

Ontology-based Systems Engineering – The Smart Way of Realizing Complex Systems

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Objective of this Talk

Clarify the Need of Knowledge for Better Systems Engineering

From ancient Roman times ...

- Systems engineering has been practiced for centuries.
- This is demonstrated by complex constructions involving hundreds and thousands of specialists.

To today's digital world...

- A world of accelerating digital change with
- exponential growth of data, information and knowledge, and
- increasing complexity of smart products.



Colosseum in Rome, 72-80 A.D.



Aqueduct of Segovia, 98-117 A.D.

Outline

Digital transformation

- How technology shapes the way of working

Model-based Systems Engineering

- From documents to shared models

Linked Systems Engineering Data

- Make systems engineering data easily accessible

Ontology-Based Systems Engineering

- Towards a knowledge perspective of systems engineering

Conclusions

The Analogue World in the 1960s

Drawing Boards Play an Important Role in Engineering

Engineers working with drawing boards.



Source: Bundesarchiv, Bild 183-70282-0001, 21 January 1960



Sud Aviation SE 210 Caravelle, 1960 – Most successful European first-generation jet airliner



Fiat 500, 1960 – Considered as one of the first city cars

Emerging Digitalization – In the 1980s

Engineers Works Document-Centric

This was where the idea of a paperless office was born ...



Source: Airbus Defence and Space



Airbus A320, 1988 – first civil aircraft with digital fly-by-wire flight control



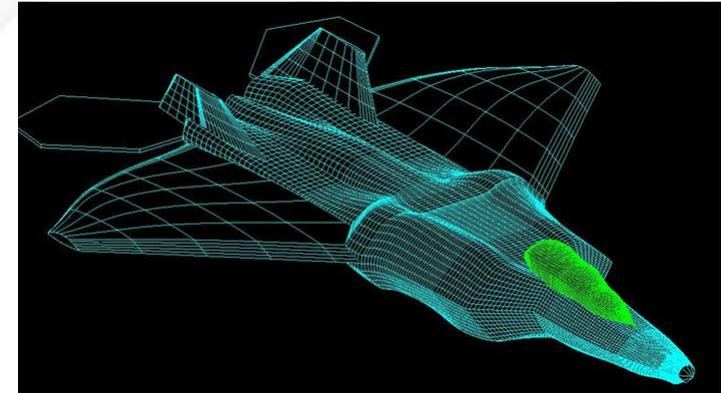
Ford Scorpio, 1985 – first car with electronic anti-lock braking system (ABS) as a standard feature

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Emerging Digitalization – In the 1990s

Breakthrough of Computer-aided Technologies

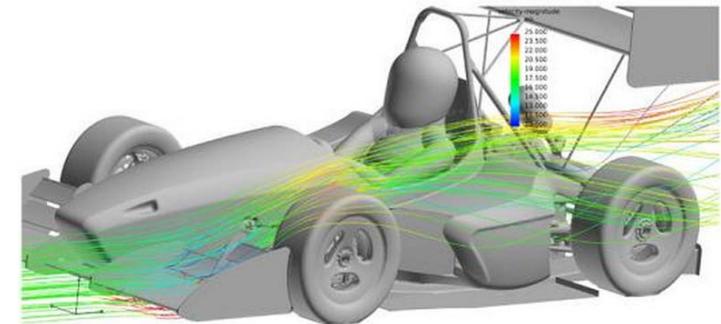
- Routine use of computer models to aid in the creation, analysis, or optimization of detailed design: fluid dynamics, structural mechanics, and multi-physics.
- But revolutions take time: real breakthrough was only in late 1990s.



Lockheed Martin F-22 Raptor, 1996, new materials like titanium and composites make up 80% of the structure by weight



Source: <http://www.glewengineering.com/>



Optimization of aerodynamics for a Formula 1 race car using a CFD (Computational Fluid Dynamics) model

Emerging Digitalization – Beginning of 2000

Concurrent Design Facilities

- Concurrent Design Facilities (CDF) are ESA's main assessment centre for future space missions.
- From isolated models to interlinked PCs.



Source: European Space Agency (ESA)



ExoMars phase B preparation accomplished by CDF in 2004



Near Earth Objects (NEO) study completed by CDF in 2005.

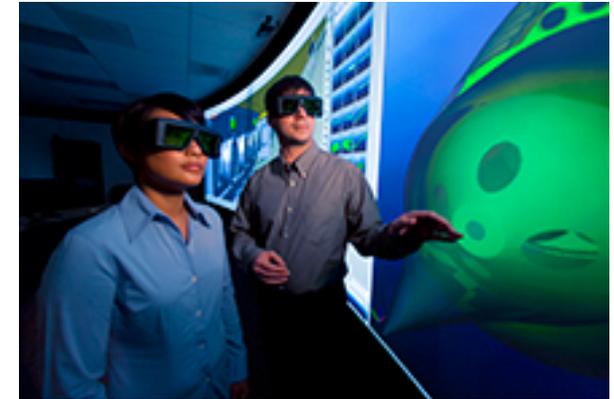
Emerging Digitalization – Today

Virtual Product Development

- Virtual prototyping, inspired by the gaming industry, turns engineers and technicians into avatars and puts them inside their designs, allowing them to explore their creations in an active, hands-on way.



Lockheed Martin, 2015 - Collaborative Human Immersive Laboratory (CHIL)



Lockheed Martin F-35 Joint Strike Fighter, design changes supported by immersive engineering



Ford, 2015 - Ford's Immersive Vehicle Environment (FIVE)

Emerging Digitalization – Today

Additive Layer Manufacturing (ALM)

- Additive Layer Manufacturing (ALM), also known as 3D printing, results in parts with 30% to 55% less weight while reducing raw material used by 90%.
- The aircraft of the future will be composed of complex parts printed using ALM.



Airbus A350 XWB, 2015 – more than 1000 parts are 3D printed replacing traditionally manufactured parts



Airbus Defence and Space, bracket for mounting antennas on telecommunication satellites



Airbus, A350 XWB bracket produced with 3D printing

Emerging Digitalization – Transition to the Future

Smart Connected Products, Internet of Things and Services

- Smart products are embedded with processors, sensors, software and connectivity that allow data to be exchanged between the product and its environment, manufacturer, user, and other products and systems.
- The data collected from these products can be then analysed to inform decision-making, enable operational efficiencies and continuously improve the performance of the product.

