Ontology-Based Decision Support Systems for Health Data Management to Support Collaboration in Ambient Assisted Living and Work Reintegration

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Abstract. The modern evolution of healthcare systems towards even more complex networks has highlighted the emerging need of a standardized and interoperable model for the management of health data. Several studies in the past years have underlined how the adoption of Semantic Web technologies can provide a valuable solution for both of the aforementioned needs. Semantic modelling of health-data can indeed provide a sound and sharable conceptualization of a patient's health condition and can leverage automatic generation of new knowledge related to the clinical contexts. In fact, thanks to reasoning processes these technologies can be used as part of decision-support systems in a variety of domains. In this paper two examples of ontologies are presented. Both models rely on a worldwide-known classification and are the basis for two decision-support tools related to the Ambient Assisted Living and Work Reintegration domains, which enable cooperation among different clinical and non-clinical stakeholders.

Keywords: ontology, semantic web, decision support system, data integration, health

1 Introduction

The evolution of healthcare systems towards more complex networks has highlighted the need of a standardized model for health-data management. Clinical personnel, rehabilitators, care-providers and non-clinical professionals need to access and interpret many heterogeneous sets of data related to the health condition of patients to provide them with optimal and customized solutions. In details, specialized personnel can exploit these data at two different levels. The first one consists in the so-called primary use of health information: in this case, data are used to deliver direct healthcare services, which are care, therapy and drug administration. The latter is the secondary use, which involves the usage of heterogeneous data for applications placed outside the process of direct healthcare delivery as, for instance, clinical research, public health surveillance and quality measurement. It consists in the analysis of aggregated data to study a variety of issues related to the health. In this second scenario, it is even more difficult for researchers and non-clinical personnel retrieving patients' data, since they are often inconsistent in formats and models. One of the most promising answers to this issue is the adoption of solutions based on Semantic Web (SW), which allows the integration of different types of data collected from different kind of patients and provides a standard set of languages to model knowledge – namely Resource Description Framework (RDF) [1] and Ontology Web Language (OWL) [2]. Domain knowledge is modeled into ontologies, explicit, shared and Description Logic-based conceptualizations of the knowledge and the relationships of the concepts composing a domain [3]. In addition, with the use of ontologies it is possible to derive new facts – which are not explicitly expressed – through reasoning, thus discovering new chunks of knowledge and adding value to several knowledge-based businesses and fields [4]. This feature is particularly interesting and enriches the scenario of the secondary uses of health data with the possibility to infer new information related to a patient's health condition in several domains.

This paper describes two ontologies that can be framed among the secondary uses of health data, since they deal with two health-related domains, the Ambient Assisted Living (AAL) and the Work Reintegration (WR) and involve both clinical and non-clinical professionals. The presented ontologies model the health condition of patients through the World Health Organization's International Classification of Functioning, Disability and Health (ICF) [5], an international standard acting as common language that allows diverse clinical and non-clinical professionals to exchange and use the patient's health data. In fact, the use of ontologies permits to support the collection and use of a vast amount of patients' data by making them interoperable, thus enhancing the collaboration among different stakeholders (e.g. rehabilitators, physicians, lab technicians, therapists, caregivers).

In the AAL scenario, the ontology is used to model the patient's health condition, from which it is possible to infer the most suitable sets of appliances to help him/her to cope with his/her impairments in everyday-life. The model serves as a Decision Support System (DSS) for the smart home designers, to support them in the design of a living environment for impaired users. In the WR scenario, the ontology is used to identify possible alternative jobs for novice wheelchair users who need to be reintegrated in the workplace after a trauma, providing a list of suitable jobs tailored on specific users. This ontology acts therefore as a DSS for vocational and rehabilitation therapists and employers, enabling them to choose the most suitable options for the to-be-reintegrated wheelchair user.

This paper is organized as follow: Section 2 presents the existing works in the fields of semantic health-data modelling for secondary uses and DSSs. Section 3 introduces the ICF as a common background for the two ontologies developed. Section 4 focuses on the description of the AAL ontology and the use of its derived knowledge in a design application. Section 5 describes the ontological model for WR and the possible inferences to support a DSS. Finally, Section 6 summarizes the main outcomes.

