Multi Agent-Supported Dynamical Integration of Electronic- with Personal Health Records on Blockchains for Ad-hoc Healthcare Quality Improvements

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Abstract. This white paper is based on the conferece paper [15] and addresses existing problems with integration of healthcare information from Electronic Health Records (EHR) and Personal Health Records (PHR) systems because of structural and semantic heterogeneity. Existing ways of PHR- and EHR collection include harvesting medical and individual data from different data sources that store different medical, not standardized data. Such a heterogeneity increases the complexity of merging PHR and EHR and lack of qualitative trust between contracting parties. On the other hand, blockchains are inherently resistant to modification of the data and are secure by design. We focus on the integration process as a main aspect for solving the heterogeneity issue. Thereby, we aim at reducing the merging complexity by defining the requirements for PHR data collection and creating an ontology for a semantically sound data-set merger for personal-centric healthcare systems and we evaluate the results with formal means. To enable trust in decentralized socio-technical healthcare system we use Ethereum smart contracts on top of the blockchain as a communication way in the context of multi-agent system.

Keywords: Personal health records, health information exchange, health information systems, multi agent, smart contract, blockchain, decentralized, peer-to-peer, e-governance

1 Introduction

In recent years, Personal Health Records (PHR) have emerged as a patient-centric model of health information exchange [17]. The main principle of PHR is that a person is the author and owner of his/her medical data that can be shared with other individuals including healthcare professionals, or automated clinical decision-support services, e.g., Evidence-Based Medicine electronic Decision Support (EBMeDS)[1]. The growing amount of personal data available increases the

[1] http://www.ebmeds.org/

role of personal-centric systems in healthcare. The classic explanation of Electronic Health Records (EHR) assumes that EHRs are created and maintained by medical professionals.

The complex analysis and processing of an integrated PHR with EHR improves the quality of healthcare by helping to mitigate diagnosis errors involving patients in healthcare decisions [21]. As EHR contains data mostly of patient diseases, PHR contains information about a patient's lifestyle, activity and regular health-state measurements, e.g., blood pressure and blood glucose taken at home. Integrated EHR and PHR cover the whole lifetime period of individuals and thus, enables the understanding of the context for an individual's health state.

Literature review [6, 9, 33] shows that most researchers provide solutions for integration challenges based on data-heterogeneity reduction in a static way by developing a new ontology, or merging existing ones. This approach is efficient for decreasing the heterogeneity of different EHR standards and a limited number of processes. However, the amount of PHR data is rapidly growing with the development of new applications and devices. The number of processes using PHR is not limited, as PHR data is also used by shared workflows. Therefore, an efficient integration of PHR and EHR requires a dynamic approach that concentrates on the process as a basis for the efficient dynamic integration of EHR and PHR, rather than focusing on data standardization. Paying attention to data-flow processes is an important part of EHR and PHR data integration as health data flows along processes in the distributed system.

According to research [13] shared blockchain technology provides a new framework for supporting business collaborations that is based on having a high-reliability, shared, trusted, privacy-preserving, nonrepudiable data repository that includes programmable logic in the form of smart contracts. Blockchain technology is used to share a ledger of transactions across a business network without control by any single entity [22]. The distributed ledger yields cost-efficient commercial relationships where virtually anything of value that can be tracked and traded without requiring a central point of control. A blockchain allows a system of independent actors to share a record of digital assets, transactions and information without the need for a central, trusted third party. It enables users to replace certain inefficient intermediary functions in different economic, social and technological systems with decentralized digital networks [4].

A smart contract is a program that runs on top the blockchain on the protocol layer and has its correct execution enforced by the consensus protocol [19]. A contract can encode any set of rules represented in its programming language such as Solidity [8] and is identified by an address (a 160-bit identifier) while its code resides on the blockchain. A smart contract is invoked by a user sending transactions to the contract address. As described in [5], Ethereum supports stateful contracts in which values can persist on the blockchain to be used in multiple invocations.

This paper fills the gap by researching the integration process of PHR and EHR in the context of dynamic decentralized person-centric systems. The main research question is how to collect and process PHR data in the context of integrated healthcare to improve the quality of diagnostics and cures. The data collection process takes place before the integration and its proper definition helps to integrate only needed data by filtering out noise for a specific healthcare-process goal. We deduce the following sub-questions from the main research question. What are the requirements for the PHR data collection? The answer to this question aims at filtering noise in preparation for EHR mergers. What is the ontology for the integration process? The ontology decreases the integration complexity while data is merged in the contexts of different processes. What is the integration process for merging dynamically EHR and PHR in a targeted way? The definition of an integration process is based on the ontology and results in a better understanding of the context where the collected data is used.

