect to the ontology concepts proposed in this paper.

In [Abanda and Tah, 2008] authors have reviewed the current state of the art of sustainable technologies in the UK construction industry and examined “the development of an ontology driven knowledge base and its usage in the development of a semantic web application.” Authors have developed an ontology within the construction domain that includes concepts like building methods, building construction material, building construction technology, and similar, together with concepts derived from other ontologies (Unified Classification for the Construction Industry), namely, elements of buildings, construction products and materials. Although currently out of scope, the work in this paper could be considered in the further development and broadening of the proposed ontology for self-sustainable human settlements when considering the settlement’s physical construction processes.

Load shifting is implemented within the SSSHS framework [Tomičić and Schatten, 2016] as one of the key mechanisms in maintaining the self-sustainability property. Demand side management represents a broader term and is in the focus of research of authors in [Naser et al., 2016]. Authors have developed an ontology in the domain of energy management in a smart home called DeSMaHo (the term deduced from “demand side management and smart home”), with a special focus on the demand side management. In the process of ontology development, authors have integrated resource & energy ontology of the ThinkHome approach [Reinisch et al., 2011] and DogOnt approach [Bonino and Corno, 2008]. Although the top-level concepts of the DeSMaHo ontology are similar to the ones proposed in the SSSHS ontology, there are three key differences in these two approaches; first, the DeSMaHo ontology assumes the use of external resources, whereas in the self-sustainable system all the used resources are produced within the system itself. Second, the DeSMaHo ontology is limited on the energy as a resource, whereas the ontology proposed in this paper covers all the resources that could be potentially used in self-sustainable systems. Third, other potential mechanisms needed for the system to be self- sustainable are not covered by this approach. However, the DeSMaHo ontology can be seen as complementary to the ontology proposed in this paper, especially considering the explicit notation for the demand side management, as one of the self-sustainability mechanisms.

4 Materials and Methods

The ontology development in this paper is facilitated by the OWL Web Ontology Language [McGuinness et al., 2004] and Protégé software, an open source ontology editor and a knowledge management system [protege, 2016]. The OWL language enables both human-readable and machine-interpretable information format. The choice for this technology is additionally argued with open standards, open source software and interfaces, making further work and collaboration on the subject together with ontology reuse and integration into other projects more feasible.

The methodology used in this research relies partially on METHONTOLOGY approach created by Fernández-López et al. [1997] and the approach described by [Noy et al., 2001]. A combined top-down and bottom-up modelling approach was used for building the glossary of terms and concept hierarchy, by first defining more broad concepts and most specific concepts, building them towards the middle levels, in more than one iteration, until the optimal model was achieved. The UML modeling language was used for metamodelling of the self-sustainable system context and relations between its top-level classes.

The elicitation of concepts and knowledge acquisition in the domain of self-sustainable human settlements and local renewable energy sources was performed through several sources:

1. An extensive literature overview on related research areas together with the re-use of existing ontologies by their integration into the developing SSSHS ontology;

2. Case-studies of existing self-sustainable systems along with informal interviews with experts [Tomičić, 2016];

3. Renewable energy system planning, design, management, simulation and sizing software such as [Mermoud, 2016];

4. Handbooks, tutorials and reports on the renewable energy uses such as [Riva et al., 2014, Burton et al., 2001, Stoffel et al., 2010];

5. Simulation results and observations derived from the experimentation facilitated by the SSSHS framework [Tomičić and Schatten, 2016, Tomicic and Schatten, 2016];

6. Manuals, diagrams and schematics published by the manufacturers of equipment used in real-world systems.

Thus, ontological choices regarding the elicitation of concepts and the derivation of ontological entities were the result of long-term processes from the above mentioned sources (1-6). More precisely, top-level entities, their relations and properties were identified through processes (2), (3), (5), as there was a systematic top-down view of the domain. The finer granularity levels were analysed through specific examples, real-world equipment, manuals and schematics (processes 4 and 6) - what would later be called “individuals” in the ontology implementation. The considerable amount of help with fine-tuning the concepts, their relationships and properties was obtained through defining the basic rules within the simulation environment (process 5), which would later be formalised via ontology axioms.

When modelling sub-classes, the important rule of all the siblings in the hierarchy being at the same level of generality was systematically followed. The “standard” challenges arose when the defined class showed to have only one direct subclass, in cases where there would be a need for additional intermediate categories, or deciding whether the representation of distinction would become a property value, or should the distinction be represented by introducing a new class. Keeping in mind the specific ontology use-cases and its scope, experimenting with the dynamics of the system in the simulation environment, and knowing the elements of the system in sufficient detail, proved to solve most of these modelling questions and challenges. Decisions on where the instances should be introduced, rather than unravel further sub-classes, were based on knowing the lowest level of granularity of the represented system, which was, again, decided by the potential ontology use-cases and applications. Having the knowledge about real-world self-sustainable systems, the level of instances was naturally aligned with the available technologies vital for the real-world implementation of the smart self-sustainable systems based on agent paradigm, such as PV modules, battery systems, controllers, wind turbines, etc.