2 Related Works

The topic of modeling the health-data is one of the main issues when tackling the interoperability among various data sources. Data integration is not an easy task: the possibility to link different health-data is complicated by the heterogeneity of data formats and different naming conventions [6]. The importance of this topic gave birth to the Semantic Web for Health Care and Life Sciences Interest Group [7], whose mission is to advocate, support and develop the adoption of SW technologies across clinical research, healthcare and life sciences. These matters have been addressed in [8], where the authors used semantic archetypes based on ontologies to provide a formal representation of knowledge deriving from health domains and integrating this model with clinical data. A similar solution is explained in [9], where the interoperability of electronic health records (EHR) is approached by turning the attention to SW technologies, providing a representation of the health-data using OWL. The issue of EHR reusability is also addressed in the European project EHR4CR [10], where the authors overcame the interoperability issues adopting a platform able to provide semantic interoperability services based on standard terminologies. In [11], the need to provide services oriented to the patients encompassing an holistic vision brought to the adoption of a SW-based approach.

The benefits deriving from the adoption of semantic-based technologies in healthcare also concern the possibility to discover new knowledge through reasoning processes. In [12], these features are used to develop a knowledge-mediated personalized care planning. The authors highlighted how the application of the SW technologies can lead to the identification of a planning system that automatically generates ad adaptive care plan, tailored on the patient's profile. In [13], the authors presented a semantic- and SWRL [14]-based DSS for clinical decision making. Doucette et al. [15] adopted a similar approach in their work, which develops a semantic framework for AI-based clinical DSS, which also supports data interoperability. Subirats et al. [16] developed an SWRL-based DSS providing a personalization of therapies in a rehabilitation scenario, using ICF as a framework.

However, the DSSs presented in these works, although leveraging on the SW interoperable capabilities, are all focused on clinical aspects and are not suitable to enhance and support the cooperation between clinical and non-clinical professionals.

3 ICF: A Sharable and Standard Language for Disability

The International Classification of Functioning, Disability and Health (ICF) [4] is a framework aimed at providing a standard tool for the description of health and its related states. It conceptualizes the functioning of an individual as a "dynamic interaction between a person's health condition, environmental factors and personal factors" [17]. ICF acts as a tool able to ease the communication among the health-stakeholders (therapists, clinicians) providing a standard and worldwide comparable description of the functional experiences of the individuals. Due to its vocabulary, which is easily interpretable also by non-clinical personnel, ICF can also be used in health-related domains, such as AAL and WR, as a common means to support and facilitate the collaboration of different actors. The classification is organized in two main parts: the first, "*Functioning and Disability"*, provides a description of the components *Body functions*, *Body structures* and *Activities and participation*; and the second, "*Contextual Factors"*, provides the means to describe the impact of the components *Environmental factors* and *Personal factors*. Each component is further deepened into Chapters, which identify the addressed domain. The functioning of a person is then described through the interaction between his/her health condition and the context where he/she acts. Each component is identified by a letter (*b* for Body functions, *s* for Body structures, *e* for Environmental factors, *d* for Activities and participation) and can be deepened by adding digits (Fig. 1). According to the number of digits following the letter, it is possible to get a code, whose length indicates the level of granularity – up to five digits.

B2 *«Sensory functions and pain»*	Component and chapter – first level item
B210 *«Seeing functions»*	Second level item
B2102 *«Quality of vision»*	Third level item
B21020 *«Light sensitivity»*	Fourth level item

Fig. 1. An example of ICF code.

The functioning or disability of an individual can be assessed selecting the suitable category and its corresponding code and then adding a qualifier (from 0-no impairment to 4-complete impairment). ICF has also been represented into an ontological model in RDF/OWL [18], which can be used as reference in the modelling of more complex ontologies. However, it has to be underlined that this model inherits some shortcomings belonging to the whole classification, such as problems regarding incongruent classification of some concepts, a lack of clarity between activities and their qualities, incorrect parent-child relationships and overemphasis on subsumption [19][20][21].

