Knowledge Fusion in Context-Aware Decision Support: Ontology-Based Modeling and Patterns

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Abstract The purpose of this chapter is twofold: (1) introducing of a semantic modeling mechanism, which is applied to achieve context-based knowledge fusion in a decision support system and (2) discovery of context-based knowledge fusion patterns. An approach to ontology-based resource modeling is proposed. The set of resources comprises sources of data/information/knowledge, problem solving resources and various actors. The knowledge fusion patterns are generalized with regard to two aspects: (1) preserving internal structures of multiple sources from which information/knowledge is fused within the ontological structure of context and preserving internal structure of the context itself, and (2) preserving autonomies of the multiple sources and the context. Six knowledge fusion patterns have been discovered. They are simple fusion, inferred fusion, instantiated fusion, adapted fusion, flat fusion, and historical fusion.

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1 Introduction

Decision support systems (DSSs) heavily rely upon large volumes of data, information, and knowledge available in different sources. Whereas several years ago the main technology used to integrate data and information from multiple sources within DSS was data fusion, today the focus of data fusion has naturally changed to knowledge fusion. The goal of knowledge fusion (KF) is to integrate information and knowledge from multiple sources into a common piece of knowledge that may be used for decision making and problem solving or may provide a better insight and understanding of the situation under consideration [1–4].

The present research is a continuation of the research on knowledge logistics. The KF technology was an important constituent of the knowledge logistics approach. As main results of that approach, a conceptual framework for context-aware operational decision support [5] was developed and *generic* KF patterns were discovered [6]. A context-aware DSS, designed according to the framework, was intended to function in heterogeneous environments like pervasive or ubiquitous ones. Semantic modeling of the environmental resources supported KF processes.

This chapter has for two objectives. The first one is a description of the semantic modeling mechanism applied to achieve context-based KF in DSS. The second objective is a discovery of *context-based* knowledge fusion patterns. While the *generic* patterns generalized KF processes taking place at different stages of building and exploitation of DSS, the *context-based* patterns are intended to generalize processes in the operational stage of the DSS functioning, i.e. the stage where the context aware functions of the system come into operation.

DSS described in this chapter is intended to support decisions on involvement of autonomous resources of a DSS environment in common activities and on planning these activities. Sources of data/information/knowledge and various actors existing in such an environment are considered as resources. Semantics is the key to ensure that several information and knowledge sources come to the same meaning of the situation and information/knowledge being communicated. This explains the fact that ontologies support most efforts on KF (e.g., [7–11]). In this chapter a mechanism to ontology-based resource modeling is proposed to overcome resource heterogeneity. This mechanism enables KF processes and allows the resources to achieve interoperability.

In the DSS, the KF technology is resorted to the following objectives: (a) integration of knowledge to create a new type of knowledge that is an abstract non-instantiated model of the current situation, (b) fusion of data/information/knowledge to produce an actual picture of the current situation that serves as the basis for problem solving and decision making, (c) problem solving, (d) inference of new relationships between knowledge objects, (e) discovery of alternative problem solving methods, (f) extension of capabilities/competencies of a knowledge object with new ones. The present research proposes KF patterns discovered at the stages of DSS functioning where the listed objectives are achieved.

The rest of the chapter is organized as follows. Section 2 introduces the conceptual framework of the developed DSS and the mechanism to semantic resource modeling. Section 3 gives an insight into knowledge fusion and summarizes the effects of it. Context-based knowledge fusion patterns are discovered and systematized in Sect. 4. Main research findings and a brief discussion conclude the chapter. Throughout the chapter, the task of planning fire response actions is considered to illustrate main ideas behind the research.

2 Context Aware Decision Support System

The objectives, this chapter aims at, are treated within a context-aware DSS intended to support decisions on involvement of autonomous resources of the DSS environment in common activities and on scheduling these activities. Sources of data/information/knowledge, problem solving resources and acting resources are distinguished in the environment. All they are considered as resources. The DSS was built following the conceptual framework presented below.

2.1 Conceptual Framework

The conceptual framework adopts the idea of ontology-based context representation. The central constituent of the framework is the application ontology (AO). This ontology represents non-instantiated knowledge of the application domain. Domain and problem solving knowledge fused from different knowledge sources make up AO. In this regard, AO can be considered as a knowledge source representing two different types of knowledge fused. AO supports an object-oriented ontology representation—it is specified by sets of classes, class attributes, attribute domains, and relationships [12].

