Evaluation of Systems Engineering Ontologies: Experiences from Developing a Capability and Mission Ontology for Systems of Systems

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***Abstract*—This study is exploratory research aimed at evaluating a core ontology for missions and capabilities in systems of systems (SoS). The core ontology is an artifact that relates capabilities and missions into a holistic view of the SoS. This ontology is an effort towards improving the conceptual understanding of SoS, and how the desired outcome of the SoS is achieved through purposeful allocation of capabilities in mission contexts. The purpose of this evaluation study is to check the coherence of the core ontology artifact. Therefore, the study is designed to generate insight, understand the patterns of ideas and associations in the ontology artifact. It employs a survey research method and the use of questionnaire and interview tools for data collection. This study covers some aspects of the FOCA methodology for ontology evaluation. The FOCA methodology implements a goal-question-metric process where the goals reflect the objective of knowledge representation, the questions justify the knowledge representation roles, and the metrics are the quality criteria of the respective goals. The paper also reflects on the experiences of ontology evaluation in general. The outcome of this study will provide a foundation for improvements and further research on ontologies and related artifacts that support the exploration of SoS.**

***Index Terms*—evaluation, ontology, systems of systems**

I. Introduction

Analyzing systems of systems (SoS) is a multi-dimensional research problem, which prompts the need for a holistic view of SoS. Our previous studies [1], [2] motivated an approach to understanding SoS from two main aspects: missions and capabilities. To support exploration of SoS design, an ontological approach was adopted, and we developed a core ontology for missions and capabilities in SoS [2], and further improved it in [3]. This core ontology is a minimal set of concepts and their relationships as they relate how missions and capabilities are linked towards the emergent behavior of the SoS. A recap of the core ontology is presented in Fig. 1, showing 15 main concepts, some attributes, and relationships. In this paper, we present an evaluation of this core ontology. The purpose of the evaluation is to check the adequacy and relevance of the ontology and to establish the need of possible improvements.

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A. Motivation and Contribution

The motivation behind this study is to seek a balance in the simplicity and usability of the core ontology. Ontologies provide different levels of conceptualization; therefore, the challenge is to determine the adequacy of an ontology for its intended purpose. A study by Brewster et al. [4] describes this adequacy as standing amidst the conflicting views of an ontology being a problem-solving method, or a representational approach.

The contribution of this study is the generation of knowledge and perspectives on what a core ontology entails. This allows us to analyze patterns of thoughts and perspectives on mission and capability views in SoS. Such an analysis paves the way for the suggestion of a modification of the ontology as well as other artifacts connected to the ontology. We achieve this through a tailored application of a specific ontology evaluation methodology.

B. Ontology Evaluation

A study by Brank et al. [5] surveys ontology evaluation techniques, and motivates why ontology evaluation is becoming important. The authors relates the need for the evaluation with the evolution in modern information systems where the basic unit of processing is evolving from data to semantic concepts. Dealing with semantics highlights the need to as much as possible minimize ambiguity. This implies how ontology evaluation is subjective to the kind, and the purpose of the ontology, such that the more complex an ontology becomes, the more reasonable it is to have different levels of evaluation [5]. A study by Brewster et al. [4] discuss trends and controversies on the adequacy of ontological knowledge conception. They discuss two views of ontologies: as a means to finding "elegant simplifying principles, or justification of complexity". The study further outlines how management and application of ontology may conflict with each other, such that "simple ontologies may be easier to manage, while scruffy ontologies might be easier to apply".

