Master's Research Project

Establishment of an Ontology for Systems-of-Systems

GABRIEL ABDALLA

ADVISOR: PROF. DR. ELISA YUMI NAKAGAWA

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Agenda

- Introduction
- Background
- Knowledge Representation for SoS
- Establishment of OntoSoS
- OntoSoS Evaluation
- Conclusions

Introduction

Introduction

- Systems-of-Systems (SoS)
  - Class of system composed of heterogeneous, independent and distributed systems
  - Growing demand
  - No well-accepted definition
  - Ontologies
    - Represent an area of knowledge
    - Methodology to build ontologies (METHONTOLOGY)
  - Systematic Literature Review
    - Knowledge Representation for SoS

Motivation

- Terminology inconsistency
- Lack of common understanding
- Challenges for stakeholders
  - Terms and concepts can vary a lot
  - Misunderstandings and misinterpretations

Objectives

- Establishment of OntoSoS
  - Ontology for Systems-of-Systems
  - Define and describe concepts and terms related to SoS
- Creation of a common vocabulary
  - Common understanding
- Knowledge sharing in the SoS community
  - Reuse knowledge
  - Support learning
- Consolidation of the SoS field

Background

Systems-of-Systems

"A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities."

(DoD, 2008)

"Systems-of-Systems are large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal."

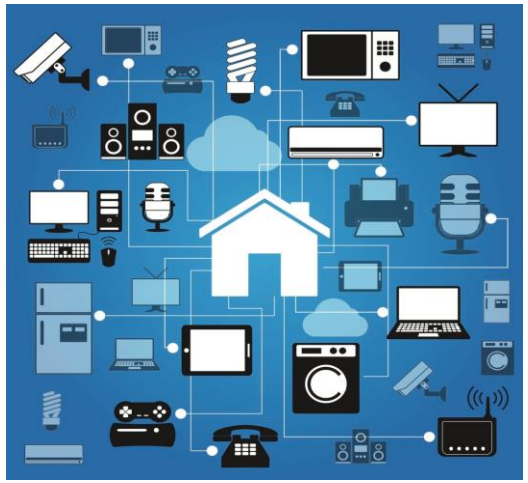
(Jamshidi, 2008)

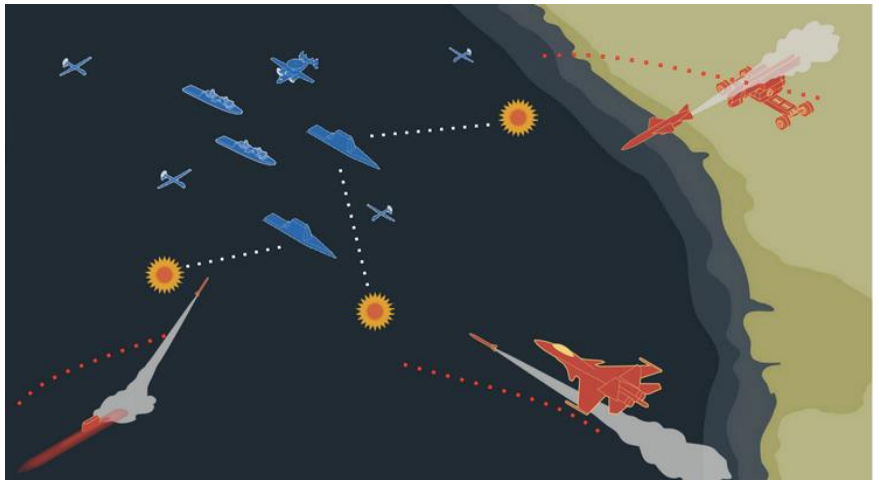
SoS Characteristics

- Operational independence
- Managerial independence
- Geographic distribution
- Emergent behavior
- Evolutionary development