4.1 The scope of the ontology

The SSSHS ontology proposed in this paper is intended to be used in the domain of smart resource management in self-sustainable human settlements. The ontology will be used both by people (when modelling, software developing, optimizing and/or observing and researching self-sustainable human settlements) and by software agents (when communicating, negotiating, decision-making, reporting, and performing other resource-management tasks), within real-world implemented systems, or simulated environments. The ontology will remain open for further optimizations as the domain of the self-sustainable human settlements develop in the future. Both scientific and engineering communities are welcome to join in the work of maintaining the ontology. Examples of types of questions that the information in the ontology provides answers to are the following:
What storage technologies are available for the modeling of a self-sustainable human settlement? Is the communication protocol between production unit X, storage unit Y, and reporting unit Z compatible? What are the consumption units that have the highest consuming rate for resource N? What consumption and storage units are able to negotiate? What storage systems are available for photovoltaic solar system? Is the consumption unit X able to reduce its consumption rate, and by which maximum factor? What production systems are available for the resource M? What types of equipment does the vendor XY supply?

4.2 Basic Concepts

Naming conventions used in this research include capitalized letters for distinct words in class names (for example, “StorageSystem” class) and lowercase naming

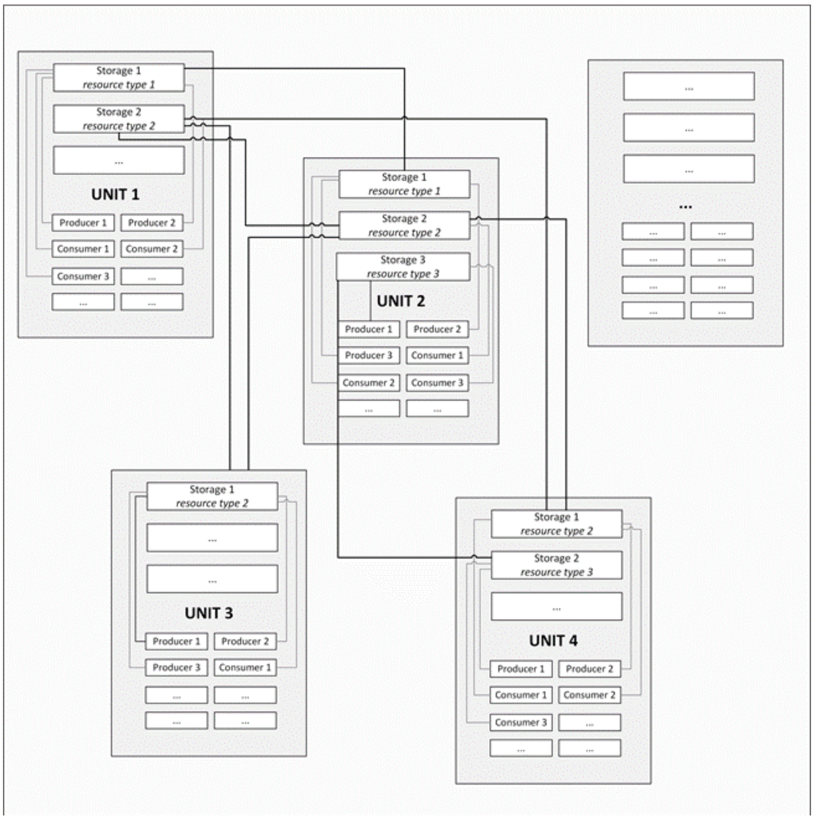

Figure 1: Top-level System Architecture of the Smart Self-Sustainable Human Settlement [Tomicic and Schatten, 2016]

for object and data properties, with words separated by the underscore (for example, "uses resource" object property).

The self-sustainable human settlement represents one of the top-level entities of the developed ontology, and its further subclasses are self-sustainable neighbourhood, self-sustainable village, city, building, or any other type of more than one human dwelling units modeled and/or organized in a way that facilitate the self-sustainability property. The dwelling units in this context may include any type of residential units/households such as houses, flats, apartments, etc. The top-level system architecture of the smart self-sustainable human settlement is depicted via Fig. 1.

The following classes were identified as independent entities on a top level of a self-sustainable system:

– **Self-Sustainable System**. A system composed of primarily human dwelling units, mutually interconnected in a network that allows for both material and informational resource exchange and communication.
– **Resource Manipulator**. A class which is a superclass to the Mediator, Producer and Consumer classes because of their practical similarities, i.e.

attributes (it manipulates resources; it is connected to storages; it has resource manipulation rates and schedules; it has a certain location, etc.).