The remainder of the paper is structured as follows. Section 2 presents related work and Section 3 discusses requirements for PHR data collection. Next, Section 4 gives an ontology for the integration of processes and Section 5 address the integration process of PHR and EHR. Section 7 compares the results of this paper to other research work and finally, Section 8 concludes the paper together with providing directions for future research.

2 Related work

We present important background literature that is the foundation for the sequel of this paper. Traditional solutions for solving interoperability issues in the healthcare domain include using a common data standard. Research [29] proves that Fast Healthcare Interoperability Resources (FHIR) [3] support PHR data and can be used for EHR-sharing. Research [32] presents the development of a Systematized Nomenclature of Medicine Clinical Terms (SNOMED CT) [34] query module that can convert a patient problem description, or clinical measurements into SNOMED CT codes. The Health Level 7 (HL7 CDA) [10] may store personal health information in a standardized way in these resulting documents. Logical Observation Identifiers Names and Codes (LOINC) [20] are used for identifying medical laboratory observations and exchanging laboratory-test information between healthcare and laboratory providers.

On the other hand, the use of an ontology can overcome issues of semantic and syntactic heterogeneity of health data to facilitate record linkage [11]. Research [14] proposes an ontology of a context information model as a basis for building u-healthcare services. Ubiquitous Healthcare means a system monitors bio-information in real-time using certain devices such as mobile equipment in a home network and provides medical examination with treatment whenever and wherever needed. Another approach for reducing the heterogeneity of health data is to provide a Wearable KaaS platform [14] to smartly manage heterogeneous data coming from wearable devices in order to assist the physicians in supervising the patient health evolution and keep the patient up-to-date about his/her status. The latter approach describes a wearable healthcare ontology.

Other researchers state that an ontology decreases the complexity of sharing medical data between different healthcare information systems and different databases when being used together with Internet-of-Things (IoT) platforms [16]. In research [24], ontologies are used for giving meaning to the silos of heterogeneous wearable data in healthcare. Furthermore, the ontology focuses on the integration process and does not describe the process of data collection that is performed before the integration takes place.

According to [35], the Agent Oriented Modelling (AOM) approach is geared towards designing socio-technical systems consisting of humans and software that are respectively termed as human agents and man-made agents. Research[18] provides the solution for heterogeneity as development of software agents and systems that attempt to reconcile ontological differences without explicit formal ontologies.

Authors of [40] propose health system architecture based on blockchain to enable patient to own, control and share their own data easily and securely without violating privacy, which provides a new potential way to improve the intelligence of healthcare systems while keeping patient data private. Research [30] assumes that each patient care event was influenced by one or more events before it. For example, a prescription may be issued only after a positive lab test was received. The notion of historical care influencing present decisions fits well into the blockchain model, where the identity of a present event is dependent on all past events. Blockchain offers numerous opportunities for usage in the healthcare sector, e.g. in public health management, user-oriented medical research based on personal patient data as well as drug counterfeiting [23].

We build non-human agents to support common international healthcare data standards to reduce the complexity of data extraction. We create an ontology to define the integration process supporting agents. The AOM approach is projected to the healthcare domain to reduce heterogeneity problems. Blockchain is used to solve data security and consistency issues while Ethereum smart contracts increase personalization of care processes and data transfer between assistant agents.

3 Requirements for PHR data collection

Processing individual data from different data-sources improves the quality of healthcare processes while it simultaneously creates new challenges. According to research [37], there exists no clear definition of PHR and the PHR data is not on a sufficient level of quality to be useful for medical decision making. Also a graphical user interface for PHR systems should be familiar to the user to reduce possible errors during data input. In contrast to PHR challenges, EHR systems exist on a national level[2] and have common data standards with international

[2] www.etervis.ee

classifiers as HL7, SNOMED CT and LOINC. The decentralization of PHR results in a complex merging of PHR with EHR for further processing. To reach our goal, we must explore the requirements for PHR data.

In Section 3.1, we analyze the stakeholders for the integration process to place the scope for the domain being analyzed. Stakeholders are then used as human agents in the goal model that guides requirement elaboration. The goal model consists of functional and quality goals, their sub-goals and actors. In section 3.2, we define primary goals for the stakeholders and sub goals. The list of goals and sub goals is used for requirements generation.

3.1 Stakeholders of integration process

Before defining system- and software requirements, the stakeholders are defined [38]. In the scope of integrated healthcare, there are different main stakeholders: individuals, researchers, healthcare professionals, state organizational units as statistics- and social departments, and insurance companies. Individuals are users of PHR systems who receive personalized medical services and use personal information to improve their health state. The improvement is achieved by receiving recommendations and reminders from Clinical Decision Support System (CDSS) processing personal data. Researchers improve the healthcare analysis results by combining both PHR and EHR. Healthcare professionals improve the quality of decision making processes that use both data from healthy and sickly periods of an individual's life. The integration of EHR and PHR improves the healthcare processes of the state by improving preventive healthcare. Insurance companies provide personalized services to individuals and businesses for encouraging a healthier way of life.