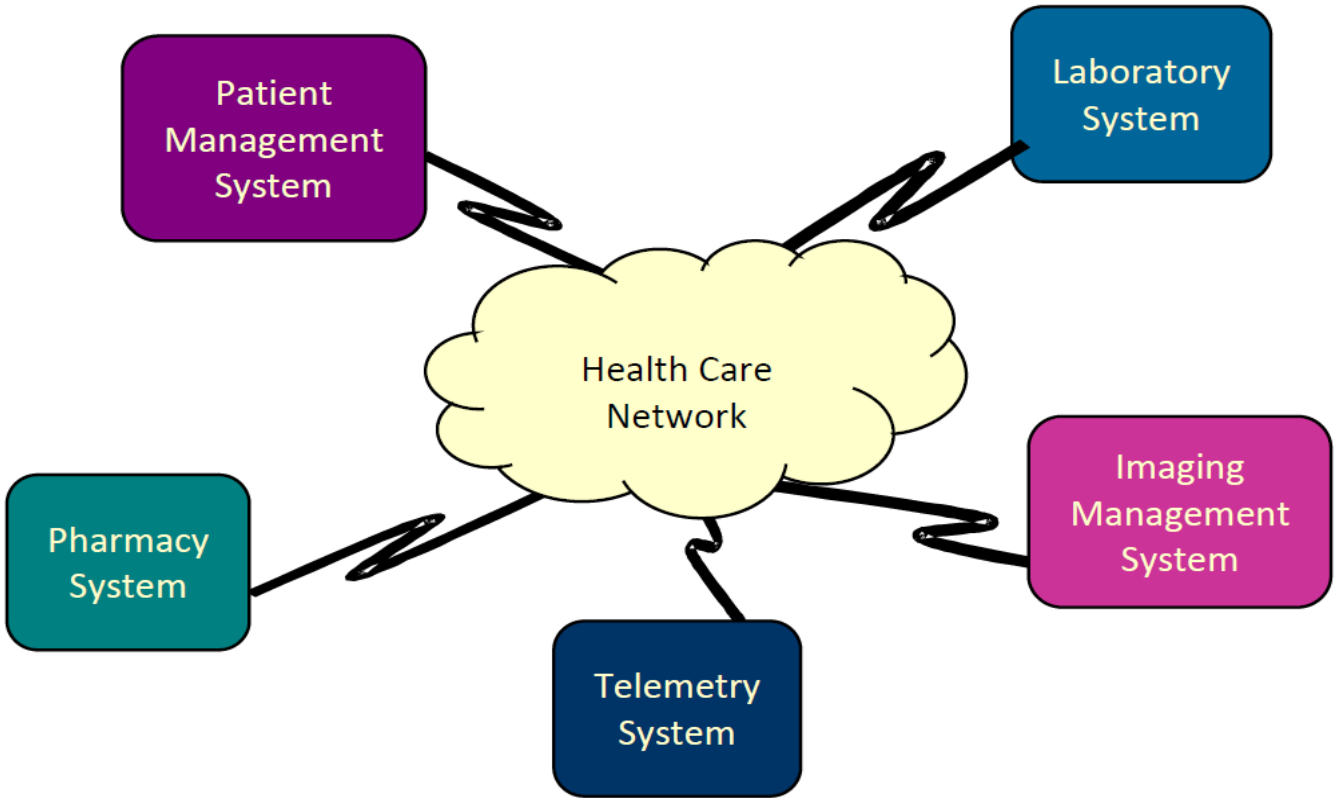
Examples of SoS

- Air defense networks
- Internet
- Global Earth Observation System-of-Systems (GEOSS)
- Smart homes





Examples of SoS



Lane, J. A. What is a system of systems and why should i care? University of Southern California, 2013.

Ontologies

"An ontology is an explicit specification of a conceptualization."

(GRUBER, 1993)

"An ontology defines the terms used to describe and represent an area of knowledge."

World Wide Web Consortium (W3C)

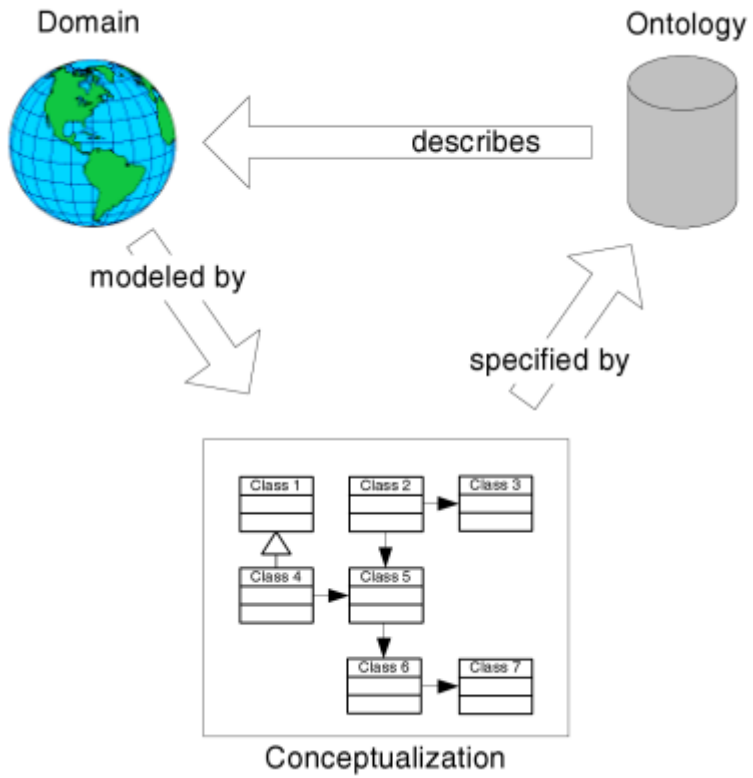
Ontologies

"An ontology is a **formal**, **explicit** specification of a **shared conceptualization**."

(Studer, Benjamins, Fensel, 1998)

- Formal
  - Ontology must be machine readable
  - Excludes natural language
- Explicit
  - Type of concepts used and the constraints on their use are explicitly defined
- Conceptualization
  - An abstract model of some phenomenon in the world
  - Relevant concepts
- Shared
  - An ontology captures consensual knowledge
  - Not private to some individual, but accepted by a group

Ontologies



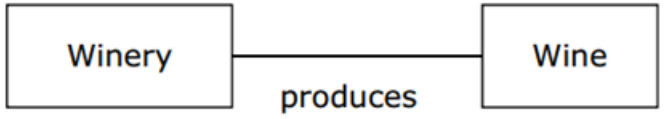
Lacy, L. W. OWL: Representing information using the Web Ontology Language. Victoria, BC: Trafford Publishing, 2005.

Ontologies – Degree of Formality

Informal

Wine is a product of a winery.

