Using Activity Theory and Causal Diagrams for Designing MultiAgent Systems That Assist Human Activities

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Abstract. In this paper, we propose to use the Activity Theory and causal diagrams for modelling human activities with the aim of facilitating the specification of an agent-based assistance system through the Prometheus methodology. As a case study, we consider the elder medication activity, a recurring, complex and context-rich activity that involves several individual and collective activities which may require assistance. From the data collected in a contextual study of the elder medication, we modeled the medical consultation and refill medicine activities. Our results demonstrate that causal diagrams allow to capture the dynamics of the modelled activity, introduce the assistance of intelligent agents, extract the multiple scenarios synthesized in the activity structure and translate them into Prometheus artifacts.

1 Introduction

Since the appearance of CommonKADS [1] and throughout the development of multiple multiagent systems methodologies [2–4], peoples' knowledge and their participation has been a key element in the system specifications. As a result, software agents have been proposed as intelligent assistants for human development activities with the purpose of learning from the expert and mimicking some limited functionality [5, 6]. In other approaches like Electronic Institutions [7], people are introduced in the decision loop through the use of User Agents that serve as an interface between them and other software agents in a regulated organization environment. This interaction typically required appropriate Human-Computer Interfaces for delivering information and capturing human feedback. But the most recent advances in pervasive computing are enabling many other alternative ways of perceiving human presence and activity [8].

For this reason, the development of multi-agent systems to assist human activities have become a tangible reality in whose design the human must be placed in the center again [9]. This assistance can take advantage of the vast Artificial Intelligence experience on the development of protocols for gathering information, negotiating, resolving conflicts, coordinating activities and allocating resources [10, 11].

By modeling human activities, we can identify the conditions that must be enabled in order to facilitate their development. For instance, in [12] is proposed an ontology to model the context of the activities of daily living (ADL). The contextual information of the ADL is used by a multiagent-based component to support the activity or prevent an older adult from the a risk associated with the ADL. Other works propose to model a specific human activity. For instance in [13] authors model the human office activities and use multiagent systems to keep track of the state of their users so it can anticipate the users needs and proactively address them.

However, in these works exist a gap between the analysis of human activities and the specification of a Multiagent system that assist the activity. Therefore, in this paper we propose using activity theory to identify the contextual information of the activity and causal diagrams for modelling the dynamics of the activity, which facilitate the process of identification of the artifacts needed to build a multiagent system with the Prometheus methodology. To illustrate our proposal, we consider as a case study the elderly medication activity, since it is a recurrent, complex and context-rich activity, which involves several individual and collective activities, such as attending to medical consultations, taking prescribed medicines and refill medicines [14].

This paper is organized as follows. In section 2, we present the theories used for modelling human activities, some philosophical and modern approaches to causality, and a brief overview of the Prometeus methodology. In section 3 we present the findings of a contextual study of elder medication regarding doctor's visit activity, the modelling of this activity using Engeström's approach and present a methodology for translating it into an annotated causal diagram. In section 4, we present how agent-based assistance can be introduced in human activities and be codified in Prometheus artifacts. Finally, we present our conclusions and future work.

2   Background

2.1   Activity Theory

The activity theory (AT) is a multidisciplinary and philosophical framework that allows us to understand and study the different forms of the human activities as an individual and collective process [15]. There are three theoretical generations of AT [16]. The first generation is grounded on the concept of *mediation* proposed by Vygosky, which refers to a human performing an activity through a device or tool to achieve a particular objective. This approach considers that activity is an individual process. The second generation was represented by the ideas of Leonti'ev, who introduced the term of *labor division* to define an activity as collective or individual. In addition, Leonti'ev also defined a three-level scheme (activity-actions-operations) to describe a hierarchical structure of activity in which the *activity* is the basic unit of analysis. An Individual activity can be part of a collective activity that involves more than one person working on a same result or objective. Individual activities are composed of *actions*, that is
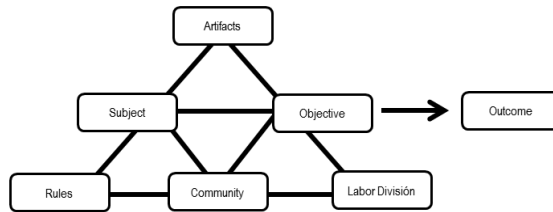
Fig. 1. Engeströms human activity system model

something that the person makes consciously to achieve a goal. Actions are comprised by *operations*, which describe how the person does the action.

