A State of the Art Survey: Business Cases Based on Semantic Web Technologies in Healthcare

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***Abstract*— Semantic web technologies promise to facilitate a long-awaited paradigm shift in the healthcare industry towards more efficiency, extended interoperability and intelligent analysis capabilities. This paper presents a critical review of current healthcare businesses incorporating semantic web technologies. Initially, it presents the potential of semantic web technologies in general and the challenges to apply them in business. State of the art businesses that use semantics to provide innovative healthcare services are pinpointed and critically reviewed. Through an analysis of their aspects, their semantic component, business models, target audience and value propositions, the competitive advantage and tangible business value of semantics in healthcare is revealed, serving as a reference for the growing number of emerging solutions in the near future.**

Keywords-semantics; semantic web; ontologies; eHealth; healthtech; business models; healthcare;

I. INTRODUCTION

Healthcare can largely benefit from technology throughout its lifecycle: from diagnosis, to hospitalization, prescription, treatment and prevention. However, complex governance structures, heterogeneity and lack of convergence in the healthcare industry are few of the reasons that such benefits of technological applications are slowly emerging. While data mining techniques can aid in certain sectors, such as diagnosis and prevention, it is the semantic web technologies that show great potential to resolve the interoperability problem, which, in turn, would benefit healthcare throughout its lifecycle.

The semantic web technologies [1] provide methods and tools to define the semantics, i.e., hierarchical models and relations between data of any particular domain in an interoperable, machine-interpretable format. The former property, interoperability, allows communications between disperse and vendor-agnostic systems on the basis of commonly established and agreed upon models, referred to as ontologies. Interoperability use case scenarios include patient data exchange between hospital and medical practice systems, exchange of clinical trial data and much more. The latter property, machine-interpretability, gives intelligent software applications the potential not only to read, but also to understand information in a way that humans do. The so-called reasoning process can utilize ontologies to deduce new information. The technology can be applied to any sector by domain experts designing a domain ontology, i.e., the taxonomy particular to the problems, peculiarities and terminology of the pertinent domain. This includes healthcare [2], where semantic web technologies have the potential to lift ailments in data sharing, Electronic Health Record exchange [3], reasoning on epidemic and patient record and drug database information [4] for prescription, prevention, care, etc. achieving cross-provider and even cross-border healthcare.

This paper presents an overview of semantic web technology applications in the healthcare industry so far, giving valuable insights, highlighting the benefits and paving the way to future achievements towards more interoperable healthcare with great clinical, economical and societal impact.

The next Section presents technological challenges and trends of semantic web technologies in several applications, including healthcare. Section 3 presents current business challenges for tech innovation and their relation to semantics. Section 4 presents a critical analysis of several concurrent businesses that offer healthcare services based on semantics. Section 5 presents conclusions from this analysis and future work.

II. TECHNOLOGICAL CHALLENGES AND TRENDS

A recent report by Gartner [5] highlights how semantic-based technologies add critical context to data. According to it, the proliferation of data poses huge challenges for businesses that want to leverage their data assets. Data scientists and business managers are advised to opt for a semantic approach in order to gain competitive advantage. Semantic technologies and knowledge graphs provide (a) the toolbox to facilitate decision making by actually making sense of rapidly growing pools of data, (b) the basis for artificial intelligence and machine learning applications (c) the possibility to make relationships and interconnections of this data with evident benefits on developing new tools and synergies [6].

Thus, Knowledge Management and semantic web technologies can be greatly beneficial to the knowledge society, i.e., a society in which the creation, dissemination, and utilization of information and knowledge has become the most important factor of production. In such an environment, knowledge assets are the most powerful producer of wealth, sidelining the importance of land, the volume of labour, and physical or financial capital. This vision requires an extensive analysis of factors and actions that promote the value of knowledge and specify critical prerequisites for the design and implementation of human centric information systems and services. However, this still pertains several challenges. Lytras et al. [5] state that as extensive communication and networking infrastructures are now implemented, a critical shift is required from the relevant verbalism to applied strategies and technologies. As literature supports "a key question within the context of the knowledge society is how we can redesign the basic structural models of the information provision to target effective models of support. Personalisation and Adaptation are only a few terms aiming to promote the need of multidimensional and non-monolithic approaches" [7].

