Knowledge Fusion in Context-Aware Decision Support Systems

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Keywords: Context-Aware Decision Support, Knowledge Fusion, Emergency Response, Response Actions Planning.

Abstract: The paper discusses knowledge fusion processes with reference to context-aware decision support. It extends the previous research work on context-based knowledge fusion patterns. The contribution of this paper is service-oriented implementation of the context-aware decision support system for emergency management. This system was used in the previous work as the basis for revealing the knowledge fusion patterns. The presentation is accompanied by examples from a fire response scenario.

1 INTRODUCTION

The decision support systems heavily rely upon large volumes of data, information, and knowledge arriving from different sources. Whereas several years ago data fusion used to be the main technology integrating data and information from multiple sources within any decision support system, today the focus of data fusion has changed to knowledge fusion. The objective of knowledge fusion is to integrate information and knowledge from multiple sources into some new common knowledge that may be used for decision making and problem solving or may provide a better insight and understanding of the situation under consideration (Holsapple & Whinston 1986; Preece et al. 2001).

In the present research, an emergence of new knowledge is considered as the distinguishing feature of the knowledge fusion processes. Any sources of data, information, and knowledge involved in the fusion processes are referred to as knowledge sources.

In the research, the knowledge fusion problem is considered applying to decision support systems intended for usage in dynamic environments. Such systems have to be context-aware in order to control environmental changes, to adapt to the current situation, and to avoid information overload. Context enables to decrease the volumes of available information and knowledge to the information and knowledge relevant to or "useful" in the current situation.

The research extends the preceding research work on context-based knowledge fusion patterns (Smirnov et al. 2013) revealed in a context-aware decision support system (CADSS) for emergency management. The contribution of this paper is the system implementation. The motivation is to illustrate knowledge fusion processes by a practical example avoiding descriptions of technical details.

The rest of the paper is structured as follows. The following Section presents the main research areas dealing with knowledge fusion and introduces different results that knowledge fusion can produce. Section 3 outlines the conceptual framework of the CADSS, discusses the place of knowledge fusion in the system's scenario, and presents some implementation issues by example of a fire response scenario. The Conclusion emphasizes the role of knowledge fusion for up-to-date decision support systems.

2 KNOWLEDGE FUSION

Recently, many research focus on knowledge fusion. Depending on the application domains the focus of knowledge fusion becomes more specific. Knowledge fusion technology supports intelligent query-answering systems aiming at providing the users with nonrecurring, consistent, unambiguous

Smirnov A., Levashova T. and Shilov N..
Knowledge Fusion in Context-Aware Decision Support Systems.
DOI: 10.5220/0005034801860194
In *Proceedings of the International Conference on Knowledge Engineering and Ontology Development* (KEOD-2014), pages 186-194
ISBN: 978-989-758-049-9

answers to their query under redundancy/lack of information (e.g., Dumais et al. 2002; Nengfu et al. 2012; Preece et al. 1999). Some researchers deal with knowledge fusion of multiple knowledge sources to build a new knowledge base (Craven et al. 2000; Gou et al. 2005; Kuo et al. 2003). Several knowledge fusion efforts are devoted to knowledge integration with the problem solving purposes (Carvalho et al. 2013; Preece et al. 1999; Smirnov et al. 2005b). A number of knowledge fusion applications deal with fusing information to obtain a model of the situation, assess it, and predict its development (Blasch et al. 2013; Boury-Brisset 2001; Erlandsson et al. 2010; Golestan et al. 2013; Pengpeng Liang et al. 2013; Sanchez et al. 2014). Context plays an important role in all the above mentioned approaches.

As it is said in the Introduction, knowledge fusion is characterized by the creation of new knowledge. The analysis of a number of knowledge fusion studies (above mentioned and additionally to them (Besnard et al. 2012; Grebla et al. 2010; Jonquet et al. 2011; Lee 2007; Lin & Lo 2010; Preece et al. 2001; Roemer et al. 2001; Smirnov et al. 2005b)) has revealed the following kinds of new knowledge obtained as the knowledge fusion results:

- new knowledge created from data/information;
- a new type of knowledge;
- a new problem solving method or a new idea how to solve the problem;
- a new knowledge about the conceptual scheme;
- new capabilities/competencies of a knowledge object (an object that produces or contains knowledge);
- a solution for the problem;
- a new knowledge source.

