D5.1
Semantic Knowledge Structures and Representation

Dementia Ambient Care: Multi-Sensing Monitoring for Intelligent Remote Management and Decision Support

Dem@Care - FP7-288199

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Abstract (for dissemination)		The purpose of this document is to describe the current content of the Dem@Care ontology and the methodology adopted to build it. First, the purpose, scope, intended users and uses, and the requirements of the ontology as identified at this phase of the project are described. Their specification has been driven by the WP2 functional requirements indentified for the three environments addressed, namely laboratory, home and nursing home, as well as by the dependencies incurring by the interaction with the WP3 and WP4 analysis components, WP6 feedback components and WP7 activities pertinent to information exchange design. Second, the relevant literature is reviewed, covering both state of the art languages for formal knowledge representation and existing ontologies covering domains and requirements relevant to those of Dem@Care. Third, the current status of the Dem@Care ontology is described, discussing the main entities it comprises and providing some quantitative metrics. Future work includes the extension of the ontology with inference rules to support the derivation of behaviour interpretations and with a model for capturing PwD profile data.

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Executive Summary

In this document the current content of the Dem@Care ontology and the methodology adopted to build it is presented. In literature, a number of ontologies have been proposed for capturing aspects relevant to the Dem@Care domain, such as the modeling of events and the representation of sensor observations.

Based on the requirements set forth by WP2 and the dependencies incurring from the interaction with the other WPs, the purpose, scope, intended users and uses, and the requirements of the Dem@Care ontology were identified. These specifications, along with the modelling insights from the relevant literature, served as guidelines for building the first version of the Dem@Care ontology that currently comprises four modules. These are: i) the lab ontology that formalises information relevant to the ecological assessment taking place in the laboratory environment, ii) the home/nursing home ontology that formalises information relevant to the monitoring of PwD in home and nursing homes environments, iii) the event ontology that formalises information relevant to the entities (e.g. objects, places) and events considered within the Dem@Care domain, and iv) the descriptive information ontology that formalises provenance relevant information about the types of data managed.

Abbreviations and Acronyms

OWL	Ontology Web Language
OWL-QL	Ontology Web Language Query Language
OWL-DL	Ontology Web Language Description Language
RDF	Resource Definition Framework
W3C	World Wide Web Consortium
XML	eXtensible Markup Language
SWRL	Semantic Web Rule Language
SPARQL	SPARQL Protocol And RDF Query Language
DL	Description Logic
DLP	Description Logic Programs
MKNF	Minimal Knowledge and Negation as Failure
KB	Knowledge Base
SSN	Semantic Sensor Network
O&M	Observations and Measurements
SensorML	Sensor Model Language
SSO	Stimulus-Sensor-Observation
SOUPA	Standard Ontology for Ubiquitous and Pervasive Applications
DUL	DOLCE+DnS Ultralite
DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering
DnS	Descriptions and Situations
FOAF	Friend Of A Friend
SEM	Simple Event Model
ORSD	Ontology Requirements Specification Document
NRF	Non-Functional Requirement
CQ	Competency Question
PwD	Person with Dementia
MCI	Mild Cognitive Impairment
MMSE	Mini Mental State Exam
FAB	Frontal Assessment Battery
PSQI	Pittsburgh Sleep Quality Index
UPDRS	Unified Parkinson's Disease Rating Scale
NPI	NeuroPsychiatric Inventory
IADL-E	Instrumental Activities of Daily Living for Elderly
ADL	Activities of Daily Life
WP	Work Package
WIMU	Wireless Inertial Measurement Unit
Philips DTI-2	Philips Discrete Tensions Indicator

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1 Introduction

Work Package 5 (WP5) serves a fundamental, twofold role within the overall Dem@Care system:

- it encodes in a structured way, the information needed by the different system services, and
- it affords the means for the customised, semantic interpretation of the behaviour of the monitored person with dementia (PwD).

WP5 works in close interaction both with WP3 and WP4 that address the monitoring of the PwD, and with WP6 that provides the interfaces to the end users. More specifically, WP5 uses as its input the information extracted by WP3 regarding physiological and lifestyle characteristics (e.g. the PwD's heart rate or activity index, light and temperature levels in the PwD's residence), and the information extracted by WP4 regarding activities typical to daily living (e.g. eating, picking up the phone) and voice-based characteristics addressing affective, cognitive, and neuromuscular speech production control aspects. Based on this information, and utilising background knowledge and automated reasoning techniques, WP5 performs the semantic fusion of the available inputs and generates the high-level interpretation of the PwD's behaviour (e.g. the PwD suffers from nocturia, the PwD has meals at irregular times and/or in inappropriate places, the PwD is having difficulty to fall asleep due to excess noise levels, etc.). Based on the WP5 derived interpretations, WP6 determines and communicates appropriate feedback to the PwD, clinician and carer(s) accordingly.

To accomplish its objectives, WP5 is organised in three tasks:

- Task 5.1, which addresses the definition and building of Dem@Care's semantic knowledge structures that encode in a structured way the information relevant to the Dem@Care domain,
- Task 5.2, which addresses the modelling and dynamic update of PwD's behavioural profile; the resulted PwD profile model and behavioural patterns will enable to endow Task 5.3 services with personalised capabilities, and
- Task 5.3, which addresses the interpretation of PwD's behaviour and the recognition of clinically relevant situations via the aggregation and semantic integration of the WP3 & WP4 observations and the utilisation of domain and clinical knowledge.

The present deliverable reports on the work carried out within Task 5.1, namely the construction of the Dem@Care ontology. Section 2 presents the requirements the ontology has to meet; as detailed, their specification is largely driven by the requirements set forth by WP2, while additional considerations issue from the afore-described dependencies with WP3 and WP4. Section 3 reviews the relevant state of the art with respect to knowledge representation languages as well as already existing ontologies addressing project-relevant fields. Section 4 reports on the ontology implementation and presents the current status of the Dem@Care ontology. Section 5 concludes the document, presenting the conclusions that were drawn and discussing future work.

2 Dem@Care Ontology Requirements

To elicit the requirements that the Dem@Care ontology needs to satisfy we followed the guidelines proposed by Suárez-Figueroa et al. in [1], since the proposed methodology allows specifying in a systematic way why the ontology is being built, what its intended uses are, who the end-users are, and which requirements the ontology should fulfil.

The outcome of the proposed ontology requirements specification methodology is documented in a template-based report called Ontology Requirements Specification Document (ORSD) [1], which contains information about:

- **Purpose:** the main goal of the ontology (i.e. the main function of the ontology)
- **Scope:** the general coverage and the degree of detail of the ontology
- **Implementation language:** the formal language of the ontology
- **Intended end-users:** the intended end-users expected for the ontology
- **Intended uses:** the intended uses expected for the ontology
- **Ontology requirements**
    - *Non-functional requirements:* the general requirements or aspects that the ontology should fulfil, including optionally properties for each requirement
    - *Functional requirements:* the content specific requirements that the ontology should fulfil in the form of groups of competency questions and their answers, including optional priorities for each group and for each competency questions
- **Pre-Glossary of terms**[1]
    - *Terms from competency questions*: the list of items included in the competency questions and their frequencies
    - *Terms from answers:* the list of terms included in the answers and their frequencies
    - *Objects:* the list of objects included in the competency questions and their answers

Before presenting the generated Dem@Care ORSD (Section 2.2), we outline the overall application context within which the Dem@Care ontology is deployed by revisit the key, WP5 relevant, requirements of the overall Dem@Care system (Section 2.1).

2.1 Dem@Care ontology application context

The first version of the Dem@Care system functional requirements is documented in D2.2 “Functional Requirements & Scenarios v1” [2], where the objectives and specific targets for

[1] These pre-glossary terms can serve as indicators for identifying classes, properties and instances of the ontology.

the three environments addressed, namely lab, home and nursing home, are presented. Subsequent ongoing WP2 investigations have led to further refined and elaborated scenario descriptions and in specific use cases that were distilled for the first version of the Dem@Care prototype, as reflected in D7.1 "System Specifications & Architecture v1" [3]. In the following, we outline the key requirements relevant to WP5, and to the Dem@Care ontology in particular.

2.1.1 Lab environment

The primary aim of the Dem@Care system in the lab environment is to assist clinicians to diagnose early state Alzheimer's disease in an objective manner, via the use of an ecological experimentation protocol that considers standardised scenarios of daily living oriented activities. During the protocol steps and their constituent tasks, a predefined set of measurements that are of clinical relevance are monitored. These measurements serve clinicians as indicators to assess cognitive, behavioural and psychological traits (e.g. gait, functional abilities, and affective state) that are related to the diagnosis of mild cognitive impairment (MCI) and of dementia.

In this setting, the overall role of WP5 is:

- to provide the means to encode the relevant information in a structured way that endorses precise semantics, and
- to afford automated reasoning mechanisms for the derivation of auxiliary assessments that meaningfully fuse the measurements into aggregated descriptions that can assist clinicians in their comparative study and subsequent diagnostic decision making.

Consequently, the primary objective of the Dem@Care ontology is to provide the vocabulary and the conceptual model for capturing the relevant information, namely the steps and tasks comprising the protocol and the pertinent measurements, the clinical characteristics of the participant, the aspects assessed, and so forth. Furthermore, and in conjunction with the inference rules addressed in Tasks 5.2 and 5.3, the Dem@Care ontology needs to support the derivation of auxiliary assessments regarding the participant's status.

2.1.2 Home environment

The primary aim of the Dem@Care system in the home environment is to promote the enablement and the safety of the PwD. This will be accomplished via the monitoring of the PwD's daily life and the provision of appropriate feedback to the PwD, the attending clinician and respective carer(s).

In this setting, the overall role of WP5 is:

- to provide the means to encode the relevant information in a structured way that endorses precise semantics,
- to afford automated reasoning mechanisms for the high-level interpretation of the PwD behaviour via the integration and semantic fusion of the information made available through monitoring
- to afford mechanisms for dynamic patient profiling so as to endow behaviour interpretation reasoning with personalisation capabilities

Consequently, the primary objective of the Dem@Care ontology is to provide the vocabulary and conceptual model for capturing the relevant information, namely activities of daily living (e.g. having meal, sleeping and napping, answering the phone, having a face-to-face conversation), clinically relevant attributes (e.g. regularity and location of meals, sleep efficiency and duration, number of telephone and face-to-face interactions), problems and situations that the clinicians needs to be informed about (e.g. missed meals, excessive napping, insufficient utterances and communication attempts), profile information (e.g. sleep routine, diet habits, exercise trends), and so forth. Furthermore, and in conjunction with the inference rules addressed in Tasks 5.2 and 5.3, the Dem@Care ontology needs to support the derivation of high-level behaviour interpretations.

2.1.3 Nursing home environment

The primary aim of the Dem@Care system is similar to that of the home environment, namely to promote the enablement and safety of the PwD via appropriate feedback to the PwD and the attending clinician(s). Compared with the home environment, where the participant may engage into any type of activity, the nursing home presents a more controlled environment, while setting forth a number of differences (e.g. multiple residents, group activities, lack of need to perform otherwise typical activities).

As such, the overall WP5 role is similar to that described for the home environment. The same holds for the ontology, whose only variation consists in extensions that may be required in order to capture aspects that are specific to the nursing home only.

2.1.4 Descriptive information

In addition to the vocabulary and conceptual model required for capturing information relevant to the three application environments addressed, the Dem@Care ontology needs also to consider descriptive information. This includes information about the types of data managed by the various system components, provenance information, such as when and how such data was made available (e.g. what sensor recorded a certain skin conductance measurement), information about their plausibility (e.g. the degree of confidence associated with a particular activity detection) and so forth. Capturing such information in the ontology, is crucial for WP5 objectives, since it significantly contributes to informed filtering and decision making about the reliability and relevance of the available information pieces during the integration, semantic fusion and high-level interpretation tasks.

2.1.5 Dependencies incurred by other WPs

As aforementioned, one of the main objectives of WP5 is to semantically integrate the different pieces of information that are provided by WP3 and WP4 and to derive high-level interpretations of the PwD behaviour. As such, the vocabulary and conceptual model afforded by the Dem@Care ontology needs to allow at first stage the representation of such information that from now on will be referred to as *atomic*. Subsequently, the ontology needs to capture, via axioms and rules, how such atomic information can lead to the derivation of information pertinent to the high-level behaviour interpretation, from now on referred to as *composite*. For example, besides the composite event of “Having meal”, the Dem@Care ontology needs to also include the atomic events of “Eating”,” Sitting at the table”, “Located in the kitchen”, etc.

In parallel, the ontology needs to ensure that it captures all information that is needed in order to realise the WP6 feedback services. This includes information required to compile the appropriate feedback to the different types of end-users (e.g. the napping statistics required to be reported to the clinician), but also information regarding the situations that serve as triggers for the delivery of the respective feedback (e.g. failure of the PwD to wake up by a predefined time triggers a respective feedback for the carer).

Furthermore, since the ontology provides the consensual conceptual framework for representing, encoding and querying information about the different types of data handled by the individual system components, it is inherently intertwined with the data exchange format addressed within WP7 for service communication. More specifically, the role of the ontology is to capture all types of entities and interrelations pertinent to the types of information described in Sections 2.1.1 to 2.1.5; thereby, it affords the structure and vocabulary when communicating information of such type. In addition to it, the data exchange format uses additional vocabulary and structure to encode system-oriented aspects (which by definition are out of the ontology scope) that are needed for the unimpeded communication of the services and components comprising the overall system.

2.2 Dem@Care Ontology Requirement Specification Document

The Dem@Care ORSD is based on the functional and clinical specifications laid out in deliverable D2.2, as well as on the scenarios and use cases described in deliverable D7.1. Additional feedback and clarifications have been elicited through iterative cycles of communication with WP2, WP3, WP4, WP6 and WP7 that progressed in parallel and were in position of providing additional input that eventually led to further refined and concretely crystallised requirements.

Consequently, it should be noted that the resulting ORSD (Table 1) reflects the ontology requirements as pertinent to the current status of the Dem@Care system; revisions and extensions will need to be carried out as the system functionalities evolve.

Table 1 The Dem@Care Ontology Requirements Specification Document

Dem@Care Ontology Requirements Specification Document	
1	**Purpose**
	The purpose of the Dem@Care Ontology is to provide the Dem@Care system with a consensual conceptual model able to represent: information that is made available via the Dem@Care physiological, lifestyle, activity and voice-based monitoring modules and via reporting (e.g. questionnaires for self-assessment, clinical record, demographics) high-level behaviour interpretations that are derived by the Dem@Care behaviour analysis services and are subsequently used to determine the feedback appropriate to the different end-users, namely PwD, clinicians, and carers The ontology is needed by the system in order to ensure the semantic interoperability of the information exchanged between the individual Dem@Care systems components and to support, in conjunction with inference rules, personalised behaviour interpretation services.

2	**Scope**
	The Dem@Care ontology has to formally represent: ▪ physiological and lifestyle data ▪ activities typical of daily living ▪ voice-based indicators of dementia-relevant characteristics ▪ information about the lab environment protocol ▪ clinical and demographic data ▪ problems and situations of clinical relevance with respect to the monitored behavioural aspects ▪ descriptive (provenance relevant) information ▪ *triangulation relations* (e.g. cause and effect relations for contributing factors)* ▪ *PwD profile data* (e.g. sleep routine patterns)* The level of granularity is directly related to the competency questions and terms identified (see part 6b of the OSRD). *(*these will be addressed in the ontology versions that will be part of the second and third prototypes of the system)*
3	**Implementation Language**
	The ontology has to be implemented in OWL 2, the officially recommended language for knowledge representation in the Semantic Web.
4	**Intended End-Users**
	The Dem@Care system considers three types of end-users (see deliverable D7.1): ▪ People with dementia (PwD), who receive feedback in the form of guidance and advice messages and provide information via questionnaire interfaces (home and nursing home environments) ▪ Clinicians, who receive feedback in the form of summaries reporting statistics, measurements and assessments of interest (lab, home and nursing home environments) ▪ Carers, who receive feedback in the form of advice and alert information so as to promote PwD's enablement and safety (home and nursing home environments) None of the three end-users groups interacts directly with the ontology, but the ontology provides the vocabulary and semantics represent and generate the information needed in order for the Dem@Care system to afford the aforementioned end-users services.
5	**Intended Uses**
	The following, application-oriented ontology uses have been identified: Use 1. To represent and query data made available by the WP3 & WP4 analysis components in terms of a common vocabulary

	Use 2. To represent, store and retrieve information about the inferred behaviour interpretations Use 3. To provide a shared vocabulary for the communication and exchange of information among the different Dem@Care components Use 4. To serve as the underlying model for the implementation of the behaviour interpretation reasoning tasks * Use 5. To represent, store and retrieve PwD profile data* Use 6. To serve as the underlying model for the implementation of patient-tailored behaviour interpretations* *(*these will be addressed in the ontology versions that will be part of the second and third prototypes of the system)*
6	**Ontology Requirements**
	a. Non-Functional Requirements
	NFR1. The ontology should adopt available standards whenever possible
	b. Functional Requirements: Groups of Competency Questions
	Competency Questions Group 1: Lab environment CQ1. What are the protocol parts? Medical consultation, clinical consultation and ecological assessment CQ2. What types of data are collected during medical and clinical consultation? Demographic data and clinical data *Group 1.1: Demographic data* CQ3. What types of demographic data are collected? Date of birth, gender, education level, laterality, weight CQ4. What is the gender information? Female, male CQ5. What are the main types of education level? Basic education, higher education, … CQ6. What are the main types of laterality? Right-handed and left handed *Group 1.2: Clinical data* CQ7. What types of clinical data are collected? Diagnosis data, cognitive abilities assessment data, neuropsychiatric/mood assessment data, motricity abilities assessment data, autonomy assessment data CQ8. What are the types of diagnosis? Healthy, Alzheimer's disease at predementia stage, Alzheimer's disease at dementia stage CQ9. What types of cognitive abilities assessment data are collected? Mini-mental state exam (MMSE), frontal assessment battery (FAB), trail making test A and B, short cognitive battery, the free and cued selective reminding test CQ10. What data are collected for MMSE? A [0-30]/30 score CQ11. What data are collected for FAB? A [0-18]/18 score CQ12. What data are collected for the trail making test? The number of seconds to complete the test CQ13. What data are collected for the short cognitive battery test? An orientation

test score, a 5-word memory test score, a clock test score and a verbal fluency test score.