The third generation of AT is represented by the ideas of Engeström, who consider the ideas of the first and second generation and adding new concepts, such as community, roles and rules to describe the *structure of human activity*. Engeström represent the human activity by a triangle (see Fig. 1) which is composed by the following concepts: a *subject* refers to the individual or sub-group chosen as the point of view in the analysis. The *object* refers to the raw material or a problem space at which the activity is directed and which is molded and transformed into the *results or outcome* with the help of *artifacts* that can be physical or symbolic. The *community* comprises multiple individuals and/or sub-groups that share the same general object and other elements such as *locations*. The *labor division* refers that every individual that participates in the activity has a role. Finally, the *rules* that refer to the explicit and implicit regulations, norms and conventions that represent actions and interactions within the activity system.

AT has been used in computer science to design computer applications, especially in the study of the incorporation of new technologies and computer human interfaces [15]. In addition, AT also has been used to model the context of human activities and to describe situations [17].

2.2 Causality

Since Aristotle, *Causality* has been used for explaining natural phenomena or processes in terms of changes [18]. Change is explained through causal relations between events, objects or states of affairs, where the second one (the effect) is a consequence of the first one (the cause), and the cause precedes invariably to the effect. In fact, Aristotle distinguished between four types of causes that intervene on a change: *material cause* (the physical matter used/consumed during change), *formal cause* (the form or plan used for transforming the matter), *efficient cause* (the agent performing the change) and *final cause* (the goal pursued by the agent).

Recently, Pearl revised Bayesian Networks claiming that directed arcs between random variables can also represent causal dependencies [19]. This is, the arc $V_1 \rightarrow V_2$ has a second interpretation which indicates that the event V_1 occurred previously or simultaneously to V_2 and that V_2 is a consequence of V_1. This assumption is different to the original statistical notion of correlation, which does not imply directionality or temporal precedence, and it is used by Pearl for developing the Do calculus, which estimates the probability of setting a condition y through the intervention of x, denoted $P(y|do(x))$, based on previous observations of the phenomenon [20].

2.3   The Prometheus Methodology

Prometheus is an iterative methodology for designing, documenting and building intelligent agent system, which uses goals, beliefs, plans and events. The main difference of Prometheus with other multiagent methodologies is that it uses an iterative process over software engineering phases rather than a linear waterfall model [2].The Prometheus methodology consists of three phases:

- The *system specification phase* focuses on identifying the basic functions of the system, along with inputs (percepts), outputs (actions) and their processing. For instance, how precepts are to be handled and any important shared data sources to model the systems interaction with respect to its changing and dynamic environment.
- The subsequent *architectural design phase* determines which agents the system will contain and how they will interact.
- The *detailed design phase* describes the internals of each agent and the way in which it will achieve tasks within the overall system. The focus in on defining capabilities (modules within the agent), internal events, plans and detailed data structures.

The Prometheus methodology is supported by an open source tool called Prometheus Design Tool(PDT), which supports building agent based system[1].

3   The Elderly Medication Activity

Medication is an activity of daily living (ADL) critical for the elderly to be independent at home [14]. This activity is associated with the medical term *medication compliance* that is defined as *the extent to which a patient acts in accordance with the prescribed interval, and dose of a dosing regimen* [21]. During aging the older adults present cognitive and sensorial changes, such as visual acuity reduction or memory loss, then they face frequent problems associated with nonadherence, such as forgetting to take their medicines or forgetting the doctor appointment. To understand the elderly medication activity, a contextual study of medication was carried out [9]. The contextual study consisted of

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[1] http://www.cs.rmit.edu.au/agents/pdt/

40-minute semi-structured and contextual interview based on Medication Management Instrument for Deficiencies in the Elderly (MedMaIDE), which is an assessment instrument for potential issues surrounding medication compliance and management in a home setting [14]. The participants were 17 elders ranging in age from 63 to 86 years old. Study results evidenced that some older adults are aware of some problems that they face to adhere to their medication, such as forget taking their medication or taking incorrect medicines and/or doses; therefore they create their own strategies to adhere to their medication, such as having a specific place to medicate, maintaining notes for indicating the purpose of taking the medicines and visiting periodically their doctor for refilling their medicines [9]. In this paper, we present the findings of the last strategy with the aim of modeling this activity using the Engreström's approach presented in section 2.1.