3.2 Domain analysis and design

Figure 1 presents a goal model, comprising functional- and quality goals with each goal decomposed into sub-goals hierarchically from top to bottom. In the person-centric system, there are both human- and non-human agents. According to [28], analyzing the problem of this socio-technical domain can be performed by using a goal model. The objective of goal models is to serve as communication media between technical- and non-technical stakeholders for generating understandable domain knowledge. We use goal models in the context of requirements-engineering processes.

The main goal is *Prevent disease* that has quality goals. The system offers some advantages to the individual to prevent diseases in the future. Quality goals: scalable, modifiable, integrable, interoperable and secure are the main quality requirements for the cross-ogranizational systems [27]. The main goal splits into two sub-goals: *Provide home care* in a regular manner and *Provide ambulatory care* assuming that it is available. The first comprises two goals: *Monitor health status* and *Keep healthy lifestyle* that involves the role of health professional and includes two goals *Provide health guidelines* and *Assess current life style*. Guidelines should be easy to understand for the individual and personalized

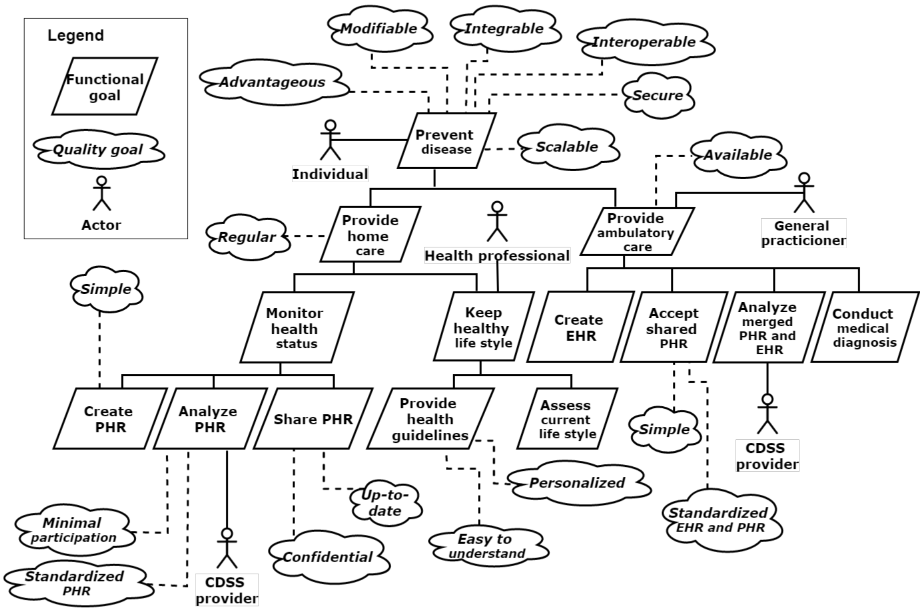

Fig. 1. The goal model for the personal-centric healthcare system.

to his specific needs. *Monitor health status* goal includes three sub-goals: *Create PHR* in a simple way, *Analyse PHR* performed by the role of CDSS provider with a minimal participation of an individual using standardized PHR, *Share PHR* including quality requirements that correspond to the security and relevance.

The goal *Provide ambulatory care* has four sub-goals. Two of them are related to the processing of shared PHR: *Accept shared PHR* and *Analyze merged PHR and EHR* performed by a CDSS provider. Accepting shared PHR needs to be simple enough for general practitioners in order to improve the results of ambulatory care. PHR and EHR should be standardized in order to prevent semantic heterogeneity. Other sub-goals correspond to the standard ambulatory care process are *Create EHR* and *Conduct medical diagnosis.*

4 An ontology for the integration process

The processing of integrating EHR and PHR requires an ontology definition to reduce semantic- and syntactic heterogeneity. Health and medical knowledge existing in both EHR and PHR is presented as an artifact in an artifact-centric business process model (ABPM) and being processed by different organizations. To build an ontology, we define the lifecycles for EHR, PHR and the merged artifact in Section 4.1. In Section 4.2, we present a meta-data model for the ontology that covers the surrounding system for the integrated data. Section 4.3

explains in more details the most important classes and their relations in the ontology.

