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An experiment in ontology use for command and control interoperability

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Abstract The article addresses the question of whether methods from ontology engineering and reasoning can help domain-experts (as opposed to laymen) when mapping concepts from domain-specific vocabularies to each other. The overarching context is military Command & Control systems, and the prospects for fostering interoperability between them. The main contribution of the article is an experiment conducted with senior military officers on mapping two artillery vocabularies to each other. Overall, the evidence is stronger that (i) hierarchical structuring of concepts, (ii) definitions of concepts and (iii) mappings to a common reference vocabulary can help domain-experts to make sound matches than help them avoid unsound ones. However, more research is needed before a verdict can be given. Though the experiment exhibits high ecological validity, using subjects who are experts in the domain of the two vocabularies that are to be mapped to each other, internal validity suffers confounding effects of previous expertise, and reliability is low, due to the low number of subjects ($N = 13$).

Keywords Semantic interoperability · C2 systems · System integration · Ontologies · SKOS

1 Introduction

In an increasingly networked world, the ability to exchange data between different information systems is becoming ever more important. Businesses, voluntary associations and government agencies alike can benefit from exchanging their data with

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others, both by increasing the efficiency of current operations and by enabling activities previously deemed impossible. However, achieving interoperability between heterogeneous information systems is non-trivial and sometimes very expensive.

The costs of insufficient interoperability in the American automotive industry have been estimated to about a billion dollars annually, delaying the time to market of new car models about two months (Brunnermeier and Martin 2002). The overall value of Health care information exchange and interoperability (HIEI)—when fully built—has been estimated to be about 77.8 billion dollars annually (Walker et al. 2005). A full review of the benefits of enterprise integration is given by Fazlollahi et al. (2012).

The increasing costs of integration have been attributed to the un-coordinated use of various semantic principles. The Gartner analysis firm estimates that somewhere between 30 and 60 % of all integration costs could be reduced by better strategies, including an improved overarching architectural perspective (Beyer 2011). Still, integrations are expected to remain costly. At least until 2016, organizations are expected to spend a larger share of IT budgets on integration than on building new systems (Lheureux et al. 2011).

Why is it so hard to attain interoperability? Ullberg et al have identified three main barriers to enterprise interoperability, i.e. reasons for incompatibilities between enterprise systems (Ullberg et al. 2009):

- Conceptual barriers: are incompatibilities arising either from the languages used (syntactic level) or the meaning of the terms (semantic level).
- Technological barriers: include file format exchange problems, insufficient database access rights, versioning incompatibilities, etc.
- Organizational barriers: include issues of data ownership, problems caused by divergent organizational policies, legislative heterogeneity, etc.

Ullberg et al conclude that ”The conceptual barriers are the most important ones because they are concerned with the presentation and representation of concepts to use for enterprise business and operations.” Nevertheless, technological barriers such as appropriate formats for data exchange are often at the forefront of interoperability discussions, sometimes clouding the issue and driving attention away from the more pressing problem of semantic interoperability. If the meaning of the terms used is not appropriately conveyed, appropriate formatting does little good. Our research, therefore, is focused on the semantic issue.

Goh has identified three main causes of semantic heterogeneity in information systems (Goh 1997):

- Naming conflicts: typically occur when different homonyms and synonyms are used in naming, resulting in different conventions that need to be reconciled.
- Scaling conflicts: involve different measurement units (e.g. kilometers and miles, or dollars and euros) that need to be converted.
- Confounding conflicts: occur when two concepts that are actually distinct are interpreted as being a single one, e.g. due to the passage of time.

In this article we address the issue of achieving semantic interoperability between different Command and Control (C2) systems, based on semantic technologies. By carefully mapping the concepts used by each system to a reference ontology, well-known methods from ontology merging and matching can be applied to achieve semantic interoperability in the sense of passing a message from one system to another without naming, scaling or confounding conflicts (Mojtahed et al. 2011).