- **Resource**. As discussed earlier, Resource instance might refer to any of the following, but not limited to: water, heat, gas, biomass, food, electricity.
- **Producer**. A Resource manipulator that produces resources further available for storage, consumption or transformation. At its lowest level it might refer for example to a photovoltaic solar array, wind turbine, hot water solar tubes, water turbine, biomeiler system, heat pumps, etc.
- **Consumer**. A resource manipulator that consumes resources at a specific rate, lowering the value of resource levels in the dedicated storage system. At the physical level, it might refer for example to a fridge, a TV, battery charger, gas cooktop, biomass stove, etc.
- **Mediator**. A Mediator instance refers to any piece of physical equipment that does not belong in a Producer, Consumer, or Storage class, but can be physically connected to their instances, and are relevant to the modeler of self-sustainable systems. For example, Mediator may refer to battery charge controllers, breakers, inverters, pressure regulators, sensors, various safety equipment, human interfaces, adapters which might include software agents, etc., which all form integral parts of the technical implementation of a smart self-sustainable environment. Mediators can also consume resources, and some are critical for the proper functioning of physical implementations (for example, inverters for using AC power from the solar systems).
- **Storage Subsystem**. A storage subsystem can be composed of multiple storage units (for example, battery pack which is composed of several connected battery units that function as one unit; or, multiple water tanks connected in a way that they have a single input and single output connector).
- **Connection**. The Connection concept describes any relevant connection between two edges such as consumers, producers, storage systems, mediators, etc., which can be used to transfer resources, data, and messages.
- **Service**. Service is able to fulfil needs and requirements of an inhabitant or a part of any of the dwelling unit subsystems. Service can for example deliver hot water for showering activity. In order to support this activity, a service needs resources (water and heat), delivering system (water pipes), storage unit (water tank or boiler) various mediators (vents, faucet, etc.). Another example is the cooking activity service. Cooking service needs resources (gas, electricity, etc.), consumer unit (cooking stove), delivering system (gas pipe, electrical wires), storage unit (gas tank, electric batteries), mediators (pressure regulator, safety fuses, etc.).
- **Location**. Storage systems, dwelling units, services, etc, are all located in some physical region, area, coordinates, rooms, or some other units of a specific location.
- **Activity**. Activities are the main triggers for activating services. Activities can be started and carried out either by the artificial mechanisms (sensors, scheduled services, etc.), or by human inhabitants (sleeping, showering, turning the heat on, etc.).
- **Environment**. The Environment entity impacts Activities through variables which trigger either automated responses in the system (via sensors), or

through the inhabitants' inputs. Environment can affect the Producer (solar irradiation directly affects photovoltaic panels, wind speed directly affects wind turbines, precipitation directly affects rainwater collectors, etc.), and the Consumer (air temperature directly affects room heaters, natural light intensity directly influences artificial lightning, etc.).

Figure 2 represents top-level entities in the proposed SSSHS ontology.

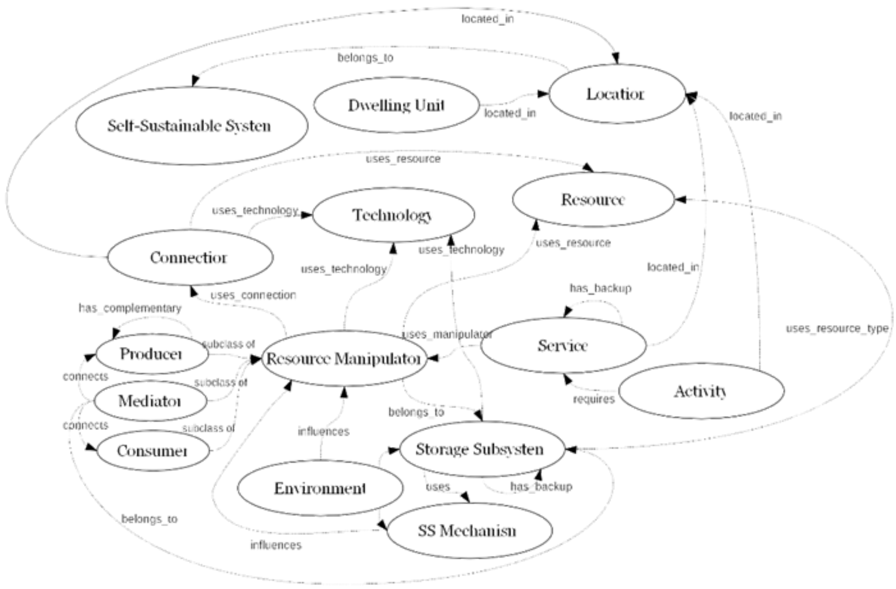

Figure 2: Top-level concepts in the SSSHS ontology and their relations

4.3 Developing Axioms in the Domain of Self-Sustainable Systems

According to Corcho et. al [2003], "formal axioms are the most powerful means of representing knowledge in ontologies (...)". The following axioms are first stated in the informal manner by using natural language, representing grounds for delivering rules and starting assumptions that enable the construction of the formal system. The epistemological axioms show constraints derived from the structure of concepts, define types of connections between concepts and cardinality constraints [Kalibatiene and Vasilecas, 2010]. In the next several subsections, some of the key concepts of resource management in self- sustainable human settlements are presented with such axioms, which will be formalized in the SSSHS ontology. The specificity of the described axioms in the context of self-sustainability is derived from the previously described elicitation of concepts and knowledge in the domain of self-sustainable human settlements and local renewable energy sources (Section 4).