3.1   Findings on the Doctor Visit Activity

All older adults (17/17) comment that they visit monthly their doctor for their medical appraisal and refilling their medicines. Thirteen older adults (13/17) use the medical appointment card to remind the appointment date. For instance, the older adult (OA-02) said: "*I have a medical appointment card*" and the OA-03 comment: "*when I go to the hospital, I carry with me my card*". Whereas, other three older adults (3/17) use a calendar where they write a note to remind their doctor appointment. For instance, the OA-17 said: "*in my calendar I enclose with a circle the appointment date and write down doctor appointment*". Only one older adult (OA-01) require that a family member remind the doctor appointment, this older adult said: "*My daughter also goes to the hospital... we have the doctor appointment the same day... she calls me*". In addition, we identify that eleven older adults (11/17) require support of a family member to go to the hospital or pharmacy. For instance, the older adult (OA-03) said: "*I go to the hospital in taxi cab or my husband takes me... I do not know how to drive a car.*", and OA-16 said: "*my son takes me... but, depends of the date, if is friday my daughter does*".

Activity Modelling. From the findings, we deduce the elements of the activity. The *subject* is the older adult who visits his doctor. The *objective* of the activity is to be assessed with his health (medical appraisal). The activity *outcome* is get a prescription, supply the medicines and schedule the next doctor appointment. Several *artifacts* are used to perform the activity, such as the medical card and calendar. Additionally, we identify the *community* involved in the activity: family members, the doctor and doctor's assistant; who has a role in the activity, for example, the doctor who gives the prescription and the doctor assistant schedules the next appointment date; and finally, the *activity rules*, that indicate when to visit the doctor and how is the medicine provided. All these activity elements are shown in Fig. 2.
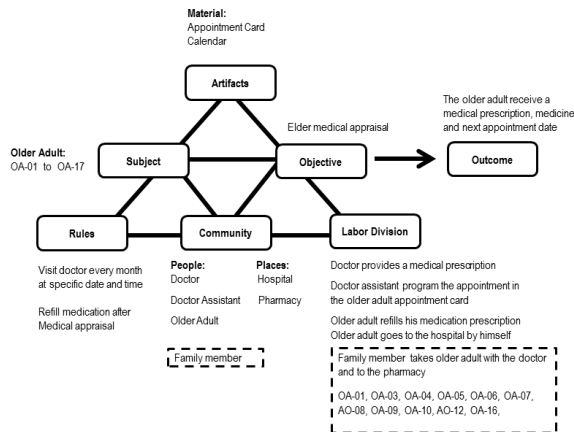
Fig. 2. Medical consultation activity elements

3.2 The Activity Causal Diagram

The activity structure proposed by Engeström identifies the main elements of the activity but it does not structure the dependencies between them or the valid sequences or alternatives that can be followed in the activity. In order to complement Engeströms approach we propose the use of causal diagrams for modelling the dynamics of the activity. In the first place we introduce the *Activitys Causal Structure* for identifying: the real-world elements that enable the execution of the activity (causes), the goal pursued by the subject (objective), and its observable consequences (outcomes).
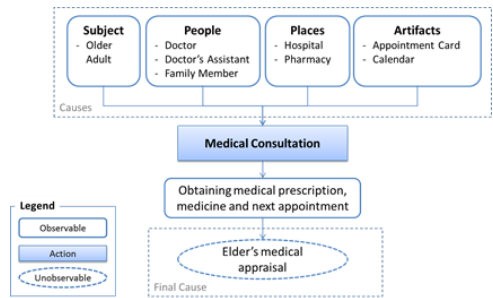