The bigger question is then, how can one determine the adequacy of an ontology? What measures can be used to establish this adequacy? Although these questions are too general and

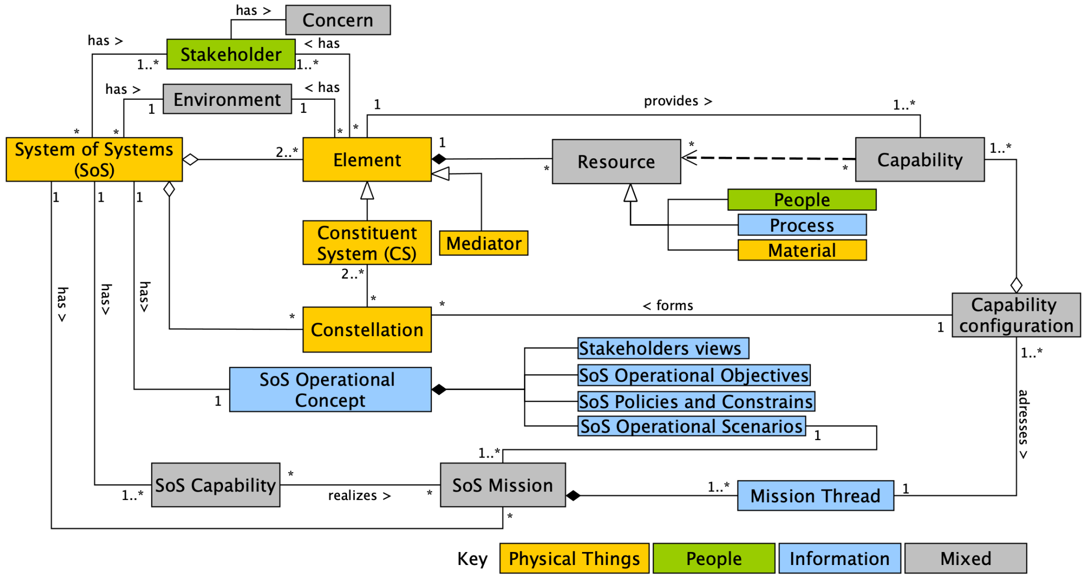

Fig. 1. Core ontology concepts and relationships.

not fully outlined in this evaluation, several studies have sought to develop measures and categories of ontology evaluation. A study by Gangemi et al. [6] developed an ontology evaluation design pattern that links ontology elements, processes, and attributes. The authors further identified three dimensions of measures for ontologies: structural, functional, and usability-profiling, which correspond to syntax and semantics, conceptualization, and pragmatics, respectively. A survey study by Raad et al. [7] grouped ontology evaluation into four categories: gold standard-based, corpus-based, task-based and criteria-based approaches. These correspond to comparison and mapping with foundation ontologies, data-driven approach, i.e. sufficiency in covering a domain, efficiency in improving a certain task, and criteria based on structural properties or other complex expert measures. Even with this categorization, the authors advise on combining methods of different categories to evaluate ontologies, if that increases the sufficiency and promotes the purpose of the evaluation.

Multiple ontology evaluation studies, including [6], [8] and [9], present ontology evaluation measures. These are quality attributes such as sensitivity, expandability, consistency, and conciseness. The commonality among these studies is the way they approach different quality criteria such as consistency and correctness. A study by Degbelo [10] further clarifies that the evaluation of the ontology embodies the correlation of the selected criteria, the strategy, and the best practices. Degbelo [10] further discusses the separation of design or modelling, and implementation stages in an ontology development process. This separation allows careful consideration of each stage as it translate towards the quality of the developed ontology. The correct implementation of these stages provides avenues for the preliminary evaluation of the ontology. The design or modelling stage includes [10]:

- Identification of motivation: this guides the scope, and therefore contains the ontology within the domain and purpose boundaries.
- Identification and alignment of ontology objects, relations and attributes: this allows one to re-use existing knowledge, minimize disambiguation, foster axiomization, and make the ontology more readily available.
- Formal specification of terms: this calls for definitions of axioms, which go hand in hand with ontology definitions.

The outcome of the design stage is a logical theory. The implementation of subsections of this theory for computation purposes is what constitutes the encoding or implementation stage of ontology development. With regard to these two stages, ontology evaluation is within the progress of ontology development as well as in ontology selection. It should be noted that our evaluation study focuses on design stage concerns.