Ontological knowledge is instantiated in the context by resources. Context represents a decision situation (the setting in which the decision occurs). A situation is represented at two levels. At the *first level* it is represented by *abstract context* that specifies non-instantiated ontology knowledge relevant to the current situation. Such knowledge is extracted from the application ontology. As two components make up the application ontology, the abstract context specifies domain knowledge describing the decision situation and problems to be solved in this situation. At the *second level* the situation is represented by *operational context* that is an instantiation of the abstract context with the actual information.

A set of contextual resources is organized to instantiate the abstract context. This set is a subset of all the environmental resources. The set of contextual resources comprises data/information/knowledge sources that can provide data values to create instances of the classes represented in the abstract context or solve problems specified in it. Then, an execution sequence of the contextual resources is determined. In this way a resource network is organized. Nodes of this network are resources providing data values and/or solving problems; network arcs signify an ordering on the resource execution.

The result of problem solving is a set of alternative decisions that can be made in the current situation. These alternatives are plans for the common activities of available acting resources. The decision maker chooses one plan from the set of alternative ones and delivers it to acting resources that are in this plan. The system facilitates the process of decision making by providing efficiency criteria that the decision maker can apply to the proposed set of alternatives.

The made decision (plan), the abstract context, and the operational context along with the resource network are saved in a context archive. The operational context and the resource network are saved in their states at the instant of alternatives generation.

In order to achieve context-based knowledge instantiation and enable KF processes the mechanism of ontology-based resource modeling is used.

2.2 Ontology-Based Resource Modeling

In the mechanism described in this subsection, the resources are represented by their ontologies. The representations of the resource ontologies are compatible with the representation of AO. The mechanism purposes the aim of an alignment of the resource ontologies and AO.

The alignment is based on discovery of semantically similar names for classes and attributes from AO and the resource ontologies. Semantic distance serves as a measure of semantic similarity. The semantic distances are calculated based on a machine-readable dictionary. This dictionary was automatically extracted from Wiktionary [13].

First, names of classes and attributes occurred in AO are searched for among concepts defined in the machine-readable dictionary. For the found concepts their synonyms and associated concepts are sought. Associated concepts are words hyperlinked in the concept definitions (Table 1).

Then, an initial semantic network is built. The found concepts (i.e., names of classes and attributes from AO), their synonyms and associated concepts are nodes of this network. The nodes corresponding to the found concepts and the nodes representing their synonyms and associated concepts are linked. The links are labeled by weights. It is assumed that weight w of a link specified between two concepts t_i and t_j is assigned as:

$$w = \begin{cases} 0,5 & -t_i,\ t_j \text{ are synonyms} \\ 0,3 & -t_i,\ t_j \text{ are associated concepts}\,. \\ \infty & -t_i,\ t_j \text{ are the same concept} \end{cases} \qquad (1)$$

Table 1 Extraction from machine-readable dictionary:example for class "Fire"

Concept	Wiktionary definition	Synonyms	Associated concepts
Fire	The often *accidental* occurrence of fire in a certain place leading to its full or partial *destruction*	–	Accidental, destruction

Names of classes and attributes from AO, for which there are no corresponding concepts in the machine-readable dictionary, are included in the network in the form as they are introduced in AO.

At the next step the semantic network is augmented with nodes representing the names of classes and attributes from the resource ontologies. This is done as described in the case of AO but with a slight difference: synonyms and associative concepts are included in the network only for the names from the resource ontologies that are different from the names the network already represents.

The links between nodes representing the same names from AO and from the resource ontologies are weighted as ∞.

Next, semantic distance *Dist* (2) is calculated between nodes representing concepts from AO and nodes representing concepts from the resource ontologies:

$$Dist(t_i, t_j) = \frac{1}{\sum_S \prod_{k=s_i}^{s_j} w_k}, \tag{2}$$

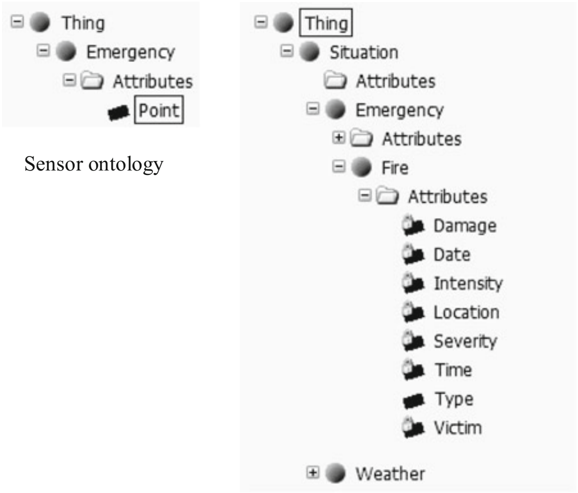
where t_i—concept from a resource ontology, t_j—AO-concept; w—weight of the link between t_i and t_j; S—a set of paths from t_i to t_j, where a path $s \in S$ is formed by any number of links between t_i and t_j passing through any number of nodes.