To better understand this scope, it can be contrasted with two other use-cases. First, it should be noted that our scenario does not necessarily require all-out integration in the sense that the sending system automatically pushes the message to the receiver, or the receiver automatically pulls it. Such requirements are characteristic of enterprise integration, e.g. of supply chains. In our scenario, however, the focus is on bridging the semantic gap between two systems. Message passing between systems can thus be initiated by a human operator on a need-basis. Second, the concern for undistorted semantics is different from many ontology applications such as search engines, library databases and the semantic web. In these applications, finding more or less related concepts is often good enough—the need for precision is not that pressing, since a human operator often easily can sift through superfluous hits. However, aiming to pass undistorted messages between C2 systems, our primary concern is exact matches between concepts—not just more or less distantly related ones. As will be evident in Sect. 3, this scope is reflected in the setup of the experimental investigation.

In traditional systems development, mapping of concepts is rarely done formally. Instead, the mapping is done as part of a requirements capturing process, and are only formally implemented as part of the resulting executable code. If changes are made to either system, requiring changes to the message passing system, the executable code has to be modified. As an alternative, we propose that domain experts document the mapping of concepts formally, as an ontology model, before this mapping is turned into code. The code can then be built from the ontology model, entailing better modifiability. When changes need to be made, these changes can be made to the ontology model, followed by automatic generation of the executable code. The advantage is that this allows the experts on the concepts to do the changes without having to be able to edit the executable code. This eliminates one important source of error (naming, scaling or confounding conflicts) and speeds up implementation.

However, it is not self-evident that domain experts are able to work efficiently with ontology engineering tools, nor that the help offered by such tools is of much use to experts. Much work has been done on ontologies for the semantic web (Horrocks 2008) and on ontologies for information retrieval (Paralic and Kostial 2003). However, the typical use-case in these applications involves a relative novice quickly wanting to get an overview of a new subject. This is quite different from the domain expert who wishes to map two vocabularies to each other. He is not interested in overly broad matches, but rather in relatively exact ones.

Thus, the overarching research question of this investigation is: Do methods from ontology engineering and reasoning help domain-experts when creating a mapping between two domain-specific vocabularies? More precisely, we have experimentally investigated three aspects:

Research question 1 Does *hierarchical structuring of concepts* help domain-experts when creating a mapping between two domain-specific vocabularies?

Research question 2 Do *definitions of concepts* help domain-experts when creating a mapping between two domain-specific vocabularies?

Research question 3 Do *mappings to a common reference vocabulary* help domain-experts when creating a mapping between two domain-specific vocabularies?

The answers to these questions are important to assess the potential of the ontology-driven approach to achieving semantic interoperability between different C2 systems.

1.1 Outline

This article unfolds as follows: Sect. 2 explores some related work. Section 3 describes the experiment setup, and the methods used. The results are briefly summarized in Sect. 4, followed by a discussion in Sect. 5. Section 6 concludes the article.

2 Related work

There are, broadly speaking, three categories of work related to this paper. The first category is technologically similar work, dealing with ontology merging and maintenance. This is a relatively mature area, featuring a number of implemented systems and tools, such as Chimaera (McGuinness et al. 2000), CTX-Match (Serafini et al. 2003), Cupid (Madhavan et al. 2001), FCA-Merge (Stumme and Maedche 2001), GLUE (Doan et al. 2003), LOM (Li 2004), LSD (Doan et al. 2003), MAFRA (Silva and Rocha 2003), MOMIS (Beneventano et al. 2003), ONION (Mitra and Wiederhold 2002), and PROMPT (Noy and Musen 2003). Choi et al offer a good survey of such tools (Choi et al. 2006). However, these papers do not address the domain of military C2 system interoperability, and do not systematically address the question of how much support users get from the methods.

The second category is work on the problem of military C2 system interoperability. Perhaps the most prominent work in this area is that conducted by the Multilateral Interoperability Programme (MIP), and its construction of the Command and Control Information Exchange Data Model (C2IEDM) (Turnitsa and Tolk 2005), now the Joint Consultation, Command and Control Information Exchange Data Model (JC3IEDM) (Bau et al. 2008). However, this research has focused on the models themselves and full automation, rather than studies involving human computer interaction and user support.