4 DSS for Collaborative Configuration of Living Environments

The AAL-DSS is developed within Design For All, an Italian research project aimed at providing elderly or impaired people with a set of tools able to cope their physiological status. AAL should assure them the ability to perform several daily life activities during their domestic lives that would otherwise be precluded or strenuous. In this context, the semantic-based DSS is composed of five sets of domain ontologies.

The ontologies were developed following the NeOn methodology [22], a methodology requiring several domain experts to collaborate. An Ontology Requirements Specification Document [23] has been drafted and then completed with a set of Competency Questions [24] – a list of the questions that an ontology should be able to answer. The related answers provided the terminology for a pre-glossary of terms, which were later formally represented into the set of ontologies using the Protégé ontology editor [25].

The first set is the User Model, which gathers a dweller's registry records (full name, date of birth, birthplace, full address, telephone number, Tax Identification Number) and describes a person's physiological status using a partially re-engineered version of the ICF ontology [18]. In this particular module, the specific ICF codes originally modelled as individuals are converted into datatype properties, in order to enable to model several health conditions using the same ICF codes. The result of this process consists of a simplified TBox, containing the datatype properties describing the four main components of the classification (Body functions, Activities and participation, Body structures and Environmental factors). For each of the components, the Chapters are also specified, providing a grade of detail with sub-datatype properties for the second and third level categories (Fig. 2). These datatype properties, linked to a Health Condition individual, allow to specify the generic qualifier (with a range of acceptable `int` value restricted to 0, 1, 2, 3 or 4) to be associated to a specific category. Following this modelling expedients, it is possible to keep the inferences strictly related to the Health Conditions and to build general SWRL rules regarding specific codes and impairments.

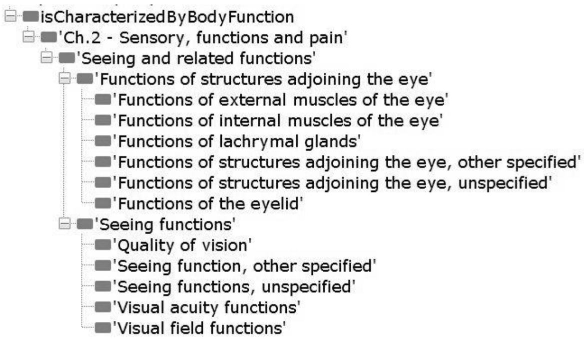

Fig. 2. An excerpt of the ICF TBox, illustrating the second Chapter of the "Body functions" component and the degree of specification with the use of datatype properties.

Every person living in the house is associated with his/her Health Conditions – modelled in a separate module –, according to an already tested Ontology Design Pattern (ODP)[26]. For each dweller, several Health Conditions can be assessed in different moments in time by clinicians. Health Conditions described by means of the ICF module can then be classified through reasoning process. In fact, the reasoning performed on the Health Condition module allows to understand if a person is characterized by a mild, moderate, severe or complete impairment and the quality of the impairment (visual, hearing, motor or cognitive).

The second set of ontologies is the Smart Object Model, which formally describes the appliances and sensors that can be potentially placed in the house and their related functionalities. This set allows to classify each appliance according to its typology (dishwasher, refrigerator, oven, etc.) and to the benefits it provides to specific categories of impaired dwellers. The description of the Smart Objects takes advantage of the HicMO [27] “grammar”, a set of XML properties able to describe the features of any appliance. The description of a Smart Object is integrated with a module describing the list of programs available for each appliance. Reasoning process on this module allows to determine the most suitable appliance for each of the dwellers modelled in the User Module.

The third set of ontologies deals with the Measurements Description and allows to model the measurements performed by a Smart Object. Each measurement is classified according to its typology (environmental, physiological or machinery if they refer respectively to rooms, people or Smart Objects) and described with a set of objects and datatype properties (Fig. 3). This model serves as a completion for the description of the appliances and provide a formal way to describe the domestic comfort metrics. Another relevant advantage offered by this module, is the possibility to get semantic interoperability among the various measurements performed by the different Smart Objects, thanks to their formal description and the use of reference ontology for the description of the physiological measurements – Vital Sign Ontology (VSO) [28] – and comfort-related measurements – Units Ontology [29].