After the semantic distances have been calculated, experts are provided with a ranked list of semantically similar concepts. This list represents concepts from the resource ontologies and semantically similar to them concepts from AO with corresponding semantic distance values. Based on the list the experts map resource ontologies and AO.

The described approach is illustrated by an example of matching an ontology-based representation of the sensor that registers the location of an emergency event against AO for the emergency management domain. Figure 1 represents the sensor ontology and a piece of AO that is relevant to the illustrative example. In this example, matches for the attribute `'Point'` from the sensor ontology are searched for in AO. In the sensor ontology the attribute `'Point'` represents a point on the map, where the emergency is taking place. The purpose is to find in AO names of classes or attributes which could be considered as similar to the attribute `'Point'`.

Part of the machine-readable dictionary relevant for the example in question is presented in Table 2. The given part is limited to the attributes `'Location'` and `'Type'` of the AO-class *Fire* to simplify the discussion. A piece of the semantic network built based on Table 2 and formula (1) is presented in Fig. 2.

Fig. 1 Specifications of emergency in sensor ontology and fire in application ontology



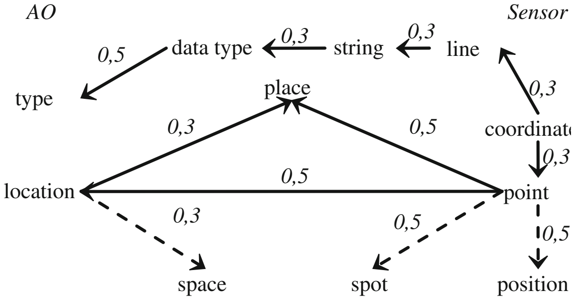
Sensor ontology

Application ontology (a piece)

Table 2 Extraction from machine-readable dictionary: example for attribute "point"

Point	A *location* or place. A point is defined by its *coordinates*	Location, place, position, spot	Location, coordinates
Location	A particular *place* in physical *space*	–	Place, space
Type	A *tag* attached to variables and values used in determining what values may be assigned to what variables	Data type	Tag

Fig. 2 A piece of semantic network relevant to attribute "Point"



The set of paths from the concept `'Point'` to the AO-concept `'Location'` comprises two paths: (1) *location* → *place* (weight 0.3), *place* → *point* (weight 0.5); and (2) *point* → *location* (weight 0.5). Thus, semantic distance between the two concepts is calculated as:

$$Dist(point, location) = \frac{1}{0.3 \cdot 0.5 + 0.5} = 1.54.$$

The set of paths from the concept `'Point'` to the AO-concept `'Type'` comprises one path: *point* ← *coordinate* (weight 0.3), *coordinate* → *line* (weight 0.3), *line* → *string* (weight 0.3), *string* → *data type* (weight 0.3), *data type* → *type* (weight 0.5). Semantic distance between `'Point'` and `'Type'` is

$$Dist(point, type) = \frac{1}{0.3^4 \cdot 0.5} = 246.9.$$

It can be seen that the semantic distance between the concepts `'Point'` and `'Location'` is much shorter than between the concepts `'Point'` and `'Type'`. So, the experts can align the attribute `'Location'` of the class *Fire* specified in AO and the attribute `'Point'` specified in the sensor ontology. This alignment means that the sensor responsible for registration of emergency locations instantiates the attribute `'Location'` of the AO-class *Fire*.

3 Knowledge Fusion

The main result of KF is synergetic effect from integration of a wide variety of information and knowledge sources. Based on an analysis of publications on KF, several types of KF can be distinguished:

- Intelligent fusion of massive amounts of heterogeneous data/information from a wide range of distributed sources into a form which may be used by systems and humans as the foundation for problem solving and decision making [1, 2]. Intelligent fusion assumes taking into account the semantic content of the sources being fused.
- Integration of knowledge from various knowledge sources resulting in a completely different type of knowledge or new idea how to solve the problem [14, 15]. Integration of different types of knowledge (domain, procedural, derived, presentation, etc.) resulting in a new knowledge type [3] and integration of multiple knowledge sources into a new knowledge object [16, 17] belong to this type of KF.
- Combining knowledge from different autonomous knowledge sources in different ways in different scenarios, which results in discovery of new relations between the knowledge from different sources or/and between the entities this knowledge represents [18, 19].
- Re-configuration of knowledge sources to achieve a new configuration with new capabilities or competencies [20].
- Knowledge exchange to improve capabilities or competencies through learning, interactions, discussions, and practices [20]. This type of KF is supported in multi-agent systems, which are composed of multiple intelligent software entities.

