Designing for Practice-based Context-awareness in Ubiquitous e-Health Environments

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Abstract

Existing approaches for supporting context-aware knowledge sharing in ubiquitous healthcare give little attention to practice-based structures of knowledge representation. They guide knowledge re-use at an abstract level and hardly incorporate details of actionable tasks and processes necessary for accomplishing work in a real-world context. This paper presents a context-aware model for supporting clinical knowledge sharing across organizational and geographical boundaries in ubiquitous e-health. The model draws on activity and situation awareness theories as well as the Belief-Desire Intention and Case-based Reasoning techniques in intelligent systems with the goal of enabling clinicians in disparate locations to gain a common representation of relevant situational information in each other's work contexts based on the notion of practice. We discuss the conceptual design of the model, present a formal approach for representing practice as context in a ubiquitous healthcare environment, and describe an application scenario and a prototype system to evaluate the proposed approach.

Keywords—context-aware modelling; clinical knowledge sharing and decision support; ubiquitous healthcare; practice-based framework; CaDHealth

1. Introduction

Ubiquitous computing has created a world of networked sociality that has generated remarkable shifts in the way professionals collaborate and share knowledge across boundaries for peer support. However, knowledge sharing for clinical decision support entails more than a transfer of information. The process is reliant on practices that support common perceptions of shared information. For example, in co-located healthcare settings, clinical decision-making often transpires in the midst of problem-based knowledge sharing and conversational encounters between clinicians about a clinical case at hand; joint critical appraisal of research evidence, published reviews, clinical guidelines; team-based formulation of a care plan; and provision of therapeutic information to patients and their care givers [1].

Typically, these decision support activities are orchestrated in an uncharted and informal manner, often occur interactively and extemporaneously [2], but are largely driven by a common ground [3] offered by the clinicians' shared work context and "knowledge-in-practice-in-context" [4, p. 64]. As e-health envisions a ubiquitous healthcare system in which practitioners share knowledge across geographical, regional and workplace boundaries in a way that adapts to user work context, it becomes imperative for research to ascertain whether the same efficiency and seamlessness that has sustained the culture of ad hoc knowledge sharing and decision support in co-located healthcare can transfer easily to cross-boundary e-health.

We use the term "cross-boundary e-health" to refer *to the notion of a connected healthcare system that allows exchange of knowledge, expertise and services among healthcare professionals, patients and/or systems across geographical and organizational boundaries.* The notion of cross-boundary e-health draws on the idea of "second opinions" [5, p. 4] in medicine, and aims to create within a global healthcare infrastructure, communities of practice that allow clinicians to share knowledge to support one another's decision in manner that takes cognisance of the differences in local contexts of work, available tools and patients' needs between the clinicians. Cross-boundary e-health involve the socio-cultural and organisational aspects of work as well as the psychology of knowledge transfer, since it is concerned with ways by which a clinician in one work setting (e.g. a clinical team, a hospital or a geographical region) is affected by the experience of another clinician in a different work setting. The challenge offered by cross-boundary e-health resonates with the challenges inherent in the design of future decision support technologies [6], for example, how to bridge the socio-technical gaps in decision support systems.

This paper presents a practice-based approach for modeling context awareness for clinical knowledge sharing in cross-boundary e-health. It draws on activity and situation awareness theories as well as the Belief-Desire Intention (BDI) [22] and Case-based Reasoning (CBR) [30] techniques in intelligent systems with the goal of enabling clinicians in disparate locations to gain a common representation of relevant situational information in each other's work contexts. We describe the conceptual design of an approach, and explore an application scenario to evaluate the approach.

The rest of the paper is organised as follows. Section 2 discusses related work. Our approach to practice-based work context modelling is presented in sections 3 to 5, where Section 3 describes the clinical work context model, Section 4 presents the practice-based context-aware reference model, and Section 5, our practice-based approach to work context representation. In Section 6, we discuss context-aware knowledge sharing. System implementation and evaluation are described in Section 7. Finally, conclusion is presented in Section 8.

2. Related Work

Several studies have focused on building context-aware models to support clinical knowledge sharing in pervasive healthcare [24]. Feng et al. [26] presented a context-aware decision support system consisting of a situation awareness model, which includes perception, comprehension, projection, and terrain models, for providing human operators with customized views of terrains and decision support services through a group of entity agents. The system incorporates a rule-based inference engine, and includes functionalities for event classification, action recommendation, and proactive decision support. Related studies that use activity theory to model context-awareness appear in [15], [28], [29]. Other approaches focus on content adaption, mostly multimedia and information content. They usually take into account the physical context or technical capabilities of a client device, e.g. a mobile phone, or the information needs of a user, e.g. a clinician, and seek to enrich or transform the original content in a way that would suit the user or device [21].

Most related approaches appear to limit the notion of context to encodings of physical entities, e.g., user and device location [10], time via sensor-enabled input devices. They do not sufficiently emphasize the fundamental role of practice as the unifying concept between meaning and action within the site of contextual manipulation that is a key concern of ubiquitous computing [8]. Only a few systems associate the notion of awareness to other concepts, such as groupware and practice [9]. For example, Kirsh [7] notes that in tracking context of work, we need go beyond the superficial attributes of who and what is where and when, to consider the highly structured amalgam of informational, physical and conceptual resources that comprise "the state of digital resources, people’s concepts and mental state, task state, social relations, and the local work culture” (p. 305). A distinguishing feature of our approach is the focus on exploring context as an interactional problem where contextual features are dynamically defined as relational attributes holding between individuals and activities [8]. A practice-based view allows us to explore context as a collection of relevant conditions, conceptual resources, and observational elements of real-world environments that make a situation unique and comprehensible. The real challenge of context-awareness in ubiquitous healthcare lies in the fact that healthcare takes places in a highly dynamic environment that relates not only to location and time, but also to complex organisational, socio-cultural, activity-related and contingent features of a situation that e-health applications must not fail to take into account.

3. Modelling Clinical Work Context

We model work practice as context-driven interactions emerging out of a clinician's engagement with the environment, drawing from their knowledge of the domain of medicine, the stereotypes of spatial-temporal ordering of work within organizational routines, including every day socio-cultural understanding of clinical practice in their workplace, as well as the contingencies that inflect how any actual clinical work gets done [13]. We aim to enable an enhanced understanding of clinical work contexts and problem requirements across distributed work settings for cross-boundary decision support. We refer to this as *practice-centred awareness model (PCA)*. We define PCA as *an understanding of other people's local work contexts, problem-solving approaches, circumstances and task requirements, which include the ontological, spatio-temporal and situational factors that provide causal explanations for and influence how they utilize available resources, and contextualize plans and procedures to solve problems and achieve task goals in the real-world.*

In developing the PCA model, we extend the basic model of Engeström's activity system [14] in order to derive a practice system (Figure 1). Next, we incorporate a context model into the PCA model. In any work situation, a clinician's choice of action is, to a large extent, shaped by a set of domain, typical, and situational factors that combine to scaffold the clinician's cognitive capabilities in solving a given problem. We model this set of factors as context. A wide range of issues surrounding the concept of context [7], [8], [15], [16] remains the single most important factor that must be addressed to achieve a computational representation of work processes at the practice level. This raises a number of questions including how to set up mechanisms to capture context. How to identify what context information is necessary. How context can be associated with an activity or a work process. Different interpretations of context exist in literature giving rise to different approaches for modelling context [8], [11].