Source: Wikipedia



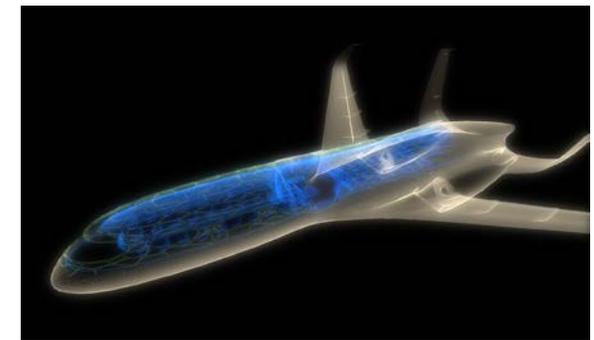
Apple iPhone, 2007 – popular smart phone



Samsung, 2011 – Smart TV



Mercedes F 015 concept smart car – supporting autonomous driving



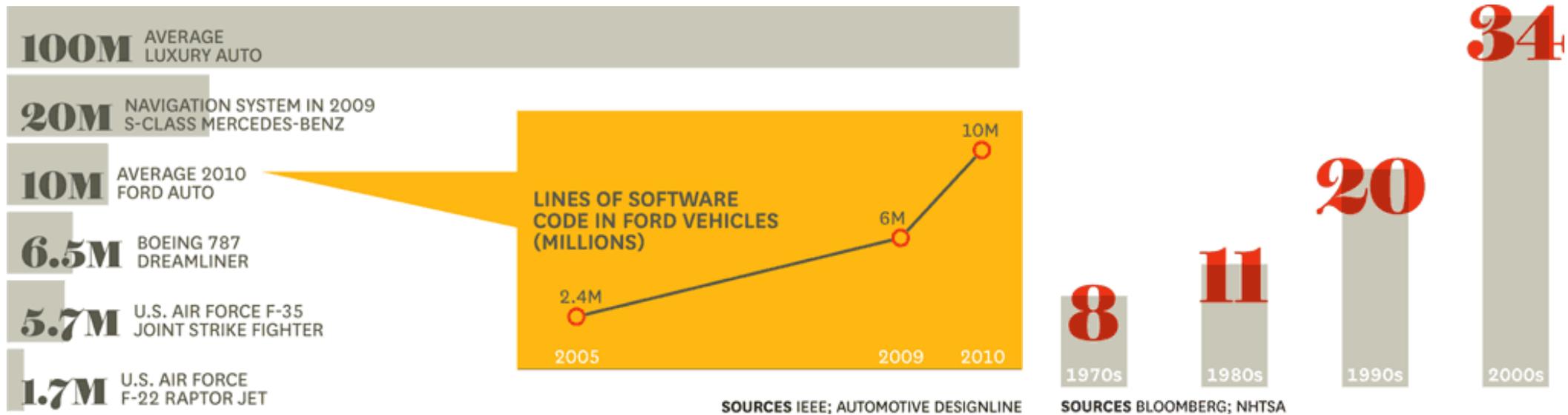
Airbus concept smart plane – supporting smart sky vision 2050

Increasing Product Complexity

Some Figures from the Automotive Industry

- Safety regulations and consumer demand for performance and convenience have led to an exponential spike in cars' software complexity.
- With more computers controlling functions like braking, annual vehicle recalls related to electrical systems have quadrupled in the U.S. since the 1970s.
- Recalls will continue to increase right along with complexity as an evidence of the burdens of complexity.

Source: Harvard Business Review, 2010



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Importance of Systems Engineering

Definition from INCOSE

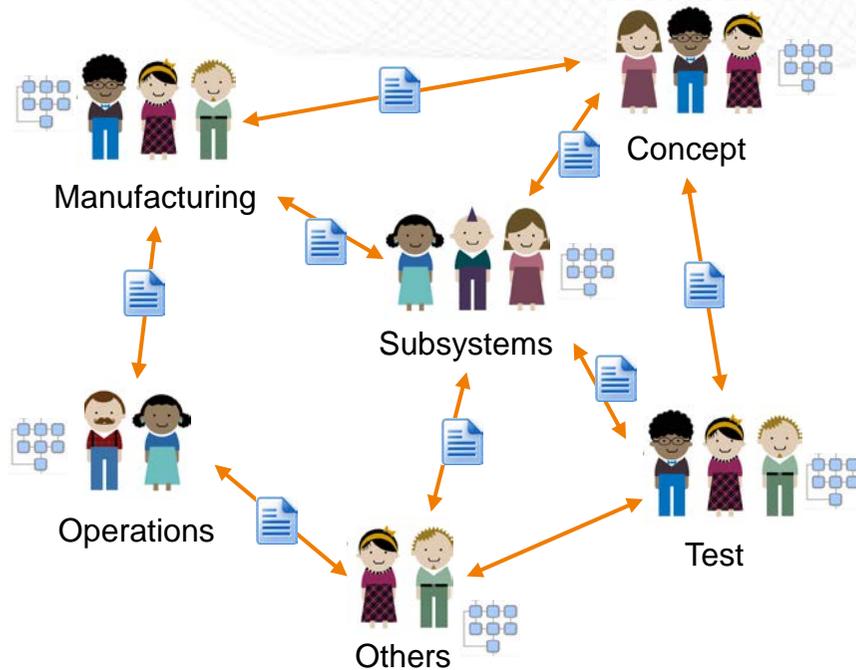
- Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems.
- It focuses on **defining customer needs** and required functionality early in the development cycle, **documenting requirements**, then proceeding with **design synthesis** and **system validation** while considering the **complete problem** including operations, cost and schedule, performance, training and support, test, manufacturing and disposal.
- It **integrates all the disciplines** and specialty groups into a team effort forming a **structured development process** that proceeds **from concept to production to operation**.
- It considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.