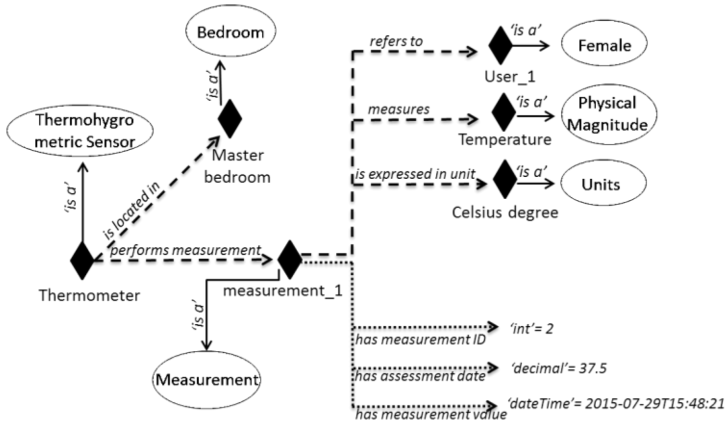

Fig. 3. An example of modelling of a Smart Object performing a measurement; dashed lines represent object properties, while dotted lines represent datatype properties.

The fourth set of domain ontologies is the Domestic Environment Model, whose goal is to provide a description of the dwellers’ house and its structures, together with the comfort metrics that must be effective in providing a comfortable and safe permanence inside the house. The description of a person’s house is performed with a simple taxonomy, which is composed of a set of classes categorizing the different rooms of a domestic environment (living room, kitchen, bathroom, etc.). Comfort dimensions are expressed as environmental measurements and allow to describe air quality (in terms of CO_2 concentration in a room), amount of illuminance and internal temperature during winter and summer. According to the typology and grade of impairment it is possible to set specific comfort dimensions for a particular dweller; for instance, a visual-impaired user characterized by hyposensitivity to light may need a customized (higher) level of illuminance to perform daily life activities.

Finally, the fifth set of ontology provides a description of the customization work provided by the designers. In this model, a description of the projects for the configuration of a living environment is provided; thanks to the entailments performed on the User Model and on the Smart Object Model, this ontology allows to formalize the choices performed by a designer (Fig. 4).

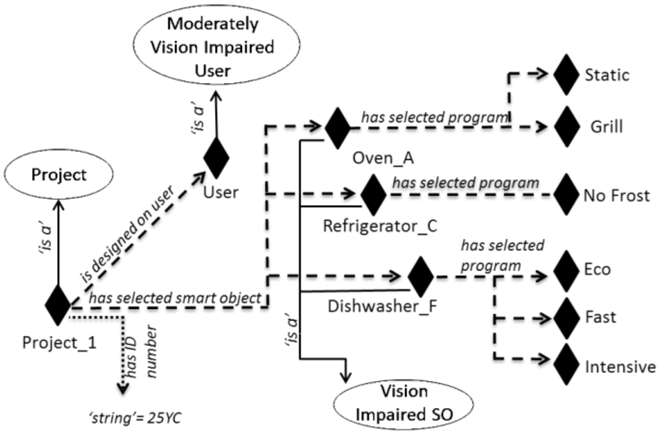

Fig. 4. An example of modelling of a Project for a moderately visual-impaired user; the designer has chosen the appliances and their programs (dashed lines represent object properties, dotted lines represent datatype properties).

The aggregated data regarding the user's health condition, the list of suitable Smart Objects, the user's house and the entailments performed by the AAL-DSS are retrieved via SPARQL queries [30] and fed to a Virtual Reality-based application that enables designers to reproduce a virtual model of the user's domestic environments.

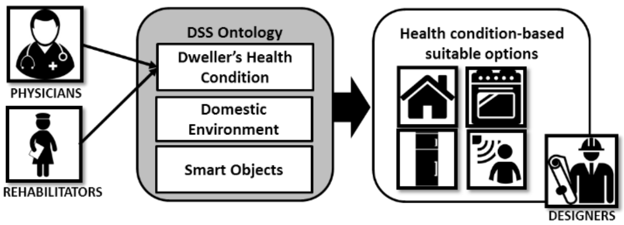

Fig. 5. An example of support to collaboration among different professionals provided by the application of ontology.