4.3.1 Resource axioms

- A Resource can be consumed at a specific location, in specific quantities, at a specific rate.
- A Resource can be produced, consumed, stored, transported, or negotiated about.
- A Resource can be consumed in an automatic or manual process.
- A Resource is consumed via specific Service in order to satisfy or enable a specific need or requirement.
- A consumption of a specific resource can lead to the production of other Resource(s).
- A consumption of a specific resource can lead to the consumption of another Resource(s).
- A Resource is being produced/collected at a specific Location.
- A Resource can be stored in a specific Storage System for latter consumption.
- A Resource has 0 or more compatible Producers that are able to produce it.
- A Resource has 0 or more compatible Consumers that are able to consume it.
- A Resource has 0 or more compatible Storages that are able to store it.
- A Resource has 0 or more equivalent Resources that can be used by the same Service instance.

4.3.2 Producer axioms

- A Producer is able to produce a specific resource at specific rates.
- A Producer is located in a specific Location.
- A Producer is connected to specific Storage System(s).
- A Producer is directly dependent on 0 or more Environment variables.
- A Producer can use 0 or more other Resources for the default resource production. For every consumed Resource, a new Consumer instance can be initialized.
- A Producer can output 0 or more resources as a byproduct(s) in resource A production. Every byproduct production can be initialized as a new producer.
- A Producer is used by 0 or more specific Services.
- A Producer uses 1 or more specific Technologies.
- A Producer is connected to 0 or more Mediators.

4.3.3 Consumer axioms

- A Consumer is able to consume some resource.
- A Consumer is located at a specific Location.
- A Consumer is connected to some Storage Unit.
- A Consumer is directly dependent on 0 or more Environment properties.
- A Consumer can produce 0 or more Resources (as a byproduct(s) in default Resource consumption).
- A Consumer is used by 0 or more Services.
- A Consumer uses 1 or more specific Technologies.

4.3.4 StorageSubsystem axioms

- A StorageSubsystem instance stores 1 Resource type.

- A StorageSubsystem is a collection of 1 or more Storage Units that perform its function as a single unit.
- A StorageSubsystem uses 1 storing Technology.
- A StorageSubsystem is connected to 2 or more Resource Manipulators.
- A StorageSubsystem has 0 or more backup StorageSubsystem(s).
- A StorageSubsystem is located at a specific Location.
- A StorageSubsystem is directly affected by 0 or more Environment properties.
- A StorageSubsystem can consume 0 or more Resources in its default opera- tion mode. For every consumed Resource type there may be 1 new Consumer instance initialized.

4.3.5 Service axioms

- A Service is operating at a specific Location.
- A Service has defined comfort levels.
- A Service uses Resource and Storage through Resource Manipulator entities.
- A Service uses Connection to deliver resources to a needed Location.
- A Service has 0 or more backup Service(s).
- A Service is able to satisfy human needs and requests, or perform a job needed by the self-sustainable resource managing system.
- A Service is consuming 1 or more Resources at a specific rate in its default operation mode.

4.3.6 Connection axioms

- A Connection connects 2 nodes.
- Nodes in the connection are instances of following classes: Producer, Consumer, Storage, Mediator.
- A Connection may use 0 or more Resources in the process of a transfer.
- A Connection can transfer physical resources or digital data and messages.
- A Connection has a cost.
- A Connection uses at least 1 Location.

4.3.7 Mediator axioms

- A Mediator can be connected to Storage, Producer or Consumer entities via the Connection entity.
- A Mediator uses specific Technology.

4.3.8 Activity axioms

- Activity triggers Service.
- Activity is located at specific Location.
- Activity has context that can be observed via sensors.
- Activity can be either human or artificial.

Axioms within the proposed SSSHS ontology are formalized and implemented in Protege by using the Manchester OWL Syntax. For example, axioms regarding the Resource Consumer are implemented as follows:

```
uses_resource some Resource
located_in exactly 1 Location
belongs_to some StorageUnit
environment_influence_domain min 0 Environment
produces_resource min 0 Resource
used_by_service min 0 Service
uses_technology some Technology
```

For the StorageSubsystem class:

```
has_backup_storage min 0 StorageSubsystem
located_in exactly 1 Location
uses_manipulator min 2 ResourceManipulator
uses_resource min 0 Resource
uses_resource_type exactly 1 Resource
uses_technology exactly 1 StorageTechnology
```

Besides the explicit ones as shown above, some of the axioms are implemented through class hierarchy, object properties, domains, and other mechanisms provided by Protege/owl. The complete axiom source file is available inside the published ontology.

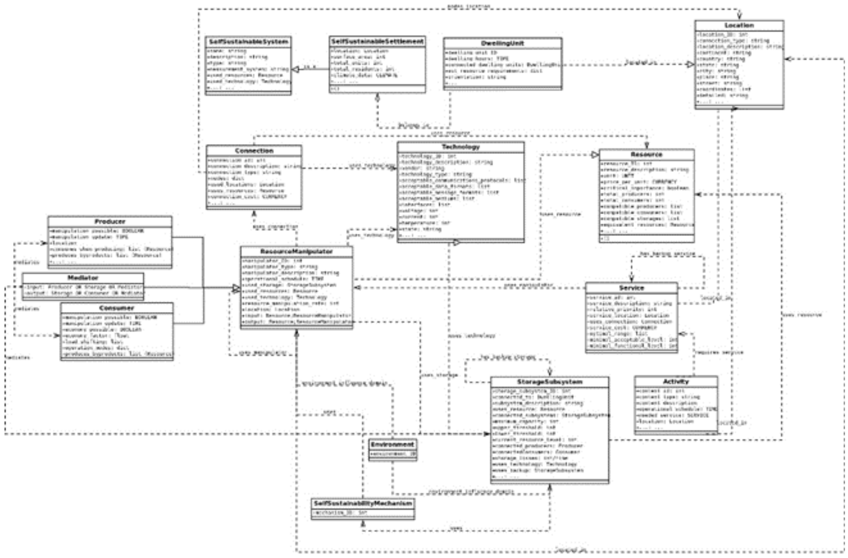

Figure 3: Top-level classes of the SSSHS ontology with object and data properties - an UML metamodel preview