Source: <http://www.incose.org/AboutSE/WhatIsSE>

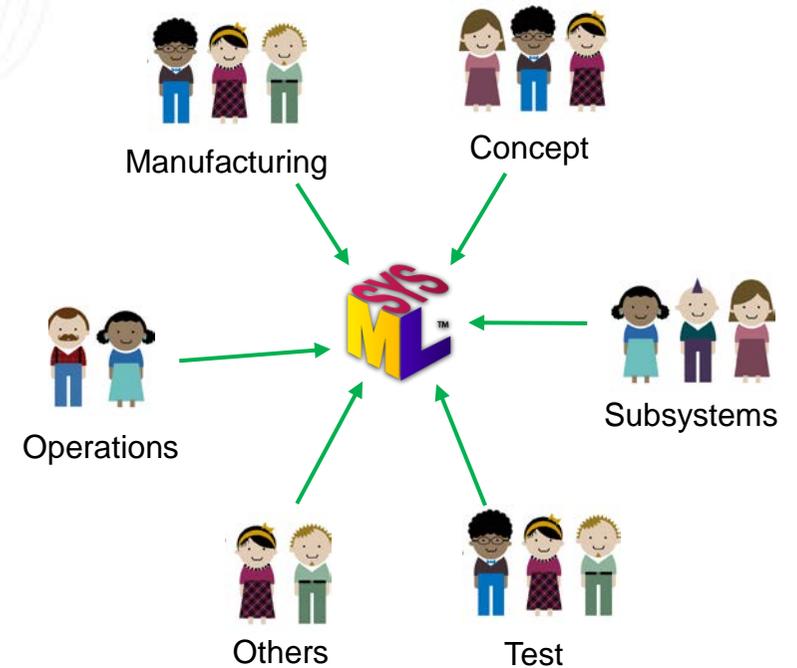
Model-based Systems Engineering

From Documents to Shared Models

Model-based systems engineering (MBSE) is the *application of modelling* to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.



Standalone models related through documents

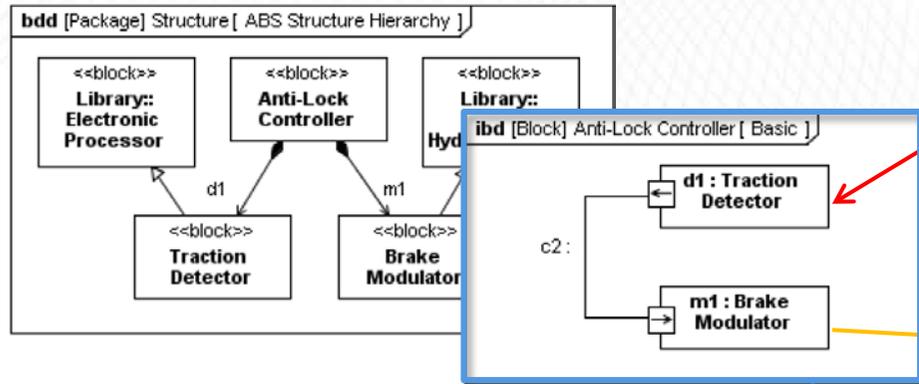


Shared system model with multiple views, and connected to discipline models.

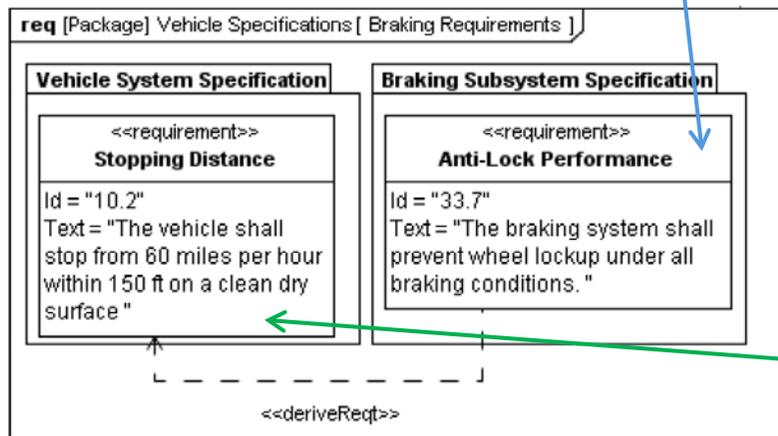
SysML Model of Anti-lock Braking System

A Simple Example

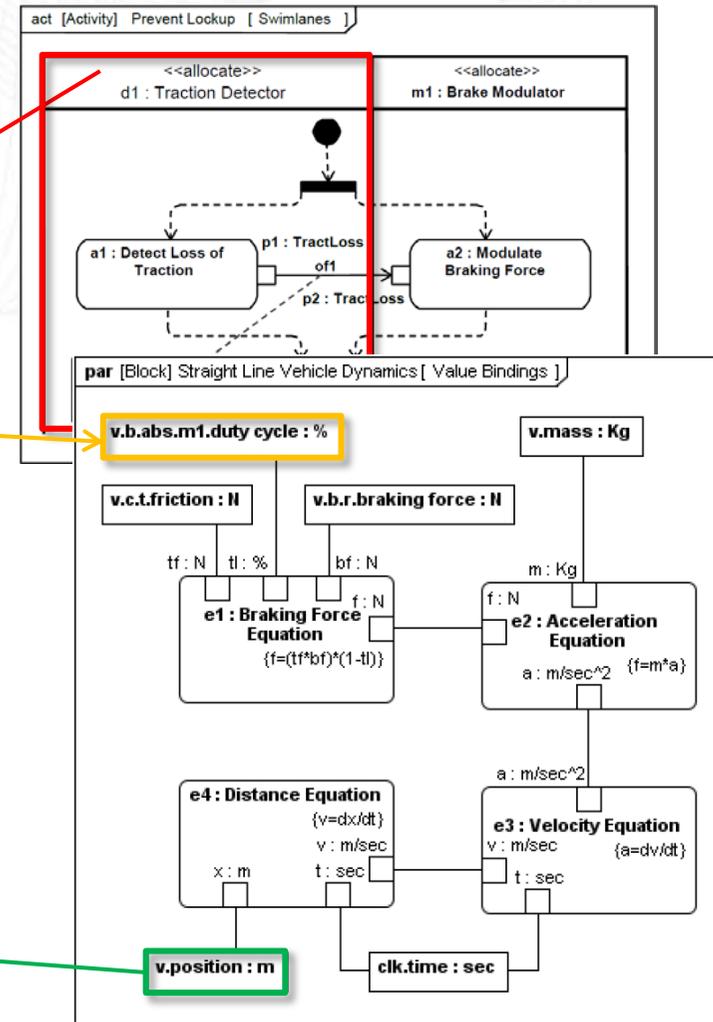
Structure



Requirements



Behaviour



Parametrics

allocate

value binding

satisfy

verify

Source: INCOSE-OMG SysML Tutorial, 2009

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Does Model-based Systems Engineering Help?