4.1 Artifact lifecycle

The lifecycle of a common data artifact in Figure 2, comprises three stages [31]. The acquisition includes states related to data creation and preliminary processing before storing. PHR is entered manually, or generated by smart devices, is filtered to eliminate noisy data and the quality of PHR is being evaluated to increase its value after which PHR can then be amended. The processing stage includes PHR normalization and analysis. During the preservation stage, PHR is classified, archived, can be shared with others and processed again. PHR is accepted by healthcare professional to be merged with EHR.

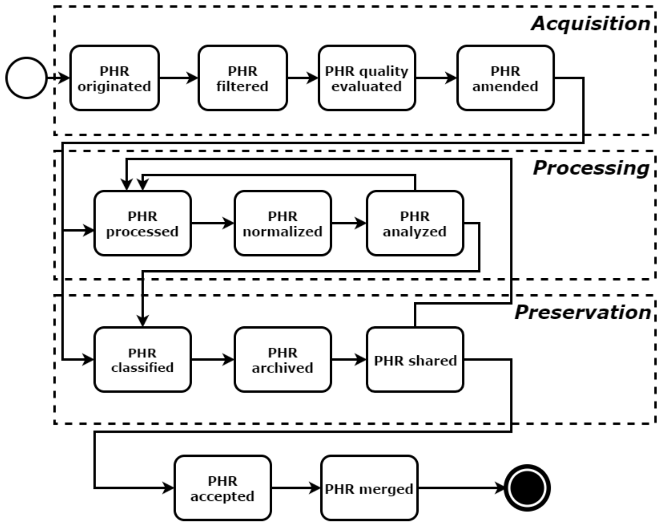

Fig. 2. PHR lifecycle

After an EHR is created in Figure 3, it is verified and amended. Processing includes three states, i.e., processed, de-identified and analyzed. Depending on the agent type being either human or non human, EHR needs to be de-identified first. Preservation consists of classification, archiving and exporting. After the EHR is available for export, it can be used in other legal organizations and merged with shared PHR.

The merged artifact in Figure 4, is originated after PHR and EHR are merged, verified and described before processing or preservation. The processing includes states processed, de-identified and analyzed. If an individual restricts access to personal data, a merged artifact is not preserved but can be processed.

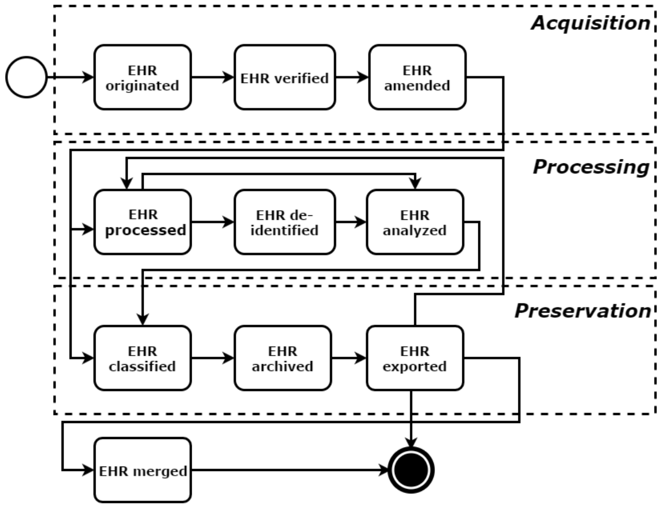

Fig. 3. EHR life cycle

In the preservation stage, the merged artifact is classified, archived and exported to external systems.

4.2 A Meta-Data model for the integration process

We consider the merged artifact in the context of a decentralized and distributed person-centric system. The meta-data model covers main classes involved in the integration process. We use an ontology engineering approach described in [12] and combine this approach with assistant agents described in research [18]. For building an ontology, we use the free and open source editor, Protégé [26], for systematic knowledge acquisition. The tool includes a graphical user interface, plugins and built-in reasoners for ontology validation. The OWL-ontology[3] describes the main classes involved in the EHR and PHR integration process. In OWL, every class is derived from the class *Thing*. Due to the limitation of space we divided class hierarchy view into two columns and give an explanation below.

An *Activity* represents the action performed by an agent and can be specific to the healthcare provider as *HealthCareProviderActivity*. *Interaction* describes an action where both person and health professional are involved. Each activity has *ActivityResult* that contains *Reccomendation*.