4.4 The Re-use of Existing Ontologies

The DeSMaHo ontology [Naser et al., 2016] covers the subject of demand side management, being one of the relevant mechanisms for the self-sustainable resource management, and is directly applicable within the "SelfSustainabilityMechanism" class hierarchy of the SSSHS Ontology. The object property "hasLoadShifting" can be directly imported with its values ("NotShiftable", "ProgramDependentlyShiftable", "AutomaticallyShiftable") to the existing SSSHS mechanisms. However, being not publicly available to the best of authors knowledge, directly importing the partial DeSMaHo ontology into the SSSHS ontology is at this point not possible, so only manual entries, according to descriptions published in the paper [Naser et al., 2016] could be implemented.

Within the hierarchy of the "WindTurbineTechnology" class, the ontology of wind energy systems [Küçük and Arslan, 2014] is practically compatible and complementary. Wind Turbine class was directly imported into the SSSHS ontology under the Technology-TurbineTechnology hierarchy, along with its object and data properties and axioms. Also, the Meteorological Tower class was imported under the Environment-ExteriorEnvironment hierarchy by using the Protege's Refactor copy/move/delete axioms option.

Context awareness ontology [Wongpatikaseree et al., 2012] is applicable directly within the "SystemActivity", "SensorActivated" class hierarchy, for more detailed knowledge representation of activity recognition. As for the DeSMaHo ontology, relevant concepts and their relations were extracted from the published paper and manually implemented into the SSSHS ontology by several methods. For example, location-based activities (Kitchen Activity, Bedroom Activity, etc.) are represented in the SSSHS ontology as human or system activities with object property "located in" tied with the exact activity Location, and Object-based activity presented in this work was implemented as a HumanActivity class within the SSSHS ontology for the reasons of intuitive clarity.

The self-sustainable systems also rely on the temporal aspects of the system's dynamics; for example, the predefined working hours of resource manipulators, possible delays or advances expressed in time units, timers, daily solar irradiation hours, during-the-day notion, etc. For this reason, the Smart Environment Time Ontology Pattern from the SmartEnv [Alirezaie et al., 2018], based on the OWL-Time ontology, was directly imported into the SSSHS ontology via the Protege import option.

The self-sustainable systems also rely on spatial aspects of elements used in the system - sensors, resource producers and consumers, storages, inhabitants, agents - placed within the observed environment. Spatial relations such as "close to", "next to", "at the left side of the x", and similar, could prove relevant to the dynamics of the observed system. For these reasons, a pattern called Geometry [Alirezaie et al., 2018] was integrated within the SSSHS ontology; the most important class called "spatial object" is used with its object property "has spatial relation" and its subclasses (such as "contains", "insideOf", "northOf", "overlaps", etc.) to describe spatial relations between entities. Geometry pattern itself is based on spatial-related ontology GeoSPARQL [Battle and Kolas, 2012] and the Open Time and Space Core Vocabularies [Cox and Little, 2017]. The above mentioned parts of re-used ontologies are visible in Figure 4 as part of the SSSHS ontology hierarchy.

Various forms of energy reduction mechanisms are encompassed within the "LowResourceMechanism" class hierarchy of the SSSHS Ontology, and the higher level of details provided in the energy-aware home ontology [Cheong et al., 2011], especially the taxonomy of physical devices, is compatible with the SSSHS Ontology through the "ResourceConsumer" class. The consuming devices are organized according to various categories: DeviceByFunction, DeviceByLocation, DeviceByStatus, DeviceByPowerMode.

In further broadening of the SSSHS Ontology, the physical implementation of the SSSHS framework would require knowledge repositories of construction processes, technology, materials, etc., obtained from the ontology presented in [Abanda and Tah, 2008], but also knowledge of construction concepts for the infrastructure such as electricity, gas, telecommunication, etc., obtained from the ontology presented in [El-Diraby and Osman, 2011], or similar.

5 Properties

The OWL ontology language supported by the Protege development platform facilitates object properties, data properties and annotation properties. Object properties define the relationships between two objects, and can be represented as edges that connect nodes in an OWL ontology graph. Data properties relate individuals to literal data such as strings, integers, decimal, double, byte, rational, etc. The annotation properties provide descriptive metadata about ontology entities and do not participate in reasoning or structural inferencing. Fig. 3 shows the UML metamodel of top-level classes in the SSSHS ontology with object and data properties.