Inside this virtual environment, the designer can place the Smart Objects by choosing from the list of most suitable options provided by the reasoning process on the Smart Object Model. As already described, the entailments are performed taking into account the user's current Health Condition: in this way, it is possible to update the list of suitable Smart Objects whenever an enhancement or deterioration of the health condition is modelled in the User Model.

To validate the ontology-based DSS implemented within the Design For All project, two specific use cases were developed. The first one foresees the configuration of a kitchen for a 68-year-old moderately visual-impaired male user, while the second foresees the configuration of a bedroom for a 70-year-old female user characterized by frailty, who needs to perform physical activity on a cycle-ergometer on daily basis. The framework allowed physicians to assess the users' Health Condition with the use of ICF: these data were later formalized in the ontology; clinical personnel, in collaboration with ergonomists, also provided specific comfort metrics thresholds for illuminance and air quality. Reasoning processes were effective in retrieving the most suitable appliances and sensors to configure both the environments, allowing the designer to make the best choices to respond to the users' needs.

Due to all the above-mentioned aspects and characteristics, this ontology acts as a cooperation environment that allows clinical professionals to provide and ICF-based assessment of the dweller's health condition. The designer can exploit this health condition to provide the users with a suitable home configuration, while rehabilitators and caregivers can monitor the improvements of the dwellers. Each clinician can deepen the data of his/her interest, just as the designer can access to global health condition data to configure the living environment. In addition, the use of ICF and VSO provides clinical personnel with descriptions and measurements able to ease the communication among physicians, domestic caregivers, rehabilitation therapists and dwellers. As a result, this semantic DSS enhances the collaboration between clinical and non-clinical professionals through the exchange of health-related data in an interoperable way, providing non-clinical personnel with aggregated and holistic data and clinical personnel with in-depth health data.

5 Collaborative DSS for Novice Wheelchair Users' Rehabilitation and Work Reintegration

The second DSS here presented is developed within an ongoing research project financed by the Italian National Institute for Insurance against Accidents at Work (INAIL) and aimed at supporting the return to work and, more in general, at enhancing the quality of life of novice wheelchair users (WUs). Moreover, the whole framework provides the WU with a new awareness in facing the new physical condition, making him/her able to deal with the challenges related to the return to work by training in safe virtual environments. On the other hand, it supports the vocational personnel and employers with technological means able to discriminate the still suitable jobs for that specific user. In this framework, the role of Semantic Web technologies is in fact to assess, with the help of clinicians, the WU's health conditions and, basing on this assessment, (1) to provide a list of eligible jobs for the WU's new health condition and (2) to set the difficulty of the training exercises in the virtual environments (Fig. 6).

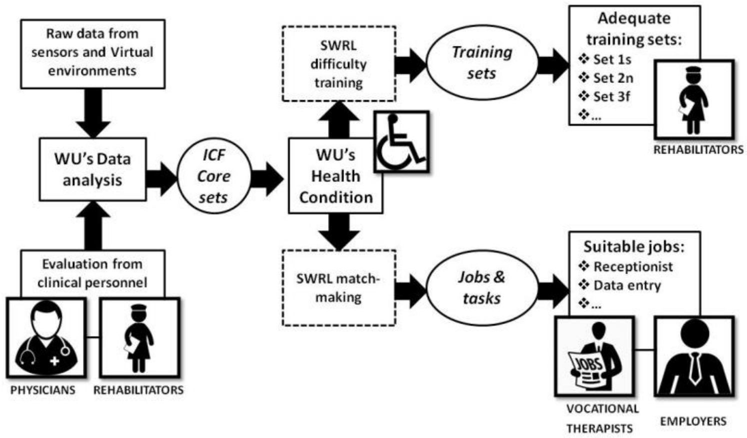

Fig. 6. A representation of how the health data flow among the three ontologies eases the cooperation among different stakeholders.