An *Agent* represents either a person, or a health professional as *Person*, or non-human agent (*NonHumanAgent*). An example of a non-human agent is CDSS, that supports a person with recommendations. We consider believe-desire-intention (BDI) agents [7] as non-human agents. This concept provides a separation of the activity of selecting a plan from a library, or an external

[3] https://goo.gl/v5ybCY

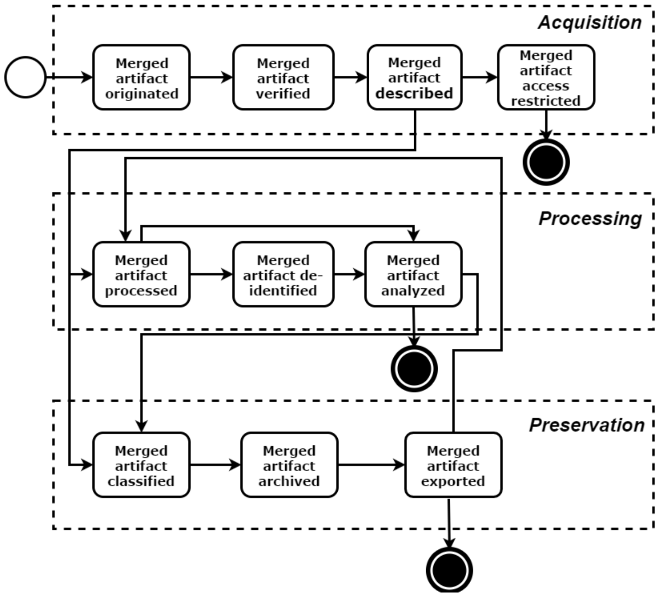

Fig. 4. Merged artifact lifecycle

planner application from the execution of active plans. *AnthropomorphicProperty* represents features of non-human agents that resemble human behaviour.

HealthKnowledge contains useful information for changing the health status of a person. In our case, it can be either *DiagnosisProbability* or *Risk* specific to a person. The *Information* contains classes responsible for information about a person's health such as *HealthRecord*, or *Guideline*. Health information is needed when a clinical decision happens based on the health knowledge.

Classes *LifeStyle* and *Behavior* are equal from the point of view that a person's lifestyle is the behavior of an agent. A *Resource* is used in the context of activities and represents the resources needed to collect and process PHR and EHR. An *Active* resource is an agent that collects and processes data. *Passive* resource is usually a device, generating the information.

4.3 Ontology graphs

The following graphs present the most important classes of the ontology from the meta-model. Important related classes and relations between them we described below.

4.3.1 Class Person The ontology of Figure 6 focuses on the *Person* class that has *Motivation* to improve his, or other persons' *Health*. *Awareness* of health status helps *Person* to maintain a healthy *Lifestyle*. A *Person* can be at

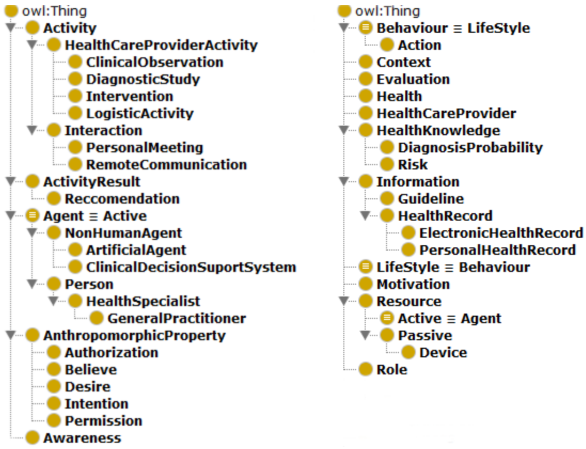

Fig. 5. The class hierarchy of the integration-process ontology

the same time a *HealthProfessional*, or a*GeneralPractitioner*. A *HealthRecord* includes health related information of a *Person* and can be a *PersonalHealthRecord* that is owned by a *Person*, or an *ElectronicHealthRecord* that is created by a *HealthSpecialst*. The *Interaction* involves an *Agent* that can be a *Person*, *HealthKnowledge* is either derived from *ClinicalDecisionSupportSystem*, or a *HealthSpecialist* and *Information* that can be a *Guideline*. *HealthKnowledge* includes *DiagnosisProbability* and a *Risk* related to health.

4.3.2 Class HealthCareProviderActivity Class *HealthCareProviderActivity* covers in Figure 7 different types of activities that can be performed in the healthcare center. Those include *Intervention* that attempts to change the status of a persons health, *ClinicalObservation* that generates information about health, *DiagnosticStudy* that describes the actions needed for diagnosis determination. The activity *LogisticsActivity* supports other healthcare-provider processes, such as admission to a ward unit. *HealthCareProviderActivity* is an *Activity* that has a transitional relation to *Resource* that can be *Active* or *Passive*. *Interaction* is another type of activity and describes the contact between person and healthcare specialist while class *HealthCareProviderActivity* contains only activities specific to *HealthCareProvider*. Each activity has *ActivityResult* that can be a *Reccommendation* to the person.