CQ14. What data are collected for the free and cued selective reminding test? A [0-48]/48 score

CQ15. What types of neuropsychiatric/mood assessment data are collected? NPI, DSM-IV criteria for depression, apathy inventory (AI) and diagnostic criteria for apathy

CQ16. What data are collected for NPI? Frequency (scale 1-4), severity (scale 1-3) and impact on care (scale 1-5)

CQ17. What data are collected for DSM-IV criteria? Absence/Presence

CQ18. What data are collected for AI and diagnostic criteria for apathy? Absence/Presence

CQ19. What types of motricity abilities assessment data are collected? Part III of the Unified Parkinson's Disease Rating Scale (UPDRS) data

CQ20. What data are collected for UPDRS? A scores [0-4]/4 for the set of subparts used (trampling when walking, trembling, rigidity, rising from a chair, posture, postural stability, gait, bradykinesia)

CQ21. What types of autonomy assessment data are collected? A [0-8]/8 score at Instrumental Activities of Daily Living for Elderly (IADL-E)

Group 1.3: Ecological assessment protocol

CQ22. What types of steps does ecological assessment consist of? Directed, semi directed, and discussion with clinician

CQ23. What are the types of directed tasks? physical directed tasks, vocal directed tasks

CQ24. Which are the physical directed tasks? Waking, counting backwards, walking and counting backwards

CQ25. Which are the vocal directed tasks? Sentence repeating, articulation control

CQ26. What is the nature of a directed task? Mono task, dual task

CQ27. Which directed tasks are mono tasks? Walking, counting backwards

CQ28. Which directed tasks are dual tasks? Walking and counting backwards

CQ29. Which are the tasks of the semi-directed step? Water a plant, pay a bill, answer the phone, turn on TV, prepare hot tea, read an article, call the psychologist, leave the room, prepare the drugbox, …

CQ30. What are the types of tasks in the discussion with clinician step? Directed discussion tasks, free discussion tasks

CQ31. Which are the directed discussion tasks? Questions about an article read, questions about the course of the semi directed tasks step

CQ32. Which are the free discussion tasks? Verbal description of a picture, free discussion about a picture

Group 1.4: Ecological assessment

CQ33. What is assessed in the walking task? Gait, latency, stress level

CQ34. What is assessed in the counting backwards task? Latency, stress level, cognitive and neuromuscular impairment

CQ35. What is assessed in the walking and counting backwards task? Gait, latency, stress level, cognitive and neuromuscular impairment (voice-based), mutual influence of cognitive activity on motor activity

CQ36. What is assessed in the sentence repeating task? Latency, stress level, cognitive and neuromuscular impairment

CQ37. What is assessed in the articulation control task? Latency, stress level, neuromuscular impairment in speech production mechanism

CQ38. What is assessed in the tasks of the semi-directed protocol step? Cognitive abilities, ability to organize efficiently several activities, functional abilities, stress level

CQ39. What is assessed in the tasks of the discussion with clinician step? Affective state, interaction, cognitive and neuromuscular impairment)

Group 1.5: Ecological assessment measurements

CQ40. What data are measured for gait assessment? Dynamic balance, step length, stopping displacement, walking speed, walking speed instantaneous

CQ41. What data are measured for dynamic balance? A [0-5]/5 score

CQ42. What data are measured for step length? Distance in meters

CQ43. What data are measured for walking speed? Speed in meters/sec

CQ44. What data are measured for walking speed instantaneous? Speed in meters/sec

CQ45. What data are measured for stopping displacement? Number of stops during task execution

CQ46. What data are measured for latency? Time in seconds

CQ47. What data are measured for stress? Time-stamped skin conductance intensity

CQ48. What data are measured for cognitive and neuromuscular assessment? Voice-based cognitive and neuromuscular indicators

CQ49. What data are measured for affective state assessment? Voice-based affective indicators

CQ50. What data are measured for interaction assessment? Voice-based interaction indicators

CQ51. What data are measured for neuromuscular impairment in speech production mechanism? Voice-based speech production indicators

CQ52. What data are measured for cognitive abilities assessment? Status (completed/omitted/incomplete), number of repetitions and duration, for each of the activities comprising the semi-directed step

CQ53. What data are measured for organizational efficiency assessment? Participant's trajectory in the experimentation room and total distance walked

CQ54. What data are measured for functional abilities assessment? Hand trajectories during activity execution

Competency Questions Group 2: Home/Nursing home environment

CQ55. What functional areas are of clinical relevance for the home and nursing home environments? Sleep, activities of daily living (ADL), social interaction, exercise and mood

CQ56. How are the statistics and identified problematic situations about the monitored functional areas reported to the clinician? In the form of daily, weekly and monthly summary reports.

CQ57. What types of questionnaires are administered for self-assessment? The PSQI and Epworth Sleepiness Scale questionnaires for sleep assessment, questionnaires for mood assessment

Group 2. 1: Sleep monitoring & assessment

CQ58. What activities (situations) are of clinical interest with respect to sleep? Night sleep (entire sleep episode), napping during the day, awakening in the midst of the sleep episode, leaving the bed (bed exit), visiting the bathroom, visiting rooms other than the bathroom, sleep apneas, periodic limb movements and micro-arousals.

CQ59. What information is of clinical interest regarding night sleep? Retiring time, bed time, sleep time, and wake up time

CQ60. What information is of clinical interest regarding a nap? Start time and duration

CQ61. What information is of clinical interest regarding an awakening? Start time and duration of awakening

CQ62. What information is of clinical interest regarding a bed exit? Start time, duration, visited locations (e.g. kitchen) and activities performed (e.g. having a snack)

CQ63. What information if of clinical interest regarding a night bathroom visit? Start time and duration

CQ64. What information is clinically relevant for sleep assessment? Sleep latency, sleep efficiency, number of arousals at night, number of awakenings at night, number of bed exits, number of night bathroom visits, number of sleep apneas, number of periodic limb movements, number of naps during the day, total duration of naps, self-assessed sleep quality (via questionnaires)

CQ65. What sleep-related situations indicate a problem or possibly problematic behaviour that needs to be highlighted to the clinician? Sleep latency less than 30 minutes, sleep duration more than 7 hours, sleep efficiency less than 85%, bed exit with visit to rooms other than the bathroom, bed exit with attempt to leave the house, occurrence of more than 5 apneas, fragmented sleep (more than 2 awakenings at night), nocturia (more than 2 bathroom visits at night), periodic limb movements occurrence, napping after lunch, napping for more than 30 minutes and a score of 5 or higher during sleep self-assessment.

Group 2. 2: ADL monitoring & assessment

CQ66. What activities (situations) are of clinical interest with respect to ADLs? Food/drink preparation and consumption activities (e.g. having meal, leaving the table, open/close fridge and kitchen presses, usage of kitchen appliances), housekeeping activities (e.g. do laundry, rubbish disposal), personal hygiene, falls, disorientation, …

CQ67. What information is of clinical interest regarding food and drink preparation? Start time and duration, activities involved in the preparation

	and their sequence (e.g. heating water in pot, adding pasta to pot) CQ68. What information is of clinical interest regarding food and drink consumption? Start time, duration, location, whether the PwD has left the table while eating, … CQ69. What information is of clinical interest regarding housekeeping? Type of cleaning/maintenance activity, start time and duration CQ70. What information is of clinical interest regarding personal hygiene? Time spent in the bathroom, … CQ71. What food and drink preparation-related situations indicate a problem or possibly problematic behaviour that needs to be highlighted to the clinician? Failure to prepare a meal, leaving fridge or cupboards open, … CQ72. What food and drink consumption-related situations indicate a problem or possibly problematic behaviour that needs to be highlighted to the clinician? Skipped meals, long duration of meals, eating in inappropriate locations, leaving table while eating, irregular eating patterns, … CQ73. What housekeeping-related situations indicate a problem or possibly problematic behaviour that needs to be highlighted to the clinician? Failure to engage in housekeeping activities (e.g. not doing the laundry or disposing of rubbish, not tidying up after meals) CQ74. What personal hygiene-related situations indicate a problem or possibly problematic behaviour that needs to be highlighted to the clinician? failure to engage in personal hygiene *Group 2. 3: Social interaction monitoring & assessment* CQ75. What activities (situations) are of clinical interest with respect to social interaction? Face to face interaction, telephone interaction, … CQ76. What information is clinically relevant for social interaction assessment? Number of people encountered per day, number of face to face interactions, number of telephone interactions, speed and speech volume, number of communicative attempts, … CQ77. What social interaction related situations indicate a problem or possibly problematic behaviour that needs to be highlighted to the clinician? Insufficient number of people encountered per day, insufficient speech utterances made per day, slow speech speed, low speech volume, speech irregularity, insufficient number of conversations had daily, lack of questioning utterances by the PwD, insufficient number of communicative attempts, … *Group 2.4: Physical activity monitoring & assessment* CQ78. What activities (situations) are of clinical interest with respect to physical activity? Indoors/outdoors incidental and dedicated physical activities (e.g. walking, running, cycling, …) CQ79. What information is clinically relevant for walking? Walk speed, distance travelled, stride length, onset time, duration, … CQ80. What information is clinically relevant for dedicated physical activities (i.e. exercises)? Onset time, duration, exercise intensity, heart rate, repetitions… CQ81. What information is clinically relevant for physical activity assessment?

Frequency, duration, …

CQ82. What physical activity related situations indicate a problem or possibly problematic behaviour that needs to be highlighted to the clinician? Inappropriate exercise duration, inappropriate exercise intensity, slow walk speed, late exercise onset times, abnormal heart rate,

Group 2.5: Mood monitoring & assessment

This will be addressed in the second and third (final) version of the ontology.

Competency Questions Group 3: Entities & events

CQ83. What are the main types of entities? Persons, Objects and Places

CQ84. What are the main categories a person may belong to? Person with dementia, carer, clinician

CQ85. What are the main types of objects? Appliances (e.g. kettle, television), furniture (e.g. bed, kitchen table), daily living objects (e.g. plate, sink)

CQ86. What are the main categories of places? Indoors and outdoors

CQ87. What are the types of indoor place? The individual house rooms (e.g. bedroom)

CQ88. What are the main types of events? Events related to a person (i.e. activities and states), events related to physiological measurements, events related to ambient measurements, and events related to objects

CQ89. What are the main types of information describing an event? The agent of the event (i.e. the referred person, object or room), start time, duration, and location (where applicable)

CQ90. What are the main categories of events? Atomic (detected by WP3 and WP4 analysis components) and complex (derived through reasoning by WP5)

CQ91. What activities are detected? Eating, drinking, dialing a number, picking up the phone, walking, sleeping, speaking, …

CQ92. What states are detected? Person posture (e.g. sitting, standing), person localisation (e.g. person in the bedroom, person near the bed), person moving, person having an apnea incidence, …

CQ93. What object related events are detected? Phone ringing, fridge open, usage of an object, …

CQ94. What ambient measurements are detected? Light level, noise level, …

CQ95. What physiological measurements are detected? Heart rate, skin conductance, …

CQ96. What activities are inferred? Having meal, preparing meal, leaving the table during a meal, leaving bed at night, taking a nap,

Competency Questions Group 4: Descriptive information

CQ97. What are the main types of data considered? Observations (i.e. information about the activities/events/states of the monitored person), reports (i.e. manually inputted data made available via questionnaires, clinical consultation, etc.), interpretation result (i.e. interpretations drawn about a person's behaviour), …

	CQ98. What are the main types of data an observation may refer to? Measurements (physiological and ambient), detected events and inferred events CQ99. What types of descriptive information are relevant to an observation? The type of data the observation refers to, the time the observation is made available to the system, its plausibility and its provider (i.e. what sensor/processing component made it available to the system) CQ100. What are the main types of data a report may refer to? Questionnaires, clinical characteristics, demographic data, … CQ101. What types of descriptive information are relevant to a report? The type of data the report refers to, the time it is made available to the system, its provider (i.e. what sensor/processing component made it available to the system) and (possibly) its plausibility CQ102. What are the main types of data an interpretation result may refer to? Problems relevant to functional areas considered, summary information, … CQ103. What types of descriptive information are relevant to a result? The type of data the result refers to, the time the result is made available to the system, its plausibility and its provider (i.e. what sensor/processing component made it available to the system) CQ104. What are the main types of sensors? Wearable sensors and fixed sensors CQ105. What are the possible types of wearable sensors? The Philips Discrete Tensions Indicator (DTI-2), the Tyndall Rev3 Wireless Inertial Measurement Unit sensor (Rev3 WIMU), the GoPro wearable camera, the wearable microphone, … CQ106. What are the possible types of fixed sensors? The Axis P13 static camera, kinect, … CQ107. What are the possible types processing components? The Rev2 WIMU signal processing software component (SPS), DTI-2 ASW, the offline speech analyser component (OSA), the complex activity recognition component (CAR), the semantic interpretation component (SI), …	
7	**Pre-Glossary of Terms**	
	a. Terms extracted from Competency Questions & their frequency	
	Protocol 1	Latency assessment 1
	Medical consultation 2	Motricity abilities assessment 1
	Clinical consultation 2	Stress assessment 1
	Ecological assessment 2	Cognitive & neuromuscular assessment 1
	Demographic data 2	Affective state assessment 1
	Clinical data 2	Cognitive abilities assessment 3
	Diagnosis 1	Interaction assessment 1
	Physical directed task 1	Organization abilities assessment 1
	Vocal directed task 1	Functional abilities assessment 1

	Mono task 1	Activity 5
	Dual task 1	Event 4
	Directed step 2	State 1
	Semi-directed step 2	Ambient measurement 1
	Discussion with clinician step 2	Physiological measurement 1
	Directed discussion task 1	Problem (problematic behaviour) 7
	Free discussion task 1	Questionnaire 3
	Waking task 1	Self-assessment 1
	Counting backwards task 1	Highlight 7
	Walking and counting backwards task 1	Sleep assessment 1
	Sentence repeating task 1	ADL assessment 1
	Articulation control task 1	Social interaction assessment 1
	Gait assessment 1	Physical activity assessment 2
	Neuropsychiatric/mood assessment 1	Mood assessment 1
	b. Terms from Answers & their frequency	
	Date of birth 1	Distance 3
	Gender 1	Start time 11
	Education 1	Status (completed/omitted/incomplete) 1
	Laterality 1	Person trajectory 1
	Weight 1	Hand trajectory 1
	Healthy 1	Duration 16
	Alzheimer's (predementia stage) 1	Sleep 5
	Alzheimer's (dementia stage) 1	Questionnaire 2
	Trail making test A and B 1	Nap 5
	Short cognitive battery 1	Awakening 2
	Free and cued selective reminding test 1	Bed exit 4
	MMSE score 1	Apnea 3
	FAB score 1	Periodic limb movement 3
	Orientation test score 1	Arousal 2
	5-word memory test score 1	Retiring time 1
	Clock test score 1	Bed time 1
	Verbal fluency test score 1	Sleep time 1
	NPI 1	Wake up time 1

	DSM-IV criteria for depression 1 Apathy inventory (AI) 1 Diagnostic criteria for apathy 1 Frequency scale 1 Severity scale 1 Impact on care scale 1 Trampling when walking score 1 Trembling score 1 Rigidity score 1 Rising from a chair score 1 Posture score 1 Postural stability score 1 Gait score 1 Bradykinesia score 1 IADL-E score Water a plant 1 Pay a bill 1 Answer the phone 1 Turn on TV 1 Prepare hot tea 1 Read an article 1 Call the psychologist 1 Leave the room 1 Prepare the drugbox 1 Questions about an article read 1 Questions about the course of the semi directed tasks step 1 Verbal description of a picture 1 Free discussion about a picture 1 Mutual influence of cognitive activity on motor activity 1 Voice-based cognitive and neuromuscular indicators 1 Voice-based affective indicators 1	Sleep latency 2 Sleep efficiency 2 Fragmented sleep 1 Nocturia 1 Skipped meal 1 Having meal 1 Leaving the table 1 Open 3 Closed 2 Table exit 1 Housekeeping 2 Personal hygiene 2 Fall 1 Disorientation 1 Face to face interaction 3 Telephone interaction 2 Speech speed 2 Walking 2 Running 1 Heart rate 2 Exercise intensity 2 Person 2 Object 2 Place 1 Person with dementia 1 Carer 1 Clinician 1 Appliance 1 Furniture 1 Indoors 1 Outdoors 1 Agent 1 Eating 1

	Voice-based interaction indicators 1 Voice-based speech production indicators 1 Skin conductance 1 Dynamic balance 1 Step length 2 Stopping displacement 1 Walking speed 3 Walking speed instantaneous 1	Drinking 1 Dialing a number 1 Picking up the phone 1 Speaking 1 Posture 1 Ringing 1 Light 1 Noise 1
	c. Objects	
	Female, male, right-handed, left-handed, dementia state, predementia stage, completed, omitted, …	

3 Background

3.1 Ontologies

Ontologies are models used to capture knowledge about some domain of interest. Formally speaking, ontologies are *explicit formal specifications of shared conceptualizations* [4][5]. They afford abstract views of the world including the objects, concepts, and other entities that are assumed to exist in some area of interest, their properties and the relationships that hold among them. Their expressivity and level of formalisation depend on the knowledge representation language used.