As a progressive process during ontology development, the ontology evaluation aims at minimizing different errors and design anomalies. A study by Fahad et al. [12] summarizes error categories and design anomalies, whereas errors are identified as impactful to the reasoning abilities of an ontology, anomalies are associated with the usability and maintainability of the ontology. Authors identified three categories of errors: inconsistency, incompleteness and redundancy errors, and various design anomalies including lazy concepts and property clumps.

All these studies in ontology evaluation point towards the need for a more structured process for ontology evaluation, a collate of quality criteria and how to go about the evaluation process. A study by Bandeiras et al. [11] collates the quality criteria from many studies, including [6], [8] and [9], into a general purpose ontology evaluation methodology, the Formal Ontology Content Alignment (FOCA) methodology for ontology evaluation.

C. FOCA Ontology Evaluation methodology

The FOCA methodology for ontology evaluation sees to it that the quality of an ontology artifact is evaluated in line with established objectives. This methodology correlates the general aspects of evaluation attributed by the roles of knowledge representation with the specific aspects of metrics specific to a particular ontology. The general overview of the FOCA methodology is summarized in Table I, where it identifies 5 goals, 13 questions, and 6 metrics. Our evaluation study adapts some aspects of the FOCA ontology evaluation methodology to measure the coherence of our core ontology. Coherence in this case is described as made of three measures: consistency, completeness, and conciseness. A study by Gomez et al. [8] elaborates on these measures:

- Consistency: This checks for contradictions in concepts, relationships, inputs, and conclusions. Here we focus on the internal representation of the ontology
- Completeness: This is a challenging aspect to deal with, because it cannot be proven, but rather incompleteness of definitions, relationships are more deducible. Here, we focus on completeness with regard to the fundamental SoS knowledge base.
- Conciseness: This checks for redundancies in definitions, concepts, or relationships. Here we focus on the use of definitions and modelling notations.

The selection of some aspects and not others aims at limiting the scope of the evaluation to focus on how the ontology approaches the SoS and its understandability. This evaluation does not include computational efficiency, and abstains from using ontology-specific terms such as competency questions and ontological commitment. These are not entirely absent in the evaluation, but rather, they are implied at a high level. Competency questions are reflected from the need to identify core concepts and their corresponding relationships as described by Martin et al. [1]. Ontological commitment is linked with the choice of representation used, i.e., "what is said to be", and "what is", this relates to explicit and implicit representations respectively. We avoid these terms to make the evaluation questions more generally understandable.

The remainder of this paper is organized as follows: Section II lists the research questions. Section III and IV describe the methodology and limitations of the study. Sections V and VI describe and discuss the findings, and Section VII concludes this study.

II. Research Questions

To evaluate the coherence of the ontology, this study addresses and to reflect on the evaluation methodology, this study addresses the following research questions (RQ):

- RQ1: How consistent is the internal representation of the ontology?
- RQ2: Is there incompleteness in the ontology with regard to how it depicts SoS knowledge?
- RQ3: How concise is the use of definitions and notations in the ontology?
- RQ4: What are the achievements and challenges of this approach to ontology validation?

III. Methodology

This study is exploratory research. It is based on a survey with questionnaire and interview tools. Implementation is limited to the evaluation of the *coherence* of the ontology, as detailed in the Research Questions described above. The study methodology included the following processes:

- Development of the survey tool: The survey questionnaire is developed to contain questions that break down the research questions into manageable contexts. This includes questions about redundancies, missing and incorrect, clarity, definitions and notations used to represent concepts and relationships. These questions are as listed in Table II.
- Selection of respondents: The selection of respondents involved convenience sampling based on reachability,

TABLE I
Overview of the FOCA Methodology [11]