4.3.3 Class Agent Class *Agent* that is presented in Figure 8 has two types: *Person* and *NonHumanAgent*. One agent can have more than one *Role* assigned and also a role might be assigned to more than one agent at the same time. An *Evaluation* is performed by an agent that has a *Behaviour*. The *AntropomorphicProperty* includes features of artificial agents that are made to resemble hu-

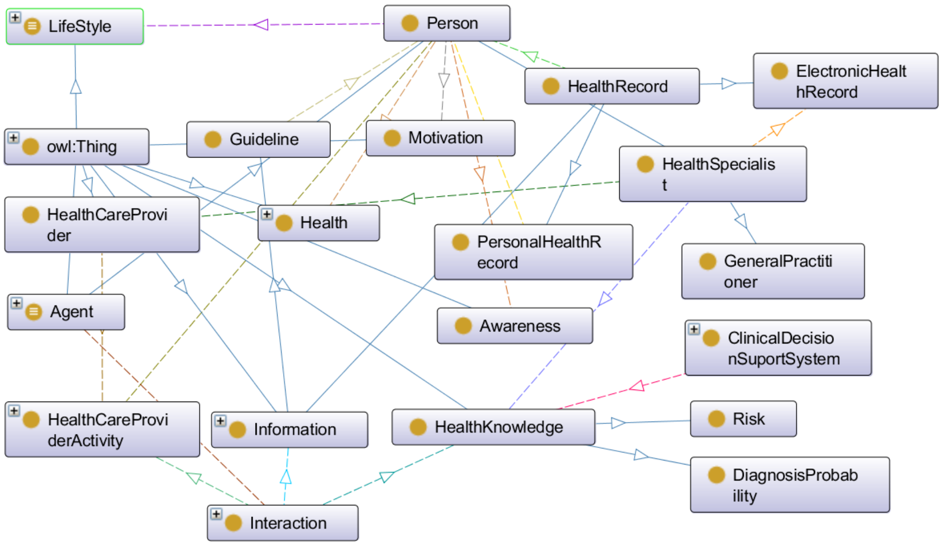

Fig. 6. *Person* focus and neighbouring classes.

man characterstics. The sub-classes of *AnthropomorphicProperty* are presented as BDI-agents.

5 Integration process

We describe the integration process in Figure 9 with the Business Process Model and Notation (BPMN) [1], a graphical representation for specifying business process model. The integration process is dynamic and involves both human and non-human agents. Non-human agents are software components that communicate with each other and support human agents with appropriate results. To solve heterogeneity issues for the integration process, we use assistant agents as described in research [18]. A human agent initiates the process that has information about data needed to be processed and an agent responsible for processing. After the process starts, the artificial agent defines the required data, that is needed to reach the final goal of the process.

PHR- and EHR data are retrieved in parallel in Figure 9 by the same, or different agents from a PHR- and EHR-managing system. After the data is retrieved, it is filtered for noise. An agent has information about processing input requirements and if the filtered data cannot be processed as is, it is merged. During the merge task, an error can occur, if it is not possible to merge the data. After the merge, data is validated and then confirmed by a human agent if needed. Different data sources can contain duplicate- or conflicting data. The data collected by each agent is processed and the results are compared. The most appropriate selected data are presented to the human agent.

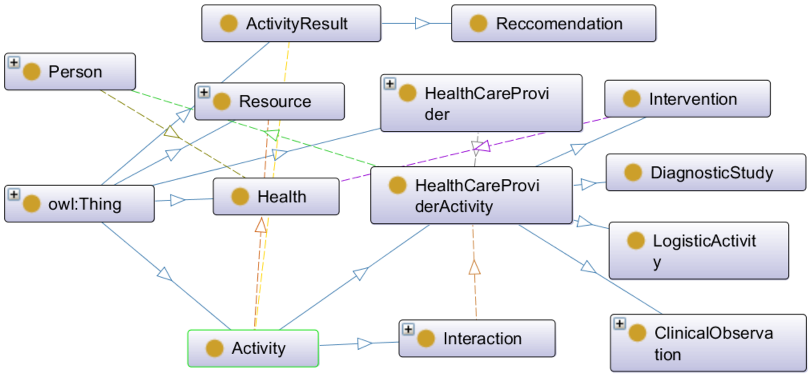

Fig. 7. *HealthCareProviderActivity* focus and related classes.