Several trends emerge around technology to represent the semantics of data. Knowledge Graphs have gotten a lot of attention as a backbone for Machine Learning, Deep Learning, and AI business use cases a trend that is expected to evolve. From a business perspective, it looks like more and more industries (agriculture, healthcare, smart cities, finance, etc.) are pursuing Semantic Technologies, often relying on Knowledge Graphs. Among the semantic-driven AI ventures those related to the healthcare space are forecasted to blossom. Using semantics to drive chatbots is also emerging [8]. Nature Language Processing (NLP) is increasingly based on ontologies to represent the semantics and understanding of speech and dialogue [9]. Data governance procedures, finally, also pertain ontologies and structured semantics.

The digitisation of many industry sectors requires information models describing assets and information sources to enable the semantic integration and interoperable exchange of data. Although this vision has gained much traction lately in many sectors, e.g., creative industry, healthcare industry, manufacturing, etc., it is still not clear how it can actually be implemented in an interoperable way using concrete standards and technologies.

Initiatives for content representation and linking can be exploited in various domains where there is a need to aggregate and fuse information in different levels of abstraction.

A prominent example is the Healthcare domain, where there is a need to coupling profile, behavioural and health knowledge to achieve human awareness and assist clinical experts in assessing the health condition of patients and help adjust and update the care plan and interventions. Another example are intelligent virtual agents, where there is a need to fuse verbal and non-verbal information, e.g., utterances, gestures and emotions, to achieve conversational awareness and provide meaningful responses to the users.

Pervasive environments, often met in healthcare-at-home technological solutions, such as Active and Healthy Ageing (AHA) and Ambient Assisted Living (AAL), present the need to deploy, manage, collect and analyse multimodal sensor observations from the Internet of Things (IoT) [10]. Semantic integration and reasoning solutions have been implemented in home care, in systems such as the AAL solutions of Dem@Care [11], i-PROGNOSIS in occupational health, such as in Healthy@Work [12] Active@Work [13] and Fit4Work [14] smart environments, such as MARIO [15] and the AHA solutions of ACTIVAGE [16].

III. Business Challenges and Semantics

Marketing technology-based, innovative products and services is a far more complicated and challenging task compared to more conventional business cases. Even the launch of new high-tech products is challenging, as usually consumers are more skeptical. Moreover, high tech startups often find it very difficult to define target market and often focus solely on R&D and expect that their super product will sell by itself. To be a successful global brand in the 21st century, a hi-tech firm needs to be market oriented, agile and locally relevant. The proliferation of smart mobile devices and the mass adoption of social media have created an utterly new marketplace where a new consumer has emerged. Spurring innovation adoption can be hard. The high tech sector that is constantly evolving and rapidly changing may cause a multitude of complications.

The central benefit of the semantic web is that it enables the extraction of knowledge patterns and useful information from unstructured content. It further empowers interoperability, integration of multiple and differentiated data sources. It appears that by integrating semantic technologies in the business pipeline, business performance is likely to be improved while new business models emerge. Literature suggests that the impact of semantic web on business performance is related to: a) Less labour hours (20-80%); b) Less cycle time (20-90%); c) Less set up (25-80%); d) Quality gain (50-500%); e) Productivity gain (2-50X; f) Increased return of assets (2-25X; g) Revenue growth (2-30X); h) Reduction of total cost of ownership (20-80%); and i) positive ROI (Return On Investment) over 3 Year (2-300X) [17] [18].

Although the benefits are clear, creating business value using semantic technology is in many ways no different from creating business value with any type of new technology. Literature suggests that there are three important aspects to take into account [19]:

Customers: companies need to understand their customers, their target group and their specific needs. In today's knowledge based economies, corporations cannot rely only on themselves to deliver innovation. Co-creation is the tool to open innovation. An emerging cross-sector

model is to bring the outside in and bridge the gap between the consumers and the brand. If not the most, it is definitely one of the best ways to engage consumers in the company, increase brand recognition and have tangible results: an increase in sales. Co–creation is the path to have increased flow of quality ideas and concepts into a firm's development pipeline.