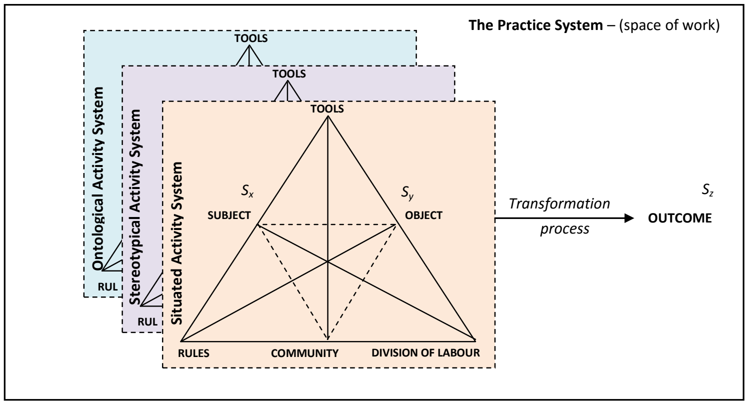

Figure 1: The practice system – an extended model of the activity system

Our model assumes a subjective view on problem-solving situations. In contrast to existing approaches where context is described in a monolithic sense or as an objectively defined situation, we argue that any choice of contextual parameters and their relative weight in describing a situation need to be subject to prevailing practices. Hence, we model context from a pragmatic point of view and introduce a taxonomic structure for making sense of work situations across boundaries (Figure 2). The model inherits from traditional models of context [8], [10], [15]. We view context as any information that can be used to characterize the situation in which something exists or happens, and which can help explain it [17]. However, in our approach the characterisation process leverages the knowledge, worldview, practices, settings and circumstances that can be used to construct a set of partially known collection of assumptions that form the integral problem-solving approaches of an organization or group of individuals, and which provide, for and within the organization or group, a schema for generating, sustaining, and applying knowledge. Our context model is divided into three main sub-categories:

- **Ontological Context:** The ontological context describes knowledge about the domain of work in relation to the activities and tasks being performed including task goals and context. Ontological context can describe such things as concepts, entities and relationships between them. The idea of treating knowledge as context is not new, and has been explored in [15], [12], [18].
- **Stereotyped Context:** The stereotyped context used to capture information about possible problem states as w concepts and problem-solving patterns associated with a place and time of work as well as the actor. Examples of stereotyped context include spatio-temporal context, i.e. the type of context that is concerned with attributes such as time or period, location, organisation, and socio-cultural context, i.e. the type of context that describes the social and cultural aspects of work and problem-solving approaches.

- **Situated Context:** Situated context captures situational information about a work process, and include things, services, people and information accessed by the people in performing their work activities.

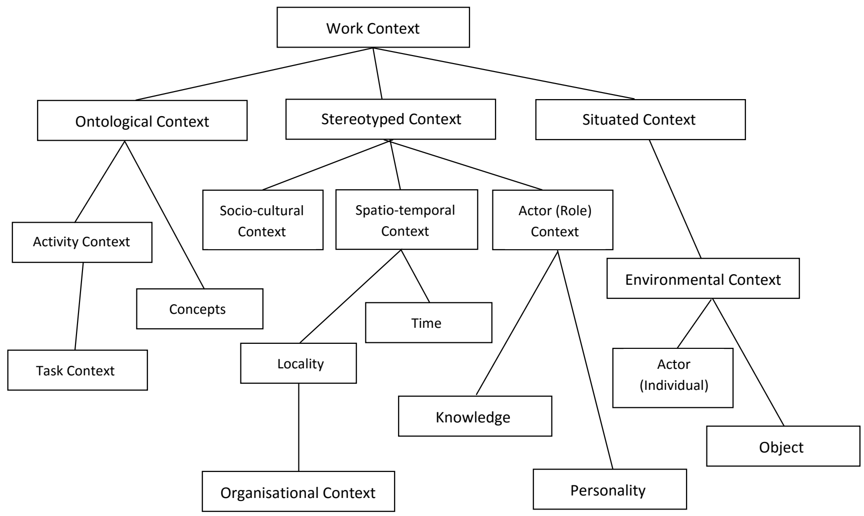

Figure 2: Proposed work context model.

4. Practice-based Context-Aware Reference Model

We describe a reference model based on our approach to work context modeling. The first step in the reference model (see Figure 3) is to acquire work context parameters associated to a work setting. This denotes the Level 0 of the reference model. Research in context-aware computing generally classifies context parameters into a number of categories including location, time, identity and activity. In this work, we argue for three broad categorisations of context, namely *ontological, stereotyped and situated context*. At Level 0, the category of context acquired includes the situated context. A computer system may acquire context parameters from simple activities or using a combination of physical and virtual devices – sensors, actuators, location-tracking services, RFIDs and software agents, including user interfaces (e.g. forms), persistent databases and cameras. In our proposed approach, context is acquired at run time. Information acquired is then sent to the context management subsystem, which transforms it into a format (e.g. using a special form of context cues, which we refer to as *practice cues*) that *the processing subsystem* (Level 1) can perceive (i.e. make sense of). Context management involves the definition of context parameters within a given work setting in order to allow for the specification of information about contexts of work and enable efficient use of the information by different context-aware systems. Hence, context management assists in the acquisition, manipulation and maintenance of a shared repository of work context information.

Level 1 – Perception: This involves the recognition of status, attributes and dynamics of relevant elements in the work environment based on the context information captured in Level 0. Within a healthcare work setting, perception involves, for example, recognising the presence and expertise of available healthcare staff, changes in hospital protocols and guidelines, available and recommended drugs, patient's vital signs, medical history and medical conditions. These elements are modelled as entities in the work environment. An entity represents any element (or object) in a work setting, which have attributes (e.g. identity, role, capability, expertise, etc.). Entities relate with each other and with their environment via actions and interactions. A situation arises out of a related set of actions and interactions aimed to achieve a specific goal. We model a situation as a situation class, a data structure that encapsulates all the relevant information about entities, their roles and goal-directed interactions, and status changes in a given work setting.