- Involving knowledge from various sources in problem solving, which results in a new knowledge product [6].

The analysis above enabled to reveal the possible effects of KF:

- new knowledge object created from data/information;
- new knowledge type or knowledge product (service, process, technology, etc.);
- new relations between knowledge objects;
- new capabilities/competencies of a knowledge object;
- new problem solving method;
- solution for a problem.

In the next section the context-aware DSS is investigated for the effects above and KF patterns behind the found effects are discovered.

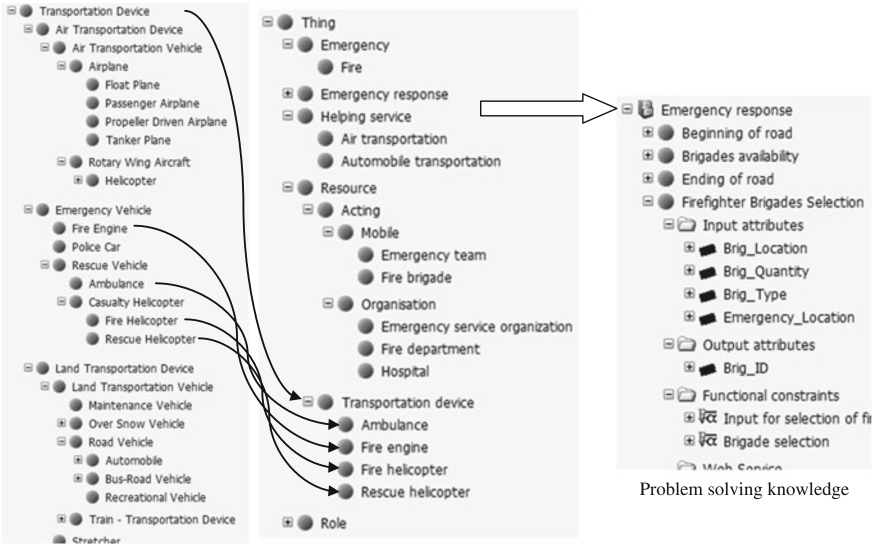
4 Context-Based Knowledge Fusion in DSS

Processes of KF are considered with references to abstract and operational contexts. At first, processes in DSS resulting in effects described in the precedent section are described. Demonstrations with examples from the fire response scenario accompany these descriptions. At the end of each description, a statement is formulated. Such a statement generalizes the KF result in terms of maintenance of the internal structure of the context and resource ontologies, and preservation of their autonomies.

4.1 Knowledge Fusion: Abstract Context

Abstract context is created from the single knowledge resource—AO. The procedure of the abstract context creation consists in selection in AO knowledge relevant to the decision situation, its extraction, and integration into a new knowledge object. This object corresponds to the abstract context, which can be considered as a new knowledge product fusing two types of knowledge.

Referring to the illustrative scenario, the abstract context is created for a fire situation. Figure 3 shows pieces of AO knowledge and abstract context knowledge. The abstract context significantly reduces the amount of knowledge represented in AO. The created context, among other things, specifies that in a fire situation the services provided by emergency teams and fire brigades are required. These teams and brigades 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 class “Emergency response”. Partly, this class is shown expanded in Fig. 3 on the right.



Application ontology

Abstract context

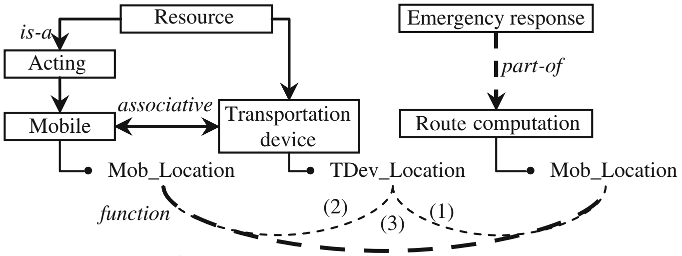
Problem solving knowledge

Fig. 3 Fire situation: abstract context (a fragment)

Statement 1. The procedure of the abstract context creation neither affects the internal structure of AO nor its autonomy. The abstract context becomes an autonomous object with a proper structure.

The knowledge integration may result in discovery of new relationships between the knowledge unrelated in AO. Figure 4 illustrates the case when AO specifies that a value for an input parameter of the routing method serves as a value for the attribute representing the current location of a transportation device (1). In this ontology the class "mobile" representing a mobile acting resource and the class "transportation device" are related by a functional relationship (2) assigning that the location of a mobile acting 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 acting resource serves as an input parameter 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 by the routing method as one of its input parameter.

Statement 2. The inferred relationships preserve the abstract context autonomy, but they change the context structure.