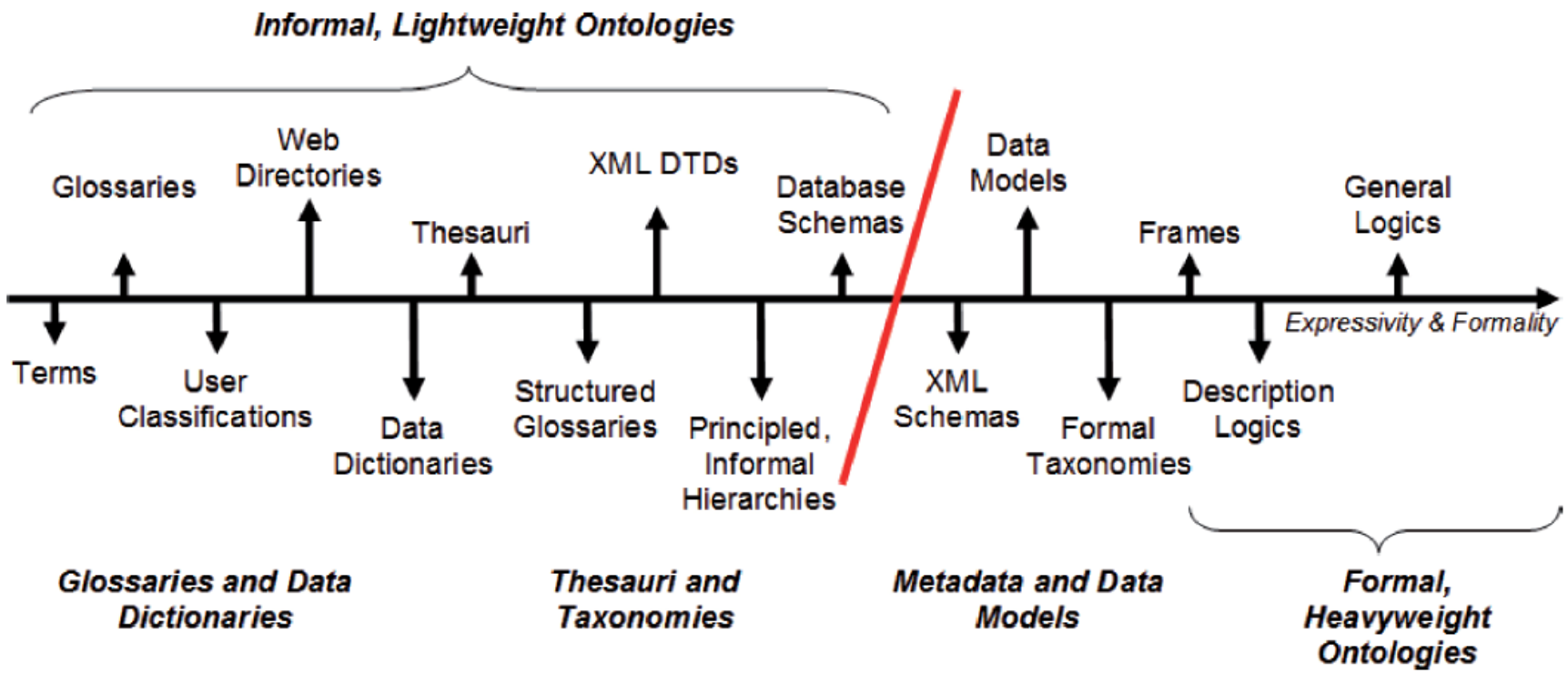
Semi-formal



Formal

```
<a:owl_objectproperty rdf:about="produces" rdfs:label="produces">
   <rdfs:range rdf:resource="Winery"/>
   <rdfs:domain rdf:resource="Wine"/>
</a:owl_objectproperty>
```

Ontology Kinds



Wong, W.; Liu, W.; Bennamoun, M. Ontology learning from text: a look back and into the future. ACM Computing Surveys, v. 44, n. 4, 2012

Uses of Ontologies

- Communication between people and organizations
- Interoperability among systems
- Systems Engineering
  - Specification
  - Reliability
  - Reusable components
  - Knowledge acquisition

Knowledge Representation for SoS

Knowledge Representation for SoS

- Goals of the Systematic Literature Review (SLR):
  - Approaches applied to SoS and their degree of formality
  - Motivations for using approaches and their space of use
  - Application domains (applied to a real case study or system)
  - Terms covered

SLR – Research Questions

- RQ 1: Which Knowledge Representation approaches have been applied to SoS?
  - RQ 1.1: What is the degree of formality of the approach (informal, semi-formal, formal)
- RQ 2: What is the main motivation for using Knowledge Representation in SoS?
- RQ 3: What application domains have the Knowledge Representation approaches of SoS been applied to?
  - RQ 3.1: Is the approach applied to a real case study / system?
  - RQ 3.2: For what purposes were the identified studies conducted? (eg., communication, interoperability, Systems-of-Systems Engineering (SoSE), or other uses)?
- RQ 4: What are the terms covered by Knowledge Representation approaches in SoS?

SLR – Search String

("system-of-systems")

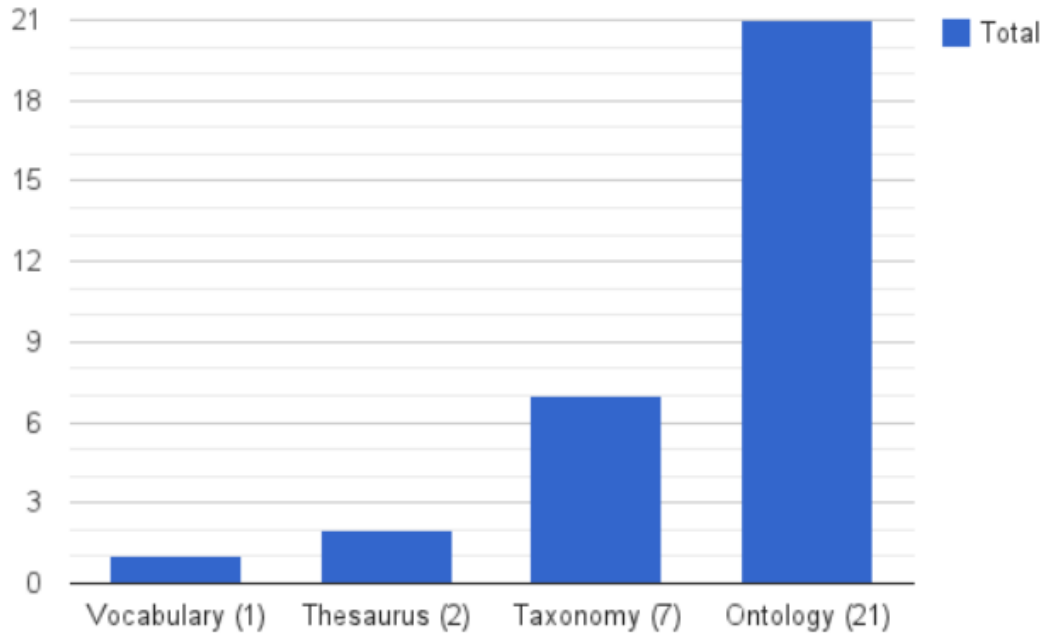
AND

("glossary" OR "classification" OR "dictionary" OR "thesaurus" OR "taxonomy" OR "ontology" OR "vocabulary" OR "schema" OR "frame" OR "hierarchy" OR "knowledge representation" OR "body of knowledge")