Within the Semantic Web, an extension of the current Web that aims to afford a common framework for sharing and reusing data across heterogeneous sources, ontologies play a key role. The Semantic Web vision is to make the semantics of web resources explicit by attaching to them metadata that describe meaning in a formal, machine-understandable way. In this effort, the Web Ontology Language (OWL) [11] has emerged as the official W3C recommendation for creating and sharing ontologies on the Web. In the following, we present the basics of Description Logic (DL) languages, on which OWL semantics are grounded, the different OWL species, as well as relevant rule-based languages.

3.1.1 Description Logics

Description Logics (DLs [6]) are a family of knowledge representation formalisms characterised by logically grounded semantics and well-defined reasoning services. The main building blocks are *concepts* representing sets of objects (e.g. `Person`), *roles* representing relationships between objects (e.g. `worksIn`), and *individuals* representing specific objects (e.g., `Alice`). Starting from *atomic* concepts, such as `Person`, arbitrary complex concepts can be described through a rich set of *constructors* that define the conditions on concept membership. For example, the concept `∃hasFriend.Person` describes those objects that are related through the `hasFriend` role with an object from the concept `Person`; intuitively this corresponds to all those individuals that are friends with at least one person. A DL knowledge base K typically consists of a *TBox T* (terminological knowledge) and an *ABox A* (assertional knowledge). The TBox contains axioms that capture the possible ways in which objects of a domain can be associated. For example, the TBox axiom `Dog ⊑ Animal` asserts that all objects that belong to the concept `Dog`, are members of the concept `Animal` too. The ABox contains axioms that describe the real world entities through concept and role assertions. For example, `Dog(Jack)` and `isLocated(Jack,kitchen)` express that `Jack` is a dog and he is located in the kitchen. Table 2 summarises the set of terminological and assertional axioms.

Table 2 Terminological and assertional axioms

Name	Syntax	Semantics
Concept inclusion	$C \sqsubseteq D$	$C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$
Concept equality	$C \equiv D$	$C^{\mathcal{I}} = D^{\mathcal{I}}$

Role Equality	$R \equiv S$	$R^{\mathcal{I}}=S^{\mathcal{I}}$
Role inclusion	$R \sqsubseteq S$	$R^{\mathcal{I}} \subseteq S^{\mathcal{I}}$
Concept assertion	$C(\alpha)$	$\alpha^{\mathcal{I}} \in C^{\mathcal{I}}$
Role assertion	$R(\alpha,b)$	$(\alpha^{\mathcal{I}}, b^{\mathcal{I}}) \in R^{\mathcal{I}}$

The semantics of a DL language is formally defined through an interpretation $\mathcal{I}$ that consists of a nonempty set $\Delta^{\mathcal{I}}$ (the domain of interpretation) and an interpretation function $\cdot^{\mathcal{I}}$, which assigns to every atomic concept A a set $A^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}}$ and to every atomic role R a binary relation $R^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$. The interpretation of complex concepts follows inductively. Table 3 shows the syntax and semantics of some of the most common DL constructors.

Table 3 Examples of concept and role constructors

Name	**Syntax**	**Semantics**
Top	$\top$	$\Delta^{\mathcal{I}}$
Bottom	$\perp$	Ø
Intersection	$C \sqcap D$	$C^{\mathcal{I}} \cap D^{\mathcal{I}}$
Union	$C \sqcup D$	$C^{\mathcal{I}} \cup D^{\mathcal{I}}$
Negation	$\neg C$	$\Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
Universal Quantification	$\forall R.C$	$\{\alpha \in \Delta^{\mathcal{I}} \mid \forall b.\ (\alpha,b) \in R^{\mathcal{I}} \rightarrow b \in C^{\mathcal{I}}\}$
Existential Quantification	$\exists R.C$	$\{\alpha \in \Delta^{\mathcal{I}} \mid \exists b.\ (\alpha,b) \in R^{\mathcal{I}} \wedge b \in C^{\mathcal{I}}\}$
Inverse	R^{-}	$\{(b, \alpha) \in \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}} \mid (\alpha,b) \in R^{\mathcal{I}}\}$
Transitive Closure	R^{+}	$\bigcup_{n>1} (R^{\mathcal{I}})^{n}$
Composition	$R \circ S$	$R^{\mathcal{I}} \circ S^{\mathcal{I}}$

3.1.2 DLs reasoning services

Besides formal semantics, DLs come with a set of powerful reasoning services, for which efficient, sound and complete reasoning algorithms with well understood computational properties are available. Example state-of-the-art implementations include Pellet [7], Racer [8], Fact++ [9] and Hermit [10].

Assuming a DL knowledge base $K = (T, A)$, typical reasoning services include:

- **Subsumption:** A concept C is subsumed by D in T (written $C \sqsubseteq D$), *iff* $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ for all interpretations $\mathcal{I}$.

- **Equivalence:** Two concepts C and D are equivalent in T (written $C \equiv D$) *iff* $C \sqsubseteq D$ and $D \sqsubseteq C$.

- **Disjoint:** A concept C is disjoint to a concept D in T *iff* in every interpretation $\mathcal{I}$ it holds that $C^{\mathcal{I}} \neq \emptyset$.

- **Consistency:** The ABox A is consistent w.r.t. T *iff* if there is an interpretation that is a model of both A and T.

- **Instance checking:** The individual α is an instance of C (w.r.t. K) (written $K \models C(\alpha)$) *iff* $\alpha^{\mathcal{I}} \in C^{\mathcal{I}}$ holds for all interpretations $\mathcal{I}$ of K.

- **Realisation:** The realisation of an instance α w.r.t. to K includes finding the most specific concepts C for which $a^{\mathcal{I}} \in C^{\mathcal{I}}$ holds for all interpretations $\mathcal{I}$ of K.

Hence, through subsumption one can derive the implicit taxonomic relations among the concepts of a terminology. For example, given the axiom `OccupiedRoom` $\sqsubseteq$ `Room` $\sqcap$ $\exists$`contains.Person`, one can infer that `Room` subsumes `OccupiedRoom`.

Satisfiability and consistency checking are useful to determine whether a knowledge base is meaningful at all. Satisfiability checking enables the identification of concepts for which it is impossible to have members under any interpretation (for example, an unsatisfiable concept, though trivial, is `OccupiedRoom` $\sqcap$ $\neg$`OccupiedRoom`). Consistency checking enables the identification whether the set of assertions comprising the knowledge base is admissible with respect to the terminological axioms. For example if `EmptyRoom` and `OccupiedRoom` are asserted as disjoint concepts, then the presence of both `OccupiedRoom(kitchen)` and `EmptyRoom(kitchen)` leads to inconsistency.

Instance checking denotes the task of finding whether a specific individual is an instance of a given concept. Realisation of an individual, a more generic form of instance checking, returns all (most specific) concepts from the knowledge base that a given individual is an instance of. Its dual is the retrieval problem that given a specific concept C, it returns all individuals that belong to this concept. This reasoning service is the central to realise the task of recognition of situation types.

A particularly appealing feature of DLs is that they are decidable fragments of first-order logic. Their decidability is largely due to the so called tree model property according to which a class C has a model (i.e. an interpretation $\mathcal{I}$ in which $C^{\mathcal{I}}$ is non-empty) *iff* C has an interpretation that defines a tree shaped directed graph. This property has a direct impact on the relational expressivity of DLs.

Falling under the classical logics paradigm, reasoning in DLs adopts the open-world assumption. Intuitively, if a fact α holds only in a subset of the models of the knowledge base KB, then we can conclude neither $KB \models \alpha$ nor $KB \models \neg\alpha$. For example, if the only available knowledge regarding the residents of a house is the assertion `livesIn(Alice,house)`, we cannot deduce based on it alone that no one else lives in the house. In contrast, formalisms adhering to the closed-world assumption make the common-sense conjecture that all relevant information is explicitly known, so all unprovable facts should be assumed not to hold. In our example, this amounts to concluding that Alice is the sole resident of this house. Hence, closed-world reasoning can be intuitively understood as reasoning where from $KB \nvDash \alpha$, one concludes $KB \vDash \neg\alpha$. Such kind reasoning should not be confused however with closed domain reasoning, which involves reasoning only over explicitly known individuals.

3.1.3 OWL and OWL 2

The Web Ontology language (OWL) [11] is a knowledge representation language widely used within the Semantic Web community for creating ontologies. The design of OWL and particularly the formalisation of the semantics and the choice of language constructors have been strongly influenced by DLs. OWL comes in three dialects of increasing expressive power: OWL Lite, OWL DL and OWL Full. OWF Full is the most expressive of the three: it neither imposes any constraints on the use of OWL constructs, nor lifts the distinction between instances (individuals), properties (roles) and classes (concepts). This high degree of expressiveness comes however at a price, namely the loss of decidability that makes the language difficult to implement. As a result, focus has been placed on the two decidable dialects, and particularly on OWL DL, which is the most expressive of the two.

Despite the rich primitives provided for expressing concepts, OWL DL has often proven insufficient to address the needs of practical applications. This limitation amounts to the DLs style model theory used to formalise its semantics, and particularly the *tree model property* [12] conditioning DLs decidability. As a consequence, OWL can model only domains where objects are connected in a tree-like manner. This constraint is quite restrictive for many real-world applications, including the ambient intelligence domain, which requires modelling general relational structures.

Responding to this limitation and to other drawbacks that have been identified concerning the use of OWL in different application contexts throughout the years, the W3C working group produced OWL 2 [13]. OWL 2 is a revised extension of OWL, now commonly referred to as OWL 1. It extends OWL 1 with qualified cardinality restrictions; hence one can assert for example that a social activity is an activity that has more than one actor: $\texttt{SocialActivity} \sqsubseteq \texttt{Activity} \sqcap \geq 2\texttt{hasParticipant.Person}$.

Another prominent OWL 2 feature is the extended relational expressivity that is provided through the introduction of complex property inclusion axioms (property chains). To maintain decidability, a regularity restriction is imposed on such axioms that disallow the definition of properties in a cyclic way. Hence, one can assert the inclusion axiom $\texttt{locatedIn} \circ \texttt{containedIn} \sqsubseteq \texttt{locatedIn}$ making it possible to infer that if a person is located for example in the bedroom of her house, then she is located in her house as well; however, it is not allowed to use both the aforementioned axiom and the axiom $\texttt{containedIn} \circ \texttt{locatedIn} \sqsubseteq \texttt{containedIn}$ as this leads to a cyclic dependency. Three profiles, namely OWL 2 EL, OWL 2 QL and OWL 2 RL, trade portions of expressive power for efficiency of reasoning targeting different application scenarios.

3.1.4 Rules

To achieve decidability, DLs, and hence OWL, trade some expressiveness for efficiency of reasoning. The tree-model property is one such example. It conditions the tree-shape structure of models, ensuring decidability, but at the same time it severely restricts the way variables and quantifiers can be used, dictating that a quantified variable must occur in a property predicate along with the free variable. As a result, it is not possible to describe classes whose instances are related to an anonymous individual through different property paths. To leverage OWL's limited relational expressivity and to overcome modelling shortcomings that OWL alone would be insufficient to address, a significant body of research has been devoted to the integration of OWL with rules.

A proposal towards this direction is the Semantic Web Rule Language (SWRL) [14], in which rules are interpreted under the classical first order logic semantics. Allowing concept and role predicates to occur in the head and the body of a rule without any restrictions, SWRL maximises the interaction between the OWL and rule components, but at the same time renders the combination undecidable. To regain decidability, several proposals have explored syntactic restrictions on rules [15][16] as well as their expressive intersection of Description Logic Programs (DLP) [17]. The DL-safe rules introduced for example in [16] impose that rule semantics apply only over known individuals. It is worth noting that in practice DL reasoners providing support for SWRL actually implement a subset of SWRL based on this notion of DL-safety.

Parallel to these efforts, a highly challenging and active research area in the Semantic Web addresses the seamless integration of open and closed world semantics. Representative initiatives in this quest include among others the hybrid formalism of MKNF knowledge bases proposed by Motik and Rosati [18], the extension of ontologies through the use of integrity constraints proposed by Tao et al. [19] and the so called grounded circumscription approach [20].

Taking a different perspective, a number of approaches have investigated the combination of ontologies and rules based on mappings of a subset of the ontology semantics on rule engines. For instance, Horst [21] defines the *pD** semantics as a weakened variant of OWL Full, e.g., classes can be also instances, and they are extended to apply to a larger subset of the OWL vocabulary, using 23 entailments and 2 inconsistency rules. Inspired by the *pD** entailments and DLP, the semantics of the OWL 2 RL profile is realised as a partial axiomatisation of the OWL 2 semantics in the form of first-order implications, known as OWL 2 RL/RDF rules. User-defined rules on top of the ontology allow expressing richer semantic relations that lie beyond OWL's expressive capabilities, and couple ontological and rule knowledge.

3.2 Ontologies relevant to the Dem@Care domain

A common prerequisite in context-aware, sensor-driven systems, such as Dem@Care, is the ability to share and process information coming from heterogeneous devices and services. This translates into a twofold requirement. First, there is a need for commonly agreed vocabularies of consensual and precisely defined terms for the description of data in an unambiguous manner. Second there is a need for mechanisms to integrate, correlate and semantically interpret these data.

The inherent ability of ontologies to formally represent knowledge with machine-understandable and explicitly defined semantics has proved particularly appealing in such systems. A number of ontologies have been proposed for modelling context at different levels of granularity and abstraction and for supporting the derivation of higher-level interpretations. *Context* refers to any information that can be used to characterize the situation of a person or a computing entity [46]; for example, the location of a person and the room temperature are aspects of context.

The rest of this section briefly reviews representative ontologies that have been proposed for modelling core aspects in context-aware environments, such as sensors and sensed data, activities, events, etc. More specifically, section 3.2.1 presents the Semantic Sensor Network ontology (SSN), a proposal towards a domain-independent and end-to-end model for describing sensors and sensor networks. Section 3.2.2 reviews SOUPA and Ontonym, two domain-independent conceptual models that address core notions, such as events, people, time, etc. Section 3.2.3 presents two domain-independent event-centric ontologies, namely the Event-Model-F and the Simple Event Model. Finally, Section 3.2.4 presents two domain-dependent ontologies that target at the recognition of complex activities in context-aware environments.