The CADSS for the emergency management domain was investigated with the object to reveal in it the listed above knowledge fusion results and to identify the processes eventuating in them.

3 KNOWLEDGE FUSION IN CADSS

The CADSS for emergency management is intended to support decisions on planning emergency response actions. The system scenario follows two main phases: preliminary and executive (Figure 1). These phases comprise several stages; at some of them knowledge fusion processes occur.

3.1 Preliminary Phase

At the preliminary phase, an application ontology, which describes knowledge of the emergency management domain, is built. This ontology represents non-instantiated knowledge of two types: domain and problem solving. The domain constituent of the application ontology represents various types of emergency events and knowledge that can be used to describe situations caused by such events; the problem-solving constituent represents problem-solving knowledge that may be required to solve the problem of planning the emergency response actions. The application ontology is the result of the integration of multiple

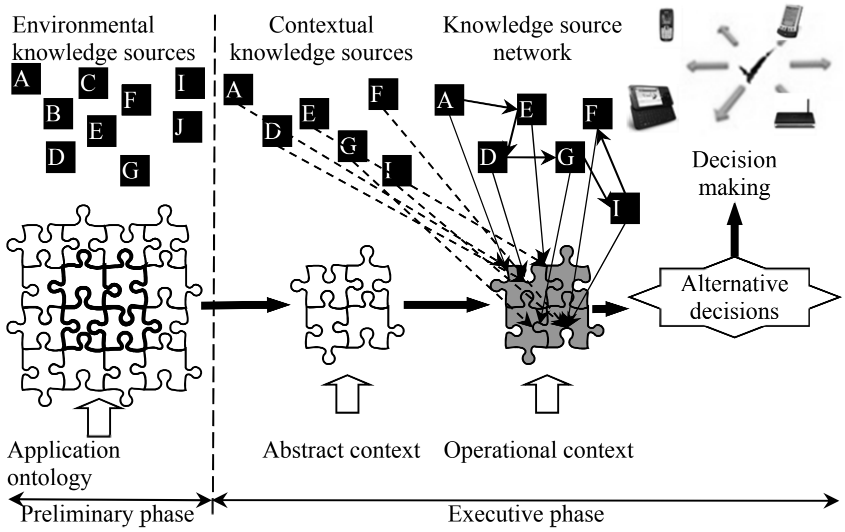


Figure 1: Context aware decision support.

required to solve the problem of planning the emergency response actions. The application ontology is the result of the integration of multiple pieces of different ontologies provided by various ontology libraries and is semi-automatically created by domain experts (Smirnov et al. 2005a). At the stage of application ontology building, the knowledge fusion result manifests as a new ontology created from multiple source ontologies, at that this ontology is of a new type. The new type comes out of fusion of knowledge of the domain type and knowledge of the problem solving type. Therefore, the stage of application ontology building produces two sorts of knowledge fusion results like a new knowledge source created from multiple sources and a new type of knowledge.

The application ontology is formalized through constraints. It is represented by sets of classes, class attributes, attribute domains, and constraints (Smirnov et al. 2003). The ontology specified in this way corresponds to a (non-instantiated) object-oriented constraint network.

The application ontology of the emergency management domain is not represented here because of its largeness.

3.2 Executive Phase

The executive phase concerns context-aware support of the decision maker with alternative decisions, decision making, decision implementation, and archiving. Context model is used to represent knowledge about the emergency situation. *Abstract context* and *operational context* represent the situation at the *first level* and the *second level*, respectively (Figure 1).

3.2.1 Abstract Context Creation

The application ontology serves as the basis for abstract context creation. This context captures from the application ontology the knowledge pieces relevant to the current emergency situation and significantly reduces the amount of knowledge represented in the ontology. The abstract context is a non-instantiated object-oriented constraint network just like the application ontology. Both components (domain and problem solving knowledge) making up the application ontology are presented in the abstract context. From the knowledge fusion perspective the abstract context is a new knowledge source created through integration of multiple pieces of the single knowledge source (the application ontology).