Final set: 31 studies

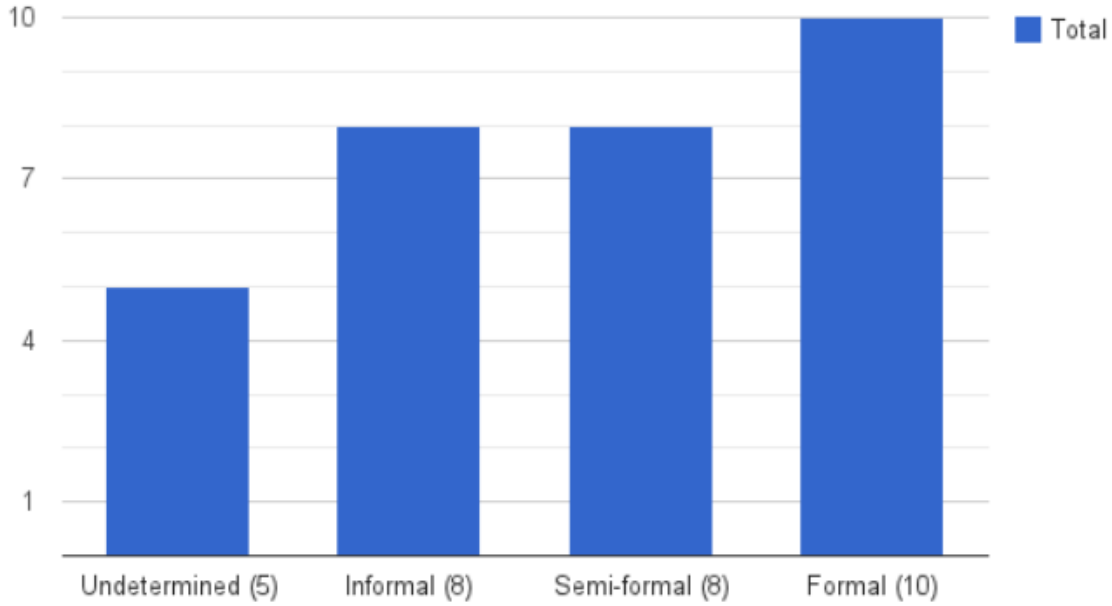
SLR Results

- RQ1. Approaches applied to SoS
  - No studies addressing glossary, hierarchy, dictionary, or frame.
  - The majority of included studies in this review is related to ontologies.



SLR Results

- RQ1.1. Degree of Formality
  - The amount of studies discussing each degree of formality considered in this study is approximately equal.
    - Informal
    - Semi-formal
    - Formal
    - Undetermined (not possible to classify the degree of formality)

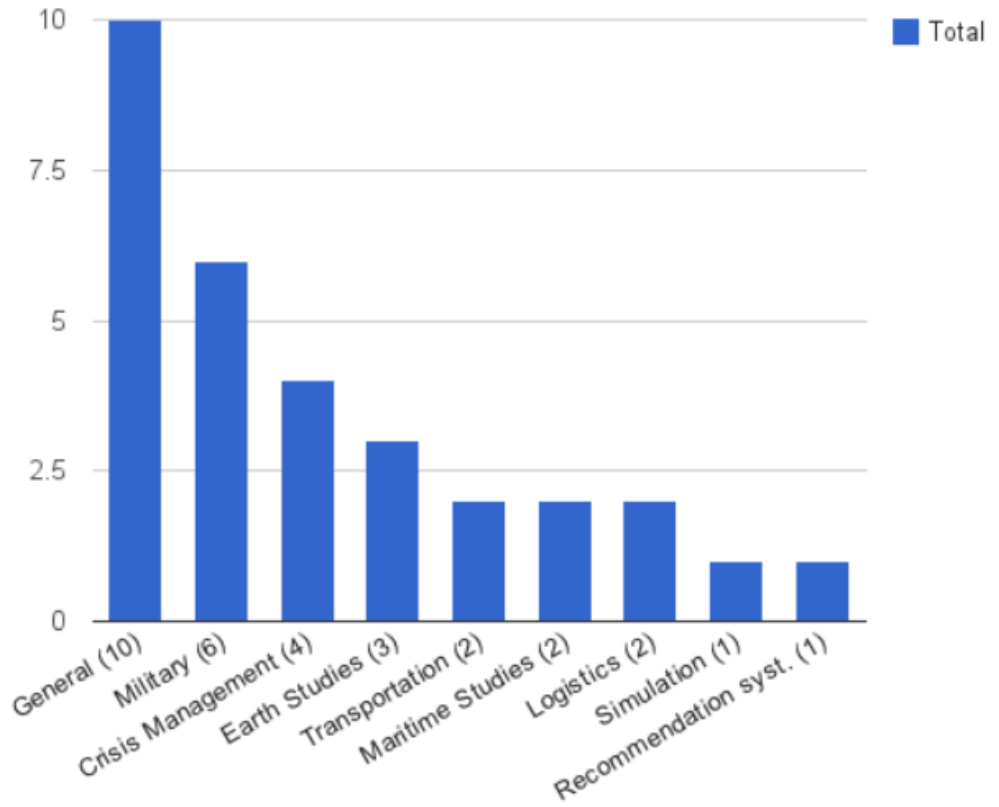


SLR Results

- RQ2. Main motivation for using Knowledge Representation approaches in SoS
  - **Terminology standardization and knowledge sharing**: information and expertise sharing (communication)
  - **SoS integration**: formal specification of systems integration (interoperability between systems)
  - **SoSE activities**: guide SoSE activities, such as SoS evaluation and requirements (support to systems engineering)
    - **SoS management**: management activities related to SoS, such as failure mitigation and crisis management.