Business models: High-Tech organizations should carefully consider business models. Companies that succeed in coupling cost-reducing technologies with innovative business models to deliver increasingly affordable and accessible products and services will gain competitive advantage [17] [18].

Technology: it is important to have a differentiated product or service that actually adds value to the end consumer. To this end, the product offering must not be easily replicated and IPR (Intellectual Property Rights) should be carefully managed.

There are, however, additional challenges to the market adoption of semantic technologies. Although significant amounts of money have been invested in the development of novel semantic technologies, industry uptake appears to have not reached its full potential. This is partly due to the fact that enterprises are unaware of the benefits that semantics can bring about to their offerings. There are specific aspects of Semantic Technologies that may explain why it is hard for these technologies to be adopted by enterprises in the mainstream market [2]:

(1) Semantic technologies are hard to explain
(2) It is not easy to describe how Semantic Technologies might fit within a business
(3) There is a lack of innovation in semantic business models. These challenges impose obstacles to the market adoption of semantic technologies.

The next Section presents instances of how those challenges are met in real applications of semantic web technologies for healthcare technology.

IV. Business Cases Based on Semantic Web TechnolOGies for Healthcare

Recent advances in pervasive computing and sensor technologies have enabled the contextualised enrichment of business processes capitalising on the ability to sense, process, combine and interpret data of different modalities. Nowadays, it is getting harder to extract useful information from the enormous amount of data that is being collected in the medical information systems or eHealth systems due to the distributed and very complex nature of this data [20].

A common question is why - given the advent of IoT, AI and multiple sophisticated medical technologies introduced each year - healthcare has not been disrupted to a significant degree up to now. A reason is that healthcare remains expensive and inaccessible to many because of the lack of business model innovation. In healthcare, most technological enablers have failed to bring about lower costs, higher quality and greater accessibility. It is believed that semantic technologies can play a pivotal role in guiding growth among healthcare businesses [19].

This Section initially presents prominent examples of semantic web technology applications in the healthcare industry, along with their pertinent value propositions, business models and target audience. It then presents an analysis over them, regarding the competitive advantage and tangible business value of semantics for a healthcare business.

A. Healthcare Businesses using Semantics

This Section presents companies or startups whose core component and business model relies on semantic technologies. These business cases, prominent to the best of our knowledge, have been identified via searching the web and specialized startup databases. Our objective is to create a listing of existing "semantic" healthtech companies and identify their value proposition, their business model, as well as the means of how semantic technologies add value to the corporation and the end consumer. Table 1 provides an overview of the aforementioned listing, while each business case is examined in detail below.

In-JeT [21] is a research company and service provider in the area of internet-based healthcare services such as telemedicine. The company offers LinkSmart® a set of middleware *telemonitoring applications able to interconnect devices, people, terminals, buildings, etc*. The Service-Oriented Architecture (SOA) and its related standards provide interoperability at a syntactic level. On top of it, the LinkSmart® middleware provides interoperability also at the semantic level. This is achieved through a semantic model-driven infrastructure, whereby services exposed by devices can be described and consumed by various applications in Ambient Intelligence, Pervasive Computing, Ubiquitous Computing, Mobile Computing and Cloud Technologies. The company's various software and hardware assets are sold together with consultancy services.

Life Semantics Corp [22], a Korean health-tech startup, has developed a platform that integrates *health record data scattered among hospitals, governments, and corporations* to create a Personalized Health Management (PHM) platform that can prepare itself for the upcoming diseases based on a disease prognosis prediction algorithm. Life Semantics developed the first commercial PHR-based data platform called LifeRecord. It develops Hospital Information Systems (HIS) and semantic web technology for application in the area of life sciences.