Goal	Question	Metric
1. Check if the ontology complies with Substitution.	Q1. Were the competency questions defined? Q2. Were the competency questions answered? Q3. Did the ontology reuse other ontologies?	1. Completeness 1. Completeness 2. Adaptability
2. Check if the ontology complies with the ontological commitments.	Q4. Did the ontology impose a minimal ontological commitment? Q5. Did the ontology impose a maximum ontological commitment? Q6. Are the ontology properties coherent with the domain?	3. Conciseness 3. Conciseness 4. Consistency
3. Check if the ontology complies with Intelligent Reasoning	Q7. Are there contradictory axioms? Q8. Are there redundant axioms?	4. Consistency 3. Conciseness
4. Check if the ontology complies with Efficient Computation	Q9. Did the reasoner bring modelling errors? Q10. Did the reasoner perform quickly?	5. Computational efficiency 5. Computational efficiency
5. Check if the ontology complies with Human Expression.	Q11. Is the documentation consistent with modelling? Q12. Were the concepts well written? Q13. Are there annotations in the ontology that show the definitions of the concepts?	6. Clarity 6. Clarity 6. Clarity

TABLE II
SURVEY QUESTIONS.

Questions
1. Are there redundant concepts? - Which ones? - What makes them redundant? - Proposed corrections?
2. Are there redundant relationships? - Which ones? - Why are they redundant? - Proposed corrections?
3. Are there missing concepts? - Which ones? - Why do you think they are core concepts? - How will they fit in with the other concepts?
4. Are there missing relationships? - Which ones? - Proposed corrections?
5. Are there incorrect concepts? - Which ones? - Proposed corrections?
6. Are there incorrect relationships? - Which ones? - Proposed corrections?
7. Are there unclear concepts? - Which ones? - Proposed corrections?
8. Are there unclear relationships? - Which ones? - Proposed corrections?
9. Is the graphical modelling consistent with the ontology definitions? - Proposed corrections?
10. Are the concepts' definitions satisfactory for the core ontology? - Proposed alternatives definitions? - Proposed additional keywords in definitions?
11. Any other remarks with regard to how the overall conceptualization for the core ontology can be improved? - What would you change? - How would you change?
12. Briefly elaborate on your work and experience in systems engineering, SoS, software engineering, connected systems, and other aspects be it in industry, research or academia that have shaped your perspectives of dealing with complexity. - Domains and focus areas? - Years of experience? - Your ideals when thinking of complexity? - Prominent challenges?

interest, and the time factor for the respondents to participate in the study.

- Data collection: The data collection process involved pretesting and administering of questionnaires to respondents.
- Data analysis: The collected data is compiled and analysed in Microsoft Excel. The analysis involved categorizing responses to show different aspects of coherence, and finding a general overview of the different concerns expressed.
- Reporting of findings: The analysed data is grouped into categories of concerns that generalize the insights and patterns of ideas.

IV. Study Limitations

This exploratory approach is flexible and adaptable to serve the purpose of this evaluation study. However, it is limited by the sample size, bias in the knowledge of the respondents and limited control over the dispersed knowledge of SoS in different communities and contexts. The FOCA methodology is described as dealing with domain ontologies which are more detailed ontologies compared to core ontologies. Nevertheless, since a core ontology is regarded as more of "an upper or a generic ontology for a domain" [13], this methodology is a guideline that is highly adaptable to different contexts by allowing the selection of measures, and depth of the evaluation process.

V. Findings

This section details the results of the ontology evaluation study. It describes the characteristics of the study and the concerns raised by the respondents. Concerns are grouped into three main categories: internal consistency of the ontology; use of the ontology; and definitions and use of modelling notations. In each category, we give a brief elaboration of our reflections on the issues raised. Additional discussion points and reflections on the overall evaluation study are detailed in Section VII.