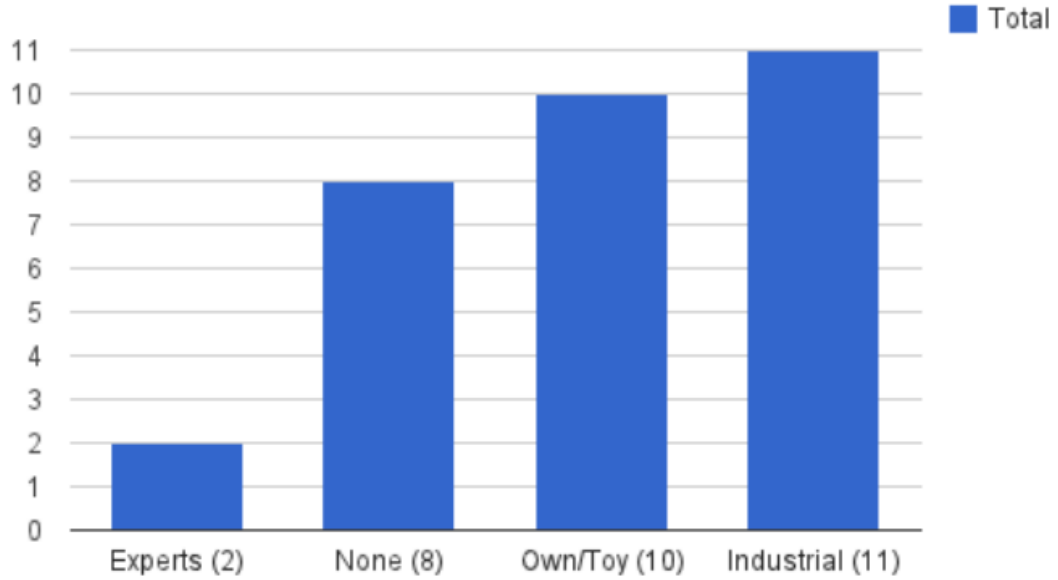
SLR Results

- RQ3. Application Domains
  - 10 studies on general domain
    - No specific domain
    - Can be applied to any domain
  - 6 studies on military domain
  - 4 studies on crisis management



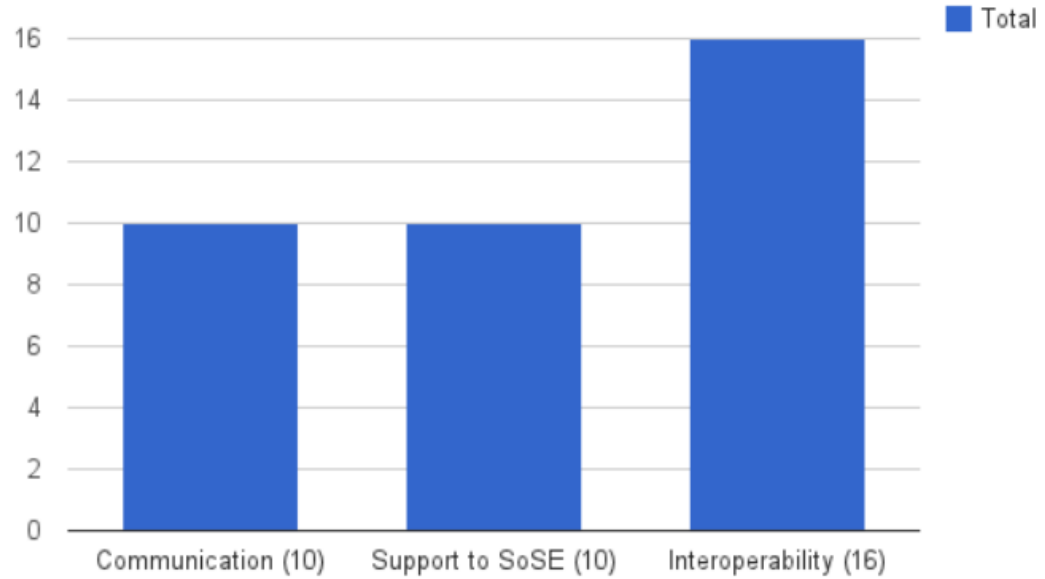
SLR Results

- RQ3.1. Subject of Study
  - 8 studies not validated
  - Formal studies were all validated
    - Own / Toy or Industrial scenario
    - Tendency to be validated



SLR Results

- RQ3.2. Space of Use
  - Interoperability of SoS (16 papers)
  - Communication and SoSE (10 papers)
  - Degree of formality x Space of use:
    - Interoperability → formal approaches



SLR Results

- RQ4. Terms covered by Knowledge Representation approaches
  - Many studies do not explicitly present terms
  - No direct relationship among the terms
  - Few terms repeated across the studies (e.g., *stakeholder*)
    - Address specific tasks
    - Do not concern with the SoS field as a whole
  - Some terms can be related to the SoS field
    - *constituent system, goal, domain*
    - *virtual, collaborative, acknowledged, directed*

SLR - Conclusion

- Formal ontology is the most used
- Interoperability is the most addressed space of use
  - More likely to use formal approaches
- Approaches for SoSE → semi-formal or informal
- Formal approaches → validation
- Many studies are general regarding domain
- No relation among extracted terms