Figure 2 presents the abstract context created for a fire situation. The created context, along with other issues, specifies that in the fire situation the services provided by hospitals, emergency teams and fire brigades are required. The emergency teams, and fire brigades are mobile resources; they can use ambulances, fire engines, and special-purpose helicopters for transportation.

In the figure, the problem-solving knowledge specified in the abstract context is collapsed in the "Emergency response" class. Partly, this class is shown expanded on the right. The class specifies the following problems:

- select feasible hospitals, emergency teams, and fire brigades;
- determine feasible transportation routes for ambulances and fire engines depending on the transportation network and traffic situation;
- calculate the shortest routes for transportation of the emergency teams by ambulances and fire brigades by fire engines;
- produce a set of feasible response plans for emergency teams, fire brigades, and hospitals.

The ontology inference supports the procedure of knowledge integration into the abstract context. This inference is based on the regularities of the ontology

Abstract context: **new knowledge source created from multiple knowledge pieces**

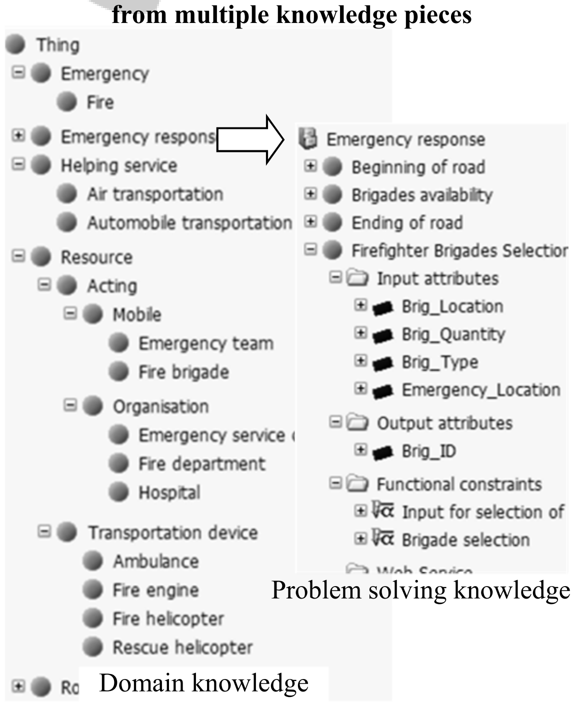


Figure 2: Abstract context (a fragment).

representation formalism used. Consequently, new ontology representation items (constraints, classes, attributes) may appear in the abstract context. This is the case of producing a new knowledge about the conceptual scheme as the result of knowledge fusion.

In the course of the abstract context for the fire situation creation a new relationship between the knowledge unrelated in the application ontology has been inferred (Figure 3). The application ontology specifies that a value for the argument representing the current location of a transportation device serves as an input argument of the routing method (1). The class "mobile" representing a mobile resource and the class "transportation device" are linked by a functional relationship (2) stating that the location of a mobile resource is the same as the location of the transportation device this resource goes by. In the abstract context a new functional relationship (3) has been inferred. This relationship means that a value for the attribute representing the current location of a mobile resource serves as an input argument of the routing method. In other words, values for the both attributes representing the current location of a transportation device or the current location of a mobile resource can be used as one of the input arguments by the routing method.

3.2.2 Operational Context Producing

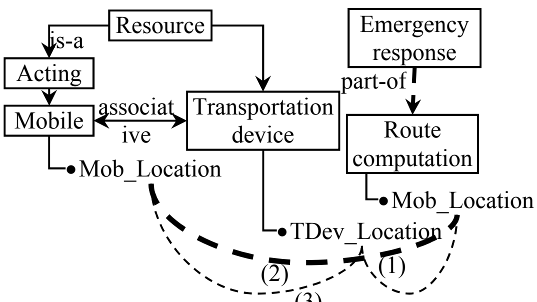
The operational context is an instantiation of the abstract context with the actual information. A subset of all available environmental knowledge sources is organized to instantiate the abstract context. This subset is referred to as contextual knowledge sources. The subset of the contextual knowledge sources comprises knowledge sources that can provide data values to create instances of the classes represented in the abstract context or solve the problems specified in it. The contextual knowledge sources with the specified sequence of their execution organize a knowledge source network. Nodes of this network are knowledge sources providing data values and/or solving the problems; network arcs signify the order of the nodes execution (Figure 4). In this figure, knowledge sources indicated by the same numbers are executed simultaneously.