3.2.1 Sensor data ontologies

In order to enable applications and services to seamlessly interoperate with sensor networks, i.e. to be able to integrate, consume and understand the sensed data, there is a need to provide semantic descriptions of sensor data based on domain independent models. The need towards standardised methods for the formal and machine-processable representation of sensor capabilities, observations and measurements beyond the syntactic interoperability provided by existing sensor standards such as SensorML [24] and O&M [25][26], has been widely acknowledge within the Semantic Web community and has resulted in the proposal of various sensor-related ontology models, such as [27][28][29][30].

In 2009, the W3C Semantic Sensor Network Incubator Group (SSN-XG)[2] was formed for the development of an OWL ontology for sensors and to further investigate annotation and links to existing standards. Based on an extensive review of sensor and observation related ontologies, the group defined the Semantic Sensor Ontology (SSN) [31], which constitutes the most recent and formal effort to define ontologies for semantically describing sensors. In the following, we briefly review the conceptual model of the proposed SSN ontology.

The Semantic Sensor Network Ontology

The Semantic Sensor Network ontology (SSN) targets at the formal and machine-processable representation of sensor capabilities, properties, observations and measurement processes. Central to the ontology is the Stimulus-Sensor-Observation (SSO) ontology design pattern [30] that provides a lightweight model for representing sensors, their inputs (called *stimuli*) and observations. Sensors are not constrained to physical sensing devices: rather a sensor is anything that can estimate or calculate the value of a phenomenon, so a device or computational process or combination could play the role of a sensor. SSO is reusable for a variety of application areas and it can be used in conjunction with other relevant ontologies. Both SSN and SSO have been aligned with the DOLCE + DnS Ultralite (DUL[3]) ontology so

[2] http://www.w3.org/2005/Incubator/ssn/

[3] http://www.loa.istc.cnr.it/ontologies/DUL.owl

as to enable the integration into more complex ontologies as a common ground for alignment, matching, translation, or interoperability.

SSN defines a number of conceptual modules that allow the representation of various key aspects in sensor networks, such as sensor capabilities, observation data, processes of sensing, sensor deployments, systems of sensors, various environmental conditions, etc. Among the provided modules, the *skeleton module* offers a lightweight, minimalistic, and flexible core ontology with a minimum ontological commitment, following the SSO design pattern. Figure 1 depicts the implementation of the SSO design pattern in the SSN core ontology, together with the alignment with the DUL upper ontology.

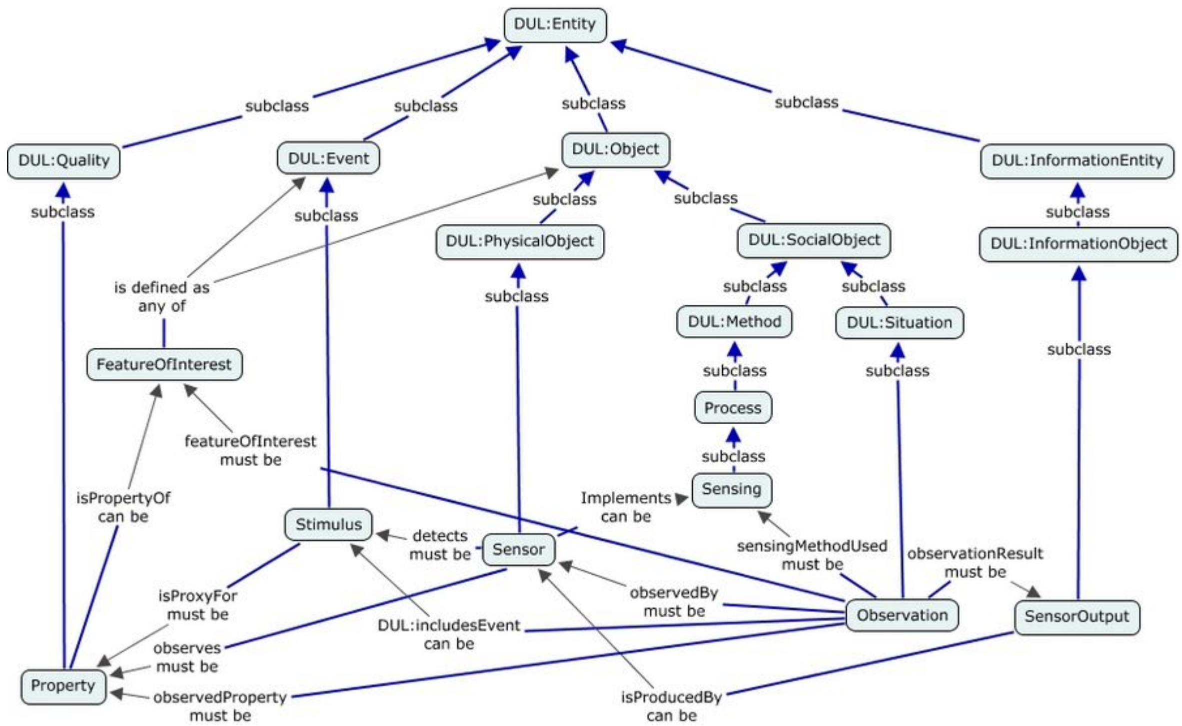

Figure 1 Alignment of SSN with the DOLCE Ultra Lite ontology[4]

The SSN skeleton ontology allows the representation of:

- **Stimuli:** They are events in the real world (i.e. changes in the environment) that trigger one or more sensors. A stimulus serves as a proxy for the actual observed property, e.g. an increase or decrease of room temperature is a stimulus that serves as a proxy for room temperature.
- **Sensors:** A sensor is any entity that implements a sensing method and thus observes some property of real world entities (things, persons, events, etc). Sensors may be physical devices, computational methods, a laboratory setup with a person following a method, or any other thing that can follow a sensing method to observe a property,

[4] http://www.w3.org/2005/Incubator/ssn/wiki/Report_Work_on_the_SSN_ontology

therefore they are not restricted to technical devices but also include humans as observers.

- **Observations:** They can be considered as the connection among stimuli, sensors and their outputs. In SSN, observations are rather contexts for the interpretation of the incoming stimuli than physical events, in contrast to O&M where observations are interpreted as events.
- **Observed properties:** They are qualities that can be observed via stimuli by a certain type of sensors, e.g. temperature.
- **Feature of interest:** A feature is an abstraction of real world phenomena that are the target of sensing, e.g. a person.
- **Procedure:** Procedure is a description of how a sensor works, e.g. a description of the scientific method behind the sensor. Sensors can be thought of as implementations of sensing methods to derive information about the same type of observed property.
- **Sensor Output:** The sensor outputs (result) represent a piece of information (a value) as outcome of an observation. The outputs can act as stimuli for other sensors.

The Smart Product[5] use case illustrates the basic modelling capabilities of SSN. The example demonstrates the semantic description of an accelerometer sensor (WiTilt 3.0[6]) attached to a knife, so as to recognise when the user is cutting something. In the following we present excerpts of the ontology relevant to the core modelling capabilities of SSN following the Turtle syntax[7] for RDF Graphs[8].

The different types of sensors are modelled in SSN as subclasses of the `ssn:SensingDevice` core class. In the example, the `WiTilt30Accelerometer` class (i.e. the class of all the WiTilt30 sensors) is defined as subclass of the `Accelerometer` class (i.e. the class of all the sensors that observe the `acceleration` property), which is the direct subclass of the `ssn:SensingDevice` class. The accelerometer sensor is defined as an instance of the `WiTilt30Accelerometer` class and it is attached (`ssn:onPlatform`) to a particular knife instance, which is both a platform and a feature of interest. Each sensor can be annotated with several measurement capabilities, such as frequency or range, through the `ssn:hasMeasurementProperty` property.

```
sk:ExampleWiTilt30Accelerometer a sk:WiTilt30Accelerometer ;
  ssn:hasMeasurementCapability sk:ExampleMeasurementCapability ;
  ssn:onPlatform sk:Knife_123 .

sk:Knife_123 a ssn:Platform , ssn:FeatureOfInterest ;

sk:WiTilt30Accelerometer a owl:Class ;
  rdfs:subClassOf sk:Accelerometer ;
  rdfs:subClassOf
    [ a owl:Restriction ;
```

[5] http://www.w3.org/2005/Incubator/ssn/wiki/Incubator_Report#Smart_product_example

[6] http://www.sparkfun.com/datasheets/Accelerometers/WiTilt-v3.pdf

[7] http://www.w3.org/TeamSubmission/turtle/

[8] The ontology is available at http://www.w3.org/2005/Incubator/ssn/ssnx/product/smart-knife

```
        owl:allValuesFrom sk:WiTilt30MeasurementCapability ;
        owl:onProperty ssn:hasMeasurementCapability
     ] .

sk:Accelerometer a owl:Class ;
  rdfs:subClassOf ssn:SensingDevice ;
  rdfs:subClassOf
    [ a owl:Restriction ;
      owl:hasValue ucum-quality:acceleration ;
      owl:onProperty ssn:observes
    ] .
```

Each sensor can produce an observation that is described as an instance of the `ssn:Observation` class. The observation class defines a number of core properties for the representation of key observation aspects, such as the entity who is observed (`ssn:featureOfInterest`), the sensor that produces the observation (`ssn:observedBy`), the observed property (`ssn:observedProperty`), the result of the observation (`ssn:observationResult`) and the time of the observation (`ssn:observationSamplingTime`). In order to describe acceleration-related observations, the `AccelerationObservation` class is defined as a subclass of the `ssn:Observation` class, restricting various SSN core properties, such as the observed property, the feature of interest and the observation result range values. The following example captures an observation about the measure value (0.98) of a knife's acceleration.

```
sk:KnifeCuttingObservation_1 a sk:AccelerationObservation ;
  ssn:featureOfInterest sk:Knife_123 ;
  ssn:observationResult sk:KnifeSensorOutput_1 ;
  ssn:observedBy sk:ExampleWiTilt30Accelerometer ;

sk:AccelerationObservation a owl:Class ;
  rdfs:subClassOf ssn:Observation ;
  rdfs:subClassOf
    [ a owl:Restriction ;
        owl:hasValue ucum-quality:acceleration ;
        owl:onProperty ssn:observedProperty
    ] ;
  rdfs:subClassOf
    [ a owl:Restriction ;
        owl:allValuesFrom sk:AccelerationSensorOutput ;
        owl:onProperty ssn:observationResult
    ] ;
  rdfs:subClassOf
    [ a owl:Restriction ;
        owl:allValuesFrom sk:Accelerometer ;
        owl:onProperty ssn:observedBy
    ] .


sk:KnifeSensorOutput_1 a sk:AccelerationSensorOutput ;
  ssn:hasValue sk:ZAxisAccelerationMeasurementValue ;
  ssn:isProducedBy sk:ExampleWiTilt30Accelerometer .


sk:ZaxisAccelerationMeasurementValue a sk:AccelerationValue ;
```

```
  sk:hasQuantityValue "0.98"^^xsd:float .
```

3.2.2 Context ontologies

This section reviews two representative domain-independent ontologies for modelling key contextual aspects, such as events/activities, devices, location, time, etc. Such ontologies provide common conceptual models to facilitate interoperability between contextual data from heterogeneous systems. Abstract notions (e.g. Activity) defined in these ontologies can be further specialised through domain-dependent ontology definitions (e.g. Eating).

The SOUPA Ontology

SOUPA [32] consists of a set of OWL ontologies that can be used to represent different types of contextual information, environmental attributes (e.g., noise level, temperature), time, space, events, people, devices, objects and software agents (Figure 2). Part of the SOUPA vocabulary is mapped on external vocabularies, such as FOAF[9] and OWL-Time[10], through class and property equivalence axioms, without directly importing them as an attempt to avoid any extra reasoning overhead.

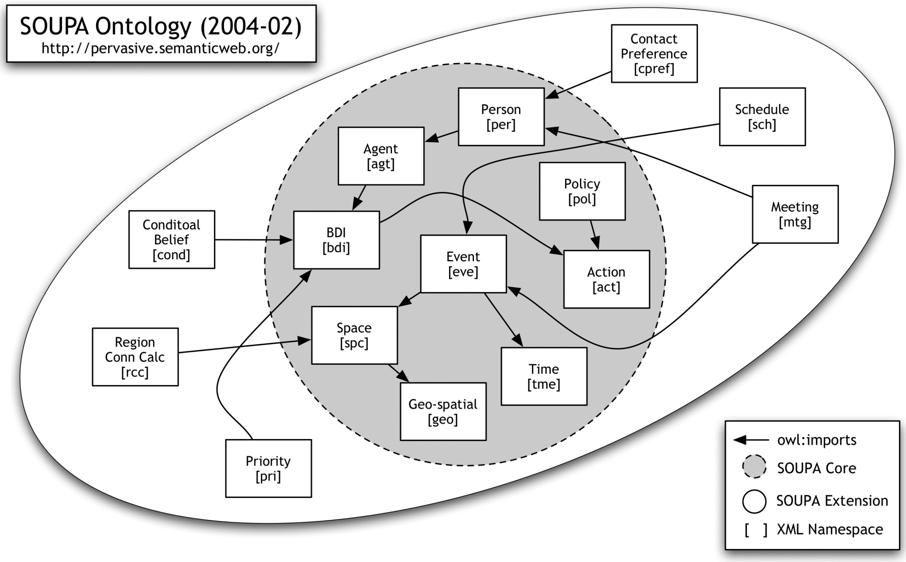

Figure 2 The set of SOUPA ontologies (source: [32])

Any entity of the domain that has temporal extensions is represented in SOUPA as instance of the `soupa:TemporalThing` class that provides a number of interval- and instant-based temporal property relations, such as *after*, *before*, *begin*, etc., in accordance to the OWL-Time ontology vocabulary. Location can be represented both in terms of a symbolic representation of space and typical geo-spatial vocabularies. In the first case, the `soupa:Geo-graphicalSpace` class represents all the spatial things that are typically found in maps or construction blueprints. There are also object properties that relate spatial entities to each other, such as the `soupa:spatiallySubsumes` property. In the geo-spatial representation

9 http://www.foaf-project.org/

10 http://www.w3.org/TR/owl-time/

model, the individuals belong directly to the `soupa:SpatialThing` class (superclass of `soupa:GeographicalSpace`) and they are described by location coordinates. The representation of time-evolving spatial information can be represented by classifying the corresponding location instance to a temporal class, e.g. `soupa:TemporalThing`.

All kinds of events in a domain, such as activities, sensing events, schedules, etc., are represented in SOUPA as instances of the `soupa:Event` class and can have both spatial and temporal extensions. In order to define temporal information about events, SOUPA defines the `soupa:Event` class equivalent to the `soupa:TemporalEvent` class, which is the domain of various temporal properties. To specifically describe events that have both temporal and spatial extensions, the `soupa:SpatialTemporalEvent` class is defined as the intersection of the `soupa:SpatialTemporalThing` and `soupa:Event` classes. In that way, spatiotemporal information can be defined through appropriate classification of the event instances to the corresponding classes.

The `soupa:Event` class is quite abstract and it does not provide core constructs for defining various event-centric relationships, such as participants or relationships among events. Such relationships can be only defined by reusing relevant event ontologies (see section 3.2.3) or by extending core classes, e.g. the `soupa:Event` class, and defining property restrictions about participants. It should be mentioned, however, that both computational entities and humans in SOUPA are considered as agents that are characterized by a set of mentalistic notions such as knowledge, belief, intention, and obligation. Under this context, the `soupa:Action` core class of SOUPA can be used (or extended) in order to define actions that are associated with agents through the `soupa:actor` property.

Ontonym

A more recent approach towards the representation of contextual knowledge is Ontonym [33]. Similarly to SOUPA, Ontonym provides a set of upper-level ontologies that can be used to describe people, sensors and events (or activities) in a domain, as well as, temporal and spatial constraints (Figure 3).

Temporal information in Ontonym is represented using the OWL-Time ontology, without defining new temporal-specific predicates. Ontonym's location ontology is an implementation of Ye's model [34]. It supports the representation of both symbolic and physical locations. Symbolic locations refer to locations using names designed for human interpretation, e.g. *kitchen*, whereas physical locations take the form of a 2D or 3D numeric array, e.g. GPS coordinates. Additionally, a location may be represented as a combination of the above types. There is also a number of properties defined for the representation of spatial relationships, such as *containment* and *overlap*. Time-evolving location information cannot be expressed directly in the model, but it can be represented using Named Graphs [35] with temporal metadata[11].

The event ontology of Ontonym provides a means of describing activities of interest, such as *a door opening*, or more complex notions with participants. An event in Ontonym is an activity or phenomenon with a temporal dimension and the `ont:Event` class is defined as the union of the `ont:InstantEvent` and `ont:IntervalEvent` classes. The temporal

[11] http://ontonym.org/time/

constraints can be defined either using directly the predicates of the OWL-Time ontology, or using Named Graphs. Particularly in the first case, similarly to SOUPA, an event instance is classified to the corresponding class, according to whether it has an instance or interval temporal dimension. Additionally, the `ont:SpatioInstantEvent` and `ont:SpatioIntervalEvent` classes represent events with associated locations and they are defined as subclasses of the `ont:InstantEvent` and `ont:IntervalEvent` classes, respectively.