It Delivers at Least Some Benefits

Shared understanding of system requirements and design

- Validation of requirements.
- Common basis for analysis and design.

Assists in managing complex system development

- Separation of concerns via multiple views of integrated model.
- Supports traceability through hierarchical system models.
- Facilitates impact analysis of requirements and design changes.

Improved design quality

- Reduced errors and ambiguity.
- More complete representation.

Source: INCOSE-OMG SysML Tutorial, 2009

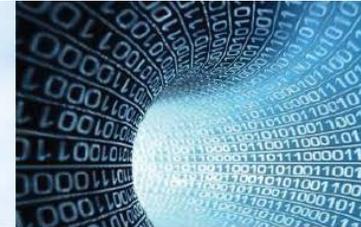
BUT ...

- Model-based Systems Engineering still lacks maturity like CAD in the early years!

Next Generation Systems Engineering

Work with Information and Knowledge

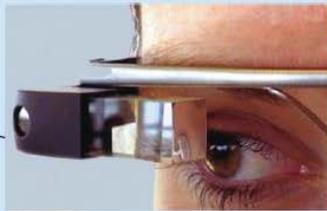
Cloud-based high performance computing support high fidelity system simulation



Advanced search query, and analytical methods support reasoning about systems



Immersive technologies support data visualization



Net-enabled tools support collaboration



Source: INCOSE SE Vision 2025

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Linked Data and Semantic Web

Objectives

- Adding machine-readable information to web pages which can be processed by third-party applications.
- Enriching datasets by linking to third-party datasets.
- Provide standards-compliant way for exchanging data.
- Enable cross-dataset queries.

Common data model

- Graph-based: nodes and arcs represent resources, their properties and values.
- Standard format RDF (Resource Description Format) with different serializations: Turtle, JSON, N-Triples, RDF/XML, ...
- Vocabularies provide semantic information about resources, e.g. Dublin Core (DC) for metadata or Simple Knowledge Organization Scheme (SKOS) for terminology.



Tim Berners-Lee: 5* Model

Web of Systems Engineering Data

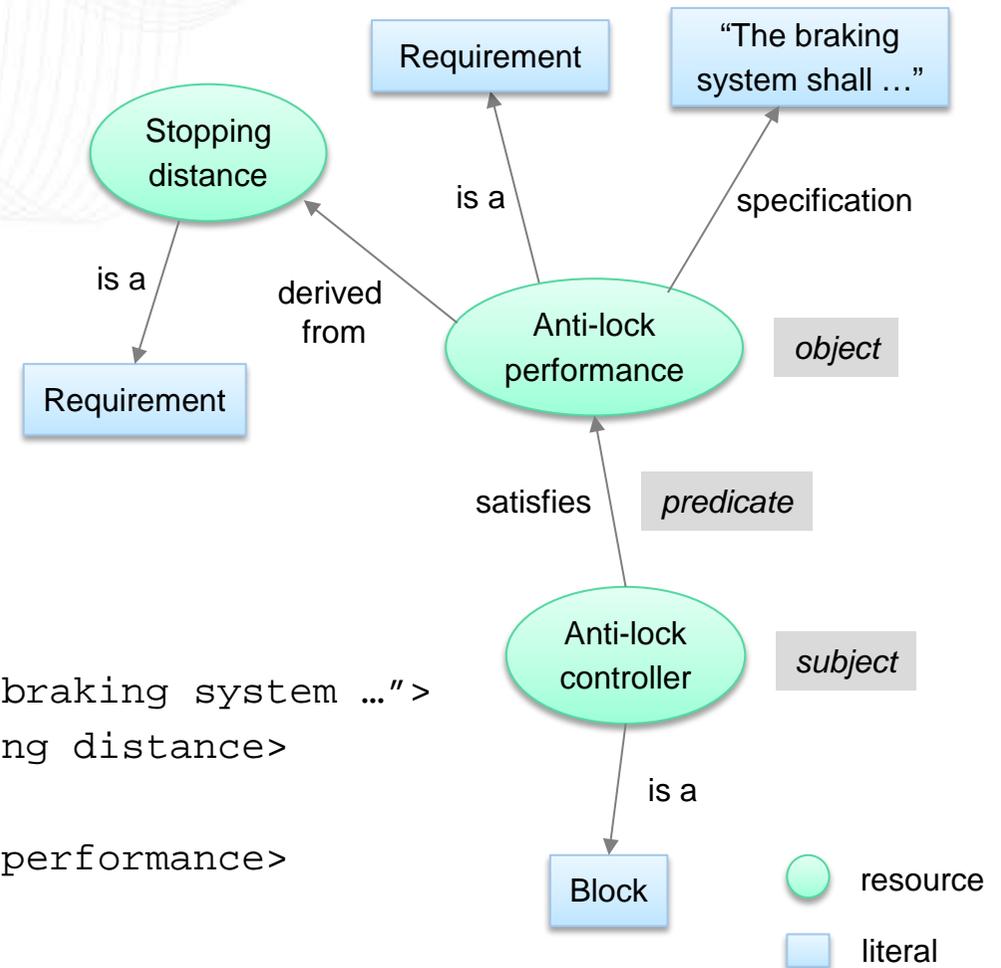
Data Becomes Accessible and Traceable

RDF Triples

- RDF makes statements about resources.
- RDF statements express a directed relationship between two resources: subject and object.
- The relationship is called property.
- RDF statements consist of three elements which are called triples:
<subject> <predicate> <object>

Example: informal sample triples

```
<Anti-lock performance> <is a> <Requirement>  
<Anti-lock performance> <specification> <"The braking system ...">  
<Anti-lock performance> <derived from> <Stopping distance>  
<Anti-lock controller> <is a> <Block>  
<Anti-lock controller> <satisfies> <Anti-lock performance>
```