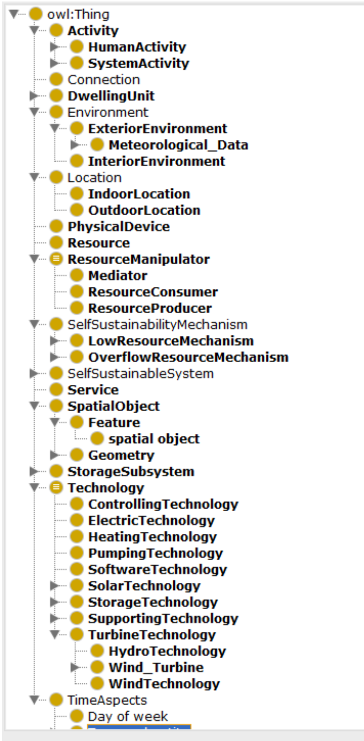

Figure 4: Class hierarchy preview of the proposed SSSHS ontology in Protege framework

Some of the object properties defined in the SSSHS ontology are the following:

belongs_to. Defines a relationship where the entity is part of the larger structure or a system. For example, the property relates dwelling unit to a self-sustainable settlement.

environment_influence_domain. Relates relevant Environment factors to entities that can be affected by these factors. For example, temperature affects battery performance, wind speed affects wind turbine performance, etc.

has_backup_storage. A recursive relation of a StorageSubsystem entity; a storage system can have a backup storage system, both belonging to the StorageSubsystem class.

has_complementary. A recursive relation of ResourceManipulator, specifically Producer class; for example, wind turbine based producer is complementary to the solar system based producer in the context of energy production.

located_in. Relates physical objects or activities to specific places.

requires_service. Relates activities to services. For example, showering activity requires water heating and water deployment services.

uses_connection. Resource manipulator relating to the Connection entity in the process of resource production, consumption, etc.

uses_technology. Relates every physical object or connection to the specific Technology instance. The technology instance describes data properties such as communication protocols, vendor, data and message formats, interfaces, electrical characteristics, etc.

uses_resource. Resource Manipulators and Storage Subsystems use resources from the Resource class for their default operation.

has_backup_service. A recursive property which relates a service instance to the backup service instance. The backup service instance is used when the main service instance is unable to deliver; both the main and the backup service are providing identical functionality.

uses_manipulator. Related Service and Resource Manipulator; a service requires one or more resource manipulators to deliver. For example, service that delivers hot showers might use Consumer (water heater), Mediator (water pump), Producer (PV system), etc., in order to realize the comfort requirements of the showering activity.

6 Ontology Consistency and Usage Scenarios

HermiT Reasoner was used within the Protege environment in order to verify the consistency of the SSSHS ontology. After its initialisation on the SSSHS ontology, the reasoner showed that the ontology is formally consistent, showing no errors or exceptions.

Fig. 5 illustrates the inferential capabilities of the proposed ontology. While "PhotovoltaicTechnology" is an asserted type, "ResourceManipulator" is an inferred type, resulting from instantiating the individual photovoltaic panel module and describing it with associated attributes.

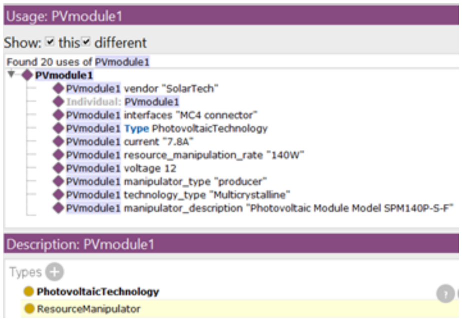

Figure 5: Adding instances and using the inferential properties of the ontology

Two example scenarios are provided for the initial ontology validation and possible use cases. The first scenario describes how the ontology could be used by the human modeler. The second scenario illustrates how the ontology could be used by the artificial (software) agents within the simulated or real-world environment.

6.1 Human Modeler Use-Case Scenario

The following scenario presents an ontology utilization example from the modeler's perspective: A small community is preparing the model of the new off-grid settlement. The process begins by defining habitants' activities and needs in terms of resource types and daily consumption estimates, following by estimating general storage and production capacities. The SSSHS ontology would provide localized climate data for initial resource dynamics calculations, as well as the overview of required compatible technologies. Based on the registered activities, the SSSHS ontology identifies services needed to enable those activities; services use resource manipulators such as energy producers, and the SSSHS ontology would infer compatible technologies and physical devices suited for the specific model requirements. For example, should there be a need for communication between certain types of devices, the ontology would enable for checking the compatibility between those devices in terms of physical connections, communication, data exchange, and/or negotiation capabilities, depending on the requirements. If the location of the settlement enables the utilisation of the lake water, the SSSHS ontology could list the compatible pumping technologies, connections, regulators, sensors, and other supporting equipment suited for specific requirements, but would also provide an integration into the existing model services within the system.

As a concrete example of competency questions, one can run the following query on the SSSHS ontology within the DL query window, to learn about technologies complementary to solar photovoltaic modules, which are currently available at location house 02 for resource production:

```
has_complementary value PVmodule1
and located_in value house_02
```

and the result of the above query being:

```
DieselGenerator2kW ,
```

an instance specifying electricity generator run on diesel fuel, available for additional, auxiliary electricity production at specified location.