The event participation relationships are expressed using roles. The `ont:Role` class and `ont:containsRole` property are used to define the roles that are played by entities within an event/activity. The `ont:playsRole` property allows an entity (person, device, etc.) to be associated with an instance of an event/activity.

Ontonym supports the representation of information relevant to sensors and the observations they make. The `ont:Sensor` class represents the set of the all the sensing devices in the domain, providing properties for describing sensor attributes and capabilities, such as location (`ont:locatedAt`), frequency (`ont:frequency`), coverage (`ont:coverage`), accuracy (`ont:precisionAccuracy`) and others. Observations are instances that describe the sensed data and they are defined in terms of the time the readings are supplied (`ont:observedAt`), the sensors that produce the data (`ont:obervedBy`) and information relevant to the observation entities, for example, the position where an entity was observed.

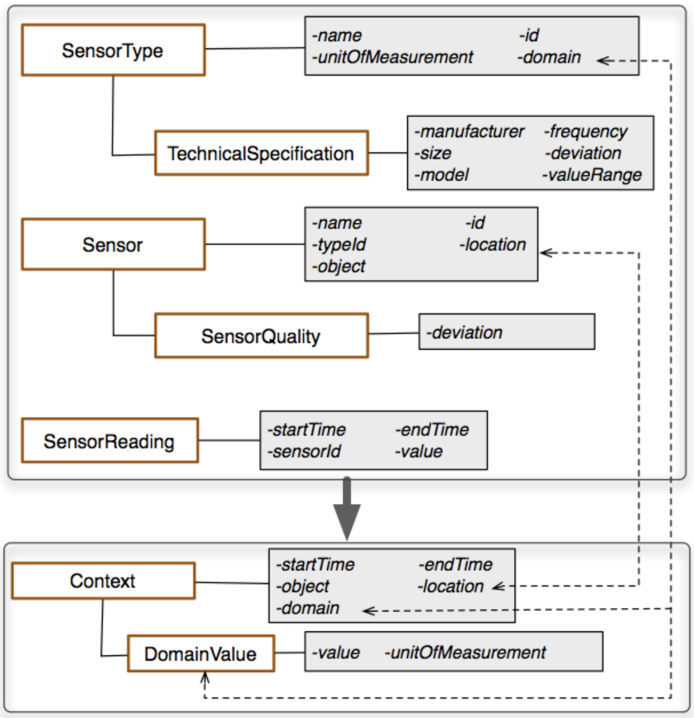

Figure 3 The basic conceptual model of Ontonym[12]

[12] http://ontonym.org/

3.2.3 Event ontologies

In addition to ontologies for modelling context in general, a number of domain-independent ontologies focusing solely on the representation of event related information have been proposed. These ontologies provide common conceptual models to facilitate interoperability between event-related data from heterogeneous systems. This section reviews two representative examples, namely the Event-Model-F and SEM ontologies.

Event-Model-F

Event-Model-F [36] defines an expressive model for capturing and representing occurrences in the real world. It is based on DUL, following the descriptions and situations ontology design pattern (DnS) [37] for modelling aspects of events, such as object participation, mereological, causal, and correlative relationships, and different interpretations of the same event (by reifying events in order to describe n-ary relations). The Event-Model-F ontology introduces six ontology design patterns that are described briefly in the rest of this section.

Participation Pattern. This pattern is used to model the participation of objects (`Object`) in events (`Event`). The participation is expressed by an instance of the `EventParticipation-Situation` class that satisfies an instance of the `EventParticipationDescription` class. The situation includes the event and the participating objects, while the description classifies the event (`EventType`) and the participants (`Role`).

Mereology Pattern. Compositions of events are expressed using the mereology pattern. The composite event and the component events are classified by the `Composite` and `Component` classes, respectively, and they are all referenced by a situation instance (`EventCompo-sitionSituation`). The situation instance satisfies a description instance (`Composition-Description`) that classifies the composite and component events. Furthermore, events may be temporally related to each other and such relations can be expressed using the DOLCE vocabulary.

Causality Pattern. In Event-Model-F, causes and effects are events and the causality pattern is used to express relationships between events that play the roles of causes and effects. The `Cause` and `Effect` classes are used to classify events as causes and effects, respectively, and the `Justification` class is used to classify a `Description` instance under the justification of some theory.

Correlation Pattern. Two or more events are correlated if they have a common cause and there is no cause-effect relationship among them (causality). The correlation pattern defines the role `Correlate` that classifies correlated events. Similarly to the causality pattern, the Justification role classifies a `Description` instance that explains the correlation.

Documentation Pattern. This pattern is used to provide documentary evidences for events. The documented event is classified by the class `DocumentedEvent` and the documentary evidence is classified by the class `Documenter`. The evidence may be a specialisation of the `Object` class or another event.

Interpretation Pattern. The perception of events heavily depends on the context and the viewpoint of the observer and the explicit modelling of such contextual views is crucial. In Event-Model-F, such different viewpoints can be expressed by instantiating accordingly the aforementioned designed patterns and binding them with the interpretation pattern. The pattern defines the `Interpretant` class that classifies the event under interpretation. Each interpretation further classifies the relevant situations, that is, the participation, mereology, causality, correlation, and documentation pattern instantiations.

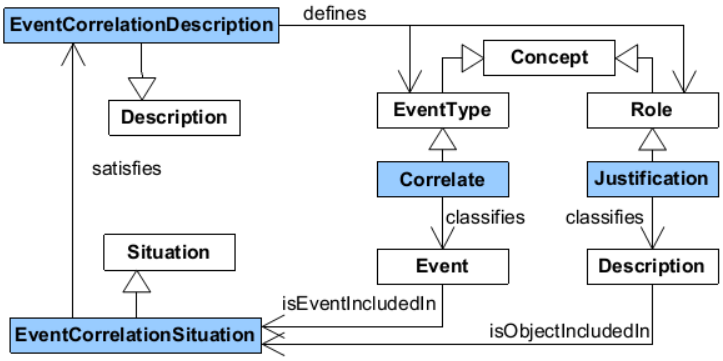

Figure 4 The correlation pattern in Event-Model-F (source: [36])

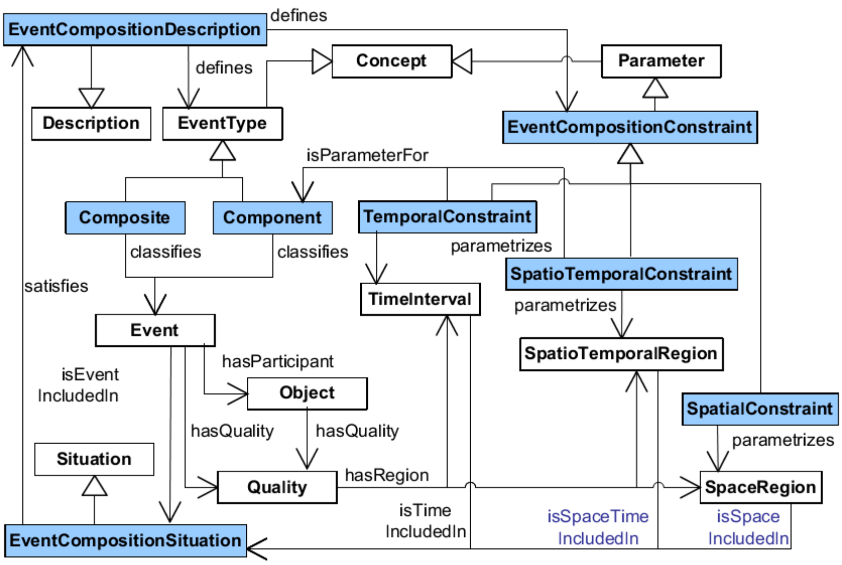

Figure 5 The Mereology pattern in Event-Model-F (source: [36])

The Simple Event Model (SEM)

The Simple Event Model (SEM) [38] is an effort to define an ontology model for events without strong semantic constraints. This decision is justified by the open nature of the Web and the need to model different (even conflicting) views of the same event. The lack, however, of strong semantic constraints, such as functional properties, disjoint classes and cardinality restrictions, hampers the ability to automatically validate and resolve model inconsistencies using formal inference mechanisms. Therefore, SEM is characterised by a tradeoff between model reusability and automated reasoning and validation capabilities. Figure 6 presents the relationships among the classes of the SEM ontology; arrows with open arrow heads symbolise `rdfs:subClassOf` properties and regular arrows visualise `rdfs:domain` and `rdfs:range` restrictions.

SEM defines four core classes: `Event` (for modelling events), `semActor` (who or what participated in an event), `Place` and `Time` (capturing where and when the event takes place). Each core class is associated with the `Type` class that is used to aggregate implementations of type systems from other ontologies, such as the Getty Thesaurus of Geographic Names. Therefore, the instance types in SEM can be either instances or classes from foreign vocabularies, targeting at the reusability of existing type vocabularies, regardless of how the types are implemented.

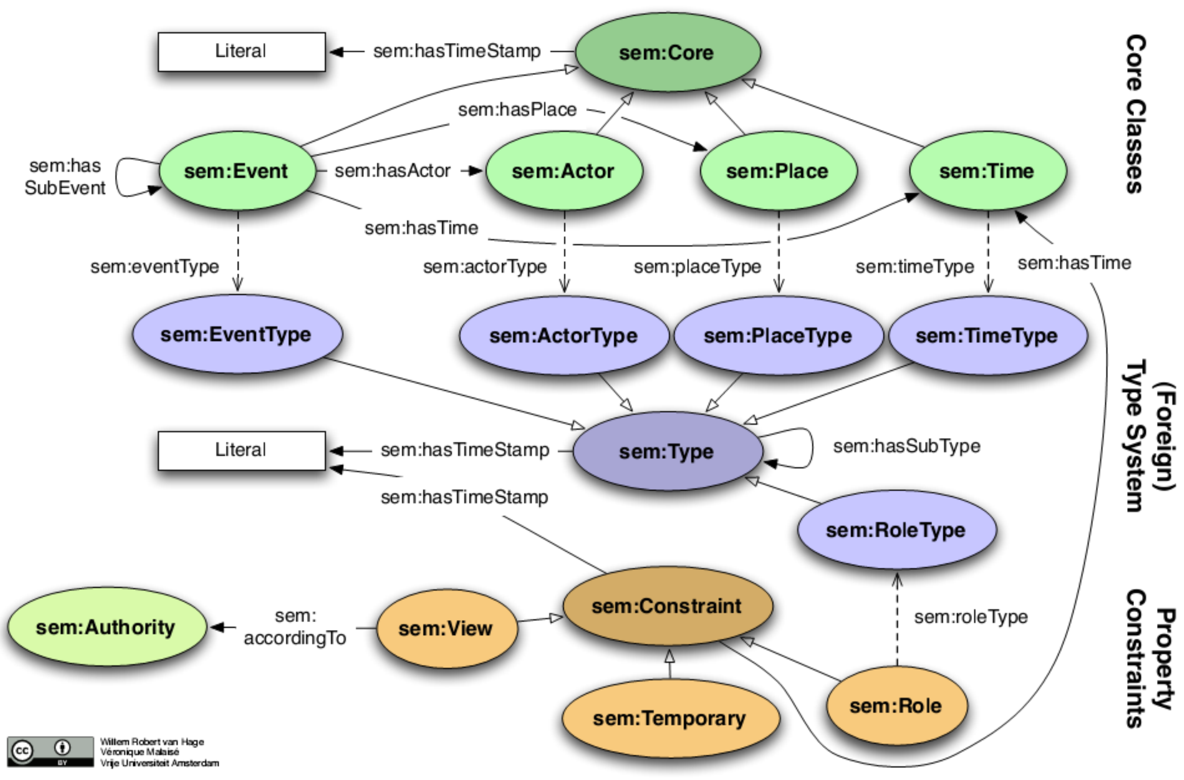

Figure 6 The classes of the Simple Event Model ontology [38]

There are two main property types in SEM: `EventProperty` and `type`. The former is used to correlate instances of the `Event` class with other instances of arbitrary classes and the latter correlates instances of the `Core` class with instances of the `Type` class. There are also two aggregation relations. The `hasSubEvent` can be used to define specialisation of events. Similarly, the `hasSubType` relates instances of the `Type` class. Finally, there are seven time-related properties: `hasTimeStamp` (for single time values), `hasBeginTimeStamp` and `hasEndTimeStamp` (for time intervals), `hasEarliestBeginTimeStamp`, `hasLatestBeginTimeStamp`, `hasEarliestEndTimeStamp` and `hasLatestEndTimeStamp` (for uncertain time intervals).

Property constraints in SEM can be defined either as a reification of the property or by turning the property into n-ary relation. The classes `Role`, `Temporary` and `View` are three types of SEM constraints for defining the role of a class instance (e.g., `Actor`) in an event, the temporal boundary within which a property holds and the different points of view, respectively. More expressive relationships among events, such as causality addressed in Event-Model-F, or active/passive actor participation semantics cannot be modelled in SEM.

SEM defines also mappings of the model on other ontologies, e.g., LODE [39], based on the SKOS vocabulary. Furthermore, the developers provide a Prolog API for SEM in order to ease the procedure of populating the ontology with instances.

3.2.4 Activity recognition ontologies

In addition to the upper-level ontologies described previously, a number of domain-specific ontologies relevant to the Dem@Care ontology requirements have been also identified [40][41][42][43][44][45]. In the following we present two of the most recent ones.

The Pal-SPOT project ontology

An OWL 2 ontology for modelling activities in smart home and smart workplace scenarios is presented in [42]. The ontology is used not only to represent activities but also relevant knowledge that can drive their recognition, including locations, objects, sensors and so forth, based on subsumption reasoning. For example, the `Sleeping` activity is defined as (in Manchester syntax[13]):

```
PersonalActivity
 and (hasActor only (hasCurrentSymbolicLocation some
     (BedRoom
      and (contains some
          (LightSensor
           and (measuresValue some integer[< 40])))
      and (contains some
          (SoundSensor
           and (measuresValue some integer[< 30]))))))
```

The main classes and properties of the ontology are graphically depicted in Figure 7. Activities are represented as subclasses of the `Activity` core class. Each activity can be associated with an actor (`Person` class), a location (`SymbolicLocation` class), a temporal characterisation (`TimeExtend` class) and an action (`Action` class). Each location can be associated with relevant contained artifacts (`Artifact` class), e.g. sensors, furniture, etc., and can be defined either as an indoor (building, room, etc.) or an outdoor location (garden, urban area, etc), based on the provided subclass hierarchy of the `SymbolicLocation` class. The `TimeExtend` class serves as the upper-level class for defining various qualitative temporal extensions, such as the time of the day an activity has been performed (morning, afternoon, etc.). The ontology does not provide constructs for the direct representation of quantitative temporal information, such as the exact time of an activity, time intervals or temporal relationships among the activities, since the underlying reasoning process for activity recognition is not based on temporal semantics (an effort to partially support the temporal characterisation of activities is presented in [43]). Finally, activities can be associated with actions (`Action` class) and postures (`Posture` class), allowing the representation of more complex situations.

---

[13] http://www.w3.org/TR/owl2-manchester-syntax/

A worth noting feature of the proposed framework is that by exploiting OWL 2's support for composition of properties and for qualified cardinality restrictions, the captured knowledge is considerably more expressive compared to that afforded by earlier frameworks that use OWL 1 DL. Despite the restrictions imposed on the use of the property composition constructor that conditions decidability, the authors argue that the use of OWL 2 DL is a satisfying compromise for effectively reasoning, while avoiding the technical and semantic complexities confronted when combining ontologies and rules.