Web of Systems Engineering Data

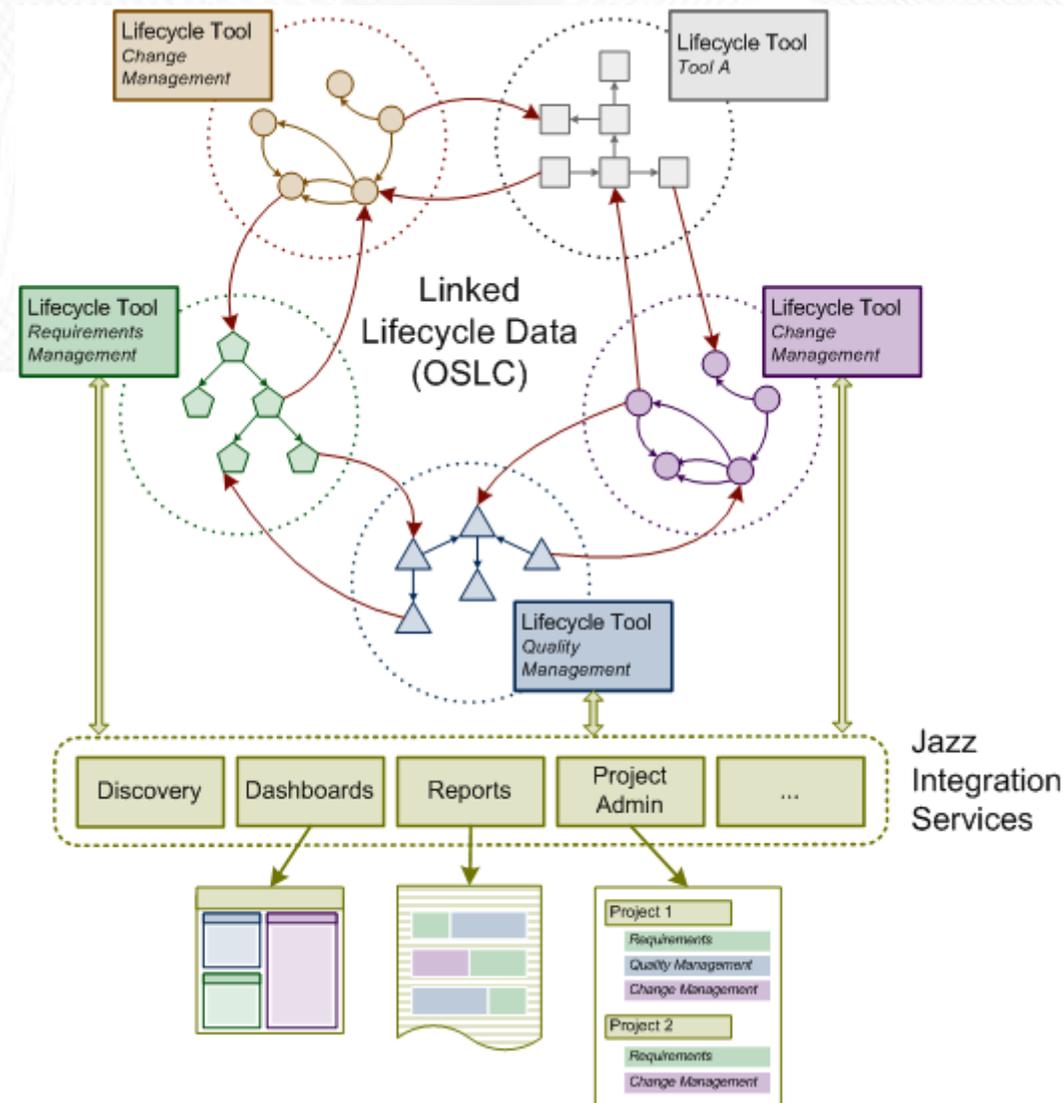
Open Services for Lifecycle Collaboration (OSLC)

Objectives

- An open community building practical specifications for integrating software.
- Specifications support common integration scenarios.
- Specifications are based on HTTP and linked data standards.
- Any resource must be accessible to multiple tools via a URI and RESTful services.

Current specifications

- Requirements Management
- Architecture Management
- Quality Management
- Configuration Management
- Change Management



Source: Open Services Lifecycle Collaboration and IBM's Jazz Platform

Web of Systems Engineering Data

Quantity of Systems Engineering Data

Example: System architecture model of a commercial airplane

Functional architecture:

- ~2.300 functions
- ~10.000 data flows

Physical architecture:

- ~5.266 equipment installations with data interfaces
- ~1.000.000 data parameters
- ~9.490 electrical connections

Total:

- ~ 60.000.000 objects
- ~180.000.000 relationships

Source: Boeing, INCOSE MBSE Working Group, 2014

Advanced Search and Query

Support Analysis Based on Linked Data

Diagramming interface

- Needed for communications with stakeholders
- But impractical for analysing millions of objects and relationships

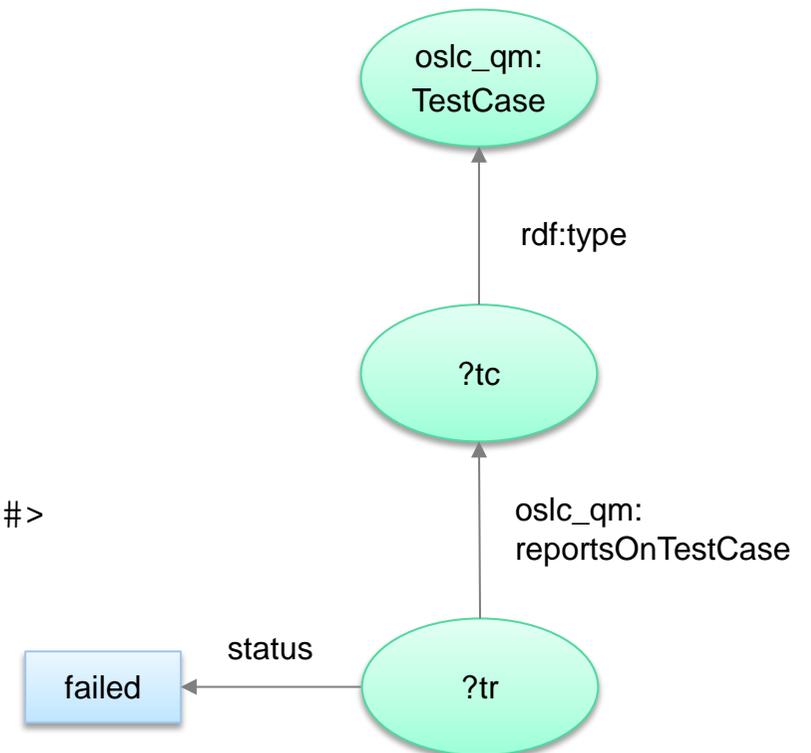
Search and query interface

- SPARQL (SPARQL Protocol and RDF Query Language) endpoints provide RDF query capabilities