The operational context reflects any changes in information incoming from the knowledge source network. The CADSS produces a special view for the operational context so that the users (decision makers) would be able to read and understand it.

The operational context is the result of the intelligent fusion of heterogeneous data / information from the contextual knowledge sources. This context is a new knowledge created from the environmental information, which is intended to be used as the foundation for problem solving and decision making. Moreover, the operational context represents a new knowledge type, namely the dynamic type.

Figure 5 presents a view for the operational context (the big dot denotes the fire location).

3.2.3 Problem Solving



(1): Route computation = F3(TDev_Location)

(2): F1(Mob_Location) = F2(TDev_Location)

inferred relationship (3):
Route computation = F4(Mob_Location)
new knowledge about conceptual scheme

Figure 3: Inferred relationship.

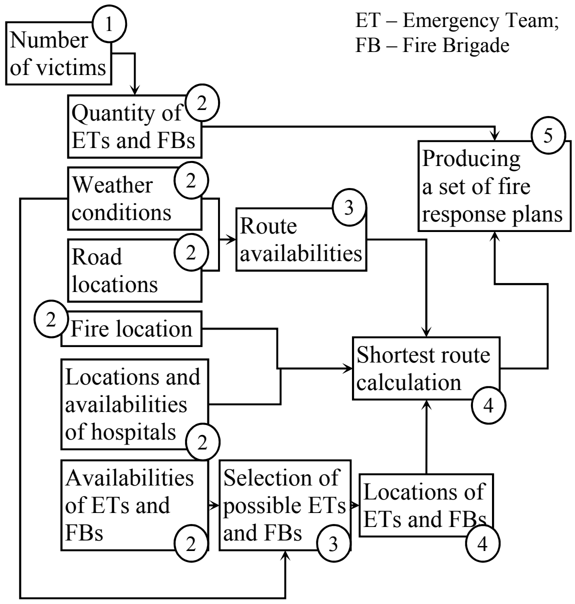


Figure 4: Knowledge source network.

The knowledge source network solves the planning problem embedded in the operational context as a constraint satisfaction problem. Consequently a set of alternative emergency response plans each corresponding to a decision that can be made in the current situation is received. An emergency response plan is a set of emergency responders with required helping services, schedules for the responders' activities, and transportation routes for the mobile responders. The process of problem solving is a process of fusion of knowledge from various sources in problem solving, which results in a solution. The solution forms a new knowledge type that is non-ontological knowledge.

Figure 5 presents a plan for actions for emergency teams, fire brigades, and hospitals (the dotted lines designate the routes proposed for the transportations of the emergency teams and fire brigades).

3.2.4 Decision Making and Decision Implementation

The decision maker chooses one plan from the set of alternative ones by selecting any plan from the set or taking advantage of some predefined efficiency criteria (e.g., minimal time of the response actions, minimal cost of these actions, minimal time of transportation to hospitals, etc.). The chosen plan is considered to be the decision.

The decision is delivered to the emergency responders included in the plan, i.e., to the actors responsible for the plan implementation. They have to approve the decision by confirming their readiness to participate in the response actions (the decision implementation). The emergency responders are enabled to participate in the approval procedure using any Internet-accessible devices. The approval of the decision by the actors directly allows ones to avoid hierarchical decision making, which is time-consuming and is not good for emergencies.

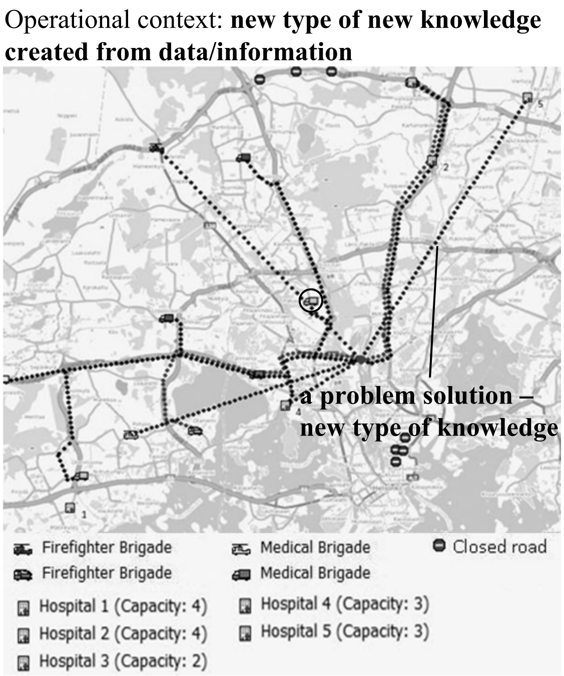


Figure 5: Operational context fused with decision.