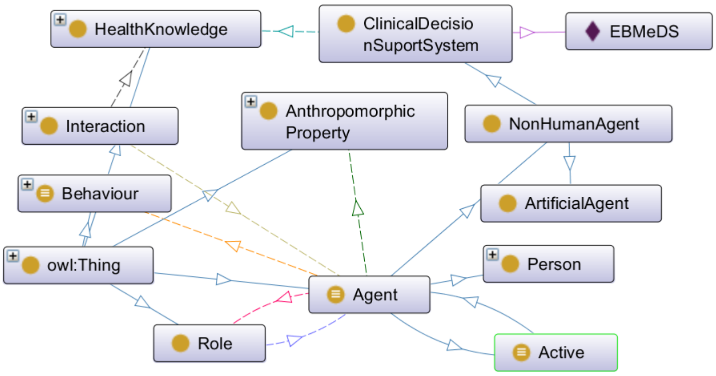

Fig. 8. *Agent* focus and related classes.

6 Running case

We consider prevention of cardiovascular disease with continuous blood pressure monitoring as cardiovascular disease is the number one killer in the US and hits more than all cancers and AIDS combined. Different studies have shown that when person's blood pressure does not drop at night, persons are more at risk for heart disease while every five percent decreases in drop in blood pressure at night reduces risk of cardiovascular disease by twenty percent.

The story shown on Figure 10 describes the basic process of personal guidelines preparation with the help of smart contracts. In our story Mike monitors his blood pressure at home. His measurements are analyzed on the background and stored to blockchain. Mike decided to share his home measurements with his doctor John and gives him a private key. Mike and John are signing the smart contract that contains personal guidelines developed by John specially to Mike that are based on the combination of Mike's historical medical records from hos-

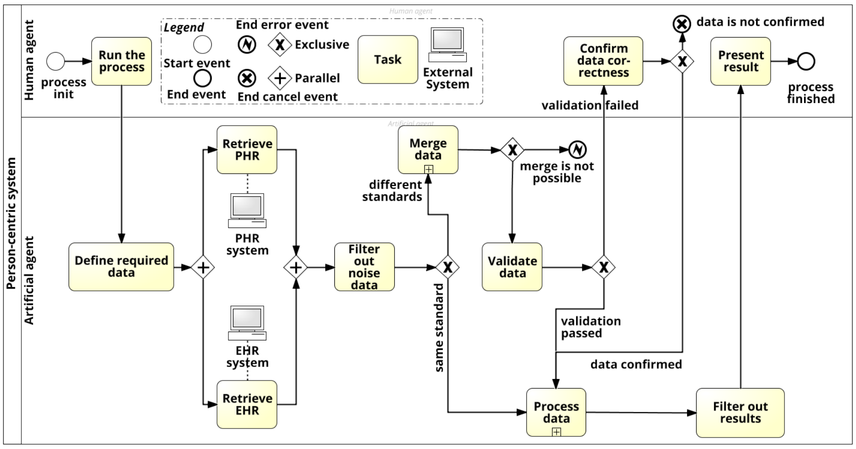

Fig. 9. BPMN diagram for the integration process

pital and continuously created measurements taken by Mike at home. Most of the Mike's data are collected on the background without active participation. John also does not need to constantly monitor Mike's home measurements as smart contract based system will notify him with alert if his attention is needed. Usage of smart contract requires some of Mike's tokens.

Medical data flow on Figure 11 describes the basic process of providing personal medical information to information brokers such as researchers and insurers. In our example Mike has collected medical data at home and decided make it valuable for other stakeholders by making it visible to medical data broker agent. Medical data broker is looking for data required by stakeholders from different domains such as insurance and pharmacy. AI broker agent connects Mike and people interested in his data. According to smart contract Mike's data is exchanged for tokens provided by data broker.

7 Discussions

Literature review shows that mostly research focuses on either decreasing the heterogeneity by merging ontologies, or the usage of a common standard. Some research considers the usage of multi-agent systems (MAS) for improving the integration processes in healthcare between EHR systems [2, 36]. In our research we use ontology in a different manner to define the integration process itself and not the data processed. Also we extend the usage of MAS to enable integration between EHR and PHR systems.

We define the integration process as a basis for healthcare quality improvement where both individual and healthcare professional are involved. As the number of PHR data sources is not limited, we first define requirements to PHR

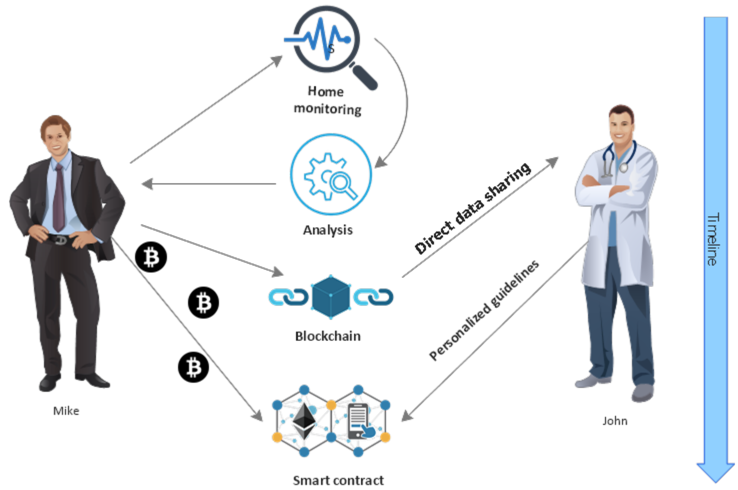

Fig. 10. Running case 1. Medical data flow between person and medical specialist.