Establishment of OntoSoS

Establishment of OntoSoS

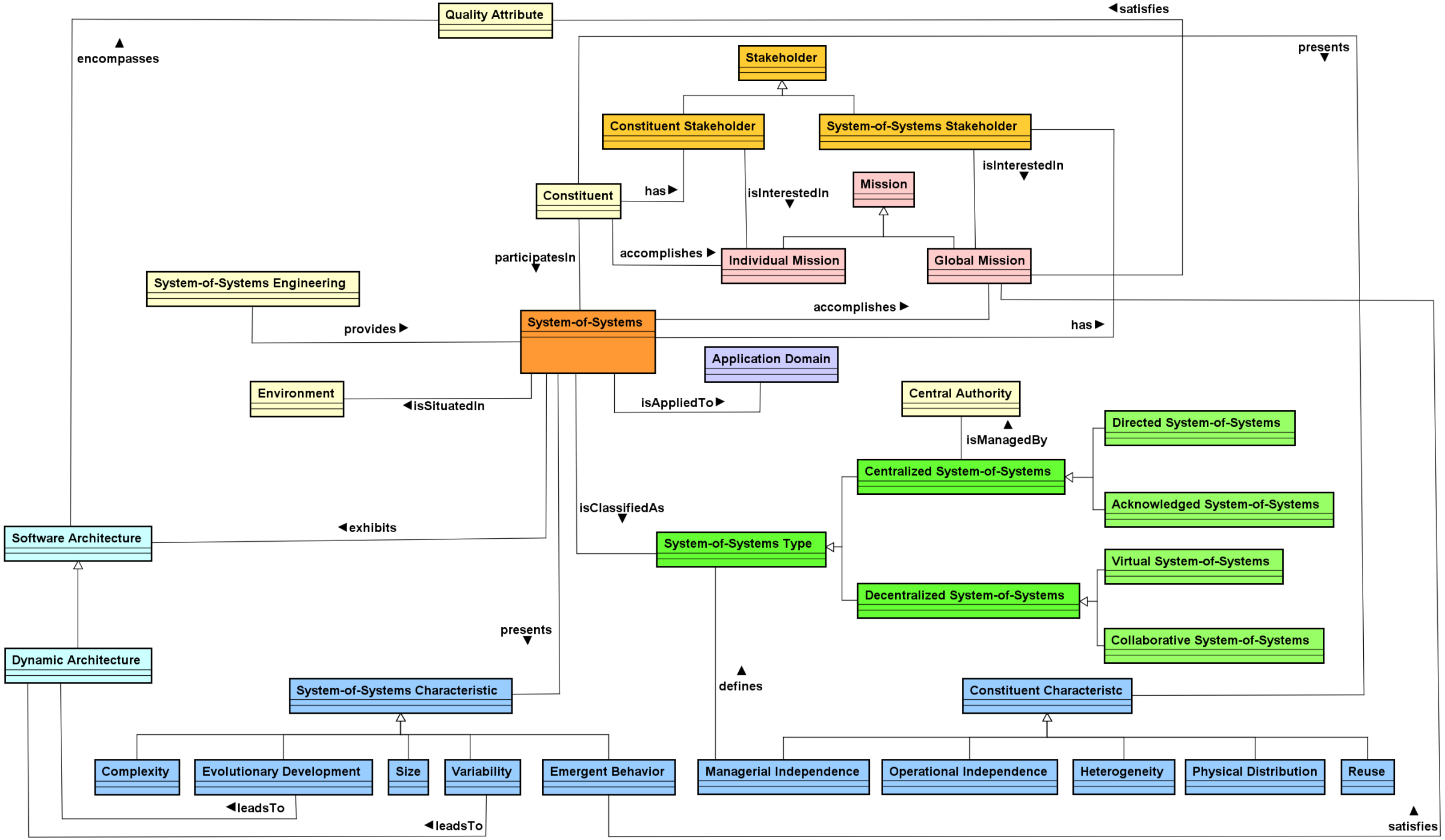
- Based on METHONTOLOGY
- Management activities
  - Planification, control, quality assurance
- Development activities
  - Specification, conceptualization, implementation, maintenance
- Support activities
  - Knowledge acquisition, evaluation, documentation, configuration management

Ontology Specification

- **Name**: OntoSoS
- **Research field**: Systems-of-Systems (SoS)
- **Purpose**: to establish a common understanding of the SoS field, facilitating the knowledge sharing and contributing to the evolution and consolidation of the field.
- **End users**: researchers, practitioners, and students.

Ontology Conceptualization

- List of terms (glossary): publications and experts' opinions
- Brainstorming meetings to refine and validate the list
- Definition of the terms
- Relationships
  - Taxonomies (definition of classes and subclasses)
  - Build binary relationships between concepts (source and target concepts)
  - Relation names (properties): verbs
  - Definition of inverse relations


Quality Attribute
satisfies
encompasses
presents
Stakeholder
Constituent Stakeholder
System-of-Systems Stakeholder
isInterestedIn
Constituent
has
isInterestedIn
Mission
participatesIn
accomplishes
Individual Mission
Global Mission
System-of-Systems Engineering
accomplishes
provides
System-of-Systems
has
Application Domain
Environment
isSituatedIn
isAppliedTo
Central Authority
isManagedBy
Directed System-of-Systems
Centralized System-of-Systems
Acknowledged System-of-Systems
isClassifiedAs
Software Architecture
exhibits
System-of-Systems Type
Virtual System-of-Systems
Decentralized System-of-Systems
Collaborative System-of-Systems
presents
Dynamic Architecture
defines
System-of-Systems Characteristic
Constituent Characteristc
Complexity
Evolutionary Development
Size
Variability
Emergent Behavior
Managerial Independence
Operational Independence
Heterogeneity
Physical Distribution
Reuse
leadsTo
leadsTo
satisfies

Ontology Implementation

- OntoSoS was implemented in Protégé tool
  - Visualization and navigation
  - Graphic implementation (OWL code generated)
  - Creation of classes, subclasses (respecting the taxonomies)
  - Definition of properties and their inverse properties


Class hierarchy: owl:Thing
owl:Thing
ApplicationDomain
CentralAuthority
Constituent
ConstituentCharacteristic
Heterogeneity
ManagerialIndependence
OperationalIndependence
PhysicalDistribution
Reuse
Environment
Mission
GlobalMission
IndividualMission
QualityAttribute
SoftwareArchitecture
DynamicArchitecture
Stakeholder
ConstituentStakeholder
SystemOfSystemsStakeholder
SystemOfSystems
SystemOfSystemsCharacteristic
Complexity
EmergentBehavior
EvolutionaryDevelopment
Size
Variability
SystemOfSystemsEngineering
SystemOfSystemsType
CentralizedSystemOfSystems
AcknowledgedSystemOfSystems
DirectedSystemOfSystems
DecentralizedSystemOfSystems
CollaborativeSystemOfSystems
VirtualSystemOfSystems