Level 2 – Conceptualisation: The main goal of the conceptualisation phase (Level 2) is to generate a knowledge base of domain-specific concepts and rules required to aid problem-solving in any work setting based on situation models generated in Level 1. The idea is to create a common pool of background knowledge that is used to assist clinicians across work boundaries in understanding one another's work situations. In our example prototype, conceptualisation is a static phase. During the process, the system generates domain-specific descriptions of generic work process independent of any particular work setting, which are stored as work practice models in the system database. At this stage, the work practice models represent models of the problem domain. First, scenario-based analysis is used to produce work process descriptions represented in three chunks of analysis: problem scenarios, problem diagnosis and action planning. In problem scenarios, the requirements of a domain task are specified as a set of sentences that convey user goals. In problem diagnosis, the sentences are reduced to a network of propositions. The propositions are iteratively analysed, based on a systematic probing method involving a set of what, why and how questions, to generate activity models, objects, responsibilities, interaction models, methods, information models, and class structure. During action planning, the final sets of propositions are used to elaborate the scenario to decide more appropriate requirements of user goals. Secondly, the set of propositions from the scenarios are analysed and synthesised into their component elemental classes called facets. Facets can be construed as perspectives, viewpoints, or dimensions of a particular domain. A faceted scheme provides a controlled vocabulary in the form of terms arranged systematically by facets and a set of rules on how to combine such terms to define conceptual descriptors, i.e. categories, of the work process. Knowledge acquired during this stage is used in

Level 4 to enable the system to address such problems as ambiguity and under-specification of perceived objects and stereotyped interactions in a work environment, and to reconcile any differences in work practices in relation to overall work goal. For example, when a clinician has to “deal with anomalous situations” [4, p. 62] or when their actions and work practices come into tension with situational, individual and organisational factors of work [20, p. 116].

Level 3 – Stereotyping: In Level 1, the system perceives information about a work environment based on recognition of relevant elements in the environment; in Level 2, the system generates generic formal conceptualisations about work situations within a domain of work. In this level, the system categorises a situation as one of a kind based on common sense knowledge about a set of possible states of affairs or prior descriptions of situations of that kind. For example, someone sends you an email describing himself as a medical doctor working in Sudan and requesting second opinion with regard to managing one of his paediatric patients with increasing diarrhea. You will assume that the child is malnourished, lives in a refugee camp, highly underweight, unkempt and an orphan. However, the child may have been well-fed, lives in the city, and is only suffering from food poisoning after a visit to the village. Though the use of the stereotype of an under-fed child may be a mistake, it provides a possible starting point for reasoning about the problem and enables efficient communication with the doctor in Sudan. Stereotypes describe a work situation based on typical characteristics of the users, an archetypal setting of their engagement in a task, including available tools and typical organisational work settings. In our example prototype, we model stereotyped reasoning by some logical distance between the perceived information (in Level 1) and the stereotype. As a starting point, we choose the best stereotype to fit the situation, using both the stereotype and the perceived information to draw conclusions.

Level 4 – Comprehension: At the comprehension level, the information perceived from the actual work environment, conceptual descriptions of the domain of work and the stereotypes are integrated to form a holistic picture of the environment, including problem requirements and patient’s needs. This involves synthesizing new knowledge by understanding and reconciling the three major information sources: cues from the work environment, domain-based conceptual descriptions and the stereotypes. One way of achieving this is to query the significance of each item of information in relation to user goals and problem requirements. The comprehension layer is the same as Endsley’s comprehension level; since the purpose of our model of awareness is to enable decision support, Endsley’s projection level is replaced with the reasoning and decision support modules in the PCA model.

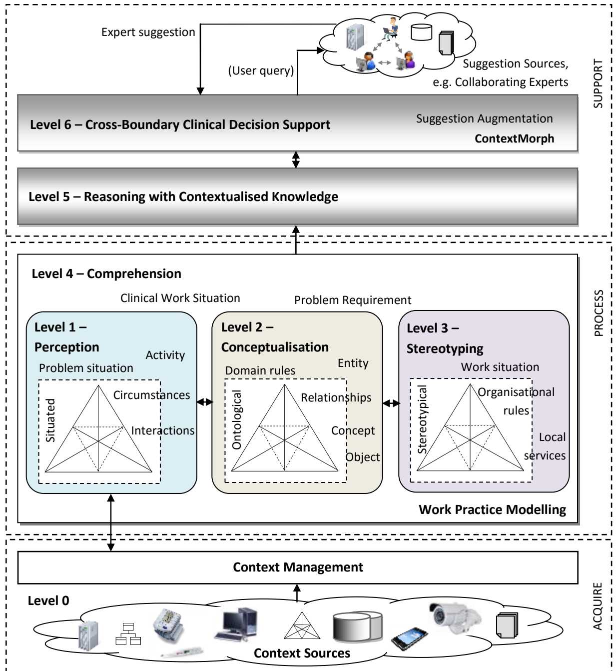

Figure 3: Practice-based context-aware reference model

5. Practice-based Framework for Representing Context of Work

To represent work practices and how they shape actions and activities variously across work settings, we need a logical formalism that relates actions and activities to the situational variables influencing work across instances of place and time. In this work, we use a modified version of the event calculus, which allows us to identify clinical work as a domain-specific activity (ontological) occurring within in a spatio-temporal space, i.e. to describe work situations in relation to instances of place and time. Let us assume a form of such logical formalism called *WorkPracticeDescription (WPD)*, in which we are given a work description at the domain level, called the *OntologicalPracticeDescription (OPD)*, and a description of the world at a certain place and time, called the *StereotypedPracticeDescription (TPD)*, and we are asked to determine what the world will look like as a result of performing the work description in the context of a given situation, called the *SituatedPracticeDescription (SPD)*, within *TPD*. Our goal is to get a pragmatic description of the work situation and its problem requirements, denoted by requisite *r*, in a manner that enables a remote agent to gain awareness of activity for cross-boundary decision support. This requires us to specify the context attributes that obtains, as well as the actions that are executed, at work setting *W*.

The predicate *obtainsAt(E, W)* defines the practice *E* that is true of a work setting *W*. The predicate *isDefinedIn(E, D)* means that practice *E* is defined in domain *D*; *happensAt(E, G, t)* means that practice *E* occurs at organisation *G* at time period *t*; *hasBel(G, N)* means that organisation *G* has belief in proposition *N*; *hasStereotype(G, hasBel(G, N))* means that organisation *G* has as stereotype their belief in *N*; *hasCircum(W, K)* means that a work setting *W* has a circumstance *K*; an activity object O_i, e.g. a patient, could have a circumstance, expressed as *hasCircum*(O_i, *K*). To express that an activity Δ requires a tool T_i, we introduce the predicate *req*(Δ, T_i). Other predicates include *locatedAt(G, R)* meaning that organisation *G* is located at region *R*; *hasPolicy(R, L)* meaning region has policy *L*; and *isaffectedBy(E, L)* meaning practice *E* is affected by *L*. Any *WPD* can be specified based on the three descriptions of type *OPD*, *TPD* and *SPD*. Assume that *OPD* is given by the predicate *isDefinedIn(E, D)*, *TPD* given by *happensAt(E, hasStereotype(G, hasBel(G, N)), t)*, and *SPD* given by *hasCircum*(*req*(Δ, T_i), *K*). Then any *WPD* can be given by the axiom:

$$\forall(x) \rightarrow WPD(x) \rightarrow obtainsAt(OPD,W) \wedge obtainsAt(TPD,Region) \wedge obtainsAt(SPD,W)$$

5.1 PracticeFrame

In representing work practice for computational design, we introduce a representational mechanism called *PracticeFrame*. A *PracticeFrame is a data structure containing the items for representing elements of a work practice in a computational system*. The aim is to connect together information used to describe work concepts and processes – at the domain level, as stereotyped schemas, and as actualised in a real-world situation – into a coherent whole capable of conveying awareness of the problem situation to an agent across the boundaries of the work setting. A *PracticeFrame* draws upon the notions of a *workframe* [21] and a *situation model* [19]. It contains a state description of work practice, and specifies particular approaches and solutions to given problems in relation to prevailing real-world circumstances. As shown in Table 1, a *PracticeFrame* consists of four sections, called frames. The first frame is header, which provides declarative information about a work setting and the problem being solved, including the place and time of work, and the work goal. This is similar to a header file in C language, for example. The remaining three sections describe the work setting and practices at the ontological, stereotyped and situated levels respectively.