The third, most relevant, category involves the use of ontology-based methods to achieve semantic interoperability between heterogeneous systems. An early work in this category was conducted by Visser et al. (2000). Working in the domain of Geographical Information Systems, Visser et al offer a conceptual architecture called Bremen University Semantic Translation for Enhanced Retrieval (BUSTER), to integrate data from heterogeneous systems. The concept hinges on using Comprehensive Source Descriptions (CSDs) of each system to be integrated along with ”semantic mappers” to bridge the gaps between different data sources. Though semantic technology has leaped forward since the original proposal of the BUSTER concept, its basic principles are similar to ours.

Obrst sketches a conceptually similar approach (Obrst 2003). Here, an argument for ontologically-based semantic interoperability is spelled out in terms of trends such as growth in loosely coupled information systems, an increasing market for business-to-business applications, and the emergence of government metadata initiatives to support cross-agency interoperability. The need for semantic interoperability has not decreased since then.

Ye et al propose an ontology-based architecture aiming to facilitate the integration of supply chains within the automotive industry (Ye et al. 2008). By means of a unified Supply Chain Ontology (SCO), semantic interoperability between different applications within the supply chain can be achieved. The terminology of each application is separately mapped to the SCO, thus facilitating the inference of the desired mapping between the two applications.

Gailly and Poels use the Resource-Event-Agent (REA) ontology to achieve interoperability between different enterprise ontologies. The authors thus manage to map the ISO/IEC 15944 and the UN/CEFACT Modeling Methodology to each other in a manner very similar to ours.

However, neither Visser et al, Obrst, Ye et al nor Gailly and Poels (2009) have conducted experiments with users, measuring the benefit to them in terms of support for a specific task.

3 Method

To investigate whether methods from ontology engineering and reasoning help domain-experts when creating a mapping between two domain-specific vocabularies, an experiment was conducted as follows.

3.1 Experimental setup

The experiment makes use of Simple Knowledge Organisation System (SKOS), a WC3 Recommendation for sharing and linking structured vocabularies—taxonomies, thesauri, classification schemes, etc. —via the Web.[1] The use of SKOS as the language of this experiment is based on the assumption that its light-weight approach to ontology will be easier to relate to for subject matter experts who are not a priori familiar with ontology concepts or tools.

The domain chosen was that of procedures and messages required for artillery C2. Specifically, one vocabulary is that mandated by the NATO standard *Artillery Procedures For Automatic Data Processing (ADP) System Interoperability* (NATO Standardization Agency (NSA) 2009) (henceforth: ASCA). The other vocabulary is that mandated by the Swedish Armed Forces in the specification of the DART text messaging format and the relevant artillery field manual (Försvarsmakten [Swedish Armed Forces] 2007) (henceforth: DART). From these two vocabularies, SKOS concept schemes were created by the authors, each scheme containing a few hundred