Object property hierarchy: owl:topObjectProperty
owl:topObjectProperty
accomplishesGlobalMission
accomplishesIndividualMission
appliesToSystemOfSystems
classifiesSystemOfSystems
definesSystemOfSystemsType
encompassesQualityAttribute
exhibitsSoftwareArchitecture
hasConstituent
hasConstituentStakeholder
hasSystemOfSystemsStakeholder
isAccomplishedByConstituent
isAccomplishedBySystemOfSystems
isAppliedToApplicationDomain
isClassifiedAsSystemOfSystemsType
isDefinedByManagerialIndependence
isEncompassedBySoftwareArchitecture
isExhibitedBySystemOfSystems
isInterestedInGlobalMission
isInterestedInIndividualMission
isInterestOfConstituentStakeholder
isInterestOfSystemOfSystemsStakeholder
isLedByEvolutionaryDevelopment
isLedByVariability
isManagedByCentralAuthority
isPresentedByConstituent
isPresentedBySystemOfSystems
isProvidedBySystemOfSystemsEngineering
isSatisfiedByGlobalMission
isSituatedInEnvironment
isStakeholderOfConstituent
isStakeholderOfSystemOfSystems
leadsToDynamicArchitecture
managesCentralizedSystemOfSystems
participatesInSystemOfSystems
presentsConstituentCharacteristic
presentsSystemOfSystemsCharacteristic
providesSystemOfSystems
satisfiesGlobalMission
satisfiesQualityAttribute
situatesSystemOfSystems


SystemOfSystemsEngineering
ApplicationDomain
SystemOfSystems
Constituent
Environment
Stakeholder
QualityAttribute
owl:Thing
SystemOfSystemsCharacteristic
Mission
SystemOfSystemsType
CentralAuthority
ConstituentStakeholder
SystemOfSystemsStakeholder
Complexity
EmergentBehavior
Size
Variability
EvolutionaryDevelopment
GlobalMission
IndividualMission
VirtualSystemOfSystems
DecentralizedSystemOfSystems
CollaborativeSystemOfSystems
CentralizedSystemOfSystems
DirectedSystemOfSystems
AcknowledgedSystemOfSystems
Heterogeneity
Reuse
ConstituentCharacteristic
PhysicalDistribution
OperationalIndependence
ManagerialIndependence
SoftwareArchitecture
DynamicArchitecture
is-a

OntoSoS Evaluation

OntoSoS Evaluation

- Survey with researchers in the SoS field
  - Population: 10
  - Number of questions: 14
- Evaluation done based on artifacts produced on conceptualization
  - List of terms with definitions
  - UML Class diagram

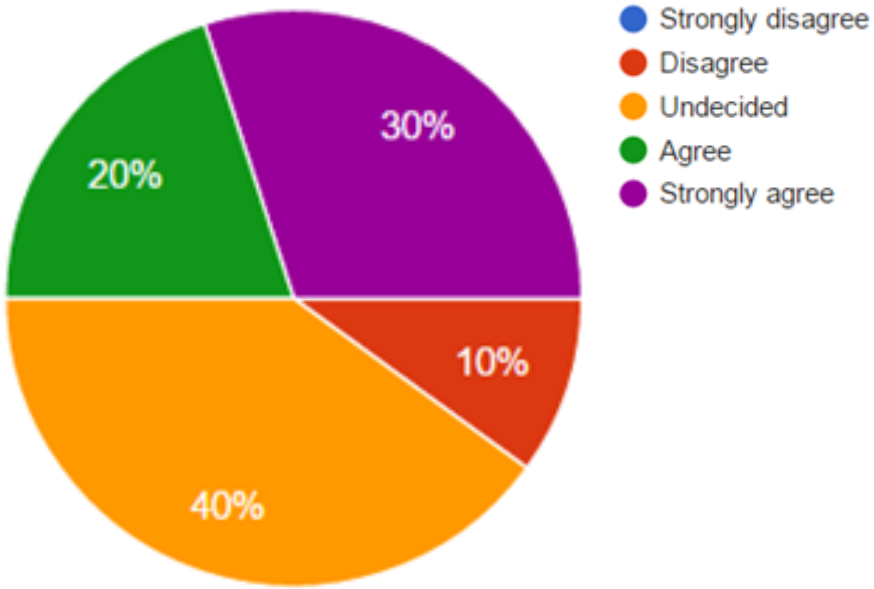
- All sections had a text area for free text

OntoSoS Evaluation

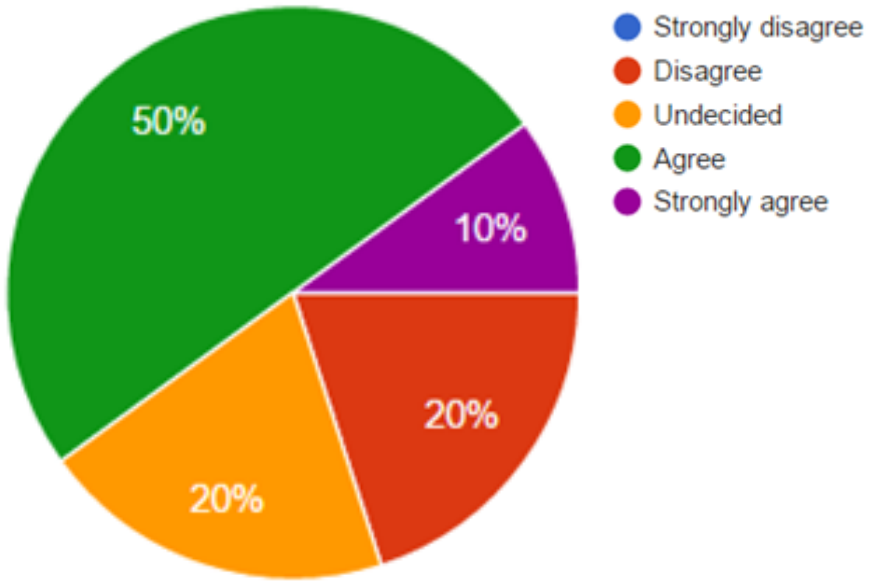
- Survey structure
  - Introduction
  - Description of concepts
  - Ontology coverage
  - Relationships
  - Additional Information