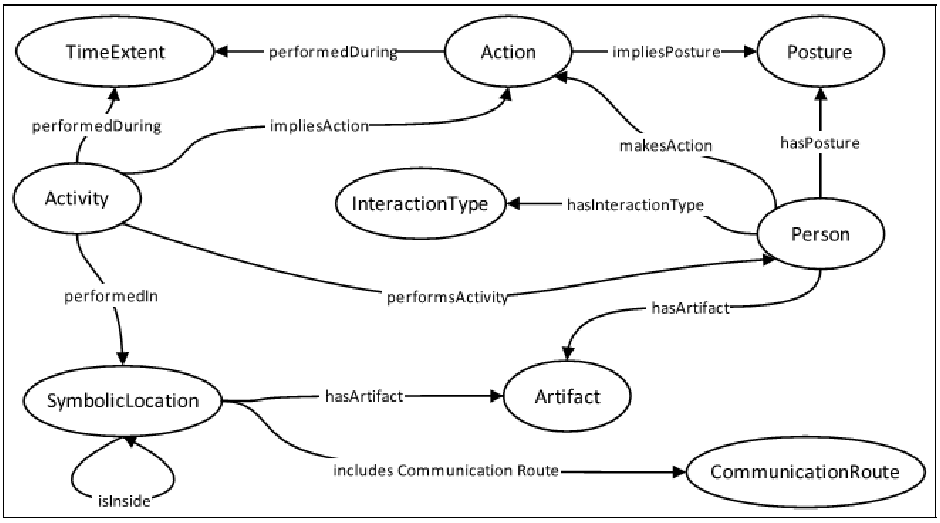

Figure 7 The conceptual activity model presented in [40]

The Semantic Smart Home ontology

In accordance with the approach followed in [40], modelling activities of daily living (ADLs) in the Semantic Smart Home Framework (SSH) in [44][45] through property restrictions in relation to equipment, location and other types of constraints, allows the inference of ADLs on the basis of the assertional knowledge made available through sensors. The developed ontologies capture knowledge related to physical equipment (such as sensors and electrical appliances), actions and activities of daily living (such as watching television and preparing a meal), location spaces (such as kitchen and living room), people and their roles, medical information, software components as well as temporal information.

In SSH, sensors are represented based on the generic conceptual model in Figure 8. Sensors are linked to a number of physical and conceptual entities such as objects, locations, and states. For example, a contact sensor is attached to a teapot in the second cupboard to the left of the sink in the kitchen. By explicitly capturing and encoding such domain knowledge in a sensor model, it is possible to infer the corresponding objects and location from the activation of the sensor.

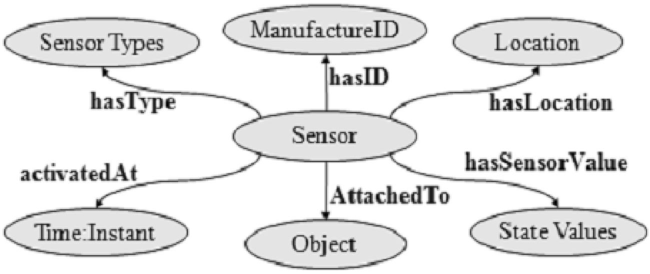

Figure 8 The conceptual sensor model proposed in [44]

Activities are described based on the conceptual model in Figure 9. An activity can be associated with other entities and concepts using a number of properties that can be categorized into three groups. The first group relates an activity with contextual information, such as time, location and actors. The second group contains properties that are used during inference of high-level activities, such as causal and functional relations. Finally, the properties of the third group allow the representation of relationships among different activities, such as mereological relationships.

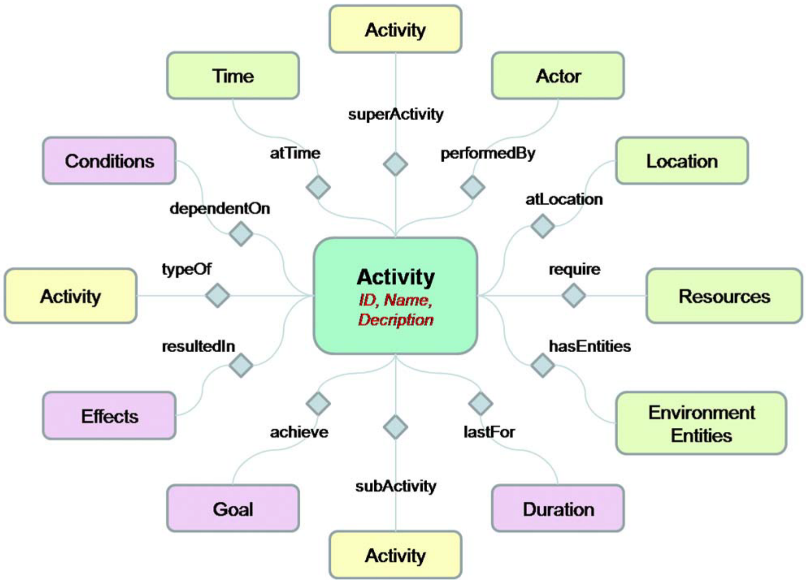

Figure 9 The conceptual activity model proposed in [44]

3.2.5 Summary

As summarised in Table 4, the ontologies reviewed in Sections 3.2.1 to 3.2.4 address scopes that partially align with that of the Dem@Care ontology requirements. However, in this phase of the Dem@Care ontology building, where the requirements undergo constant refinements, we preferred to use these ontologies as modelling guidelines rather than to directly reuse their relevant parts. This choice has been backed up by several other factors. First, though SSN has begun to achieve broad adoption and application within the sensors community as well as used various organizations from academia, government, and industry, we currently opted for a more concise modelling that can be aligned with it in the future, if required. Similar considerations apply for the event-centric ontologies. Second, unlike SSN, there is currently no context ontology that has achieved broad adoption. Finally, the domain-specific activity ontologies are inevitably focused on the particular application domains and as a result present significant deviations from the intended scope of the Dem@Care ontology.

Table 4 Summary of reviewed ontologies

Ontology	Abstraction level	Scope
SSN	upper-level	Sensor modelling
SOUPA	upper-level	Context modelling
Ontonym	upper-level	Context modelling
Event-Model-F	upper-level	Event modelling
SEM	upper-level	Event modelling
Pal-SPOT	domain-specific	Activity recognition
Smart Home	domain-specific	Activity recognition

4 The Dem@Care Ontology

In this Section, we present the current content of the Dem@Care ontology (version 1.1 – 02 November 2012). The modelling of classes, properties and individuals has been guided by the competency questions of the Dem@Care ORSD (Section 2.2) and by further input and feedback made available during the time of the ontology building by the clinical and technical partners involved in the relevant WPs. Furthermore, whenever possible, the guidelines provided by standards and best practices available have been followed. For example, for the formalisation of temporal notions, the OWL Time[14] ontology has been used.

The formalisation has been performed keeping also in mind the need to have an ontology that will support the planned reasoning tasks, namely the derivation of customised behaviour interpretation services addressed in Tasks 5.2 and Task 5.3. Since many of the exact reasoning-incurring dependencies could not be specified during this phase of ontology building, we opted for a concise modelling that covers the foundational notions identified through the competency questions, while in parallel enforcing modularity and separation of concerns so that extensibility and future ontology updates are facilitated.

To this end, the ontologies reviewed in Section 3.2 served us as valuable references for distilling the advantages and disadvantages of alternative modelling solutions and the tradeoffs and restrictions pertinent to differing scopes, before making our modelling choices. For example, for the modelling and formalisation of descriptive information, our choices have been largely shaped by the SSN ontology. Similarly, the modelling of events has been based on the study of relevant modelling paradigms adopted in the ontologies described in Sections 3.2.2 and 3.2.3, and the need for reconciliation with the Dem@Care-specific traits. The activity-specific ontologies though providing useful insights for reasoning tasks could not be directly reused as their scope and granularity differs significantly from that of Dem@Care.

The implementation of the ontology has been carried out using Protégé[15] (version 4.2 beta; build 278). This allowed us to work with modular ontologies, while benefiting from the integrated reasoning support to validate the ontology from the formal point of view using two state-of-the-art OWL reasoners, namely HermiT and Pellet. For visualisation purposes we used the Concept Map Ontology Editor[16], since compared to Protégé, it allows a more intuitive representation of the properties associated with a class.

In the following, we present the main classes of the Dem@Care ontology, we discuss the need for constant checking and validation of the ontology against the requirements the ontology is expected to meet, and conclude with some ontology metrics.

4.1 Dem@Care ontology - version 1.1

The current version of Dem@Care ontology (version 1.1 – 02 November 2012) includes four ontology modules, namely:

- the lab ontology, which formalises the information relevant to the lab environment,

[14] http://www.w3.org/TR/owl-time/

[15] http://*protege.stanford.edu/*

[16] http://www.ihmc.us/groups/coe/

- the home/nursing home ontology, which formalises information relevant to the home and nursing home environments,
- the event ontology, which formalises information relevant to the entities and events considered within the Dem@Care system, and
- the descriptive information ontology, which formalises provenance relevant information

4.1.1 The Lab ontology

The lab ontology formalizes the types of information relevant to the ecological assessment addressed in the lab environment.

The main classes of the lab ontology are:

Class `Protocol`
This class is used to encapsulate information about the protocol followed for experimental assessment in the lab environment. Individuals belonging to this class are instantiated along with the following object property assertions:

- `hasProtocolParticipant`: it indicates the person participating in the protocol; its value is an individual of the `lab:Participant` class which specialises the `event:Person` class. The different types of participants (i.e. healthy control participants, participants with Alzheimer's disease at predementia stage and participants with Alzheimer's disease at dementia stage) are defined via restrictions on the values of the property `hasClinicalDiagnosis`, leading to three respective subclasses, namely `HealthyControlParticipant`, `ParticipantWithDementia`, `ParticipantWithPredementia`.
- `hasProtocolAssessor`: it indicates the person that administers the protocol; its value is an individual of the `event:Clinician` class
- `hasProtocolStep`: it indicates the steps that comprise the protocol; its value is an individual of the `ProtocolStep` class.
- `date`: it indicates the date of the protocol realization; its value is an individuals of the `time:dateTime` class[17]

Class `ProtocolStep`
This class represents the possible types of steps comprising the protocol via its subclasses that currently include the classes `DirectedActivitiesStep`, `SemiDirectedActivitiesSte` and `DiscussionWithClinicianStep`. Individuals of the `ProtocolStep` class are instantiated along with `involvesTask` property assertions. This object property links the `ProtocolStep` and `Task` classes, enabling to describe which tasks are included in each step of the protocol; the tasks currently comprising the directed activities step, the semi-directed activities step and the discussion with the clinician step are shown in Figure 10, Figure 11 and Figure 12 respectively. Further assertions about the start and end time of each step can be stated using the `startTime` and `endTime properties`, whose values are individuals of the `time:Instant` class.

[17] Any temporal information in Dem@Care ontology is represented using the OWL Time ontology vocabulary (`time:` prefix)

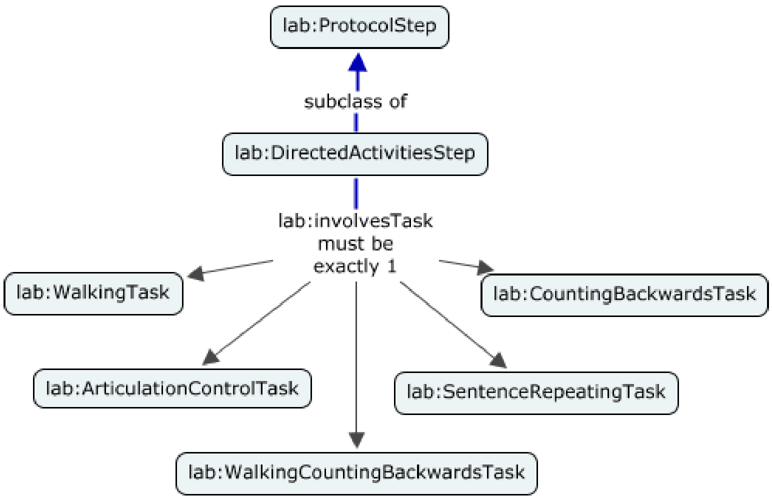

Figure 10 The tasks comprising the directed activities protocol step

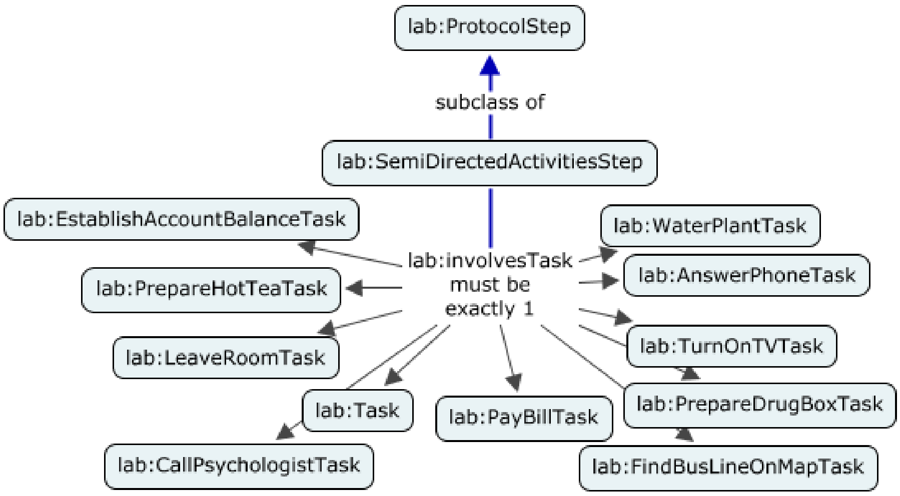

Figure 11 The tasks comprising the semi-directed activities protocol step

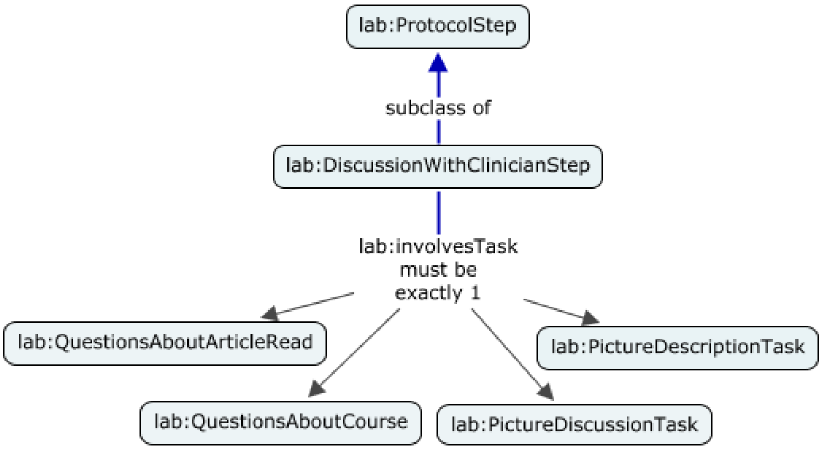

Figure 12 The tasks comprising the discussion with clinician protocol step

Class `Task`
This class represents the possible types of tasks involved in the protocol steps. Individuals of the `Task` class are instantiated together with respective assertions of the `measuredData`. Individuals belonging to the `Task` class may also be instantiated along with the object property assertions `startTime` and `endTime` that indicate the start and end time respectively of the task realization; the values of both these properties are individuals of the `time:Instant` class.

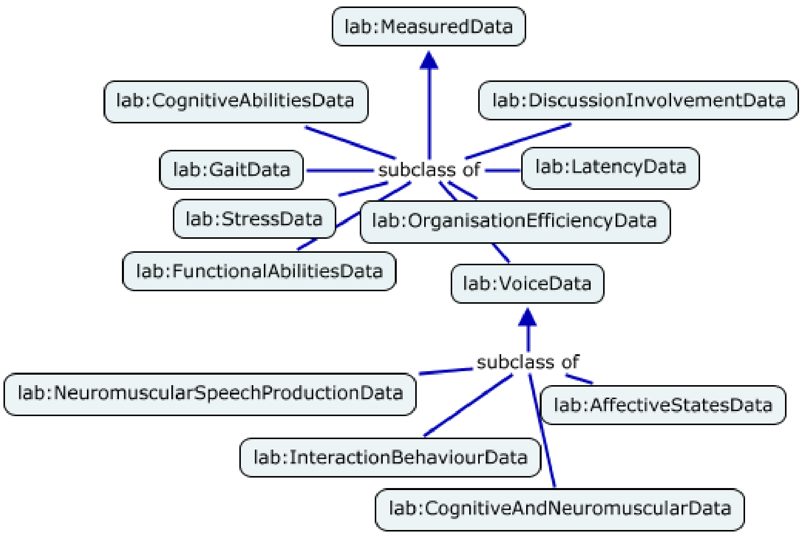

Figure 13 The MeasureData class hieararchy

Class `MeasuredData`
This is the top-level class of the different types of data that are measured during the experimental protocol and, as show in

Figure 13, it is currently specialised into eight subclasses.