1 http://www.w3.org/2004/02/skos/

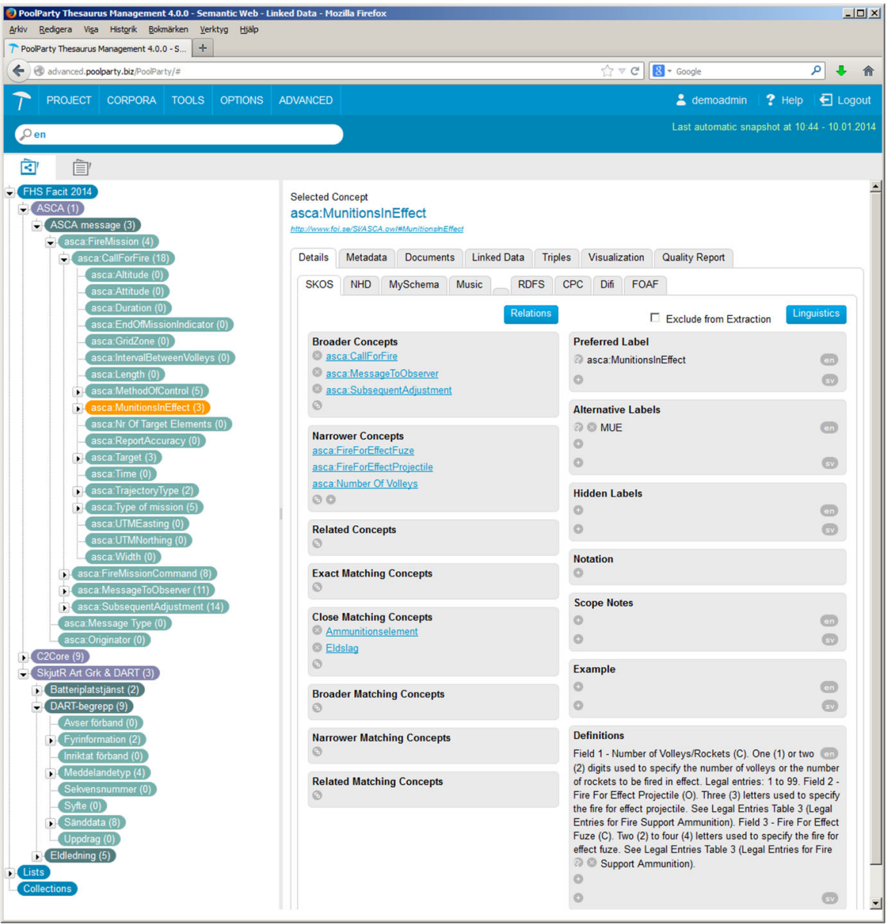


Fig. 1 The experimental environment – PoolParty. To the *left*, the three vocabularies ASCA, C2Core and DART can be seen. For the selected concept, lists of broader and narrower concepts are seen in the *middle*, along with matching concepts from the other vocabularies. To the lower *right*, concept definitions are given

concepts. The concepts were assigned definitions (copied verbatim from the reference documents, or sometimes from external sources such as DBPedia/Wikipedia) and ordered hierarchically using the SKOS `Broader`, `Narrower` and `Related` relations based on the reference documents. Furthermore, a third vocabulary was created based on the Command and Control Core (C2 Core for short) an XML-based standard for data exchange proposed by the US Department of Defense C2 Data and Services Steering Committee (2011). As C2 Core is intended for data exchange, it was used as a *common reference vocabulary* that the other two were linked to, using the `ExactMatch` and `CloseMatch` relations. All three vocabularies were created and maintained in SKOS format on the PoolParty Thesaurus Server.[2] PoolParty is depicted in Fig. 1.

[2] http://www.poolparty.biz

In order to investigate the three research questions, four versions of the setup were created. In the most extensive version, the ASCA and DART vocabularies were (i) hierarchically structured, (ii) defined using the `Definitions` property, and (iii) mapped to the C2 reference vocabulary. In a more sparse version, there was no mapping to the reference ontology, but hierarchy and definitions. In the most sparse versions, only hierarchy or only definitions remained. In the following, these four setups are encoded as DSM, DS, S or D, respectively (D—definitions, M—mappings, S—structure). Regardless of setup, the task for the subjects was the same: Map ASCA and DART concepts to each other, as many as possible, using `ExactMatch`, `CloseMatch` or `Broader/Narrower` matching relations.

3.2 Preliminary testing

Before the actual experiment, two preliminary tests were conducted. First, a colleague of the authors (PhD familiar with ontologies and with some basic knowledge of artillery terminology) was subjected to the task. His feedback resulted in a number of improvements to the experimental setup, including the importance of making abbreviations explicit and the use of prefixes in concepts to clearly indicate which vocabulary a concept belongs to (e.g. `asca:Smoke Screen` rather than just `Smoke Screen`). Second, a former artillery officer (retired lieutenant colonel) was subjected to the task. His feedback resulted in a number of corrections regarding the terminology and the mappings to the C2 Core reference vocabulary.