Table 1: Illustration of PracticeFrame

PracticeFrame
#Header_frame
work description: text
locality: name of place
time-period: date
name of organisation: name
requisite: set r of user queries and problem requirements
work goal
ontological_frame :
Δ_{AS} : set of elements of the activity system as defined by domain knowledge
ORAS(r): ontologically relevant attribute set with respect to r
C_i: set of domain context items, including required expertise, resources and problem-solving methods (PSMs)
set of domain specifications
set of domain entities
set of ontological roles
set of domain permissible actions
#Stereotyped_frame
Δ_{AS} : set of elements of the activity system as is likely obtained in the locality and time
SRAS(r): stereotyped relevant attribute set with respect to r
C_i: set of stereotyped context items, including availabilities, e.g. available expertise, beliefs, intentions, resources and PSMs
set of stereotyped entities
set of stereotyped roles
set of likely actions
#Situated_frame
Δ_{AS} : set of elements of the activity system as exists and perceived from the environment of work
SRAS(r): situated relevant attribute set with respect to r
C_i: set of situated context items, including available expertise, resources, patient's history, costs and PSMs
set of actual entities
set of actual roles
set of actual actions
set of percepts
#End

5.2 Making Sense of a Work situation using the PracticeFrame

Any subset of work practice descriptions may be applicable to multiple work settings. As a result, we need to consider sufficient attributes of each work setting in the making sense of a work situation so as to infer a work situation with high degree of certainty. Usually, reasoning is performed over all possible situational variables μ of *W* in order to determine the description with the highest likelihood. In what follows, we introduce a formalisation of cross-boundary sense-making a clinical work situation using the Demspter-Shafer theory (DST) of evidence [22]. DST allows dealing with absence of preference, which results in indeterminacy due to limitations in available information and resources for problem-solving. In using DST, we assume that descriptions of work practices constitute “a structure of beliefs”, i.e. sets of organisational and situational issues that guide and shape problem-solving in a work setting. Generally, beliefs that influence decision-making in a clinical work setting are derived from three primary sources: the domain of work, the stereotypes about the work setting, and the circumstances of problem-solving in this setting. Any such description *WPD* is represented by a set of information items denoting a view of *W*. *WPD* contributes its impact by assigning a belief. This assignment is called the *basic belief assignment* denoted by the function m:$2^{\mu} \rightarrow [0, 1]$, which assigns an evidential weight to $WPD \subseteq \mu$. So, according to WPD's description, the probability of a description is given by a "confidence interval": *[Belief(W), Plausibility(W)]*. The lower boundary of the interval is the belief measure, which accounts for all evidence that supports the claim that WPD is an actual description of W:

$$Belief(W) = \sum_{WPD|WPD \subseteq \mu} m(WPD)$$

The upper boundary of the confidence interval is the plausibility confidence, which accounts for all evidence that do not rule out the given description (e.g. domain specification that lends credence to a description):

$$Plausibility(W) = 1 - \sum_{WPD \cap \mu \neq \emptyset} m(WPD)$$

For each possible description, DST gives a rule for combining the evidence in the descriptions. According to this rule, the orthogonal sum m_1 and m_2 is given by:

$$(m_1 \oplus m_2)(A) = \frac{1}{K} \sum_{B \cap c = A} m_1\,(B) m_2(C)$$

where K = $\sum_{B \cap c = A} m_1\,(B) m_2(C)$ for A $\neq \emptyset$ and $m_1(\emptyset) = 0$, $m_2(\emptyset) = 0$

Based on the computed belief attached to a WPD, a system is able to make a conclusion about the actual description of W using rules that seek to enable inferences based on what is known about the ontological, stereotypical and situated factors in W. This approach to reasoning over W directed towards action resonates with the idea of practical reasoning. Consider the rule in Table 2:

Table 2: An example rule for making sense of a clinical work situation

```
likely_factor (A, B)
        : = factor (A, B) [F ← DEFINE(WPD, 𝔻) | F ← percept]
likely_factor (A, B)
        : = factor (A, B) [dc ← GET_DEGREE_OF_CERTAINTY(sugg) Λ
        dc > threshold Λ
        ¬  in_conflict_with (damper)]
```

The first rule states that the most likely factor in a work practice description is the one defined based on WPD and domain specification $\mathbb{D}$, or the one perceived by the system. If the rule fails, then the likely factor becomes the one with the degree of certainty associated to it greater than a given threshold, and provided there is no strong conflict between the factor and the damper.

6. Context-Aware Knowledge Sharing

Having presented the practice-based structure for representing work context, we describe in this section our approach for leveraging the structure to enable cross-boundary clinical decision support in e-health. The approach, which we refer to as *ContextMorph* [23], is based on the case-based reasoning (CBR) methodology (Figure 4). A key assumption of CBR is that, in real-world problem-solving, people understand new experiences in terms on past ones, which naturally lends the methodology to problems of reasoning about situational context [18] and work practices [23]. The use of context to guide CBR has offered a new and powerful way of enclosing contexts with cases and embedding cases in general domain models in order to enhance the possibilities to simulate user behaviour and generate appropriate recommendations, enable intelligent situation awareness and decision support [26], [27], and facilitate knowledge-intensive reasoning in socio-technical systems.

In applying CBR in this work, we are guided by a number of concerns that have, over the years, shaped research methodologies in CBR. Hence, in what follows, we will seek to provide answers to the following questions: How are the cases structured? How is the retrieval mechanism of the cases defined, and what are the selection strategies for finding similar cases? How are selected cases revised, enriched and adapted to suit the requirements of a new case? And finally, how are suggested cases stored in the case library? In addressing these concerns, researchers have variously sought to adapt the classical CBR cycle of retrieve, reuse, revise and retain [30]. From a work practice-centred perspective, our approach is to author, structure and analyse cases in terms of the ontological, stereotyped and situated attributes describing a work context as the interactive, circumstantially adapted practice of people, set within an organisation's physical, socio-cultural and conceptual context, rather than just a well-defined flow of predefined processes.