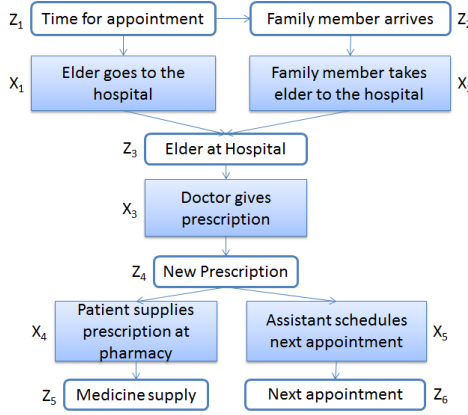**Fig. 3.** The causal structure of the medical consultation activity

Fig. 3 illustrates the causal structure of the *Medical Consultation activity*, based on the activity structure given in Fig. 2. On one hand, the older adult, the artifacts (appointment card, calendar), and the community (family members, the doctor, the doctors assistant, hospital, pharmacy) are represented as *causes*. On the other, obtaining a new medical prescription, medicine and a new appointment (*the outcome*), can be observed immediately after the consultation, meanwhile the elders medical appraisal (*the objective*) is evidenced only through these outcomes. To this causal interpretation of the activity we incorporate the other two elements missing from the Engeström theory: rules and role division. Role division enumerates the list of actions performed by each agent, meanwhile rules constrain the way on which these actions must be performed. In order to order actions and represent the different ways the activity can be carried out, we express them as a set of subgraphs $cause \rightarrow action \rightarrow effect$. Then we chain them together by following this principle: An action X_1 precedes another action X_2 if exist some cause of X_2 that is a direct or indirect effect of X_1, expressed as Causes$(X_2) \in$ Anc (Effects(X_1)). An arc connecting an effect Z_1 of X_1 to an action X_3 or a precondition Z_2 of X_3 is redundant if the graph already has a directed path from Z_1 to Z_2 or X_3. The resulting graph is *minimal* if it does not have *redundant* arcs and constitutes a Directed Acyclic Graph (DAG) if there are no cycles on it.

Definition 1. *An Activity Causal Diagram is represented by $D = \langle G, X, Z, I, F \rangle$, where G is a minimal DAG which arcs denote causal dependencies between observable conditions (Z) and actions (X), and which have at least one causal path from the initial condition $I \in Z$ to every set of outcomes $F_i \in F$, being $F_i \subset (Z \setminus I)$.*

Fig. 4 shows the causal diagram of the *Medical Consultation activity*, constituted by the five actions described in the labor division of Fig. 2. It has six observable conditions or events (Z_1-Z_6) and five human actions (X_1-X_5). Despite actions do not have explicit preconditions and postconditions in the labor division description, these are expressed by using the elements of the activity structure (see Fig. 3). The initial condition is the appointment date (Z_1) and there are three possible outcomes of the activity: (Z_4, Z_5, Z_6), (Z_4, Z_5) and (Z_4). Given that the objective is not directly observable, this is not included in the causal diagram.
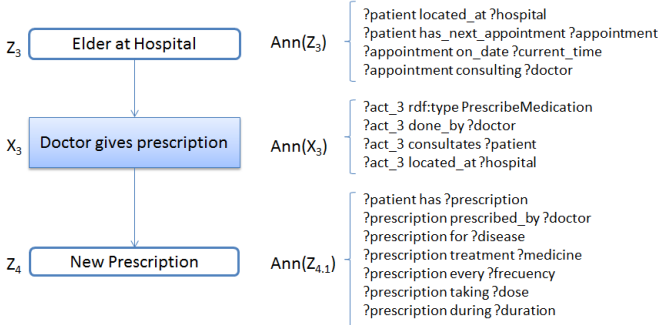
3.3   Semantic Annotations

In order to make explicit those dependencies between activitys elements we introduce the use of semantic descriptors over causal diagram nodes. Observable condition and action nodes are annotated with a conjunctive query, represented by a list of statements ⟨subject, predicate, object⟩ where the subject is a variable, the predicate is a label representing an attribute or relationship, and the object is another variable or constant; variables are denoted by a question mark prefix. Fig. 5 illustrates the annotation of two observable conditions (Z_3 and Z_4), and one action (X_3) from Fig. 4.