A. Study Characteristics

As an exploratory study, the outcome of this research is subjective to the type and domain of respondents. The general aim was to obtain diverse responses from both industrial and research settings in different domains. Tables III and IV summarize the characteristics of the study. They detail the views of the respondents on complexity, and the number and type of respondents, the target plan versus the actual respondents, respectively. In Table IV, respondents are represented by respondents' identification (ID) *R1–R12*. Eight out of twelve respondents responded to the last question on views of complexity, therefore only R1 to R8 are shown in Table IV. The remaining respondents who participated in this survey are in the following domains:

- R9: Operational Analysis, conceptual design and product development
- R10: Model driven engineering, software architecture and engineering
- R11: SoS, Decision support systems and data analysis
- R12: Systems engineering and entreprise architecting

The rationale behind seeking to understand the respondents' views on complexity, and corresponding prominent challenges as far as complexity is concerned is to understand the motivation behind the respondents' views on the study. In these responses several words stand out: emergent, interoperability, behavior and evolution, which are a good coverage of SoS challenges.

TABLE III
STUDY RESPONDENTS AND RESPONSES

Characteristic	Value
Selected number of respondents	15
Received responses	12
Conducted interviews	8
Involved organizations	3
Type of organization	academia, research institute, company

B. Internal Consistency of the Ontology

With regard to redundancies and incorrectness of ontology concepts and relationships, several concerns were raised. These highlighted what is primary to SoS and what can be considered secondary, including:

- Stakeholder-related and capability-related concepts: The ontology mentions *stakeholders, stakeholder view, people* and *concerns*. Stakeholders bring heterogeneity in the SoS and this is among the factors motivating SoS. However, the current distribution of these concepts in the ontology can be better streamlined, or minimized to simplify the ontology. Similarly, *capacity, SoS capability,* and *capability configuration* are all forms of capabilities that can be streamlined in a hierarchy showing their dependence on each other.
- *Element, CS* and *constellation*: The way these three concepts are represented in the ontology presents some redundancies or incorrectness when correlated with SoS knowledge. Among the concerns of the interconnection is whether the use of the *element* concept adds significant value in the ontology and how it is reflected in the existing SoS knowledge base.

Our reflection:
These concerns point us in multiple directions, including:

- Clearly separating capabilities-related concepts may be more useful. The *capability* concept in the ontology reflects the independent *CS capability* and *capacity configuration* is a descriptive organization perspective of a system. More clarity in its representation in the ontology would be beneficial.
- A common way to describe an SoS is that it incorporates multiple *systems*, not multiple *elements*. Since the inclusion of *element* is meant to differentiate CS from non-CS parts of the SoS, perhaps the use of *system*, may replace *element*. However, this must also take into consideration a system as a technical, as well as sociotechnical entity, and convey distinguishing factors between CS and non-CS systems.

C. Use of the Ontology

Respondents highlighted possible missing and unclear concepts and relationships that reflected how well the ontology

TABLE IV
RESPONDENTS' DOMAINS, VIEWS ON COMPLEXITY, AND PROMINENT CHALLENGES.

ID	Domain	Views of complexity and prominent challenge
R1	SoS, Ontologies	*Complexity* is when you cannot understand a system or artifact by simply looking at its pieces or parts alone. There is something more happening when you add them all together, i.e., emergence! (1+1=3). *Prominent challenges:* to be able to predict, mitigate and understand emergent behaviors and capabilities at an early design stage.
R2	Model driven software engineering	*Complexity* is when you need to use: abstraction of unnecessary details so one can focus on the higher-level structure and behavior, modularity for breaking down the system into smaller, manageable and independent components to facilitate dealing with large systems and automation of repetitive and error-prone processes. *Prominent challenges:* scalability as systems grow in size and complexity. Interoperability and consistency as different systems are often developed independently. Evolution as requirements evolve.
R3	Requirements engineering	*Complexity* is something that cannot be completely mastered, such that there will always be unforeseen an unexpected or unwanted emergent behavior. *Prominent challenges:* unexpected and unwanted behavior.
R4	Safety Critical Systems	*Complexity* can introduce fallacies in your system, e.g. when embedding complex functions, applications and components. This necessitates the use of tactics, standards, best practices, in handling the unintended interactions and behaviors in a system should be employed. *Prominent challenges:* how to handle unknown unknown faults in the presence of novel technologies which is to be incorporated in future systems.
R5	SoS, Safety assurance	*Complexity* in SoS refers to the challenges and characteristics arising when multiple, independently operating systems are integrated to achieve higher-level functionality. *Prominent challenges:* interoperability, heterogeneity, and emergence.
R6	Conceptual design research	*Prominent challenges:* Traceability in SoS design process and balancing the multiple dimensions of the design space.
R7	Software and systems engineering	*Complexity* in SoS refers to structural and behavioral intertwined properties, autonomy, collaboration, intricate interactions (dynamic and evolutionary) and emergent behavior. *Prominent challenges:* harnessing emergent behavior for achieving desired goals.
R8	SoS, Mission simulations	*Complexity* is phenomena that cannot fully be explained by being reduced to its parts, it is irreducible, e.g. an aircraft as a design is not a complex system, but piloting an aircraft is. The difference is the phenomena that occurs when using the system in an uncontrolled/complex environment such as the airspace.