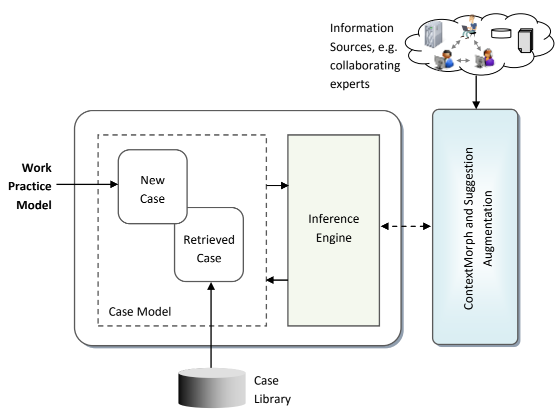

Figure 4: Context-aware case-based reasoning

The work context model presented earlier generates a work practice model instance as a new case, which then becomes the input to the CBR component. From a practice-centred approach, this input denotes contextualised pieces of knowledge representing an experience [1]. In this sense, a case represents particular strategies for carrying out an activity in a given context, the tools for achieving the goals of the activity, and the circumstances and experiences that influence activity performance. Figure 5 depicts such a case-based structure work practice representation.

A case model includes the activity being performed, the locality and time of work, available tools as well as descriptions of the socio-cultural contexts of work. In other words, cases in the case model have domain, context and situation features. Past cases are retrieved from the case library, and consist of a finite history of time space information about the work situation in a particular context [27, p. 12] as well as abstract rules of the domain of work. Case model ensures that both the new and retrieved cases adhere to the same representational format. The case structure reflects the practice-centred approach proposed in this work, i.e. representations of work settings in terms of the vocabularies of the ontological, stereotyped and situated factors describing a work setting based on attribute-value pairs, i.e. intensional descriptions. Next, the case structures are passed onto the inference engine (Figure 5). The retrieved cases are used to suggest solutions that are reused, tested and adapted to suite the new problems described by the user's work setting. We use similarity matching – a widely used reasoning mechanism in the CBR research community, which involves matching the work practice instance against a retrieved case for similarity measures based on a number of attribute values.

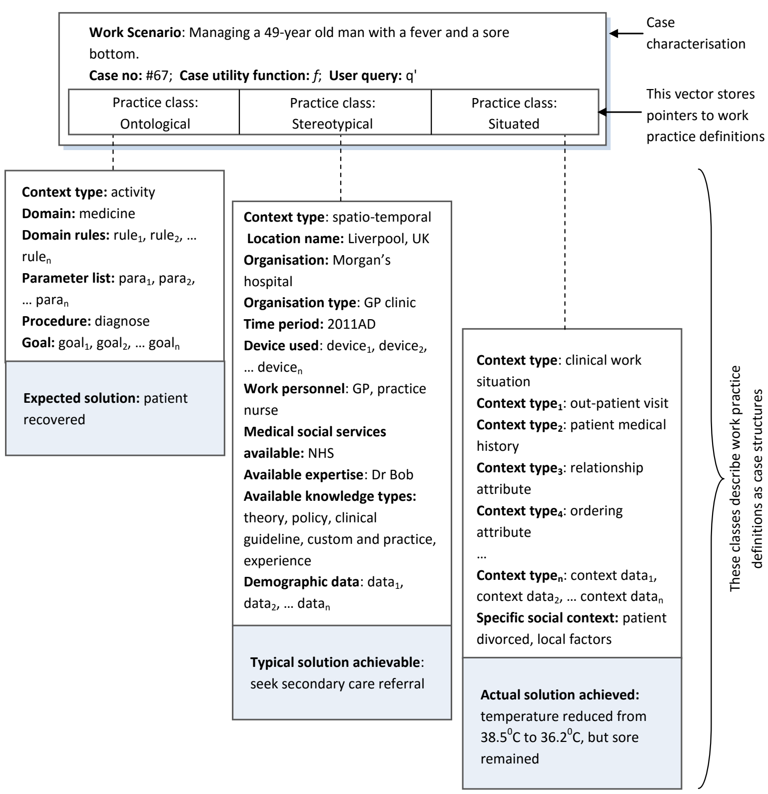

Figure 5: A case-based structure for representing work practice within a PracticeFrame as a contextualised work setting

From a practice-centred approach, the similarity computation of two instances of clinical work settings be reduced to three components: a concept-based, which focuses on ontological descriptions of concepts and their relationships in the activity domain, a role-based similarity, which seeks to identify attributes (e.g. artefacts) that have the same role and considers them as corresponding attributes, and a context-based similarity that seeks to obtain a representation of a real-world setting by identifying a finite set of attributes with associated constraints on the attribute values. The constraints on attribute values are specified either as "allowed" values (e.g. values which should be present if the attribute matching is to occur) or "prohibited" values (e.g. values considered, but which should not be present if the attribute matching is to occur).

Table 4: Operations for PCA generation process

Require: parameter *W* is the information set describing the user's work setting or contextualised case
Require: parameter μ is the set of all possible descriptions of a given problem-solving situation within the domain $\mathbb{D}$
Require: parameter *r* is the problem requisite obtained from user query q or system generated precept
Require: parameter *damper* is a vector of string describing the coordinative artefacts and practice used for damping variability in work practice during ContextMorph
Require: parameter *W'* is the information set describing the remote agent's work setting
Generate *OPD, TPD, SPD*
    OPD ← getOntologicalPractice(string *W*, vector<string> $\mathbb{D}$ [domain], *ORAS(r)*)
    TPD ← getStereotype(string *W*, vector<string> organisation, vector<string> region, string history, *TRAS(r)*)
    SPD ← getSituatedPractice(string *W*, vector<string> precept, *SRAS(r)*)
Get *OPD', TPD', SPD'*
    OPD' ← getOntologicalPractice(string *W'*, vector<string> $\mathbb{D}$)
    TPD' ← getStereotype (string *W'*, vector<string> organisation, string region, string history)
    SPD' ← getSituatedPractice(string *W'*)
GENERALISE(*OPD', TPD', SPD'*) → *WPD'*
GENERALISE(*OPD, TPD, SPD*) → *WPD*
DEFINE(WPD, $\mathbb{D}$) → $\{d \mid d \in \mathbb{R}, d(WPD, \mathbb{D}) \leq d(\mu, \mathbb{D})\}$
COMBINE(*WPD, WPD', damper*) → $[0,1] \subset \mathbb{R}$
GENERATE_PRACTICE_AWARENESS_INFO(*WPD, WPD', r*) → *PAI*
return (*PAI*)

Since in-depth exploration of CBR is outside the scope of this work, we have adhered to the rapid prototyping method proposed for such situations where CBR applications are not to be developed from scratch [30]. This method follows the similarity definition in myCBR tool [30], and uses a straightforward case representation structure with a case base *D* made up of $(W_i)_{i \epsilon [1,|D|]}$ samples described by a set of features *F* with numeric features normalised to the range [0, 1]. In this representation, let *q*, *W* be instances of a clinical query and clinical case, where $W = W_1, \ldots, X_n$ and each W_i is described by a vector $(W_{i1}, \ldots, W_{1|F|})$ of numerical features representing some object. Assuming that the case representation consists of *n* number of features with feature weights x_i, the similarity between *q* and *W* can be computed as follows:

$$Sim(q, W) = \sum_{i=1}^{n} x_i \times Sim_i(q_i, W_i)$$

The feature-specific local similarity measure is given by Sim_i, and *Sim* represents the global similarity measure (Stahl and Roth-Berghofer, 2008). It is common for local similarity measures to be represented as similarity tables that simply evaluate all pairwise similarity values for symbolic features or *difference-based similarity functions* that map feature differences to similarity values for numeric features.