Example: a simple query that lists all failed test cases

- All triples that match the query are joined

```
PREFIX osc_qm: <http://open-services.net/ns/qm#>
PREFIX dcterms: <http://purl.org/dc/terms/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT ?tc
WHERE {
  ?tc rdf:type osc_qm:TestCase .
  ?tr osc_qm:reportsOnTestCase ?tc ;
     osc_qm:status "failed"^^xsd:string .
}
```



Traceability and System Views

Navigation through Systems Engineering Data

With the help of SPARQL one can

- Use project views and queries to understand the complex web of data.
- Understand the system structure and relationships.
- Perform requirements tracing and impact analyses.

The image displays three screenshots of the De-Icing RELM software interface, illustrating various system views and their relationships.

- Overview View:** Shows a dashboard with several colored boxes representing different views: Change Requests, My Tasks, Top Level Functional Requirements, Top Level Non Functional Requirements, Top Level Environmental Requirements, Top Level Functional View, Detailed Concept View, Analysis View, and Test View.
- Functional View:** Displays a hierarchical structure of requirements and functions. It includes sections for Top Level Requirements, Functional Requirements, Top Level Functions, and System Context. The System Context section lists various system components like itsAir_Data_System, itsElectrical_Power_Gener, itsPilot, itsPneumatic_System, and itsSuI_ice_removing.
- Non-functional Requirements Refinement view:** Shows a detailed view of requirements and solution attributes. It includes sections for Top level Requirements, Refined Requirements, Solution Attributes, and Analysis Models. A specific requirement is highlighted: "The inflation pressure for boot chambers shall be less than 21 psi".

Source: CRYSTAL project, <https://www.youtube.com/watch?v=zeFiGSwMsUc>

Improved Visualization for Seamless Navigation

Benchmark: Google Maps and Google Earth

Different views

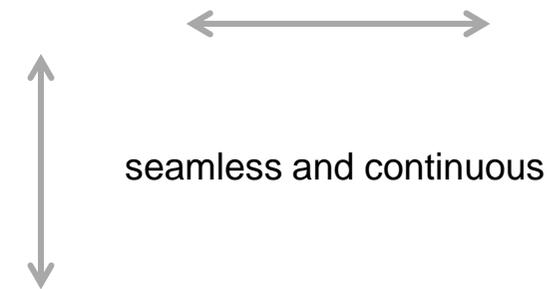
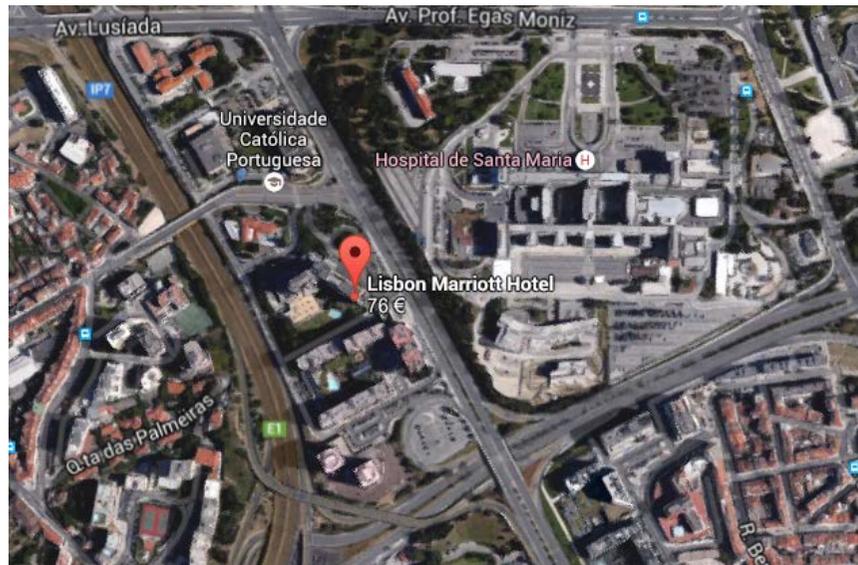
- Map view
- Earth view
- Street view

Horizontal scanning

- Connections
- Routes

Vertical scaling

- Scale 1: 100 000
- Scale 1: 10 000
- Scale 1: 1 000



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CRYSTAL – Critical sYSTem engineering AcceLeration

Facts

- ARTEMIS Innovation Pilot Project (AIPP)
- 70 partners from aerospace, automotive, rail and health care domain
- Project duration: May 2013 – April 2016
- Further information: <http://www.crystal-artemis.eu>

Objectives

- Drive forward Interoperability Specification (IOS) towards standardization and advance systems engineering through ontologies.
- Allow loosely coupled tools to share and link data based on standardized and open web technologies.
- Cover the whole product lifecycle of embedded systems development and provide ready-for-use industrial tool chains.