3.3 Conduct of the experiment

The actual 13 subjects were all students in the Advanced Command Program (majoring in military technology) at the Swedish National Defence College, being majors (army, marines or air force) or lieutenant commanders (navy). The experiment was first introduced with two lectures on information fusion, ontology use for semantic interoperability and an introduction to SKOS and PoolParty. Then a hands-on part ensued, where the subjects did a tutorial exercise aimed to foster familiarity with SKOS and PoolParty proficiency. The tutorial contained a mapping exercise similar to the one in the actual experiment. Before turning to the actual experiment, the subjects filled out a short self-assessment form where they stated their familiarity with (i) Swedish and (ii) NATO artillery terminology relative to the rest of the group.

Approximately one hour was allocated to the actual experiment. The authors were available throughout the session to answer any questions regarding the comprehension of the task, though not questions related to its solution. The session ended with a brief discussion, where the subjects were allowed to share any thoughts on the experiment, the vocabularies or the concept of semantic interoperability using ontology methods.

3.4 Marking and evaluation

In order to evaluate the results and answer the research questions, the results of each individual had to be marked. The marking template was created in an iterative fashion as follows:

1. The mappings to the C2 Core reference vocabulary (which were available to some, but not all, of the actual subjects) were used to infer mappings between the ASCA and DART vocabularies. For example, by transitivity of `exactMatch`, if concept A in ASCA has an `exactMatch` relation to concept B in C2 Core, and concept B in C2 Core also has an `exactMatch` relation to concept C in DART, then it can be inferred that concept A in ASCA has an `exactMatch` relation to concept C in DART. The inferencing also used heuristic rules, such as transitivity of `closeMatch`, that may produce unsound mappings.
2. The inferred marking template was manually reviewed by the authors, removing unreasonable relations and adding reasonable relations not inferred. This work was carried out supported by careful reading of definitions, procedures (NATO Standardization Agency (NSA) 2009) and field manuals (Försvarsmakten [Swedish Armed Forces] 2007). In particular chapters 2.7, 2.8, and 2.9 of the Swedish field manual were very useful, as they relate Swedish and NATO terminology.
3. The resulting marking template was applied to *anonymized* versions of the solutions of the subjects. This generated lists of *sound* and *unsound* matches, for `exactMatch`, `closeMatch`, `relatedMatch`, `narrowMatch` and `broadMatch` relationships. Based on these lists, a *new manual revision* was made of the marking template, to correct unreasonable results in the marking process. It should be stressed that the lists where anonymized, so it was not possible to bias the results by making the correction template favor some experimental subjects over others. However, this procedure allows the marking to incorporate—in a sense—the combined knowledge of all the subjects, because all of their answers have had the chance to influence the marking procedure. More precisely, any respondent answer deemed unsound by the marking template was manually screened, anonymously, and a verdict was reached by looking at definitions, procedures and field manuals.
4. The third step was re-iterated again, now with the revised marking template.
5. The marking template was again subjected to expert assessment by the retired artillery lieutenant colonel. This time, each subject answer in the `exactMatch` category—again anonymized—was examined, whether deemed sound or unsound by the marking template. This feedback resulted in a few additional corrections to the marking template.
6. The final marking template was applied to the solutions of the subjects, leading to the results detailed in the next section.

As the marking template is crucial to the experiment, it is worth to re-iterate the quality controls employed to make sure that the marking template is more correct than the mappings created by the experimental subjects:

1. The subjects were only given an hour to solve the task, with incomplete information as per the experimental setup. The authors have spent several days carefully reading the relevant definitions, procedures (NATO Standardization Agency (NSA) 2009) and field manuals (Försvarsmakten [Swedish Armed Forces] 2007) during the creation of the experimental materials including the marking template.
2. The subjects, though domain experts, were not allowed to discuss their results with each other or the authors. By contrast, when preparing the experimental materials

including the marking template, the authors had the benefit of discussing with each other and the retired artillery lieutenant colonel to reach well-reflected decisions.

3. The iterative creation of the marking template incorporates the combined knowledge of all the subjects, since any answer deemed incorrect by the marking template has been manually screened by the authors.
4. The marking template was created with the benefit of automated inference, minimizing the risks for trivial mistakes, omissions and inconsistencies. This is a marked contrast to the subjects, where the experimental conditions in the treatments without structure and definitions deliberately made it more difficult to get an overview and be consistent.