(1): Route computation = F3(TDev_Location)
(2): F1(Mob_Location) = F2(TDev_Location)
inferred relationship (3): Route computation = F4(Mob_Location)

Fig. 4 Inferred relationship

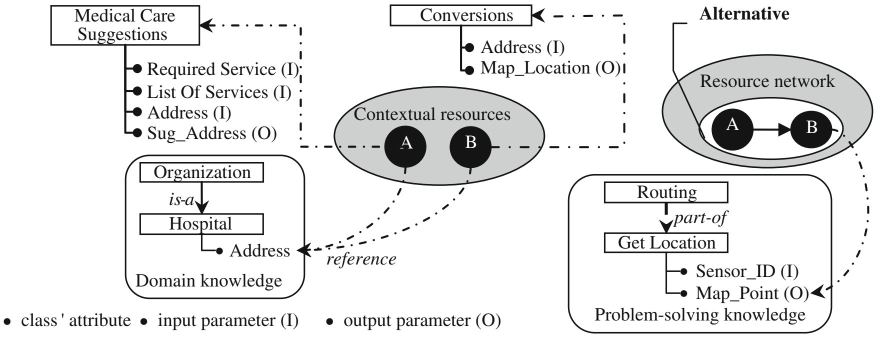


Fig. 5 Discovery of alternative problem-solving methods

The abstract contexts are reusable components of DSS. Reuse of an abstract context in settings when available resources are not intended to solve problems that are specified in this context enables to find an alternative problem-solving method. A basic condition for finding alternatives is availability of resources that provide methods that can be reused to solve the specified problems.

Figure 5 illustrates the case when the abstract context specifies routing problem as a hierarchy of methods one of which (*GetLocation*) returns the current locations of objects in the format of coordinates of a point 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 contextual resources comprises no sensors dealing with static objects like hospitals. But this set comprises some other resources. One of them (*A*) implements a method (*MedicalCareSuggestions*) intended to make recommendations on which medical care organizations can be used to access a specific medical service. This resource contains a private database with information about hospitals. The other resource (*B*) implements a method (*Conversions*) that converts the address format into the format of coordinates. The execution of the methods *MedicalCareSuggestions* and *Conversions* one after another is an alternative way to calculate the hospital locations in the format of coordinates. Optionally, the methods *MedicalCareSuggestions* and *Conversions* can be included in the abstract context.

Statement 3. If alternative methods are included in the abstract context then the structure of this context is changed. Otherwise, its structure is preserved. In any case, the autonomies of the abstract context, and the sources implementing the alternative methods are preserved.

Summing up the statements for the abstract context, KF can produce a new knowledge product, identify new relationships between knowledge objects, and discover alternative problem solving methods.

4.2 Knowledge Fusion: Operational Context

An operational context is produced through the semantic fusion of data/information from multiple data/information resources within the ontology structure of the abstract context. The result of this kind of fusion is a new knowledge object (operational context) created from data/information.

In case of fire, the operational context is a GIS-based representation of the fire situation. This representation is supplemented with characteristics of the fire situation specified in the abstract context. Examples of such characteristics can be seen in Fig. 1—the attributes of class “Fire” specify them. As well, the operational context represents information about traffic situation, available routes, weather conditions, and found acting resources (their locations, availabilities, capacities, transportation devices being used, etc.). According to the abstract context (Fig. 4) the main acting resources are emergency teams, fire brigades, and hospitals.

Statement 4. As soon as the resources start instantiating the abstract context, they lose their autonomies. Sources of information and data preserve their structures; problem-solving resources dissolve within the operational context. The operational context is a new knowledge object without autonomy.

Referring to the main purpose of decision support, which is solving the problems of organization of an association or community of autonomous entities joined for a common purpose and planning their joint activities, the problem of planning fire response actions is solved for the fire situation. For the emergency teams, fire brigades, and hospitals a plan for their joint actions is produced. An example of such a plan is shown in Fig. 6. The dotted lines indicate the routes to be used for the transportations. This result relates earlier independent objects.