To this purpose, a set of three domain ontologies is developed. Also for this DSS, the NeOn methodology for ontology development has been chosen, since it provides a framework able to assess the purpose of the semantic models through the Ontology Specification Requirements Document and the list of Competency questions.

The first set of ontologies foresees the modelling of four ICF Core Sets [31] – corresponding to the main causes that force a person on a wheelchair: Spinal Cord Injury, Traumatic Brain Injury, Stroke; Vocational Rehabilitation Core Set is added as a fourth set to better address work reintegration. Together with this module, following the same ODP characterizing the AAL-DSS, the set describes the WU's registry record and Health Condition. Therefore, this model allows to provide a holistic view on the WU's health condition and to assess his/her residual functional capability. Since the focus of the project is very specific, it was preferred to develop the ICF Core Sets ontologies from scratch, instead of reusing the already existing ontology – which would have been too wide for the WU's Health Conditions description. Since some of the categories belonging to different ICF Core Sets are the same, a meta-model is implemented. In this meta-model it is possible to state the equivalency between the same categories and to classify them according to the four ICF components. For instance, the category "b126 – Temperament and personality functions" is used in all the four considered Core Sets. It is modelled as datatype property inside all the respective Core Sets models and then, in the meta-model, it is set as equivalent among the different tokens of this same category; in this way, it is possible to model exhaustively the ICF Core Sets domains while avoiding redundancy of the information.

The second set of ontologies provides an ICF-based description of the jobs and the tasks composing them. Its goal is to assess the impairment typology and the maximum grade of disability that is acceptable to perform a certain job. Each job is thus analyzed assigning it ICF-based employment factors, with the aim of identifying the acceptable conditions that a worker must fulfill to perform that job. For instance, a specific job like Receptionist can be suitable for WUs with a grade of impairment in the codes "b2300 – Sound detection", "b2304 – Speech discrimination", "s250 – Structure of the middle ear" and "s260 – Structure of the inner ear" lower or equal to 1.

Assessment of WU's health condition, conducted periodically, is also necessary to set the training difficulty in the virtual environment: to achieve this goal, a third set of ontologies describing the training sets is developed. Following the same design pattern used for the jobs' modelling, each training set is described in the terms of the typology of impairment and the maximum grades of disability for a WU to perform the training set. It is indeed fundamental to provide the patients with challenging tasks, which are neither too difficult nor too easy [32] to avoid the onset of negative feelings such as frustration or boredom. The matching between the WU's Health Condition, the list of eligible jobs and the assessment of the training difficulty is performed through two sets of SWRLs.

According to this approach, the DSS allows clinical personnel (physicians and rehabilitation therapists) and different health care structures (different hospital wards, rehabilitation structures) to periodically assess the WU's progresses and provides vocational therapists and rehabilitators with an up-to-date tool to evaluate (work-related) residual capabilities. The model then provides employers with reasoned suggestions regarding WU's suitable jobs and with a set of environmental modifications that can be implemented to ease the WU's reintegration in the working place. The DSS is therefore able to enhance the cooperation between clinicians, rehabilitators and non-clinical stakeholders. This DSS is part of a framework which will be validated and later integrated into the return to work process adopted by INAIL as a further development of this work.

6 Conclusions

This work addresses the secondary use of health-related data with SW technologies, describing two DSSs. Both of them are based on a worldwide-known standard (International Classification of Functioning, Disability and Health) and allow to model into ontologies the patient's health condition. Thanks to reasoning processes, it is possible from these formalized models to infer several new information regarding different health-related domains – such as Ambient Assisted Living and work reintegration. This information can be enriched and used by a variety of clinical and non-clinical professionals who may intervene to improve several aspects of impaired patients' lives. Relying on ICF and its structured vocabulary provides a common language for clinicians, rehabilitators, vocational personnel and non-clinical personnel (designers and employers), offering a standard for the description of a patient's functioning, thus enhancing cooperation among different actors both from health and not health related fields. In addition, ICF's structure represents a suitable means to allow the development of ontologies with Semantic Web standard technologies. The developed ontologies can also be aligned with the upper-level ontologies [33], thus providing a common semantic framework for data interoperability and granting horizontal scalability.

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