To summarize: while the marking template might still contains disputables and errors, it is very reasonable to assume that it represents a far more correct mapping than any of the individual subjects'.

4 Results

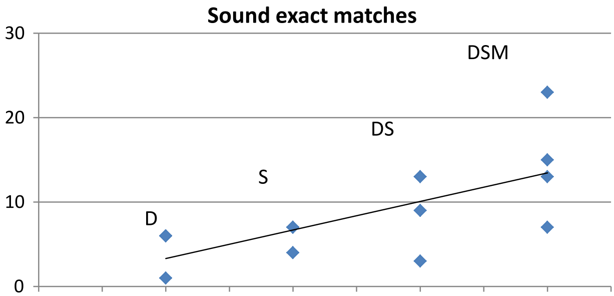
The number of sound and unsound exact, broad, and narrow matches by subject is given in Table 1. Furthermore, self-assessed levels of expertise with the two vocabularies are given, according to the key in the caption.

The table deserves a few remarks. First, the `closeMatch` category is absent. The reason is that the subjects' interpretation of what constitutes a close match was too diverse to really be meaningful. Second, subject exact matches have been deemed sound when the corresponding marking template entry is either an exact or a close match. This choice is the reflected best solution resulting from the deliberations

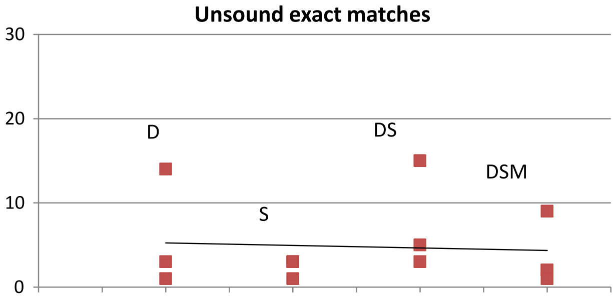
Table 1 Overview of the results, per respondent.

Subject	Support	Sound exact	Sound broad	Sound narrow	Unsound exact	Unsound broad	Unsound narrow	Expertise DART	Expertise ASCA
1	DSM	15	24	3	2	12	1	4	3
2	DSM	23	0	0	9	0	0	2	2
3	DSM	13	0	0	2	0	0	1	1
4	DSM	7	0	0	1	0	0	2	4
5	DS	13	14	2	5	0	12	1	1
6	DS	3	0	0	15	0	0	4	3
7	DS	9	0	0	3	6	5	1	1
8	S	7	0	0	3	0	0	1	1
9	S	7	3	1	3	2	0	1	1
10	S	4	2	3	1	13	12	1	1
11	D	6	0	3	3	1	12	1	4
12	D	6	0	6	14	1	10	1	1
13	D	1	0	0	1	0	0	2	2

Expertise is self-assessed, encoded as follows: *1* less familiar, *2* equally familiar, *3* more familiar, *4* much more familiar than the rest of the group



(a) Sound exact matches



(b) Unsound exact matches

Fig. 2 The impact of the different support levels on the number of sound and unsound exact matches. D – definitions, M – mappings, S – structure. The linear trends are least-square fits of the data. Since the x-axis categories are ordinal (with the order of D and S arbitrary), the quantity of the trend slope is arbitrary, but its sign is not

described in Sect. 3.4. Third, the numbers of broad and narrow matches should be interpreted with caution. For example, since the concept `Call For Fire` sits at the top of the concept hierarchy in ASCA, mappping (almost) any DART concept as a narrower concept is sound, but conveys very little useful insight.

The difficulty to interpret the numbers of broad and narrow matches, combined with the scope described in Sect. 1, lead us to focus on the exact matches in the following. A graphic overview of these results is given in Fig. 2a and b, respectively.