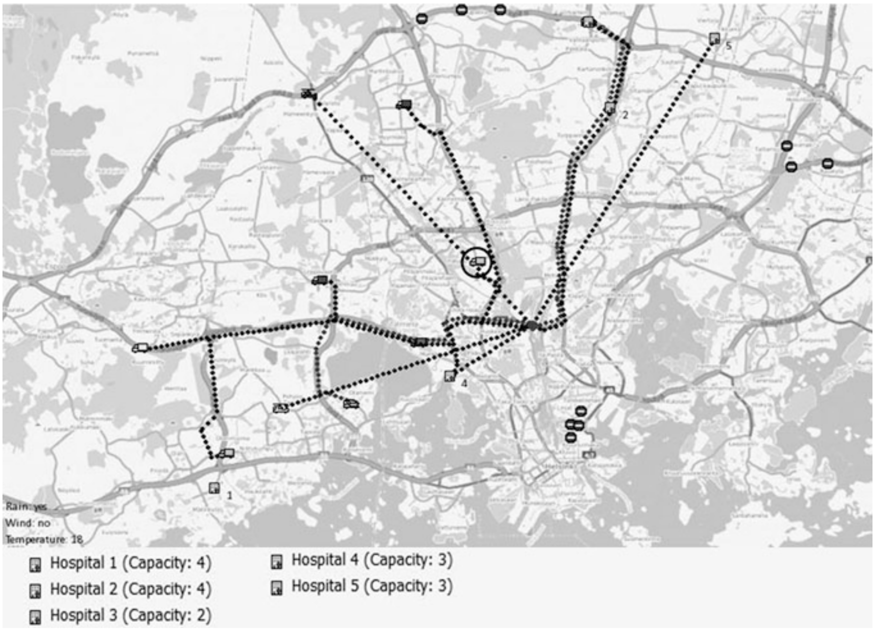


Fig. 6 Plan for actions: new relations and new knowledge product

To proceed from the above, problem solving results in new relations between resource entities represented in the operational context. Moreover, the result of problem solving is a new knowledge product (plan for actions) of a new type.

Statement 5. Resources involved in problem solving lose their autonomies and dissolve within the operational context. New relations between the resource entities affect the internal structure of the operational context.

New relations between the knowledge represented in the operational contexts can be discovered based on a comparative analysis of the operational contexts accumulated in the context archive. Finding the same entity in different operational contexts may lead to revealing new relations for this entity.

For example, the emergency team encircled in Fig. 6 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 (Fig. 7). This suggests that the emergency team in question is a part of one of the hospitals represented in the operational contexts together with this team. Based on the operational context (Fig. 7) it can be judged that most probably the team is a part of hospital 5 represented in this context since the context does not

Fig. 7 History for an emergency team

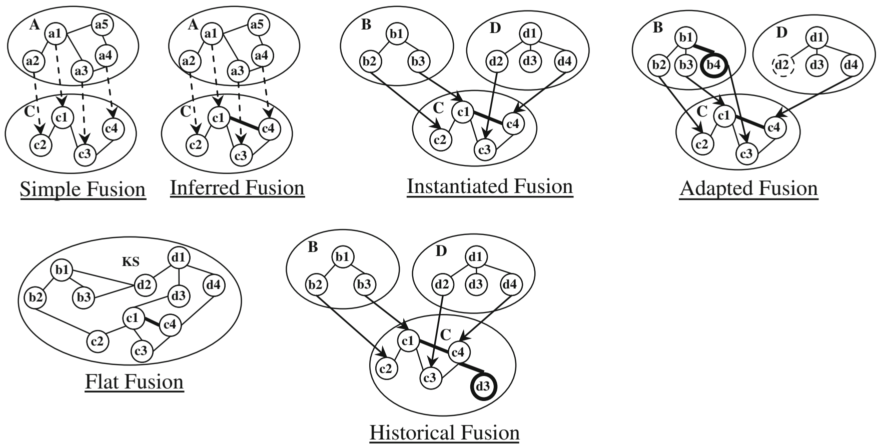
represent any other hospitals from Fig. 6 except this one. *Part-of* relation between the hospital 5 and the encircled emergency team is the new revealed relation.

Statement 6. The operational context and resources are not autonomous in the context archive. The new relation changes the structure of the operational context. The resources preserve their structures.

The resource network responsible for the instantiation has to adapt to the changing situation. In some cases, the network can be adjusted to the changed situation. An example of such a case is when a knowledge source failed, but its actions can be delegated to another resource or redistributed between other resources. This can lead to an extension of the capabilities/competencies of these resources with new ones.

For instance, an emergency team has failed in the course of actions because of road destruction, ambulance blockage, etc. This team was trained to rescue operations. If such operations are required in the current situation, then in some cases these operations can be delegated to available emergency teams. In such cases the profiles of teams agreed to take part in the rescue operations are extended with this new capability.

Statement 7. The operational context and the resources are not autonomous in the course of actions. Introducing a new capability to knowledge objects changes their internal structures.



Simple Fusion Inferred Fusion Instantiated Fusion Adapted Fusion

Flat Fusion Historical Fusion

A, B, D – nodes of the knowledge source network;
C – context;
KS –new knowledge source of new type

Fig. 8 Context-based knowledge fusion patterns in DSS

Summarizing the results of KF for the operational context, KF can produce a new knowledge object, new relations between knowledge objects, a new knowledge product of a new type, and extend capabilities/competencies of a knowledge object with new ones.