ContextMorph involves two major processes: in the first process, the practice awareness information (PAI) is generated; in the second process, the suggestion provided by the agent is augmented and adapted to *W*. It is extremely help to view the first process as an association between the description of an actual work situation *W*, the set of all possible descriptions of such work setting within a given domain μ, the domain specifications about how the given problem is solved $\mathbb{D}$, and the damper (as the modulating device). The best description for *W* is the description closest to $d(WPD, \mathbb{D}) \leq d(\mu, \mathbb{D})$, where d is measured as the semantic distance between the sets *OPD*, *TPD*, *SPD* and $\mathbb{D}$. We define sets of operations, in Table 4 (PCA) and Table 5, for the ContextMorph process. The operators act on partial descriptions of work practices. They include: GENERALISE(*OPD*, *TPD*, *SPD)* → *WPD:* takes three sets of partial descriptions of a work setting *W*, which are obtained on the functions *getOntologicalPractice()*, *getStereotype()* and *getSituatedPractice()* respectively. GENERALISE() finds the most appropriate set of descriptions *WPD* for *W*. DEFINE(WPD, $\mathbb{D}$) → $\{d \mid d \in \mathbb{R}, d(WPD, \mathbb{D}) \leq d(\mu, \mathbb{D})\}$: determines whether a set of work practice descriptions for a work setting WPD complies with the specifications of the domain of work $\mathbb{D}$. COMBINE(*WPD*, *WPD'*, *damper)* → $[0,1] \subset \mathbb{R}$: computes the similarity between two work practice descriptions by applying a similarity metric so as to combine the work practice descriptions using *damper* as modulator. MORPH_SUGGESTION(*WPD*, *sugg*) → $\{s \mid s \in 2^S, s \neq \emptyset\}$: determines whether a suggestion *sugg* can be "morphed", i.e. transformed to the context and requirements of a work setting given by *WPD*. MORPH_SUGGESTION() yields a value s, which is element of the power set of S, where S denotes a dynamically defined set of items that ascertains whether *sugg* can be morphed, is organisation-specific, region-specific, or domain-defined, or whether the evidence in the suggestion is based on theory, research, experience, organisational or regional policy, custom and practice, or trial and error}. GENERATE_PRACTICE_AWARENESS_INFO(*WPD*, *WPD'*, *r*) → *PAI:* generated PAI for the remote agent, and AUGMENT_SUGGESTION(*WPD*, *sugg*, *r*) → *adapted_sugg:* augments sugg as a structure for supporting user decision.

7. Implementation

Preceding discussions have focused on details of the main abstractions and mechanisms of the approach proposed in this work. In this section, we describe the development of an initial prototype to demonstrate the proposed approach. We refer to the prototype as *Context-Aware cross-boundary clinical Decision support system in e-Health (CaDHealth)*.

We first describe an example application scenario to illustrate the use of *CaDHealth*. Consider a clinical work situation for managing a post-operative breast cancer patient. Bob is a general practitioner (GP) in a remote area in the UAE. Bob has a patient, Alice who recently had a breast cancer surgery. While managing Alice post-operatively, Bob has to decide whether Alice needs adjuvant therapy, since not all women with breast cancer need adjuvant therapy. Such decisions are usually made at multidisciplinary team (MDT) meetings. However, Bob is able to find a UK-based consultant oncologist, Mr Smith, who is inclined to offer "second opinion" to assist them. Mr Smith wants to gain an understanding of Bob's clinical work situation (practice-based awareness) and Alice's circumstances in order to provide Bob with the most effective suggestion (cross-boundary decision support). The MDT headed by Bob was to employ CaDHealth in seeking "second opinion" from Mr Smith. For one month, we gathered data in a pilot study to illustrate the case example. The data included descriptions of work situations occurring in the course of providing care to the post-operative breast cancer patient, and were obtained by note taking. The data include work context parameters as shown in Table 6. The data describing the context of clinical work situations include ontologically-related parameters (i.e. information obtained from domain specifications of the task of adjuvant therapy), situational information captured through available hardware sensors, cameras and actuators (e.g. location and time of work), and stereotyped information derived from organisational records and settings, e.g., policies, guidelines and available resources for work.

Table 5: Operations for the ContextMorph process

Require: parameter *W* is the information set describing the user's work setting or contextualised case
Require: parameter μ is the set of all possible descriptions of *W* within the domain $\mathbb{D}$
Require: parameter *r* is the problem requisite obtained from user query q or system generated precept
Require: parameter *damper* is a vector of string describing the coordinative artefacts and practice used for damping variability in work practice during ContextMorph
Require: parameter *W'* is the information set describing the remote agent's work setting
Require: parameter *PAI* is the system generated practice awareness information
Require: parameter *sugg* is the textual description of the remote agent's suggestion
Generate *OPD, TPD, SPD*
    OPD ← getOntologicalPractice(string *W*, vector<string> $\mathbb{D}$ [domain], *ORAS(r)*)
    TPD ← getStereotype(string *W*, vector<string> organisation, vector<string> region, string history, *TRAS(r)*)
    SPD ← getSituatedPractice(string *W*, vector<string> precept, *SRAS(r)*)
    Get *OPD', TPD', SPD'*
    OPD' ← getOntologicalPractice(string *W'*, vector<string> $\mathbb{D}$)
    TPD' ← getStereotype (string *W'*, vector<string> organisation, string region, string history)
    SPD' ← getSituatedPractice(string *W'*)
GENERALISE(*OPD', TPD', SPD')* → *WPD'*
DECONTEXTUALISE_SUGG(*sugg, WPD')*   */* De-Contextualise sugg with reference to WPD'*/*
GENERALISE(*OPD, TPD, SPD)* → *WPD*
RECONTEXTUALISE_SUGG(*sugg, WPD)*   */* Re-Contextualise sugg with reference to WPD */*
DEFINE(WPD, $\mathbb{D}$) → $\{d \mid d \in \mathbb{R}, d(WPD, \mathbb{D}) \leq d(\mu, \mathbb{D})\}$
COMBINE(*WPD, WPD', damper)* → $[0,1] \subset \mathbb{R}$
GET_DEGREE_OF_CERTAINTY(*sugg*) → $\{dc \mid dc \in [0,1] \subset \mathbb{R}$
MORPH_SUGG(*WPD, sugg*) → {s | s $\in 2^S$, where S = {"organisation-specific", "region-specific", "morphable", "domain-defined", "theoretical", "research", "experiential", "policy", "custom and practice", "trial and error"}, s $\neq \emptyset$}
AUGMENT_SUGGESTION(*WPD, dc, sugg, r*) → *adapted_sugg*
return (*adapted_sugg*)