Hi3 Solutions [23] provides HIT products, education, and consulting services that enable clients to engage effectively in *health information exchange, health data integration, and health care quality measurement* required to establish and comply with evidence-based best practices in health care. The mission of Hi3 Solutions is to accelerate widespread adoption and compliance with emerging HIT standards by offering the information integration infrastructure necessary to enable the use of health

information exchange standards, meaningful health care quality and performance measures, and standardized clinical decision support capabilities.

Intrepid Analytics [24] is using text analytics and custom medical ontologies, to be able to analyze online posts and reports to *anonymously track disease spread in near real-time,* as well as attributes, such as the medicines reported to be taken and subsequent reactions. This helps healthcare and regulatory bodies to stay on top of the quickly changing healthcare landscape.

Ontoforce [25] developed Disqover, a *semantic search platform that integrates various life-sciences data*. The platform uses semantic web technologies including ontologies in RDF and LinkedData, additionally supported by an indexing engine. The platform integrates private, public, and third-party data resources, all searchable via a single interface. Search results are enhanced by predefined data types. Ontoforce provides an integrated search of 80+ databases. The company also provides customizable visualizations: graphics, plots, tables, charts and maps.

Mendelian's [26] online technology addresses the needs of patients, physicians, providers, payers, and pharma. They provide for the best tools to *get the right diagnosis with speed and accuracy*. By continuously adding, curating and analysing conditions, symptoms, and genes along with clinical tests they aim to build the most comprehensive Rare Disease Knowledge Base. The patient can fill in a questionnaire with their signs and symptoms via an online form. The Mendelian engine processes then the information and provides a link to a detailed report to share with the doctor. The process is similar for physicians. Doctors enter patient's symptoms and clinical features. The input is processed semantically and provides an output with likely causative diseases genes and mutations.

SemanticMD [27] enables customers to *find, connect and license medical imaging data with expert annotations*. Customers can automate their data collection as well as use NLP to annotate radiological and clinical reports for search and analysis. SemanticMD Annotate enables teams to organize medical image annotation projects in a fun, flexible way and output the results for easy analysis by machine learning algorithms.

Teamarrayo [28] leverages the value of existing data sources, both internal and external, to transform them into ontologies and appropriate data models. In turn, it enables *data management and added value from data processing tools*. They provide bioinformatics services that include data curation, informatics ontologies (i.e., Gene Ontology, ChEBI, etc.). Their know-how also pertains to loading and utilizing large public data sources such as 1000 Genomes, TCGA, CCLE, and others.

Ontotext [29] is a company that utilizes semantic medical coding of patient records to help transform the raw patient data into structured knowledge. Its pipelines are designed to process large volumes of *patient records and to extract and semantically index data about patient diagnoses, treatments, medications and events timing*. All extracted medical data is normalized to resolvable instances from the medical Knowledge Graph. Thus, the extracted information is ready to be semantically fused with the LinkedData generated from multiple references public dataset (covering disease and symptoms, anatomical structures, generic drugs and products and much more).

Pangaea [30] is a domain expert in *bioinformatics, molecular biology, data engineering and machine learning*. The company aspires to help life science companies determine 'what data exists' and organize it in specific scientific or clinical contexts. Thereby, they are able to analyze and interpret it effectively, making the most from their investment in such data.

Seminte [31] provides assistance in preparing products for new markets by the use of international terminologies. SemInte assists in mapping an existing product's interface language to international terminology or in the development of a new product. The *process ensures that products are compliant to standards, data can be reused, compared and exchanged across third-party systems*, e.g., for EHR. SemInte identifies data required in specific documentation, creating datasets based on terminology e.g., SNOMED-CT, ICD-10, etc. needed, facilitates quality review process and helps with the technical dialogue with the vendors who shall implement the exchange standards (HL7-CDA and IHE-XDS) and data sets.

Healx [31] is a biotechnology company integrating artificial intelligence with expert pharmacology to *discover treatments for rare diseases, to share assets and to accelerate their uptake by clinical trials* [32] within as soon as two-years time. To achieve this, Healx has developed a comprehensive AI-based drug discovery platform for rare diseases, named HealNet. Their revenue model is asset sharing (e.g., clinical trial databases) across individuals and groups.