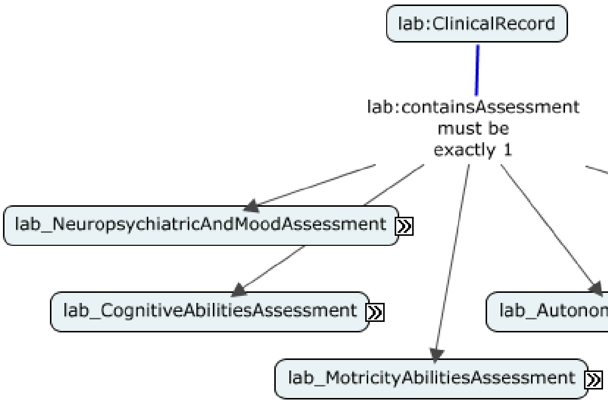

Figure 14 The types of assessment performed during medical and clinical consultation

Class `ClinicalRecord and` **Class** `ClinicalAssessment`
These classes are used to represent the clinical characteristics that are collected during the clinical and medical consultation phases taking place in the lab environment. The subclasses of `ClinicalAssessment` correspond to the different clinical characteristics that are collected during the medical and clinical consultation phases taking place in the lab environments. Figure 14 shows the possible types of clinical and medical assessment. The `ClinicalRecord` class allows their aggregation via assertions of the object property `containsAssessment`.

4.1.2 The Home/Nursing home ontology

The home/nursing home ontology formalises information pertinent to behaviour interpretation in the home and nursing home environments.

The main classes of the home/nursing home ontology are:

Class `Problem`
This class is used to represent information about problems encountered by PwD. Problems are defined as direct or indirect instances of the Problem class and can be associated with one or more events that are considered as the contributing factors (`possibleContributing-Factor`). The ontology also defines the `highlight` datatype property (domain: `Event`, range: `boolean`) that is used to define whether an detected event should be highlighted to the clinician as significant for further investigation, e.g. when the PwD takes a nap after lunch or visits the kitchen during a bed exit at night. Figure 15 depicts an excerpt of the current hierarchy of problems.

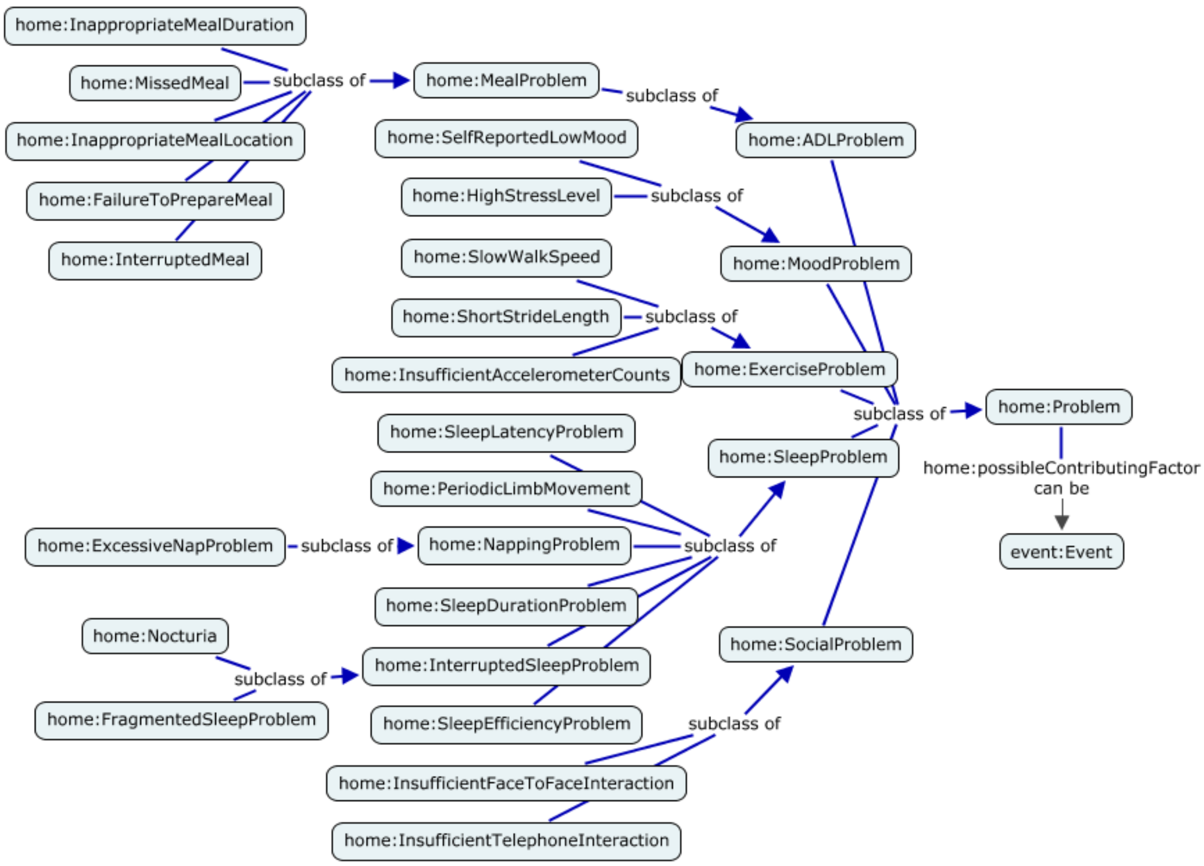

Figure 15 Excerpt of the Problem class hierarchy

Class `DaySummary`

Day summaries contain information about the performance of patients in daily activities, such as sleep, eating, exercise, mood and social interactions.

Figure 16 shows the hierarchy of summaries. Individuals of summary classes need to be instantiated with two property assertions relevant to the patient referred to (`forPatient`) and the date (`date`), as well as with property assertions pertinent to the summary type they describe.

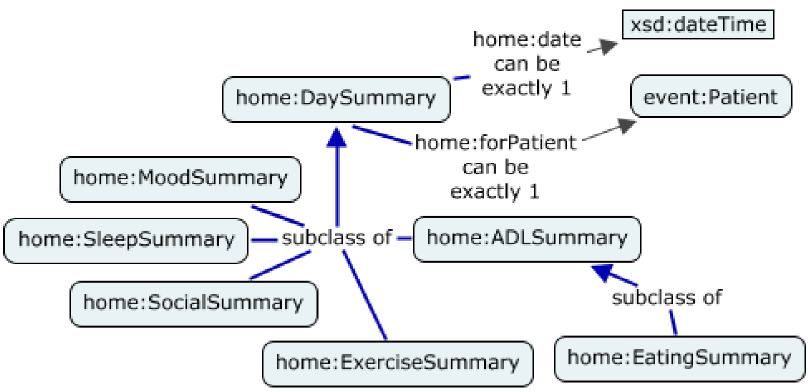

Figure 16 Excerpt of the DaySummary class hierarchy

The object and datatype property assertions that can be stated for the different types of daily summaries are specified in corresponding subclasses.

For example, individuals belonging to the `SleepSummary` class are instantiated together with the following, among others, property assertions:

- `sleepduration`: it indicates the duration of sleep during the night
- `lightLevel`: it indicates the light level during the sleep at night
- `numberOfArousals`: it indicates the number of arousals during night sleep
- `numberOfAwakening`: it indicates the number of awakenings during night sleep
- `numberOfBedExits`: it indicates the number of bed exits during night sleep
- `numberOfNaps`: it indicates the number of naps during the day
- `sleepBedTime`: it indicates the time when the PwD turns off the lights
- `sleepTime`: it indicates the time when the PwD falls asleep at night
- `sleepEfficiency`: it indicates the amount of time spent sleeping as a percentage of total amount of time spent in bed at night
- `sleepLatency`: it indicates the time difference between the time the PwD went to bed and the time the PwD fall asleep
- `totalDurationOfNaps`: it indicates the total number of naps during the day
- `wakeUpTime`: it indicates the time when the PwD wakes up

Class `Questionnaire`
This class serves as the top-level class of the possible questionnaire types that are administered to the PwD for eliciting self-assessment data. It currently has two subclasses, namely `SleepQuestionnaire` and `MoodQuestionnaire`.

4.1.3 The Event ontology

The event ontology formalizes the types of entities (e.g. objects, places) and events (e.g. activities, states) relevant to the Dem@Care purposes.

The main classes of the Event/entity ontology are:

Class `Entity`
This class is used to represent any physical entity in the Dem@Care domain and currently has three subclasses, namely `Person`, `Object` and `Place` to represent the different types of persons (e.g. patient), objects (e.g. telephone) and locations considered. Indicative subclasses include: `Cup`, `Fridge`, `Telephone` (subclasses of `Object`), `Patient`, `Clinician`, `Carer` (subclasses of `Person`), `Bathroom`, `Kitchen` (subclasses of `Place`). Figure 17 shows an excerpt of the current `Entity` class hierarchy.

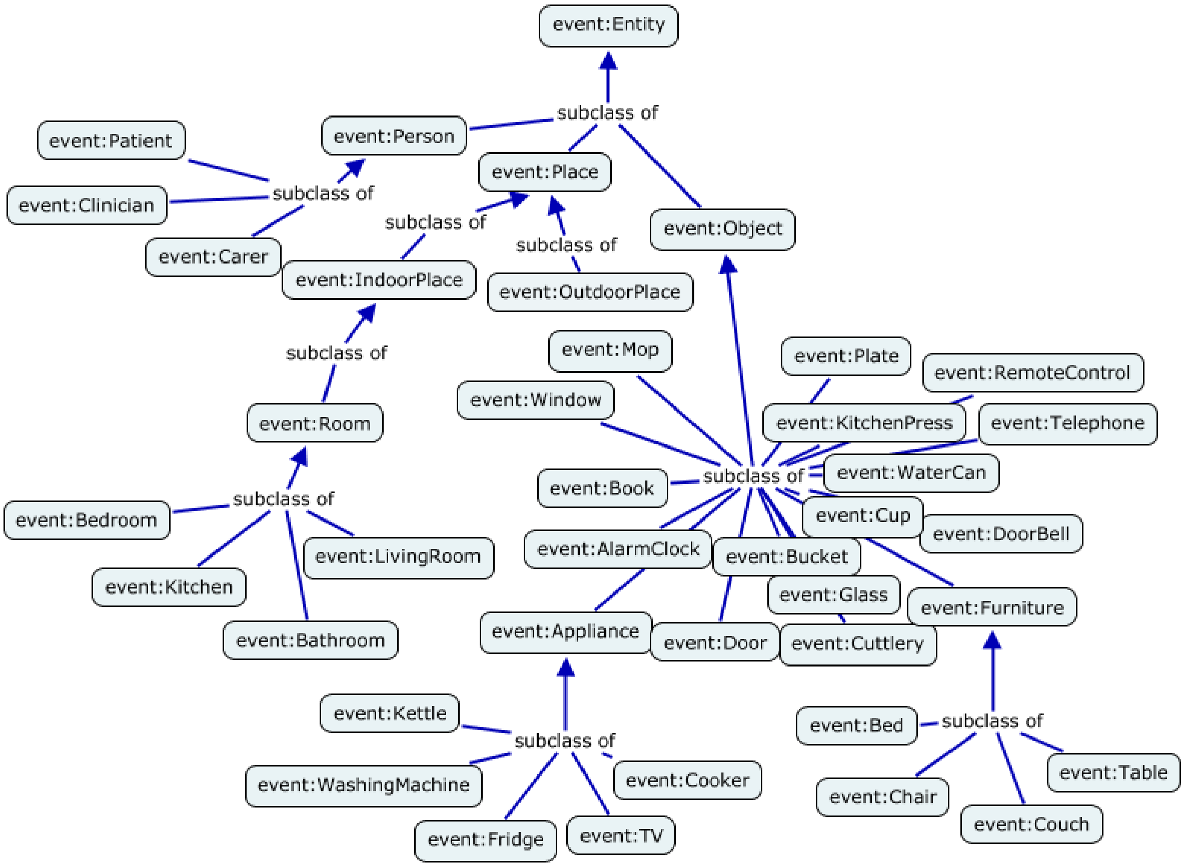

Figure 17 Excerpt of the Entity class hierarchy

Class `Event`
This is the top-level class of the event hierarchy and is currently specialised into four subclasses, namely `Activity`, `State`, `Measurement` and `ObjectEvent`.
Individuals belonging to this class (and its subclasses) need to be instantiated along with the following object properties assertions:

- `startTime`: it indicates the start time of the event; its value is an individuals of the `time:Instant` class[18]
- `duration`: it indicates the duration of the event; its value is an individual of the `time:DurationDescription` class
- `hasAgent`: it indicates the agent participating in the event; its value is an individual of the `Entity` class. Linking events and entities, this property captures agentive information, i.e. the agent (actor) of the event, as well as any other event-entity relationship, e.g. the relation between a temperature measurement and the room referred to.

[18] Any temporal information in Dem@Care ontology is represented using the OWL Time ontology vocabulary (`time:` prefix)

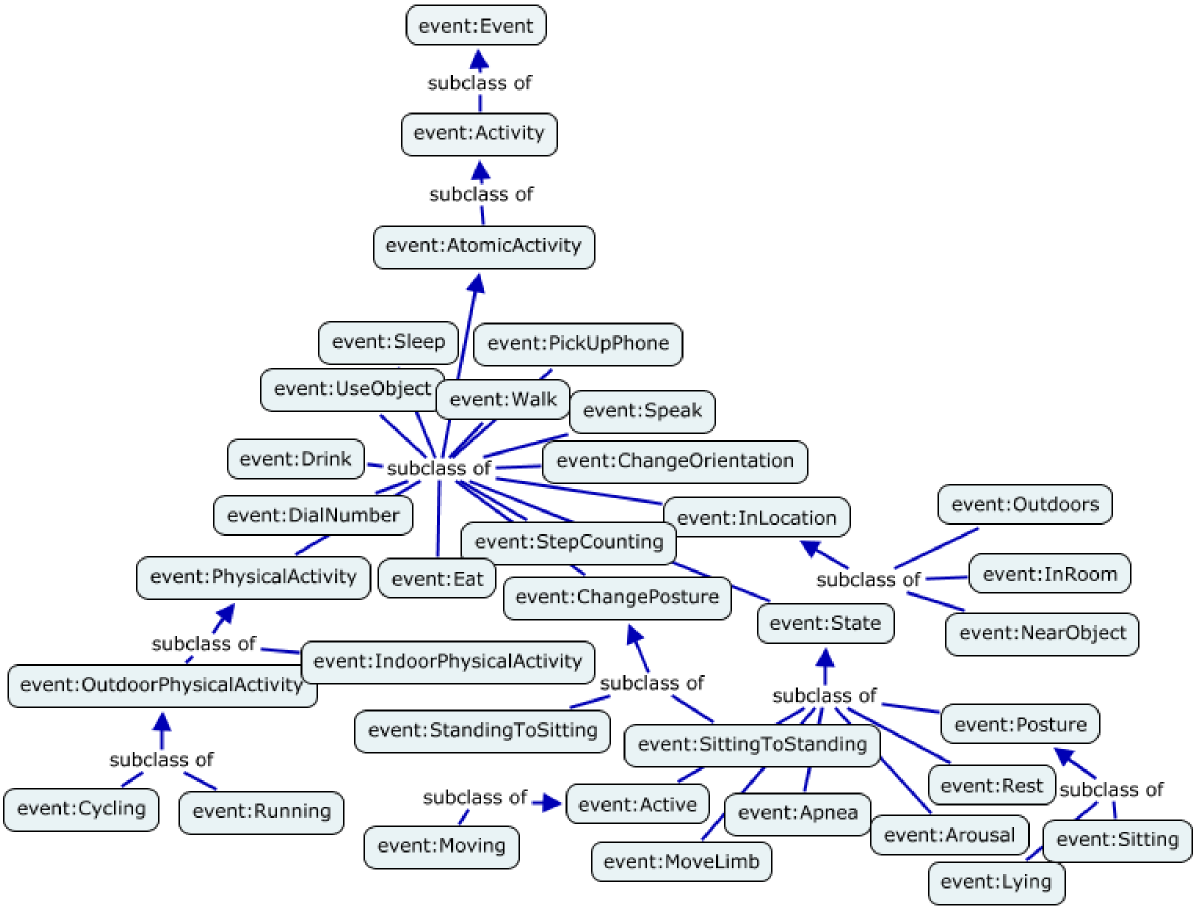

Figure 18 Excerpt of the AtomicActivity class hierarchy of the Event/Entity ontology

Class `Activity`

This class represents the possible activities the PwD may engage into. It currently has two subclasses, namely `AtomicActivity` and `ComplexActivity` that represent activities detected by means of WP3 and WP4 monitoring and analysis components, and activities inferred by WP5 respectively. Excerpts of the hierarchies of the `AtomicActivity` and `ComplexActivity` classes are shown in Figure 18 and Figure 19 respectively.