4.3 Context-Based Knowledge Fusion Patterns

The discussion above enables to distinguish patterns of context-based KF (Fig. 8). These patterns use maintenance of internal structures of contexts and knowledge sources and preserving their autonomies as the criteria. It is suggested, that essentially, all kinds of resources considered above can play a role of knowledge sources.

- *Simple fusion*: selection of pieces of knowledge from one or more knowledge sources and their integration into a new knowledge object. Initial knowledge sources preserve their internal structure and autonomies; the new knowledge object (context) becomes autonomous object with a proper structure.
- *Inferred fusion*: inference of new relations between the unrelated pieces of knowledge extracted from the same knowledge source and fused into existing context. The context preserves its autonomy, but its structure is changed.
- *Instantiated fusion*: semantic fusion of data/information from multiple sources within the ontology structure of context resulting in a new knowledge object created from data/information. The context and the sources of data & information preserve their internal structures but lose their autonomies.

Table 3 Correspondences between Statements and KF patterns

Statement	Phase of DSS functioning	Meaning	Knowledge fusion pattern
1.	Abstract context creation	Integration of multiple knowledge pieces from the same knowledge source into a new piece of knowledge	Simple fusion
2.	Abstract context creation	Inference of new relationships between originally unrelated concepts	Inferred fusion
3.	Abstract context reuse	Discovery of alternative problem-solving methods	*Not defined*
4.	Operational context producing	Instantiation of the abstract context with values from multiple data/information/knowledge sources	Instantiated fusion
5.	Generation of a set of alternatives	Problem solving	Flat fusion
6.	Contexts archiving	Discovery of new relationships between entities	Historical fusion
7.	Decision implementation	Gaining new capabilities/competencies by elements of knowledge source network	Adapted fusion

- *Adapted fusion*: adaptation of the existing knowledge source network to the context that results in gaining new capabilities/competencies by elements of the knowledge source network. The context and the initial knowledge sources do not preserve their autonomies; the structures of the knowledge sources may be changed.
- *Flat fusion*: fusion of knowledge from multiple knowledge sources to solve a problem specified in context. The solution represents a new knowledge product of a new type. The initial knowledge sources dissolve within the new knowledge object. The context and the knowledge sources do not preserve their internal structure and autonomies.
- *Historical fusion*: revealing new relations for the same knowledge object based on a comparative analysis of different contexts this object has been involved in. The context loses its autonomy, its structure is changed. Knowledge sources representing the object in question preserve their internal structures, but lose their autonomies.

The correspondences between the formulated statements and the patterns are given in Table 3. It must be pointed out, that any patterns for the Statement 3 have not been discovered. This can be explained by optional change of the abstract context structure when a new alternative problem-solving method is found. An assumption here is that the considered aspects of generalization are not sufficient to discover such a pattern.

5 Conclusion

In this chapter a conceptual framework for a context-aware DSS was introduced. An approach to ontology-based resource modeling was proposed within this framework. Usage of this approach within the framework allows the autonomous resources to make for achievement of a common purpose and to participate in joint actions. Besides this, the semantic resource models enable context-based KF processes taking place in DSS. Such processes were investigated and context-based KF patterns were discovered.

Comparatively to the existing approaches dealing with ontology based modeling of heterogeneous sources [21–23], the proposed approach introduces a measure for semantic similarity that takes into account, besides typical lexical relations, associations existing between the compared concepts. This is believed to give more accurate results, since the concepts are compared in their broad semantic environment.

While semantic modeling is a subject of many research studies, discovery of KF patterns is not a hot research topic. Up to now, some general patterns like unstructured fusion [24], convergence [14], fractal fusion [14], knowledge recombination (includes two patterns: KF and knowledge reconfiguration) [20] have been mentioned in a few research works. These patterns were discovered as a generalization of processes of knowledge interchange and combination (integration) in different distributed organizations and as a specialization of technology fusion patterns.

The present research was limited with two views on context-based KF. It was one of the reasons for a pattern that generalizes discovery of alternative problem-solving methods was not defined. Some future research is required to consider more aspects of interactions between the knowledge being fused and the contexts. Probably, the future research will enable to build formal models for KF patterns and provide some ideas which pattern is appropriate to use in the current state of the situation.