Table 2 offers the mean number of sound and unsound exact matches by the level of support given to the subjects. As can be seen, the mean number of sound exact matches is strictly increasing with the level of support given in terms of definitions, mappings and structure. The pattern of unsound exact matches is less clear-cut.

Table 2 Mean number of sound and unsound exact matches by the level of support

Support	Mean sound exact	Mean unsound exact
D	4.3	6.0
S	6.0	2.3
DS	8.3	7.7
DSM	14.5	3.5

5 Discussion

As seen in Fig. 2a, the individual differences in sound exact matches between subjects with the same treatments are substantial. Nevertheless, there is a positive trend in sound exact matches as a function of ontological support: not even the best subjects with the D or S treatment did better than the worst subject with the DSM treatment. However, the experiment is not sufficient to untangle the effects of the D, S, and M treatments from each other, nor from the confounding effect of previous expertise.

As seen in Fig. 2b, the individual differences in unsound exact matches between subjects with the same treatments are about as large as the differences between subjects with different treatments.

Overall, the evidence is stronger that ontological support can help domain-experts to make sound matches than help them avoid unsound ones. However, more research is clearly needed before a verdict can be given.

5.1 Reliability

The small number of participants in the study ($N = 13$) is a limiting factor. It would clearly have been preferable to have a larger sample, in order for the results to be more reliable. With a larger sample, it would have been possible to use standard techniques such as analysis of variance (ANOVA) to unequivocally establish the presence of the measured effects. As of now future work is required to further investigate the effects.

5.2 Validity

The validity of the experiment decomposes into several parts. A major threat to internal validity is the confounding effect of previous domain expertise (i.e. familiarity with the employed vocabularies). Any future experiments should take care to examine the self-assessments before assigning treatments to subjects, in order to be sure that the treatments are roughly equally distributed over levels of expertise. Still, the effects of previous domain expertise should not be overestimated. While the 15 sound exact matches of (high expertise) subject 1 could be attributed either to expertise or to the DSM treatment, the 13 sound exact matches of (low expertise) subjects 3 and 5 must instead be attributed to the DSM and DS treatments respectively. And to explain the difference between subjects 2 and 13, who had equal previous expertise, the difference between the DSM and D treatments is the foremost plausible explanation. Still, the internal validity is not very strong. A larger number of subjects with treatments better distributed over levels of expertise would have been preferable.

However, ecological validity is strengthened by the fact that the experiment was conducted with actual subject-matter experts from the military. While most experimental research in software engineering is probably carried out with computer science students, the answer to our research questions cannot be appropriately answered without subject-matter experts. This is worth to dwell on: if two C2 systems—or indeed any two information systems—are to be connected, the people involved will be domain experts, familiar with one of the systems, though probably not with the other. This is the kind of situation we wish to investigate, and it cannot be properly done with regular computer science students who are not sufficiently familiar with any of the systems. In this respect, the experiment precisely matches the conditions to be examined, strengthening ecological validity.

6 Conclusions

The experiment described has investigated the case when two vocabularies are to be mapped to each other by domain experts. Overall, the evidence is stronger that (i) hierarchical structuring of concepts, (ii) definitions of concepts and (iii) mappings to a common reference vocabulary can help domain-experts to make sound matches than help them avoid unsound ones. However, more research is needed before a verdict can be given. Though the experiment exhibits high ecological validity, using subjects who are experts in the domain of the two vocabularies that are to be mapped to each other, internal validity suffers confounding effects of previous expertise, and reliability is low, due to the low number of subjects ($N = 13$).

Interesting future work includes re-doing the experiment with a larger population of subjects, thus enabling more ambitious statistic analysis, including ANOVA, to conclusively establish the effects. In addition, it would be interesting to redo the experiment with stronger computer support in the form of a heuristic matching tool (e.g. Giunchiglia et al. 2004) and a mapping verification tool (e.g. Cohen 2013) integrated in the PoolParty environment. Another interesting future investigation would be to expand the experiment from the requirements phase (the current mapping of vocabularies) to the implementation phase. This could be accomplished by including computer science students to work in tandem with the domain experts in order to convert the mapping to actual code to connect the two C2 systems.

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