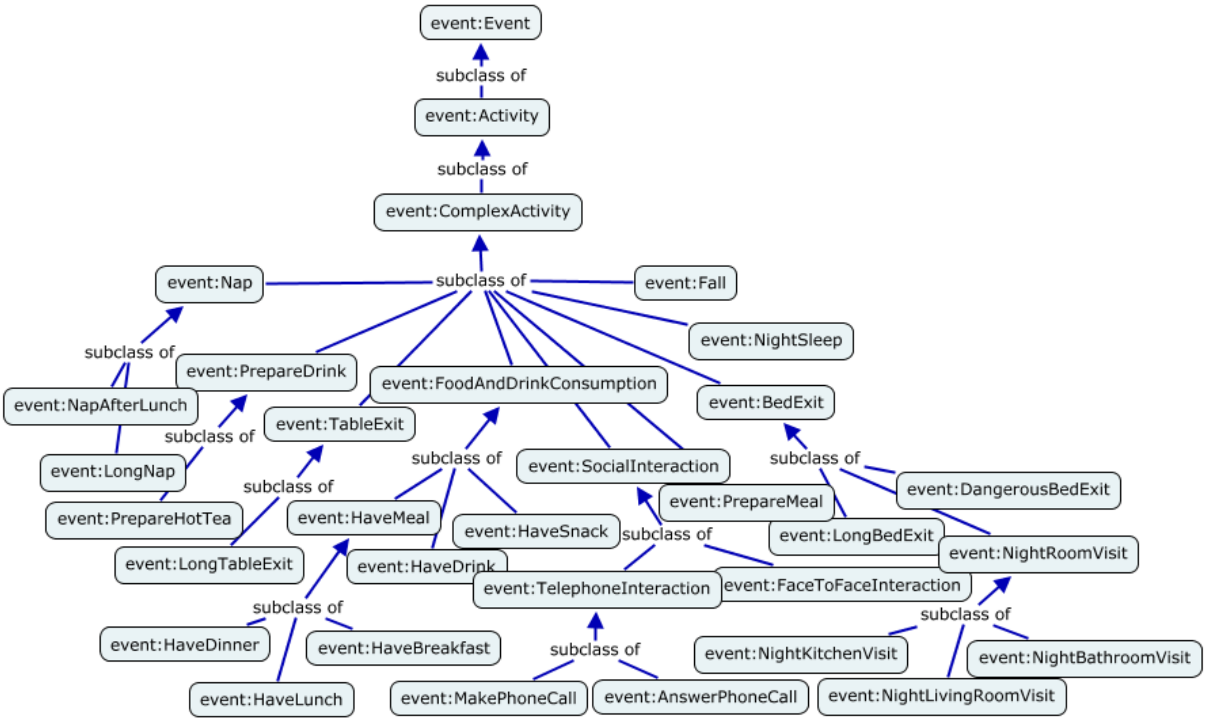

Figure 19 Excerpt of the ComplexActivity class hierarchy of the Event/Entity ontology

Class `Measurement`

This class has currently two subclasses, namely `PhysiologicalMeasurement` and `AmbientMeasurement`, and represents the possible physiological and ambient measurements that may be monitored. Individuals of the `Measurement` class are instantiated together with two assertions, one stating the quality being measured (`hasQuality`) and one stating the measured value (`hasValue`). Figure 20 shows an excerpt of the Measurement class hierarchy.

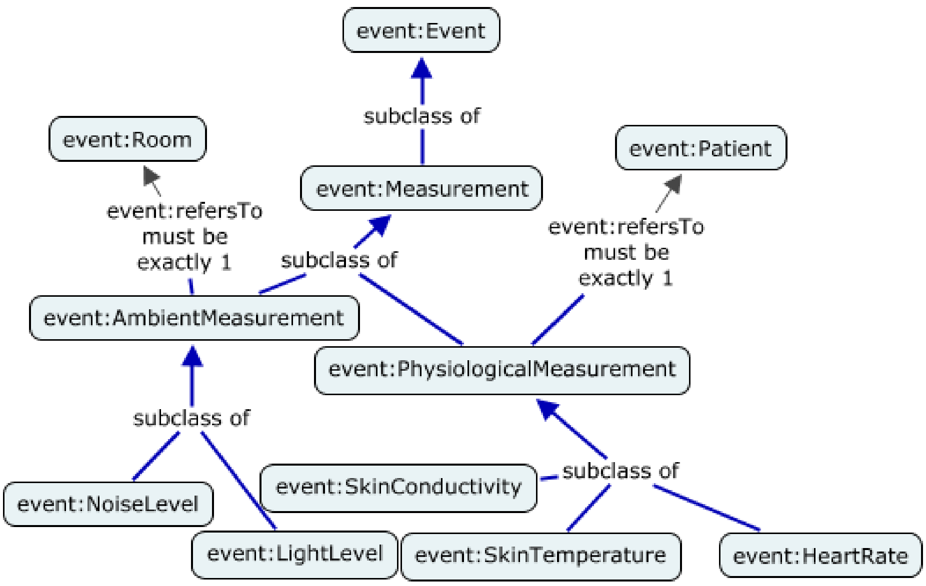

Figure 20 Excerpt of the Measurement class hierarchy of the Event/Entity ontology

4.1.4 The Descriptive ontology

The descriptive information ontology formalizes provenance relevant information, adding an additional abstraction level on top of the home/nursing home, lab and event/entity ontologies that enables to capture and associate descriptive attributes.

The main classes of the descriptive information ontology are:

Class `Observation`
This class encapsulates information about elicited observations relevant to the behaviour of the monitored PwD. Individuals of this class (and its subclasses) are instantiated together with the following property assertions:

- `refersTo`: it indicates the event to which an observation refers to; its value is an individual of the `Event` class of the Event/Entity ontology
- `hasPlausibility`: it indicates the plausibility of the observation
- `hasReportingTime`: it indicates the time the observation becomes available
- `isProvidedBy`: it indicates the provider (sensor, processing component or human) of the observation; its value is an individual of either the `event:Person` class or the `desc:Sensor` class, or the `desc:ProcessingComponent` class

The class `Observation` has currently three subclasses, namely `AtomicEventObservation`, `InferredEventObservation` and `MeasurementObservation` that are defined based on restrictions on the values of the `isProvidedBy` and `refersTo` properties. As shown in Figure 21, individuals of the `MeasurementObservation` class may only refer to measurements (i.e. to individuals of the `Measurement` class of the Event/Entity ontology) and are provided by a sensor, individuals of the `AtomicEventObservation` class may only refer to events detected by the WP3 and WP4 analysis components (i.e. to individuals of either of the `event:AtomicActivity`, `event:State` and `event:ObjectEvent` classes of the event ontology) and are provided by a processing component, while individuals of the `InferredObservation` class may only refer to inferred activities (i.e. to individuals of the `event:ComplexActivity` class) and are also provided by a processing component.

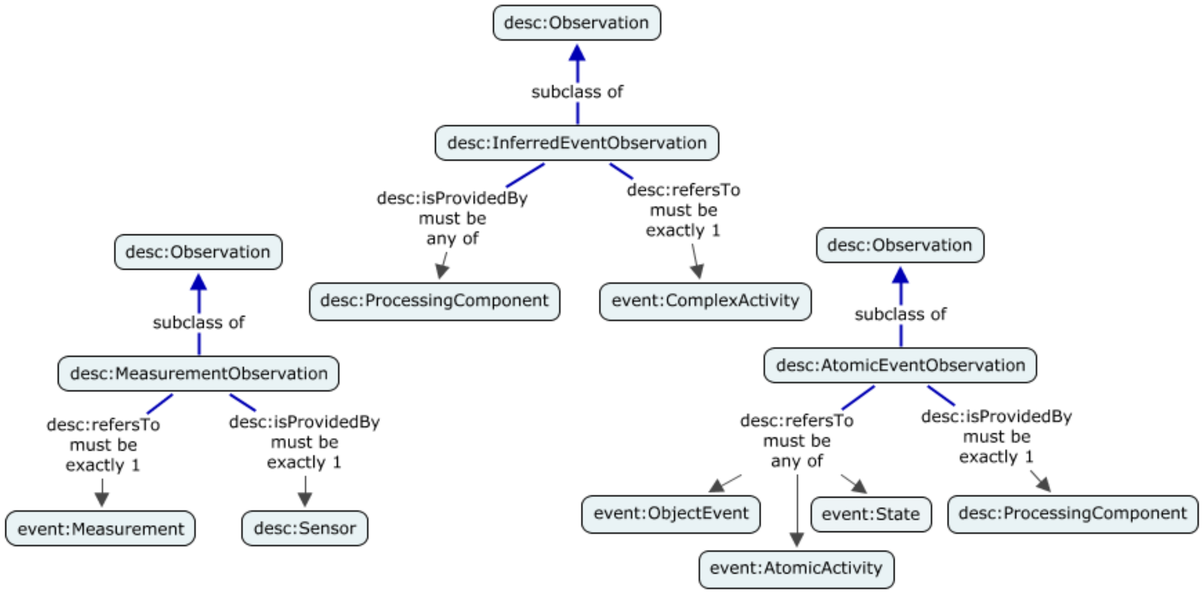

Figure 21 The subclasses of the Observation class

Class `Report`
This class encapsulates information about manually inputted data such as the self-assessments provided by the PwD herself via questionnaires and clinical and demographics characteristics that are collected during clinical and medical consultation. Similar to the `Observation` class, individuals of this class are instantiated together with the following property assertions:

- `refersTo`: it indicates the manually inputted information to which a report refers to; its value is an individual of either of the `Questionnaire`, `ClinicalRecord`, and `DemographicsRecord` classes defined in the home/nursing home and the lab ontologies respectively
- `hasReportingTime`: it indicates the time the report becomes available
- `isProvidedBy`: it indicates the person that provided the report (e.g. patient, clinician); its value is an individual of the `event:Person` class.

`Using the hasPlausibility` property, assertions about the plausibility of the reported data may be also stated.

Class `InterpretationResult`
This class encapsulates information about interpretations drawn about the behaviour of the PwD. Similar to the `Observation` and `Report` classes, individuals of this class are instantiated together with the following property assertions:

- `refersTo`: it indicates the referred to interpretation-related information; its value is an individual of the `home:Problem class`, or the `home:DaySummary class`, or the `lab:ExperimentalAssessment` class
- `hasPlausibility`: it indicates the plausibility of the derived interpretation
- `hasReportingTime`: it indicates the time the interpretation becomes available
- `isProvidedBy`: it indicates the processing component that generated the interpretation; its value is an individual of the `ProcessingComponent` class

Class `Sensor`
This class represents the possible types of sensors that are used by the system. It currently has two subclasses, namely `WearableSensor` and `FixedSensor`, which are further specialised into the different types of sensors currently deployed by respective subclasses as shown in Figure 22. Individuals of this class are instantiated together with an `attachedTo` property assertion that indicates the entity (person, object or place) the sensor is attached to.

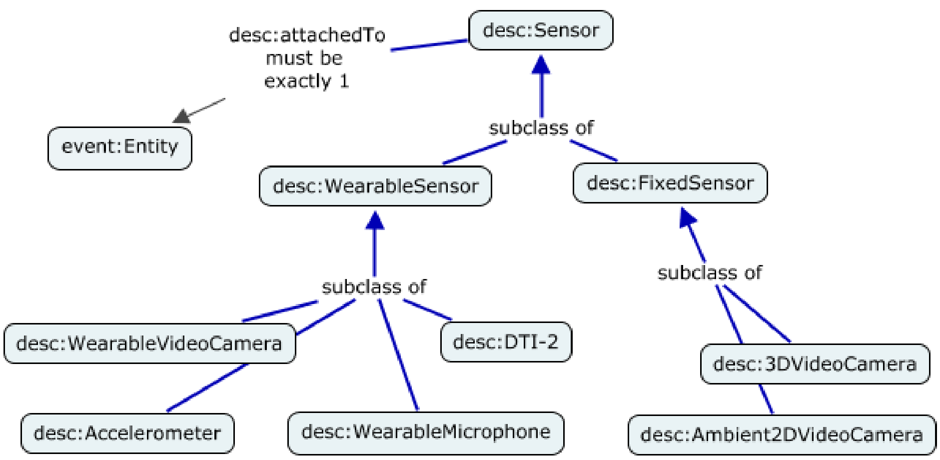

Figure 22 The Sensor class hierarchy of the descriptive information ontology

Class `ProcessingComponent`
The individuals of this class correspond to the system software components (e.g. WIMU SPS, DTI-2 ASW, OSA) as specified in D7.1.

4.2 Ontology revision and assessment

The ontology is constantly checked against the requirements in order to ensure that it adequately covers the knowledge that it is expected to capture. As a consequence, formalisation and revision activities have been carried on iteratively, and will do so for the remaining duration of the project, as the use cases and requirements evolve. To be aligned with the three-staged implementation of the system prototype, the ontology revisions will be documented in the Deliverables D5.2 "Multi-parametric behaviour interpretation v1", D5.4 "Multi-parametric behaviour interpretation v2" and D5.6 "Multi-parametric behaviour interpretation v3" respectively that coincide with the release of the three system prototype versions, and will be accompanied by respective ontology releases.

To assess the ontology we need to validate it with respect to the requirements described in the Dem@Care ORSD. As this phase of ontology building has taken place during the first year of the project, the services that would allow us to populate the ontology and query it have not been implemented yet. Hence, to validate it, we populated the ontology manually and performed representative SPARQL[19] queries that were indentified based on the ORSD competency questions.

4.3 Ontology metrics

In this section, we present some detailed metrics about the current version of the Dem@Care ontology, as provided by the ontology metrics view in Protégé. Figure 23 presents the summary of these metrics.

Metrics

Axiom	1470
Logical axiom count	819
Class count	266
Object property count	74
Data property count	115
Individual count	50
DL expressivity	SHOIQ(D)

Figure 23 Dem@Care ontology metrics summary

The DL expressivity of the current version of the ontology is *SHOIQ(D)*, where *S* stands for the base language (atomic negation, concepts intersection, universal restrictions, limited

[19] http://www.w3.org/TR/sparql11-query/

existential quantification), complex concept negation and transitive properties, *H* for role hierarchies (i.e. subproperties), *O* for nominals (i.e. enumerated classes and object value restrictions), *I* for inverse properties, *Q* for qualified cardinality restrictions and *(D)* for the use of datatype properties.

Class axioms

SubClassOf axioms count	537
EquivalentClasses axioms count	11
DisjointClasses axioms count	12
GCI count	0
Hidden GCI Count	8

Figure 24 Class axioms metrics

Figure 24 shows a number of metrics regarding the class axioms currently defined in the ontology. As illustrated, excluding subclass axioms, the ontology is not particularly rich at the moment. This however is natural, since the primary objective at this stage was to provide the conceptualisation (classes, properties, individuals) necessary to encode the information specified by the competency questions, while the definition of axioms and rules for inference falls within the activities addressed in Task 5.3.

As shown in Figure 23, the Dem@Care ontology contains quite a number of object and datatype properties to make assertions about the individuals described in the ontology. Further statistics about the ontology properties are shown in Figure 25 and Figure 26 respectively, where already a number of axioms have been used to ensure the precise capturing of the property semantics via the use of example of range and inverse property axioms.

Object property axioms

SubObjectPropertyOf axioms count	7
EquivalentObjectProperties axioms count	0
InverseObjectProperties axioms count	9
DisjointObjectProperties axioms count	0
FunctionalObjectProperty axioms count	0
InverseFunctionalObjectProperty axioms count	0
TransitiveObjectProperty axioms count	1
SymmetricObjectProperty axioms count	0
AsymmetricObjectProperty axioms count	0
ReflexiveObjectProperty axioms count	0
IrrefexiveObjectProperty axioms count	0
ObjectPropertyDomain axioms count	38
ObjectPropertyRange axioms count	30
SubPropertyChainOf axioms count	0

Figure 25 Object property axioms metrics

Data property axioms

SubDataPropertyOf axioms count	27
EquivalentDataProperties axioms count	0
DisjointDataProperties axioms count	0
FunctionalDataProperty axioms count	0
DataPropertyDomain axioms count	43
DataPropertyRange axioms count	53

Figure 26 Data property axioms metrics

5 Conclusions

In this document we provided the requirement specifications and the state-of-the-art analysis relevant to the building of the semantic knowledge structures addressed within Task 5.1. We also described the current status of the Dem@Care ontology that encodes in a structured way the vocabulary and the precise semantics of the information exchanged between the different system services.

Future work includes the further enhancement of the ontology in two directions. First, to provide additional ontology constructs for the representation of PwD profile information; second, to enhance the reasoning capabilities of the ontology by enriching the supported semantics both at the terminological level, by defining additional class and property axioms, and at the assertional level by incorporating inference rules. The additional inference capabilities will afford the derivation of behavioural interpretations with personalized capabilities, as well as the validation and resolution of inconsistencies using formal inferencing mechanisms.

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