B. Discussion

TABLE I. HEALTHCAE AND TECHNOLOGY COMPANIES BASED IN SEMANTIC WEB TECHNOLOGIES AND THEIR PERTAINING ATTRIBUTES.

Company	**BUSINESS MODEL**				
	Semantic Component	***Value Proposition***	***Domain***	***Revenue Model***	***Target Customer***
In-JeT	Ontologies, Semantic Annotation, Semantic Middleware	Support patients in managing their chronic diseases efficiently and help healthcare professionals provide better care with more frequent, reliable and relevant data about health status.	Health Management, Telemedicine/AAL	Asset Sale, Consultancy	B2C, B2B
Life Semantics Corp	HL7 FHIR	Offer a total health management solution through a platform by utilising collaboration models with various healthcare related industries like insurance, finance, food and fitness.	Health Management, EHR	Asset Sale	B2B
Hi3 Solutions	HL7/v2/CDA/FHIR, HIT Standards	Health Information Technology vendor. They provide HIT products, education, and consulting services that enable their clients to engage effectively in health information exchange, health data integration, and health care quality measurement	Health Information Exchange, Healthcare Quality Measurement	Asset Sale, Consultancy	B2B
Intrepid Analytics	Data Mining, Medical Ontologies	Offer an AI platform focused on the healthcare industry- specifically for the biotech industry and patients. The platform supports the ingestion and organization of molecular and drug information. Home-grown medical ontologies support the integration and classification of data sets.	Health Information Exchange, Disease Tracking	Asset Sale, Consultancy	
Ontoforce	Semantic Search, Ongologies, LinkedData	Effortlessly extract “information” from public, third party and private big data and present them in a way they can be easily interpreted and used to support smart decisions.	Health Data Discovery, Health Data Visualization	License-based	B2B
Mendelian	Rare Disease Knowledge Base	Rare Disease Diagnosis, Faster - A search engine for rare diseases.	Health Data Discovery, Rare Disease Diagnosis	Freemium	B2B, B2C
Semantic MD	Semantic Annotation, Semantic Search, NLP, Ontologies (SNOMED, ICD-9/10)	SemanticMD provides a SaaS-based platform that enables the rapid training of medical image analysis applications and classifiers.	Health Data Discovery, EHR	SaaS	B2B
Teamarrayo	Data Mining, Ontologies (Gene Ontology, ChEBI)	Accelerate scientific research by providing solutions for data consolidation, management and visualization to scientists and clinicians.	Health Data Discovery, Health Data Visualization	Data as a Service	B2B
Ontotext	Data Mining, Semantic Annotation, LinkedData	To transform how organizations identify meaning across diverse databases and massive amounts of unstructured data by combining a semantic graph database with text mining, and machine learning.	Health Data Discovery, EHR	License-based	B2B
Pangaea	Data Mining, Ontologies	Pangaea’s value proposition is that it helps end users such as scientists, clinicians and researchers with little or no IT experience to find 'what data exists' and execute their analysis from a single web portal regardless of underlying tools and applications.	Health Data Discovery	Asset Sale	B2B
Seminte	Ontologies (SNOMED-CT, ICD-10), HL7-CDA, IHE-XDS	Making Healthdata sharable and compareable	Health Information Exchange, EHR	Asset Sale, Consultancy	B2B, B2G
Healx	Data Mining, Ontologies	Healx’s value proposition is about *asset sharing* (for example, making available clinical-trial databases that record the effectiveness of most drugs across therapeutic areas and diseases, including rare ones). Healx promises more *personalization* by revealing drugs with high potential for treating the rare diseases covered.	Health Data Discovery, Rare Disease Diagnosis	Asset Sharing	B2B

After examining real-world business cases of healthcare and technology, the benefits of semantic web technologies to them are clear. We may conclude that the findings from this state-of-the-art survey regarding those benefits are in line with previous studies in literature [17] [20], outlining the advantages and performance boosts in business due to semantic web technologies. Specifically, our review pinpoints the following benefits and advantages to the respective business cases examined:

- **The maximization of the value of information:** data online and offline is in abundance. As proved by the cases of Interpid Analytics, Teamarrayo, Mendelian, Pangaea and Healx semantic technologies can assist in making sense of these data, extracting knowledge patterns or detecting

previously unknown trends or details, that could be leveraged for disease management, new clinical trials and rare disease diagnosis. Health management solutions like In-Jet and Life Semantics Corp further prove how a researcher, medical practitioner or patient can maximize the value of information (for example coming from a variety of sensors that monitor activity, bio-signals etc) for effective self-monitoring.

- **Facilitated information diffusion:** Semantic search bridges the gap between humans and machines, and takes us further on a quest for meaningful information and knowledge discovery. The business cases of Hi3 Solutions, Ontoforce, SemanticMD, Ontotext that all constitute successful corporate examples that add value through knowledge modeling and flexible information sharing. When data is released from individual applications the diffusion of knowledge is empowered.
- **Greater level of future-proofing and re-use**: to illustrate how business performance is strengthened by utilizing semantics for future-proofing and re-use, we will utilize the example of rare diseases. Rare diseases can take many years to diagnose. This represents an odyssey for patients, a challenge for physicians, a headache for care providers, a waste of resources for payers and missed opportunities for pharma. Diagnosing Rare Diseases is no small feat. Indeed, according to Mendelian, it takes on average 8 years and 4 specialists, often involving misdiagnoses. The fact is that there are over 8,000 rare conditions, the information on them is scattered across multiple sources and new research is published every day. By leveraging knowledge graphs and proprietary semantic web technologies, healthcare technology providers like Mendelian and Healx have the opportunity to extract new phenotypes from recent publications, access results from past studies so as to guide clinical investigations and assist in diagnosis. Such a knowledge structure can have another side effect. It is not rare in clinical trials that researchers discover that a drug is more effective on treating a completely different symptom (the case of Viagra constitutes a well-known example in this respect). Providing medical researchers and clinicians the ability to search and identify such cases easily and in a meaningful context by leveraging knowledge graphs and ontologies can evidently facilitate decision support, re-use of knowledge and clinical interventions.

From a business perspective, semantic adoption is still in its infancy, though the potential is huge. Most of the companies in our study are startups, which means that they are still developing their business models and their viability depends on funding. However, the fact that many of them, such as Healx, have raised millions of euros to scale up shows that investors and industry experts are eager to invest in such initiatives and believe in their sustainability.

As in healthcare technology knowledge extraction and information integration is pivotal for success, startups should consider adding a semantic component to their product suite and develop a business model based on a strong competitive advantage. Business models from the domain of e-retailers and electronic stores are the most common among high tech market providers. However, new semantic business models need to be different so as to address new customer needs and add value across the buyer's journey.

V. Conclusion and Future Work

To meet the challenge for high quality and efficient care, highly specialized and distributed healthcare establishments have to communicate and co-operate in a semantically interoperable way. Despite the complexity of current semantic web technologies, several businesses have realized the vision of bringing research to the industry and applied these technologies for profit. After examining real business cases and their pertaining technological and business aspects the benefits of this practice are clear. Technologies such as Data Mining, Semantic Annotation and Search, Ontologies and LinkedData already provide tangible solutions to problems such as Health Management, Telemedicine, Health Information Exchange, EHR and Health Data Discovery, servicing not only healthcare but also the life science research.

As for future research directions, we consider expanding the survey but also diving deeper into categorizations and analysis of criteria. Many more business cases are emerging and have to be added to future more in-depth reviews. In parallel, this review has only scratched the surface it terms of criteria, categories and clustering of the various semantic components and domains, i.e., problems the companies solve, from a technological perspective, as well as the value propositions, revenue models and customer bases from a business perspective. Finding the pertaining groups and strategies of companies in a more in-depth analysis survey can reveal significant trends and methods for applied semantic web technologies in healthcare in the coming future, with real, tangible business value.

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