7.1 Prototype Development

The central design objective of *CaDHealth* system is twofold: 1) to facilitate awareness of work practices and contexts across organisational and regional boundaries in pervasive healthcare, and 2) to enable clinical decision support at the work practice level. *CaDHealth* is designed as a practice display system; the display includes a visualisation of the *PracticeFrame* – a representation of located clinical problem-solving based on the ontological, stereotyped and situated work practice descriptions. The system is developed as a frame-based representation of the situations and circumstances of a clinical work setting at the work practice level. It supports users in two principal ways:

- *Use of a Practice Display:* This describes the practice information, which the system provides to the oncologist in a remote work setting to enable them to gain knowledge (i.e. awareness) of the user's work practice situation and patient's needs to enable them to offer appropriate suggestions, and
- *Provision of Enriched Decision Support Information Display:* The suggestion provided by the oncologist is enriched by the system by infusing into it more information (e.g. from the system database) and morphed for contextual adaptability to provide the user with context-aware information (and enriched suggestion) to support their clinical decision.

Table 6: Context parameters for making sense of a clinical work situation

Parameter	**Sub-parameter**	**Description**
Locality		The region or country where the activity is performed
Organisation		The hospital where the activity is performed
User		The user of the system
Role		The role of the user in the activity
Group		The group consisting of the user and other people involved in the work The role of the group
Role		The name and description of the activity being performed
Ontologically-related parameters	Activity	Domain specifications about the activity being performed
	Problem-solving specifications	
Stereotypes	Policies and guidelines	Norms (at the organisational and national levels) that govern how activities are actually performed
	Available resources	Descriptions of resources, e.g. laboratory services, diagnostic tools, etc., available for post-operative treatment.
Clinical case	Age	Age of patient
	Sex	Sex of patient
	Treatment history	Patient's treatment history with regard to present clinical case
Situational parameters		E.g. a patient's subsequent compliance with any treatment recommendation, risk of relapse, and potential side effects of any course of therapy on patient are usually take into account
Time period		The period (i.e. day, month and year, or just month and year) during which the activity is performed

The *CaDHealth* system architecture and Web-based user interface of the implemented prototype are depicted in Figure 6 and Figure 7 respectively. The system architecture consists of three main components: the *CaDHealth* user interface (UI) layer, a cross-boundary collaboration layer and the PCA Manger. The UI and the cross-boundary collaboration layers are designed as client-side applications, whereas the PCA Manager, integrated into a HIS, constitutes the *CaDHealth* server. The backend include a knowledge repository and the core system database. The knowledge repository stores domain models and practice models and percepts, i.e. the semantic, practice and perceptual memories respectively; the core system database is the working memory and stores clinical work processes and practice-aware decision models. In addition to these components, the infrastructure is able to connect to external and cloud-based services, such as location-tracking services, sensors, actuators, RFID (Radio-Frequency Identification) readers, situation models as well as regional, organisational and domain-specific services. Because *CaDHealth* is integrated into a hospital's larger HIS, the architecture includes a firewall, which ensures that 1) sensitive patient information, e.g. in patients' health record or a hospital's institution guideline, is annonymised before being used in cross-boundary decision support, and 2) only authorised and authenticated agents and services are granted access.

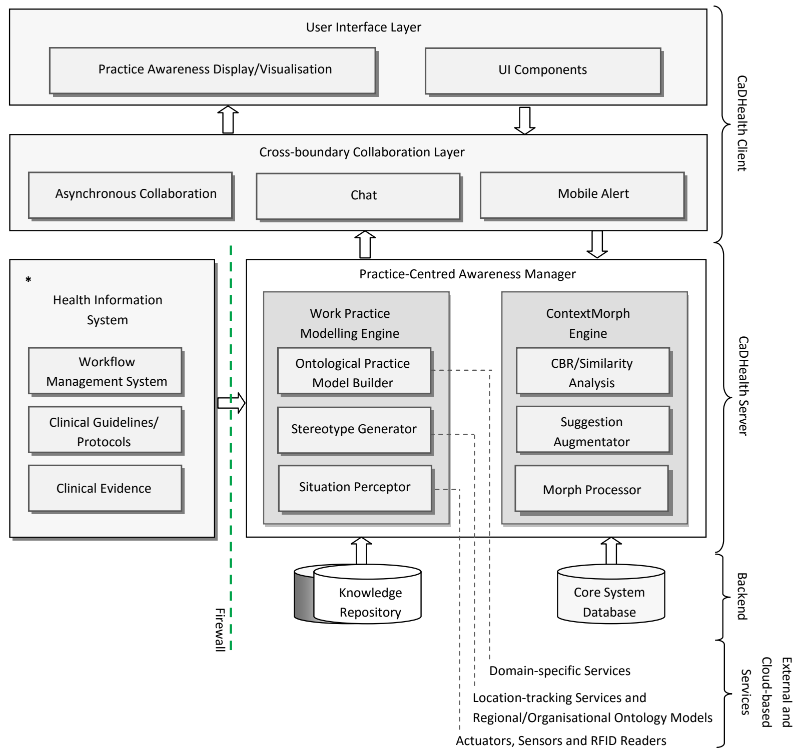

Figure 6: CaDHealth architecture

We use RDF to represent information for the *PracticeFrame* – including ontological practice represented as domain ontologies, stereotypical practice represented as organizational patterns and templates, and situated practice represented as context information. We use the Jena toolkit, which includes a wide range of model stores for the knowledge repository and libraries for query. The *ContextMorph* engine was implemented using myCBR engine, with the inferencing rules implemented using Drools. The PCA Manager was implemented in Java. It reads descriptions of the *PracticeFrame* encoded in RDF (N3 notations), and generates HTML pages for the cross-boundary collaboration and UI layers. The collaboration layer was implemented using an open-source jQuery chat plugin, whereas the UI portal was coded in JavaScript.