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References

1. Scherl, R., Ulery, D.L.: Technologies for army KF. Final report, Monmouth: Monmouth University, Computer Science Department, West Long Branch, Report no. ARL-TR-3279 (2004)
2. Alun, P., Hui, K., Gray, A., Marti, P., Bench-Capon, T., et al.: Kraft: an agent architecture for KF. Int. J. Coop. Inf. Syst. **10**(1–2), 171–195 (2001)
3. Holsapple, C.W., Whinston, A.B.: Building blocks for decision support systems. In: Ariav, G., Clifford, J. (eds.) New Directions for Database Systems, pp. 66–86. Ablex Publishing Corp, Norwood (1986)

4. Phan-Luong, V.: A framework for integrating information sources under lattice structure. Inform. Fusion **9**(2), 278–292 (2008)
5. Smirnov, A., Pashkin, M., Chilov, N., Levashova, T.: Constraint-driven methodology for context-based decision support. J. Decis. Syst. **14**(3), 279–301 (2005)
6. Smirnov, A., Pashkin, M., Chilov, N., Levashova, T., Haritatos, F.: Knowledge source network configuration approach to knowledge logistics. Int. J. Gen. Syst. **32**(3), 251–269 (2003)
7. Bossé, É., Valin, P., Boury-Brisset, A.-C., Grenier, D.: Exploitation of a priori knowledge for information fusion. Inform. Fusion **7**(2), 161–175 (2006)
8. Gu, J., Xu, B., Chen, X.: An XML query rewriting mechanism with multiple ontologies integration based on complex semantic mapping. Inform. Fusion **9**(4), 512–522 (2008)
9. Yao, J., Raghavan, V.V., Wu, Z.: Web information fusion: a review of the state of the art. Inform. Fusion **9**(4), 446–449 (2008)
10. Little, E.G., Rogova, G.L.: Designing ontologies for higher level fusion. Inform. Fusion **10**(1), 70–82 (2009)
11. Dapoigny, R., Barlatier, P.: Formal foundations for situation awareness based on dependent type theory. Inform. Fusion **14**(1), 87–107 (2013)
12. Smirnov, A., Pashkin, M., Chilov, N., Levashova, T.: Knowledge logistics in information grid environment. Future Gener. Comp. Syst. **20**(1), 61–79 (2004)
13. Wiktionary, the free dictionary. Internet: http://en.wiktionary.org/. Accessed 10 Oct 2012
14. Lee, K.-R.: Patterns and processes of contemporary technology fusion: the case of intelligent robots. Asian J. Technol. Innov. **15**(2), 45–65 (2007)
15. Grebla, H.A., Cenan, C.O., Stanca, L.: Knowledge fusion in academic networks, BRAIN: Broad Res. Artif. Intell. Neurosci. **1**, 2 (2010). http://www.edusoft.ro/brain/-index.php/brain/article/download/60/145. Accessed 10 Oct 2012
16. Kuo, T.-T., Tseng, S.-S., Lin, Y.-T.: Ontology-based KF framework using graph partitioning. In: Chung, P.W.H., Hinde, C.J., Ali, M. (eds.) Proceedings of IEA/AIE 2003. LNCS, vol. 2718, pp. 11–20 (2003)
17. Gou, J., Yang, J., Chen, Q.: Evolution and evaluation in KF system. In: Mira, J. Alvarez, J.R. (eds.) Proceedings of IWINAC 2005. LNCS, vols. 2718, 3562, pp. 192–201 (2005)
18. Laskey, K.B., Costa, P., Janssen, T.: Probabilistic ontologies for KF. In: Proceedings of the 11th International Conference Information Fusion, IEEE (2008). http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=-4632375. Accessed 10 Oct 2012
19. Jonquet, C., LePendu, P., Falconer, S., Coulet, A., Noy, N.F., et al.: NCBO Resource Index: ontology-based search and mining of biomedical resources. J. Web Semant. **9**(3), 316–324 (2011)
20. Lin, L.Y., Lo, Y.J.: Knowledge creation and cooperation between cross-nation R&D institutes. Int. J. Electron. Bus. Manag. **8**(1), 9–19 (2010)
21. Wache, H., Voegele, T., Visser, U., Stuckenschmidt, H., Schuster, G., Neumann, H., Huebner, S.: Ontology-based integration of information—a survey of existing approaches. In: Proceedings of the Workshop on Ontologies and Information Sharing at the International Joint Conference Artificial Intelligence (IJCAI), pp. 108–117 (2001)
22. Kalfoglou, Y., Schorlemmer, M.: Ontology mapping: the state of the art. Knowl. Eng. Rev. **18**(1), 1–31 (2003)
23. Shvaiko, P., Euzenat, J.: A survey of schema-based matching approaches. J. Data Semant. **4**, 146–171 (2005)
24. Chen, J., McQueen, R.J.: Knowledge transfer processes for different experience levels of knowledge recipients at an offshore technical support center. Inf. Technol. People **23**(1), 54–79 (2010)