If some of the emergency responders are not able to participate in the plan then, in some cases, the plan can be adjusted. The option of plan rejection is provided for due to the rapidly changing emergency situations – something may happen between the moment when the decision is made and the time when the emergency responders receive the plan. The plan adjustment implies a redistribution of the functions appertaining to the refused emergency responders between the other plan participants.

In the CADSS, emergency responders are represented by their profiles. If an emergency responder agrees to participate in some activity that its profile does not provide for then this profile is extended with a new capability. This is the case of fusion of implicit (unspecified capabilities) knowledge and explicit (profile) knowledge. The knowledge fusion result is gaining new capabilities / competencies by a knowledge object.

3.2.5 Archival Knowledge Management

The decision, the abstract context, and the operational context along with the knowledge source network are saved in a context archive. The operational context and the knowledge source network are saved in their states at the instant of the alternatives' generation. The archived components are the objects of archival knowledge management.

The archival knowledge management pursues several goals (e.g., revealing user preferences, grouping users with similar interests, decision mining, etc.). With reference to knowledge fusion, the main intention of the archival knowledge management is inference of new knowledge based on the accumulated one. For instance, new relations between the knowledge represented in the operational contexts can be discovered based on a comparative analysis of these contexts accumulated in the context archive, i.e. based on fusion of the knowledge represented by the operational contexts. Finding the same instance in different operational contexts may lead to revealing new relations for this instance.

The archival knowledge management enables to reveal explicit knowledge from the hidden one and new relations between originally unrelated knowledge. The both outcomes are interpreted as a new knowledge about the conceptual scheme, which refine the existing representations.

For instance, the emergency team encircled in Figure 5 participated in different emergency response actions. Some operational contexts in which this team appeared and then participated in corresponding actions do not represent any instances of the class *Emergency response organization* specified in the abstract context. This suggests that the emergency team is a part of one of the hospitals represented in the operational contexts together with this team. Based on the operational context (Figure 6) it can be judged that most probably the team is a part of hospital 5 represented in this context since the context does not represent any other hospitals from Figure 5 except this one. *Part-of* relation between the hospital 5 and the encircled emergency team is the new revealed relation. This relation is an outcome of inductive inference.

3.2.6 Abstract Context Reuse

Reuse of an abstract context in settings when the available knowledge sources are not intended to solve the problems specified in this context is a reason to search for a new configuration of the knowledge source network so that this new configuration would be able to solve the specified problems. Search for a new configuration implies search for knowledge sources that can solve the problems using the methods specified in the context as well as search for alternative problem solving methods. A basic condition for finding alternatives is an availability of knowledge sources that provide methods that can be used to solve the specified problems.

If alternative methods have been found, they get specified in the abstract context. That is, the abstract context gets extended with the new knowledge about the conceptual scheme. The knowledge source network is reconfigured accordingly. The new configuration gains new capacities.

Figure 6: History for emergency team.

Reuse of an abstract context can produce several knowledge fusion outcomes. Namely, a new problem solving method can be found, a new knowledge about the conceptual scheme can appear, and a new configuration of the knowledge source network with new capacities / competencies can be organized.

The abstract context (Figure 2) was reused in settings where the knowledge source intended to provide information about hospitals' locations missed. The abstract context specifies the routing problem as a hierarchy of methods one of which ('GetLocation') returns the current locations of objects in the format of point coordinates on the map. In the example under consideration it is required to determine the locations of hospitals. The method 'GetLocation' uses data from sensors.