Fig. 4. The medical consultation causal diagram

Annotation variables refer to the elements of the activity structure (e.g. ?patient, ?hospital, ?prescription), and to the attributes of those elements (e.g. ?disease, ?medicine, ?frequency). Predicates describe relationships between activity entities (e.g. located_at, has_next_appointment), and properties of activity entities (e.g. on_date, prescribed_by). An observable condition can be annotated with multiple sets of annotations for indicating the different ways on which the event might occur. For instance, the new prescription might include medication ($\text{Ann}(Z_{4.1})$) or not($\text{Ann}(Z_{4.2})$).

Fig. 5. Examples of semantic annotations

In action descriptions, actions execution is denoted by the variable ?act_i, the action is identified by a type (?act_i rdf:type ActionName), the agent performing/initiating the action is identified through the property done_by, and other
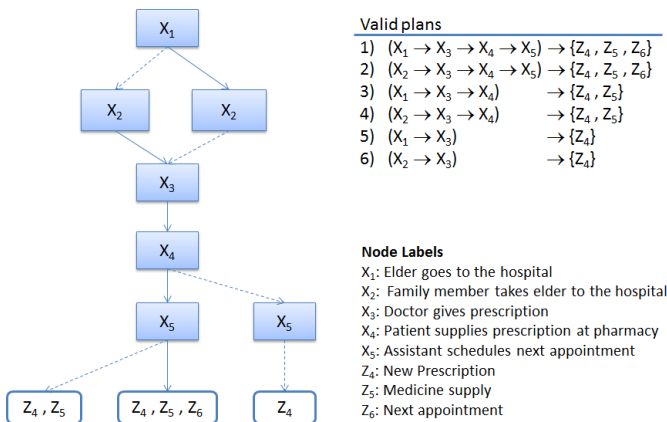
attributes linking the action with its causes are also included (e.g. consultates ?patient, located_at ?hospital). Action and observable condition annotations are represented by $\text{Ann}(V_i)$, where V_i represents an action X_i or an observable Z_i, respectively. The set of variables used in $\text{Ann}(V_i)$ are denoted by $\text{Var}(\text{Ann}(V_i))$.

3.4   The Activity Binary Decision Diagram

The activity causal diagram in Fig. 6 codifies the different ways on which the *Medical Consultation activity* is carried out: unassisted (denoted by X_1) or assisted by a family member (denoted by X_2). Additionally, there exist three possible outcomes for the activity: getting a prescription, medicine and a new appointment (Z_4, Z_5, Z_6); getting a prescription, medicine and being discharged of further consultation (Z_4, Z_5); and finally, getting a prescription without medication and being discharged of consultation (Z_4).The resulting alternative plans are better illustrated by generating the Binary Decision Diagram (BDD) of the activity causal diagram [22].

Fig. 6 illustrates the BDD obtained from the Medical Consultation causal diagram. The Activity BDD is a compact representation of a decision tree that summarizes the valid sequences of actions (plans) that start in the initial condition and end with the achievement of the possible outcomes of the activity. In this BDD, a solid arrow outgoing from a node X_i indicates that X_i is executed as part of a valid plan, whereas a dotted arrow outgoing from X_i indicates that the omission of X_i is part of another valid plan. Actions are ordered in the BDD according to the partial order obtained from the precedence relations between nodes of the activity causal diagram that produces the minimal number of nodes. Valid plans identified by traversing the BDD are also listed in Fig. 6.


Valid plans

1) $(X_1 \rightarrow X_3 \rightarrow X_4 \rightarrow X_5) \rightarrow \{Z_4, Z_5, Z_6\}$
2) $(X_2 \rightarrow X_3 \rightarrow X_4 \rightarrow X_5) \rightarrow \{Z_4, Z_5, Z_6\}$
3) $(X_1 \rightarrow X_3 \rightarrow X_4) \qquad \rightarrow \{Z_4, Z_5\}$
4) $(X_2 \rightarrow X_3 \rightarrow X_4) \qquad \rightarrow \{Z_4, Z_5\}$
5) $(X_1 \rightarrow X_3) \qquad\qquad \rightarrow \{Z_4\}$
6) $(X_2 \rightarrow X_3) \qquad\qquad \rightarrow \{Z_4\}$

Node Labels

X_1: Elder goes to the hospital
X_2: Family member takes elder to the hospital
X_3: Doctor gives prescription
X_4: Patient supplies prescription at pharmacy
X_5: Assistant schedules next appointment
Z_4: New Prescription
Z_5: Medicine supply
Z_6: Next appointment

Fig. 6. The Medical Consultation BDD

4   Assisting Human Activities through Multiagent Systems

Causal diagrams can be used as a bridge between the analysis of human activities and the specification of a MultiAgent System that assist that activity. It allows introducing the assistance of intelligent agents and it can be used for making the system specification following the Prometheus Methodology.