- Experts’s suggestions were gathered and organized into groups and subgroups

Survey Results

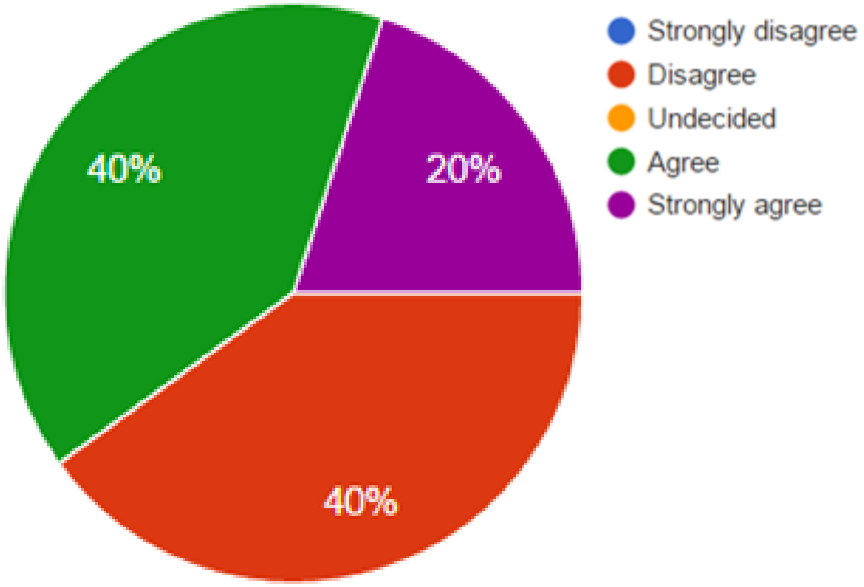


Description of Concepts

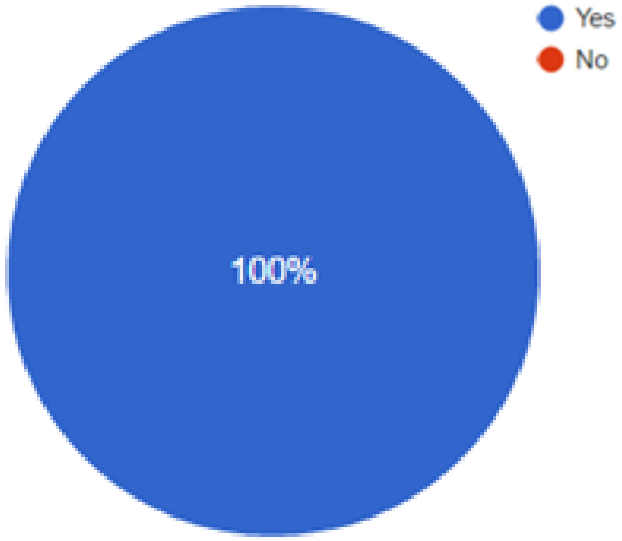


Ontology Coverage

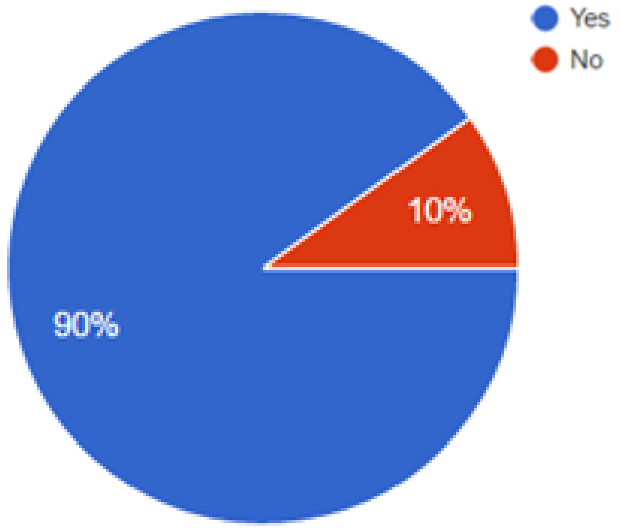
Survey Results



Ontology Relationships



Need of an ontology for SoS



Consider using in next project

Conclusions

Main Contributions

- Consolidation of the SoS field
  - Consensus about the knowledge
  - Facilitate communication and knowledge sharing
- Establishment of a vocabulary to improve understanding
- Guidance to software engineers
- Contribution to the SoS learning

Difficulties and Limitations

- Conceptualization
  - Many meetings conducted
  - Long discussions and different points of view
- Evaluation
  - Delay to receive responses
  - Responses received after the deadline
- Limitations in evaluation results
  - Suggestions summarized and grouped (analysis limitation)
  - Researchers' experience
  - High number of undecided answers
  - Suggestions mapped to feasible refinements in the ontology

Future Work

- Keep enhancing the ontology
  - Add more concepts, relationships, increasing the ontology coverage
  - Evaluation in the industry (with software engineers and practitioners), comparing with experts' suggestions.
- Use OntoSoS as a learning material, conducing an experiment to evaluate knowledge obtained with the ontology
- Guide software engineers when building SoS from requirements analysis to maintenance

Future Work

- Integrate OntoSoS with a system
  - Create an web interface to explore OntoSoS (improving collaboration among researchers)
  - Build a search engine to find concepts and relations
- Use OntoSoS as a SoS repository
  - Instantiate SoS in the ontology
  - Create individuals for the concepts (constituents, stakeholders etc)

Master's Research Project

Establishment of an Ontology for Systems-of-Systems

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