collection to filter out noise data first. Then we define an ontology for the integration process in order to set up main entities and their relations in the scope of simultaneously processing of PHR and EHR. The ontology includes both the individual's and healthcare specialist's area of responsibility that are in a close relationship. Finally, we define the integration process as an interaction between healthcare professional and assistant agent in MAS that support the human agent with intelligent and dynamic healthcare-data processing.

An evaluation of the ontology we perform with the HermiT reasoner that is based on a novel hypertableau calculus [25] to provide much more efficient reasoning than any previously known algorithm. The integration process we validate with the Signavio[4] tool that checks BPMN diagrams for existing conflicts. We evaluate our solution by analyzing similar research results and using the framework for evaluation in design-science research (FEDS) [39]. We select the evaluation goal as rigor because we want to ensure that our artifact causes an observed outcome. The integration process of EHR and PHR happens in a socio-technical environment and therefore is a purely technical artefact where human risk and effectiveness strategies are required. In the context of this paper, we determine the technical properties to evaluate the maintainability and functionality.

Our solution presents the dynamic integration process. Its maintainability assumes changes implementation via new agent creations, or the modification of existing ones. If we need to add a new data source to the process then we just need to add a new agent. The functionality of design includes interoperability

[4] https://www.signavio.com/

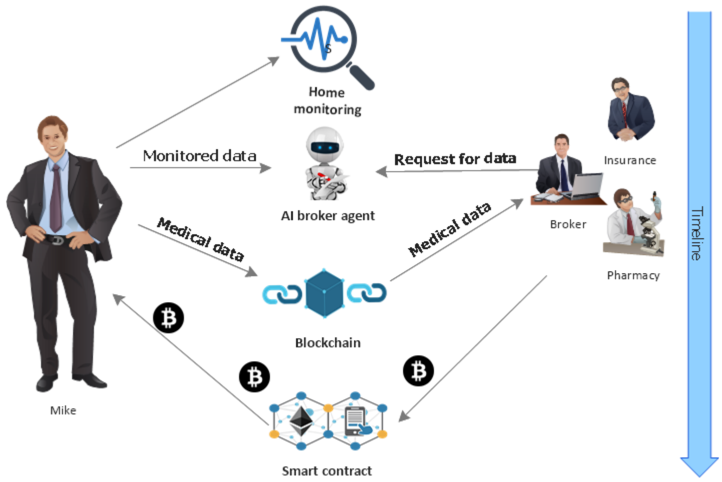

Fig. 11. Running case 2. Medical data flow between person and data broker.

as a main process for collecting and processing data. Data that is collected from different data sources is filtered by its accuracy and context.

8 Conclusion

We consider the dynamic integration of EHR and PHR from the process based point of view. We propose requirements for collecting PHR in the context of healthcare quality improvement. Then we define an ontology for the integration process describing main classes and their relations involved in the integration. Finally, we use an ontology for building the process by using a BPMN notation that includes both human- and non-human agent interactions.

To improve the quality of diagnostics and cures, PHR data needs to be collected continuously by a person. PHR is either entered manually, or imported from external PHR-based system. Processing of PHR requires filtering out noise first and happens in a dynamic way with participation of both human- and non-human agents. Requirements for PHR data collection are aimed to meet the main functional goal of preventing disease. To meet that goal, data is collected by a person in a simple and trustful way and support data sharing options with healthcare professionals. The ontology for the integration process focuses on a person and his activities. The integration process includes BDI agents reducing the problem of data heterogeneity problems by dividing the functionality and responsibility for data collection from different data sources and processing. The integration process starts from a required data definition that limits the scope of valued data. After the required PHR and EHR data is collected, noise data is filtered out first. If collected data is not standardized it is merged and validated. After processing, the results are filtered in order to present only valuable information.

We evaluated the design presented in this paper by comparing the results to other research results in the same area. Literature review shows that other research solves healthcare data heterogeneity problems without considering the merge problem in the context of an integration process. We define a dynamic integration process as a solution for healthcare quality improvement. Still, the design presented in this paper lacks a real use case and social evaluation as it involves individuals and healthcare professionals. Future work comprises conducting a case-study based evaluation of the design and prototyping technical solutions in order to ensure the compatibility with existing processes in healthcare.

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