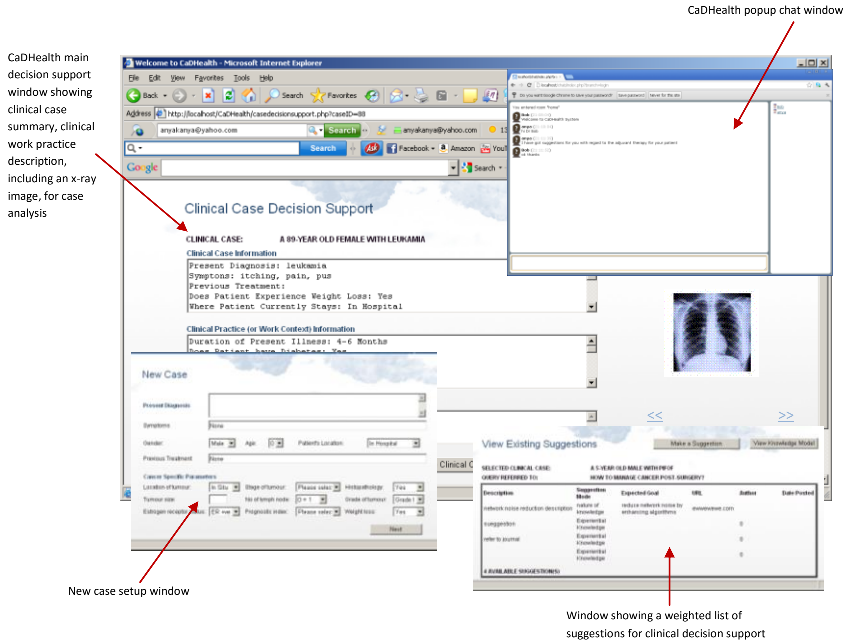

Figure 7: CaDHealth prototype – with practice display

A key challenge in the example scenario is to enable the system to generate a display of Bob's clinical work practice in such a way that the oncologist can gain sufficient awareness of the MDT's problem requirements and contribute appropriate suggestions to support their decisions on the case. In the UK, the oncologist uses breast cancer adjuvant treatment guideline, where the complex process of specifying the right course of adjuvant for a patient cannot be entirely comprehensively captured by rules.

7.2 Evaluation

In this section, we present an experimental study to evaluate the performance of *CaDHealth* by determining how much significant utility the system provides to an end user clinician. A more elaborate evaluation of the system is presented in [25]. Recent studies in context-aware applications for decision support particularly in complex, dynamic, and ubiquitous environments, have emphasized the need to take system evaluation beyond typical usability testing. For a context-aware pervasive system designed from practice-centred perspective, a measure of this utility includes how much the system "fits" into an organisation's system of work practices for added benefits. In this experimental study, participants were asked to gauge the utility and performance of CaDHealth in terms of work situation classification and effectiveness of decision support. Specifically, the participants were to determine, 1) given a specific clinical task and work situation, if the system is able to construct a true representation of the situation, and, 2) given a user query based on the work situation and a suggestion, if the system is able to build an appropriate set of enriched decision support information. In addition, we estimate the effectiveness of the practice display in terms of the reduction in the cognitive load of the users. We adopted the freeze-probe technique – the Situation Awareness Global Assessment Technique (SAGAT) proposed by [19], which includes metrics for assessing work situation awareness based on direct measurements. The method has been criticized because it focuses on quantifying a subjective phenomenon, and because scenario freezes may disrupt performance. The method has, however, been applied with reported success in studies focusing on command and control performance [19], and, thus, has strong potentials for providing valuable indications as to the effectiveness of an awareness system.

Table 7: Prediction accuracy in work practice information classification

	Participant A		**Participant B**		**Classification Accuracy (%)**	
	Number of Predictions	**Numbers Correct**	**Number of Predictions**	**Numbers Correct**	**A**	**B**
Ontological Work Practice	24	24	21	20	100.00	95.24
Stereotyped Work Practice	14	12	16	15	85.71	93.75
Situated Work Practice	9	8	10	8	88.89	80.00
Total	47	44	47	43	93.62	91.49

1) Work practice classification

Two clinical experts participated in the study. Sampling was purposive and sought clinicians interested in research and cross-boundary clinical decision support who might critically appraise the tool and provide recommendations for its future enhancement. Participants were asked to monitor a simulation of a work practice display [25] for 94 simulation runs (47 for each participant). The simulation consists of animated screenshots of the *CaDHealth* prototype inter-connected to portray clinical decision making scenarios created jointly with the participants. SAGAT uses expert knowledge to develop questions and probes that assess a participant's awareness of a work situation [25]. It involves freezing the simulation at randomly selected intervals during which participants are probed as to their perceptions of the user work situation at that time.

Since a primary role of *CaDHealt*h was to classify a PCA information item into three categories of work practice, namely the ontological, stereotyped and situated work practices, the accuracy of this classification was used as a performance measure. The accuracy of the system was measured in terms of work practice classification by comparing the practice display information about a scenario with a participant's classification of the same scenario during a freeze. When the work practice category assigned by *CaDHealth* is different from that of the expert clinician, the specific classification is deemed inappropriate. As shown in Table 7, *CaDHealth* achieves an average accuracy of 92.56% in classifying work practice information items for tasks A (93.62%) and B (91.49%). This high level of performance is an indication that classifying work practice information increases the accuracy of PCA systems in enabling cross-boundary decision support. A distinguishing feature of the *CaDHealth* approach is that it provides clinicians with the capability to represent decision support information based on three broad taxonomies – the ontological, stereotyped and situated work practices.

2) Decision enrichment

The simulated decision processes (in miliseconds) were compared with standard clinical guidelines for the same decision processes (Figure 8). Two thresholds were defined to determine the utility of the practice-centred information. The upper threshold indicates that though a process deviates from the clinical guideline (as defined by the region encapsulated by the thresholds), the practice-centred has a significant utility because does not lead to error. The lower threshold shows practice-centred information with potentials to lead to error if applied to decision making. In our experiment with 400 simulation runs, over 52% of the practice-centred information (i.e., workarounds and work processes that have deviated outside of the defined threshold boundary) goes above the process value threshold, indicating that some practices have a positive value and occur as a result of optimizing the multi-objective of care delivery within a given situation. As shown in Figure 8, divergence of work processes occurs mostly towards the end of the process; in [25], we investigated the effectiveness of the CaDHealth approach in raising awareness about medical practice and evaluated its impact on clinical decision-making processes.

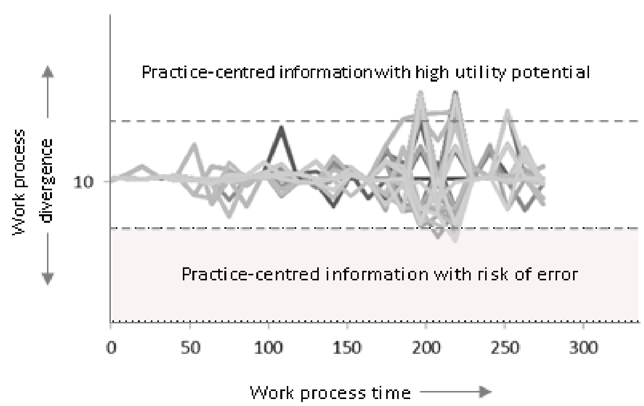

Figure 8: Evaluation of the decision enrichment potential (i.e., utility) of practice-centred information

8. Conclusion

The conceptual model of a system for formalising and representing clinical work practices for cross-boundary knowledge sharing in ubiquitous e-health environments is described. The approach is based on activity and situation awareness theories, as well as CBR and the BDI theory in AI. It draws from a notion of context-awareness as an interaction problem with a view to representing work practices as a context parameter for representing situational information in the design of computational systems for e-health. A key contribution of the paper is a conceptual model for bridging the socio-technical gap in employing clinical work practice as an artifact for the design of information technologies for clinical knowledge sharing in e-health. By integrating multiple techniques across diverse disciplines, our approach will potentially lead to the design of more effective systems to support knowledge sharing in ubiquitous healthcare. Future work will include incorporating and validating the approach in a real-world healthcare setting.

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