represents an SoS and what could make it more reflective of SoS. These are summarized as follows:

- SoS are identified as engineered systems, a representation of SoS should therefore capture the essence of engineered systems which include: key performance indicators (KPI) and mission success criteria, communication aspects, architecture, system states, the highlight of and differentiation between capability and function. The inclusion of more mission concepts to improve the understanding of missions in SoS may constitute an improvement.
- Missing links among the different capability-related concepts, as well as association description for all relations. Specifying missing links among capability concepts will show a cause-effect relationship, for example, whether an SoS capability is a result of individual capabilities or capability configurations, and creates a more visible differentiation between an *SoS* and a *capability configuration*.
- Clarity of mediator concept: The *mediator* concept should have a large impact on the *SoS capability*. It would benefit from a direct relation to *resource* rather than *element*. Other views on mediators is that they have one distinguishing character compared to CS, that is, a mediator has no purpose outside the SoS, meaning the SoS is the mediator's reason for being. It cannot disconnect from the SoS to achieve other goals. The respondents also brought to question whether all SoS elements that are not CS, are mediators, hinting on the possible existence of something in-between, subject to discussion.
- Clarity of SoS operational concept: Suggestions to rethink the value of breaking down this concept as done in the ontology, and re-evaluate how a CS and SoS viewpoints may affect what is really contained in this concept.
- Color coding: the used color coding as seen in Fig. 1 translates differently in different domains, for instance when the focus is on technical versus socio-technical systems, and this becomes more prominent in application areas such as in defence.

Our reflection:
These concerns point us in multiple directions, including:

- Incorporating behavioral aspects into the ontology and this is part of our future work. This will expand the ontology to highlight what the CS and SoS go through in terms of their states; possible KPI, i.e., effects of actions; critical success factors, i.e., cause of success; and how these factors are developed.
- Focusing on what is really primary to SoS and what can be considered secondary, as this will shape what is core and what can be domain specific, therefore reserving the need to identify or include secondary relationships and some association descriptors.
- Balancing quantity and clarity, even with the identification of missing concepts and relationships, finding the balance between concepts in the ontology versus keeping it simple is crucial, especially because it is a core ontology. Should all ideas go into the core ontology, or perhaps there should be a structure of several related ontologies? This is highly debatable and may be different for different communities. The aim is to have a simple core ontology, which may be supported by other ontology structures, such as: decision attributes, resource attributes, and process definitions.

D. Definitions and Use of Modeling Notations

A number of responses highlighted concerns based on the use of modeling notations. These relate to the kind, multiplicity, descriptions of concepts and relationships, and the correlation between definitions and the actual graphical representation. This correlation is a reflection of the consistency and reproducibility of the ontology from the definitions. These concerns are summarized as follows:

- A need to improve coherence between concept definitions, relationships and the graphical modelling. A good start is to have close connection among directly relatable concepts, e.g., *mediator* to *constellation* and *constellation* to *SoS capability*. Such connections limit ambiguity. Another highlight is the need to link concepts in the definitions, and overall creating a connection that reads as a story in definitions and is easily translatable in graphical representation.
- Modelling notations: Several modelling-related concerns were raised, this ranged from closed loops in the ontology, to the use of different kinds of association relationships, and their implications. For example, the generalization *element, mediator, CS*, the aggregation relationships between *capability, capability configuration*, *element, SoS* concepts, highlight some concerns for revision and further refinement of the ontology.