4.1   Incorporating Intelligent Assistance to Human Activities

So far, the causal diagram only reflects human actions, which execution depends on the free will of each person and in consequence it cannot be controlled but modeled through observation. In order to assist the modeled human activity we can incorporate the participation of intelligent agents upon this structure. Depending on the functionality desired, an agent action can be added for: 1) *enabling* a condition (X_E), or 2) *sensing* the effects of an action (X_S). Fig. 7 shows how these two operations can be introduced around human actions. Note that the human action X_1 is replaced by an arc causes(X_1) → effects(X_1), indicating that its effects might be observed with or without assistance.
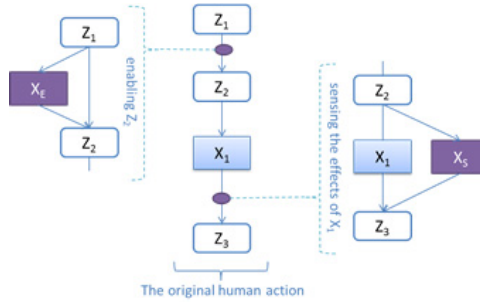

Fig. 7. Introducing agent actions for assisting human activities

Agent actions can be whether atomic or composite and are represented as X_i' to distinguish them from human actions X_i. Composite actions can implement specialized protocols or be broken down into another causal diagram. These assistance actions are attributed to new agent roles identified by variables in their respective semantic annotations. Original human actions are removed from this extended diagram in order to obtain the *assisted-activity causal diagram*, which only contains actions and events that can be observed by software agents. Fig. 8 shows an example of two actions introduced for: 1) reminding the doctors appointment to the patient (atomic enabling action), and 2) keeping track of his GPS location for verifying if he attended the appointment (composite sensing action). Both actions are performed by an agent in charge of assisting to the patient (Z_1') and use the patient cellphone as notification and tracking device.

In this example, X_1' and X_2' assist the human action X_1. Similarly, the medical consultation activity is assisted by another AssistantAgent that reminds to the family member when he has to take the patient to the doctors appointment, a HospitalAgent that connects to the clinical expedient database for getting patients prescription and next appointment, and a SmartHomeAgent that monitors changes on medicine dispenser levels.

## 4.2   Translating Causal Diagrams to Prometheus Artifacts

The translation from activity structures and causal diagrams to a Prometheus system specification is made in two phases: 1) stating the main system goals, and 2) expressing scenarios. In the first phase the main system goal is stated as assisting the ⟨human activity⟩ and it is decomposed in as many goals as documented activities we have: each activity objective constitutes a goal.
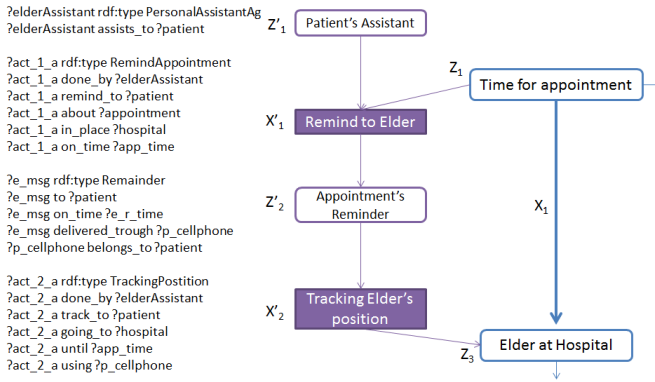
**Fig. 8.** An example of two actions for assisting medical consultation (with annotations)