When planning the needed electricity production capabilities, knowing the power consumption of the most power-hungry consumers is evident. The SSSHS ontology could be queried in order to get such consumers, which are specified for example by consuming 1kW or more power:

```
ResourceConsumer
and maximum_capacity some xsd:integer[>=1000]
```

with query returning the instances of air conditioning unit AC1 (1100W), electrical convection heater ConvHeater1 (2000W) and water heater HybridWaterHeater01 (2500W).

To list all the available components for required technology in certain usage context, for example for usage in solar electricity production, one can run the following query:

```
usage_context value "solar"
```

The result of this query lists the currently available components:

```
BatteryPack01
Inverter1
PVmodule1
PVmodule2
Photovoltaic_H1Z2Z2-K_Cable
batt_fuses-inc44prl12
c_breaker1
c_panel
charge_controller_CTG44
comb_box_7277
e_display_CRZ55
panel_fuses_crk77
```

The modeler can also query: which of the human activities require system services? [*HumanActivity and requires service someService*], and the ontology returning ManualEntry and PhysicalActivity subclasses along with the instances cleaning, cooking, drinking, showering. And which of these services use Water- Tank01? [*uses storage value WaterTank01*].

To the modeler of the self-sustainable system, this knowledge system could significantly increase the effectiveness and precision in modeling such complex systems.

6.2 Artificial Agents Use-Case Scenario

Software agents might use the SSSHS ontology within the simulation or real-world environment. For example, agents can use the ontology within the SSSHS framework to identify all consumption units which are able to reduce their consumption rates, and the maximum factor possible for the reduction. Together with the knowledge of relative priority of consumers, this information is crucial in decision making processes oriented towards maintaining the self-sustainability of the system. If the agent seeks resources, it might use the inferential potential of the ontology to identify devices of its type with which it can communicate and negotiate about resource transfers. Depending on the specific devices' locations, the agent could further query the ontology about connection details, such as resource transfer costs and distances, and decide whether the transfer would be acceptable. The updated input from the environment, stored within the SSSHS ontology, could directly influence the behaviour of agents which are reacting to perceived changes. For example, should cloudy weather decrease the input on the water heating and the current hot water usage trends indicate a possibility of hot water deficit, agents can use the ontology to identify available complementary technologies and try to use their capacities for generating additional energy for heating water.

Tighter integration between the existing SSSHS framework and the SSSHS ontology is planned in future research, where agents managing resource allocations within the framework would use the knowledge and full inferential capabilities of the proposed ontology. The core concept of such system is depicted via Figure 6, with the SSSH Ontology providing critical input to framework's mechanisms, where LR and

OR mechanisms relate to framework's means to manage critical events of resource deficiencies and overflows, respectively, as described in [Tomicic and Schatten, 2016].

Before the simulation starts running, the system initialises by using the knowledge contained in the SSSHS ontology: by using queries from within the Python environment and Owlready2 package, it identifies the relevant simulation entities such as storage subsystem, resource producers, resource consumers, their relationships and parameters. The simulation framework runs by the defined logic until the threshold event has been observed; depending on the event nature, the framework triggers further actions either on the basis of resource potential depletion, or resource surplus accumulation and potential loss. Either way, the ontology is queried on the available self-sustainability mechanisms, the possibility of their usage, and in the next step, the framework obtains detailed knowledge about present resource manipulators - their possibilities of frugal operation modes, their relative priorities, the potential for negotiation, information about supported negotiation algorithms between manipulators, etc. The basic code required to get and load ontology, and running some basic queries is listed as follows.

```
from owlready2 import *
onto = get_ontology("path_to_ontology_file")
onto.load()
# running basic queries; list technologies
# with MC4 interface:
onto.search(interfaces = "MC4")
# query for SSSHS framework's economy mode
# with identifying highest
# relative priority consumers:
onto.search(relative_priority = 1)
```

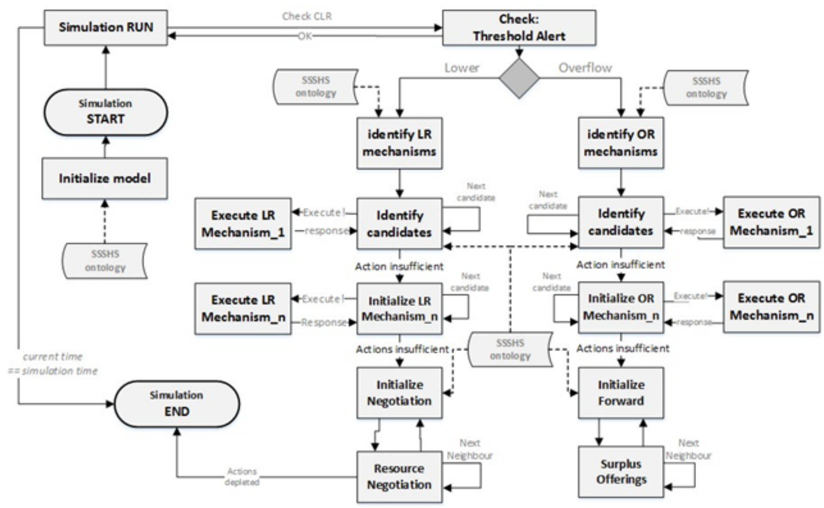

Figure 6: The newly proposed ontology providing critical input to the SSSHS simulation environment

Other important competency questions relating to the SSSHS framework are possible to implement through queries; for example, which resource producers are connected with BatteryPack01? [*ResourceProducer and belongs_to value BatteryPack01*]; Which mechanisms for managing low resource events that use multi-agent system technology are available? [*LowResourceMechanism and uses_technology value MultiAgent*]; identify all the resource consumers with highest relative priority and which have economy mode available for activation [*relative_priority value 1 and ResourceConsumer and economy_mode factor some xsd : decimal*[<= 1, > 0]]. All of the stated queries can be successfully run on the published SSSHS ontology.