Our reflection:
The incorrectness and lack of clarity pointed out by the respondents concern how definitions relate to the graphical modelling. This brings us to a possibilities and trade-offs when developing a conceptual understanding. This is particularly important because on the one hand, the aim is to re-use existing definitions, while on the other hand, the objective is to get the concepts related in their simplest form possible.

- We could see this as an opportunity to further represent the ontology using an ontology language to be able to infer the type of relationships used, and test them for different domain levels. However, this does not exempt us from the requirement that we find a balance in how direct or implied the relationship among these concepts can be and still convey an acceptable understanding of SoS. This is because we want to create a core understanding which is inclusive of different communities' and contexts' views of how missions and capabilities create SoS interactions.
- This also leads to reflection on what is primary versus secondary concepts as highlighted in Section V-B.

- Closed loops in the ontology give us an opportunity to think of the different forms of errors in the ontology. A study by Baumeister et al. [14] discusses various kinds and impacts of anomalies in ontologies, highlighting these as errors which may result from factors such as, the use of definitions and rule-based reasoning. This is an area for further exploration and discussion in the continuing part of this research work.

E. Other Concerns

Other mentioned concerns include the choice of concepts, definitions, and correlation with regard to what is an SoS.

- Why does a constellation necessarily mean two or more CS? Saying that the CS is not part of the SoS while it is solving the problem/mission thread means that the SoS must be able to both instruct/guide constellations and single CS, because essentially a constellation is put together to solve a specific issue, which in this context is the mission thread.

Our reflection:
This point of view is subject to interpretation, but also elaborated by the responder that, an SoS must have the possibility to include several CS in order to be an SoS, otherwise it is just an integrated system, so having a constellation meaning two or more CS serves better purpose for the conceptualization. This distinguishes collaborative efforts of multiple systems from efforts of a single CS, even when used within the same mission thread.

- An SoS has different task levels: SoS-level tasks, constellation-level tasks, and CS-level tasks. An SoS enables the creation of constellations that solve problem instances from the problem domain. A mission is one example of a possible problem context. The SoS needs to have the mechanisms to determine what capabilities are needed to solve a problem instance, and the ability to induce corresponding CS to form a constellation that solves that problem instance. A mission thread is a kind of constellation level task. Additionally, each CS is independently operated so it could go about solving problems/tasks that have no relation to the SoS. These are CS-level tasks that come from the CS owner or operator, and the SoS is not involved. If a constellation must consist of at least two CS, then there is no easy distinction between solving a CS-level task (i.e., something the CS accomplishes itself, without involving the SoS) and an SoS mission thread/constellation level task that the capability configuration determines can be solved using only one CS.

Our reflection:
This again goes back to thinking about what a constellation is. We argue that a constellation must essentially include two or more CS, and that a single CS performing an SoS task within a mission thread is simply a standalone system, not part of a constellation as CS.

- The notion that all SoS-level tasks can be formulated as missions, meaning SoS-level task is a generalization of mission. Arguably, a respondent suggests that not all SoS are mission-oriented. This implies that some concepts may not be applicable in every SoS such as the concept of *SoS operational concept*.

Our reflection:
Much of the conceptualization of the word mission is related to the defence sector and therefore has more of defence-specific meaning. However, now that different version of UAF is working towards incorporating mission concepts, from where we stand this is to be a more general view of the concept of a mission.

F. Reflection on the Ontology Validation Methodology

Reflecting on the ontology evaluation methodology used in this study, how can we motivate that it provides a reasonable validation of the ontology, and how does it inform of the challenges of ontology evaluation to a wider SE community?