In the second phase, since the activity structure and the causal diagram synthesizes several cases (one for each older person interviewed), the activity BDD is used for identifying all the possible scenarios in the activity. In our case study we modeled six scenarios: one for each valid plan (see Fig. 6). The assisted-activity causal diagram is used for delimiting the subgraph that represent each scenario. This subgraph is constituted by: a) the initial condition (I), b) outcome nodes considered in the plan (F_i), 3) the sequence of actions X_i' that assist human actions X_i in the selected plan, and 4) other observable conditions Z_i and Z_i' in the path from I to F_i. Each node of the subgraph constitutes a step in the scenario and it is listed according to some partial order given by the causal diagram. Multiple partial orders indicate that there exist activities which can be performed in parallel without affecting the outcome achievement. Observable conditions Z

are classified as goal steps, atomic actions X with effects on Z are classified as *percept* steps (e.g. checking patients electronic expedient), atomic actions X with effects on Z (e.g. Remind appointment to Elder) are action steps, composite actions X are represented as calls to another *scenario*, and steps introduced for awaiting for person actions are included as *other*. Fig. 9 illustrates the goal overview and the scenario for Medical Consultation activity when the patient goes by himself to the hospital.
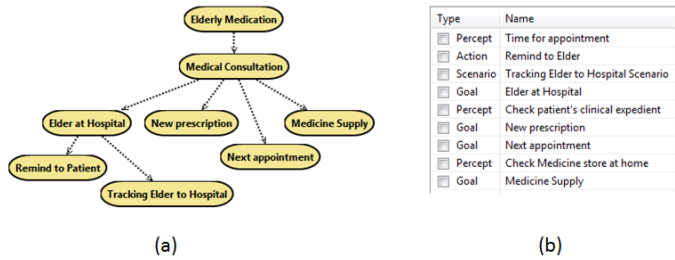
Fig. 9. Goal overview (a) and scenario (b) for medical consultation (alone)

On the other hand, annotations made over the assisted-activity causal diagram are used for additionally identifying protocol, actor and data artifacts, as well as their relationships with other artifacts already included in the scenarios. Fig. 10 shows the analysis overview of the activity obtained after modeling all other possible scenarios. Annotations provide further information such as actions parameters and data fields, indicated by the predicates on statements where they appear as subject. Roles are represented by variables used for identifying agents (e.g. ?patient, ?doctor).
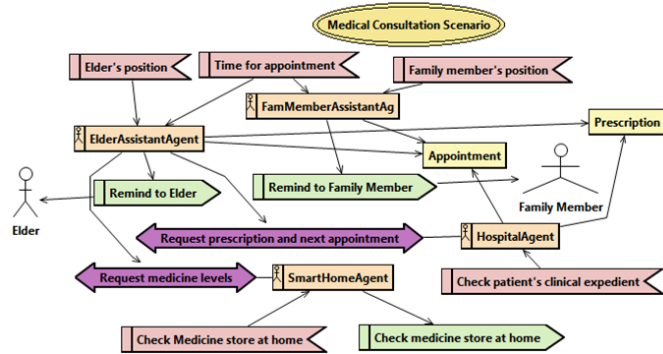
Fig. 10. Analysis overview for the medical consultation activity

Agent types included in the analysis overview are obtained from the community component of the activity structure, i.e. people participating in the activity (PersonalAssistantAg) and places enhanced with sensing capabilities and information systems (e.g. SmartHomeAg, HospitalAg).

5   Conclusion and Future Work

We motivated the use of the Activity Theory and causal diagrams for closing the gap between the analysis and the development of intelligent agent-based systems that assist daily living activities. For this purpose we introduced the activity causal diagram which structures the activity dynamics in such a way that enables extracting the different scenarios synthesized in the Engeström activity structure. Additionally, causal diagram's semantic annotations capture the relationships between activity elements and provide a formal language that can be used as the system ontology. Next we showed how intelligent agents assistance can be embedded in this causal diagram and be translated into artifacts of the Prometheus methodology.

We anticipate the implementation of a probabilistic decision making mechanism for converting the Causal Diagram into a Causal Bayesian Network where plan accuracy could be improved through parametric and structural Bayesian learning (IC* Algorithm [19]).

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