7 Discussion

The SSSHS ontology proposed in this paper represents the further step of an ongoing research focused on the self-sustainability of human settlements and self-sustainable systems in general. Although the framework for modelling, simulating and observing the dynamics of resource management within the self-sustainable systems showed promising results, the need for a common language and knowledge repository in the domain of self-sustainable systems becomes apparent in the implementation phase of such systems by using currently existing technology derived from myriad of different vendors. Current literature and technology overview illustrates a number of incompatibility issues emerging from the heterogeneity of devices, protocols, data and message formats, standards, modelling methods, custom simulation platforms, software agents, etc. The ontology has the potential to address those issues directly, both from the human point of view in collaborative research and engineering efforts, and from the software agents' functionality, mutual interactions and system integrations.

Although developed in the domain of self-sustainable human settlements, the SSSHS ontology has the potential to broaden its domain knowledge to self-sustainable systems in general. For the purpose of illustrating the proposed ontology's diverse potential, the following short example tackles apparently disjoint application domain: the MMORPG game playing. In this example, the self-sustainable system itself is the party of players organized for the purpose of achieving a common goal. Resources can be modelled as skills, equipment, knowledge, etc., needed to resolve a quest. Resource manipulator can represent the player, the NPC, certain structure, or any other game entity that is able to produce or consume resources or mediate in the process. Storage can represent player inventory; service can represent a given quest; location, environment and activity can be related directly towards the self-sustainable human settlement.

The proposed research questions were tackled throughout the paper; interoperability issues (research question 1) was discussed through sections 1-3; the re-use of existing ontologies (research question 2) was discussed in detail in subsection 4.4; the key concepts of the ontology (research question 3) were defined in subsection 4.2; and the ontology application areas (research question 4) were discussed through use-cases within Section 6.

This paper presented and argued the current need for developing an open ontology for systems using heterogeneous devices and intelligent software components such as smart self-sustainable human settlements, but also related research areas such as Internet of things, smart cities, smart residential buildings, smart grids, smart home environments and similar. The existing body of research showed several efforts that proved to be complimentary to the SSSHS ontology development (see subsection 4.4), but none of them showing the broad holistic expressiveness required by the highly heterogeneous domain of self-sustainable systems.

The process of building this ontology started years before even considering about building one. Visiting off-grid sites, making notes, interviewing residents of self-sustainable settlements, modelling small-scale renewable energy systems, dealing with hardware and software technologies, developing IoT solutions, and finally, developing the SSSHS simulation framework for self-sustainable human settlements, all accumulated with the SSSHS ontology proposal and development. Knowing the system from the top, abstract classes, to the individual units, parts, and components with physical properties, their possible relations and interactions, but closely coupled with human activities, proved to compose the knowledge core needed for pursuing this effort. However, mistakes were naturally made at the beginnings, and many of them were revealed during the reasoning process and by querying the ontology with competency questions; some of them were noticed during simulation runs on the SSSHS framework, which revealed certain aspects of system's dynamics which were not considered before. Near the end, it was a fine-tuning process, optimising the ontology by using the available resources more or less simultaneously, until all the conflicts and/or inconsistencies were resolved. In conclusion - the experience in the domain and "going out in the field" is of paramount importance.

The self-sustainability and the ontology concepts, together with an extensive literature overview of related areas, were elaborated in more detail within sections 1 - 3. In section 4, the paper continued with describing the research materials and methods, together with the ontology development methodology and process (ontology scope, knowledge elicitation, basic concepts, system architecture, class hierarchy, axioms, properties and the integration of existing ontologies). Section 5 elaborates some of the extracted object properties within the SSSHS ontology which formally define relationships between objects. Section 6 argues the ontology consistency, its inferential potential, and presents two possible use-case scenarios for the initial ontology validation.

The next step in the ongoing research related to smart self-sustainable human settlements includes integrating the newly developed ontology with the agent-based SSSHS framework for modeling and simulating smart self-sustainable human settlements in the context of resource allocation and management. The final goal would be the development of the graphical modelling tool which would enable visual modelling of self-sustainable settlements with the automatic code generating capabilities. The modelling tool would have been based on the meta-model derived from the proposed ontology, and the model created in the modelling tool would serve as a direct input to the SSSHS framework environment.

The proposed SSSHS ontology is available in OWL format at the GitHub service (https://github.com/tomicic/SSSHSontology).

Acknowledgment

This work has been supported in full by the Croatian Science Foundation under the project number IP-2019-04-5824.

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