- Individual views: This methodology collects individual opinions which are guided by views of the respondent related to their experience and domains. It therefore provides a dynamic look into the ontology and henceforth prospective research directions. This is as advantageous as it is subjective.
- Open ended questions: The exploratory nature of the research questions, i.e. their openness, supported the inclusion of different perspectives from the respondents. The openness of the interview questions, that sought what?, how?, and why? encourage argumentative responses which open the responses to more viewpoints. Moreover, these questions are closely coupled, almost interactive with each other to allow a free flow of information and connections among the different concerns.
- Although convenience sampling is a reasonable starting point, establishing a conceptualization for an area calls for more focus group discussions. These can be specific forums and groups of organizations such as INCOSE. Industry responses showed the need for more correlation with existing standard developments such as unified frameworks that combine different components of capability and mission concepts.

VI. Discussion

In this evaluation study, the aforementioned concerns and reflections zoom in to discuss how the concepts and their corresponding relationships make sense, and zoom out to check if and how they satisfy the intended use of the ontology. The challenge is to find a balance on how to keep the ontology precise, robust, and practically useful. This is to facilitate that ontology concepts and relationships set a foundation from which other artifacts, such as domain-specific ontologies, can be developed.

The exploratory research approach adopted in this paper is inconclusive and subject to sampling and interpretation bias. Nevertheless, the approach offers a thought process, which can stimulate one's perception of what constitutes an SoS. It therefore offered good process to challenge the coherence of the ontology artifact, and overall open the ontology conceptualization to more discussion.

In the development of the ontology, the evaluation study, and research discussions, several issues were re-iterated and discussed. These may translate to possible improvements points in the continuation of this work:

- The implication of having the *SoS operational concept* in the ontology: in its current use, this concepts reflects documentation requirements for an SoS. It seems out of phase with the other ontology concepts which are more concrete to design and operation of the SoS. For future considerations, the inclusion of this concept may not be necessary for the purpose of the ontology.
- With regard to how the ontology evaluation study was conducted, there was a suggestion that an instantiation would have created more understanding of the ontology and prompted better responses in the survey. This is plausible; however, an instantiation of the ontology would have directed respondents into a specific thought process out of their own areas of influence, and that would have voided the aim of the respondents having an unfiltered view of what is core to an SoS.
- As concepts, *ontologies* and *architectures* are significantly related to each other because they both describe concepts and their relationships. However, meanwhile, ontology creates conceptual models that guide design tasks, architecture guides decision making through trade-offs. This can explain why the developed core ontology does not include any specific concept explicitly named *architecture*. The core ontology's focus is to facilitate an ontology-driven architecture for SoS. A study by Fahad et al. [12] mentions the crucial role of the ontology-driven architecture in facilitating the interoperability of heterogeneous systems.

With regard to diversity in respondents' orientation, although the data collection aimed at finding diverse perspectives, industry responses were hard to come by. For later studies, using other data collection methods, such as focus groups, may work better for industry respondents. As a research approach, this evaluation study has allowed us to see how wide and deep the ontology concerns can go, so that we can think beforehand what is feasible within the context of our work and suggest future research work.

VII. Conclusion and Future Work

This study evaluated the core ontology, raised different concerns, and proposed different suggestions to improve the coherence of the ontology artifact. The documentation categorizes these concerns for understandability and structured analysis to express the main concerns but hide the nitty-gritty details. The proposed suggestions include improvements in the use of modeling notations, definitions, further simplifications, and possible inclusion of other concepts.

Future work includes the extension and improvement to the ontology. The extension aims at including behavioral aspects. The improvement aims at finding a balance between logic, reuse of definitions, correctness of graphical notation, and formal representation. Inevitably, there will always be some trade-offs. In our case these trade-offs come with the view that the ontology is with respect to mission and capability in SoS, and purposely aims at simplifying exploration of SoS.

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