The set of environmental knowledge sources comprises no sensors dealing with static objects like hospitals, and this set comprises some other sources. One of them implements a method ('MedicalCareSuggestions') intended to make recommendations what medical care organizations can be used to access some specific medical service. This source contains a database with information about the hospitals. The method 'MedicalCareSuggestions' returns the hospitals' addresses in an address format. The other source implements the method ('Conversions') that converts the address formats into the format of coordinates. The successive execution of the methods 'MedicalCareSuggestions' and 'Conversions' is an alternative way to calculate the hospital locations in the format of coordinates.

In the abstract context the methods 'MedicalCareSuggestions' and 'Conversions' are not specified as an alternative to the method 'GetLocation'. A set of constraints have to be introduced to get this alternative explicitly specified. This introducing leads to the extension of the abstract context with new knowledge representation items, that is new knowledge about the conceptual scheme of the abstract context.

3.2.7 Service Oriented Architecture

The CADSS is implemented as a set of services. Its architecture comprises three groups of services. The first group is made up of core services responsible for the registration of the services in the service register and producing the model of the emergency situation, i.e. for the creation of the abstract and operational contexts.

Web-services forming the second group are responsible for the generation of alternative plans for actions and the selection of an efficient plan.

The third group comprises services responsible for the representation of the environmental knowledge sources and the emergency responders and implementation of their functions.

The composition of services is applied for the organization of the services representing the contextual knowledge sources (contextual services) to instantiate the abstract context. The abstract context specifies an abstract workflow of the required composite service. The services communicate in terms of their inputs/outputs to create a service execution sequence. If alternative services available a set of sequences is created. A specific alternative is chosen based on the principles of maximum functionality, maximum access interval, and minimum service weight.

Principle of maximum functionality. For the services that implement several functions, usage of one service implementing several functions is considered more expedient than usage of several services implementing the same functions separately, *i.e.* $\left|WF_n \bigcap FN\right| \to \max$ for the n^{th} service, where WF_n – the set of functions the n^{th} service implements, FN – the set of functions specified in the abstract context.

Principle of maximum access interval. If there exist several services that are accessible over the interval $[t_0, T]$ at different time intervals $\{\Delta t\}$, then selection of less number of services whose overall access intervals cover the interval $[t_0, T]$ is considered to be more efficient. At that, the interval $[t_0, T]$ must be fully covered by the intervals Δt_i^n (Δt_i^n – the i^{th} access interval for the n^{th} resource, $\Delta t_i^n \in \{\Delta t\}$), *i.e.* $[t_0, T] \subseteq \bigcup_{n=1}^{NR} \bigcup_{i=1}^{nt} \Delta t_i^n$ (nt – number of intervals Δt_i^n over the interval $[t_0, T]$ for the n^{th} resource, NR – number of contextual services).

Principle of minimum weight. This principle is used to evaluate the efficient selection of alternative services. Alternative services are services implementing the same functions but differing in their locations, costs, *etc.* Weight of a service is calculated as $W = \alpha(1-N) + \beta T_r + \gamma C$, where N – the service's competence / reliability, $N = (0,1)$; T_r – the average access time to the service relatively to the access time that is maximum among the access times for the alternative services; C – the cost of information acquisition from the service relatively to the cost of information acquisition that is maximum among the costs for the alternative Web-services; α, β, γ – relative importance of the parameters for the particular service ($\alpha + \beta + \gamma = 1$).

The above principles do not pretend to be sufficient to produce optimal service networks; they provide for efficient service network configuration.

4 CONCLUSIONS

Various knowledge fusion processes were investigated. These processes produce different knowledge fusion outcomes. The places of knowledge fusion in the context-aware decision support system for emergency management were indentified. In this system, the knowledge fusion outcomes were found. Knowledge fusion enables to create a new knowledge. Such new knowledge allows the systems to adapt to the current situations efficiently. Therefore, it can be concluded that efficiency of up-to-date decision support systems depends heavily on their abilities to management of knowledge fusion processes.

ACKNOWLEDGEMENTS

The present research was partly supported by the projects funded through grants 12-07-00298, 13-07-12095, 14-07-00345, 14-07-00427 (the Russian Foundation for Basic Research), the Project 213 (the Russian Academy of Sciences (RAS)), the Project 2.2 (the Nano- & Information Technologies Branch of RAS), and grant 074-U01 (the Government of the Russian Federation).

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