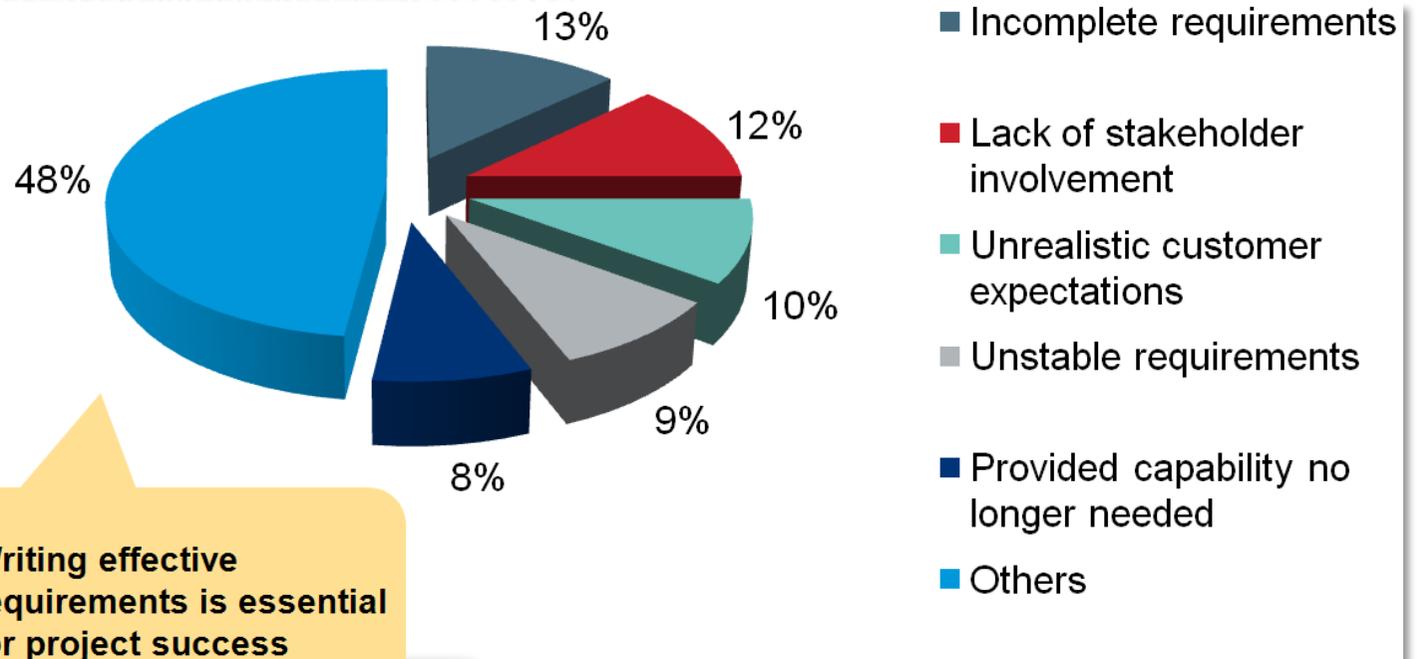
The Requirements Quality Issue

- The quality of requirements has a major impact on schedule, cost and scope of projects.
- Badly written requirements are a well-known source of project failure.
- The quality of requirements shall be assessed through an appropriate and sufficient set of quality indicators.

Joint work with



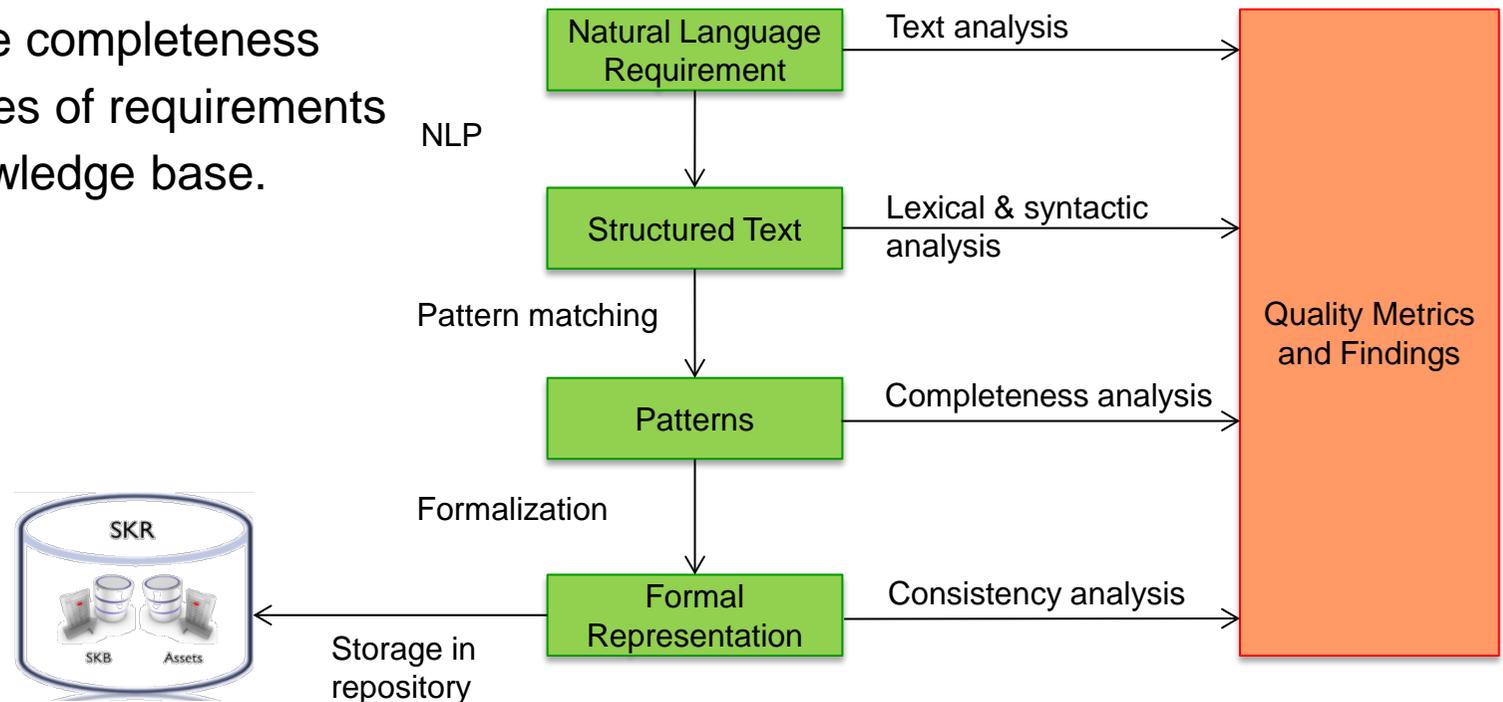
Universidad
Carlos III de Madrid



[Source: CHAOS Report, The Standish Group International, Inc., 2003]

Approach

- Natural Language Processing (NLP) is a staged process (tokenization, normalization, disambiguation, ...) that transforms requirements into structured text that allows further processing.
- Pattern matching and formalization transforms structured text into knowledge representation structures such as semantic graphs.
- Semantic graphs enable completeness and consistency analyses of requirements against the system knowledge base.



Controlled Vocabulary

Terminology

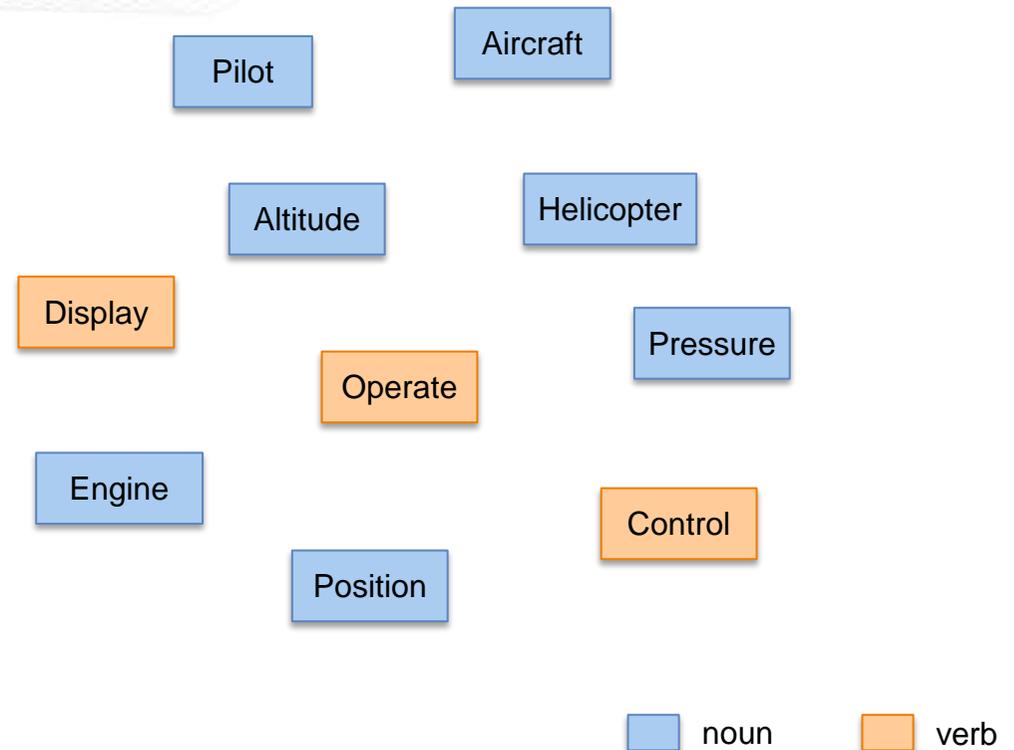
- Concepts are introduced to represent things in the domain with a name and optionally a textual definition.
- All systems engineering processes should use standard terms in requirements, models, test cases, ...

Categories of terms

- Domain-specific terms
- General language terms
- Syntactically relevant terms
- Forbidden terms

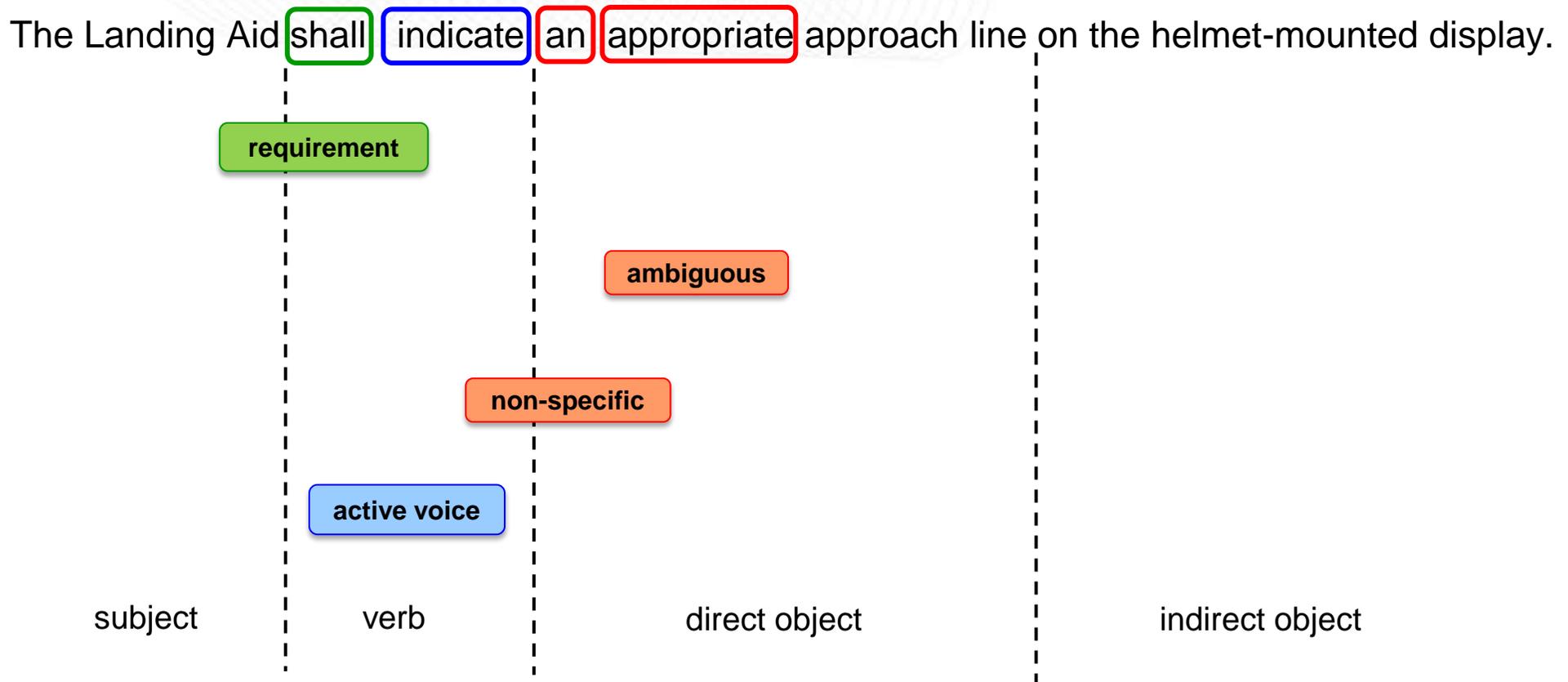
Syntactic tags

- Noun, verb, adjective, adverb, ...



Example: Lexical and Syntactic Analysis

- Identify language defects, e.g. passive voice or missing “shall”.
- Detect requirements with ambiguous or weak wording.



Conceptual Model

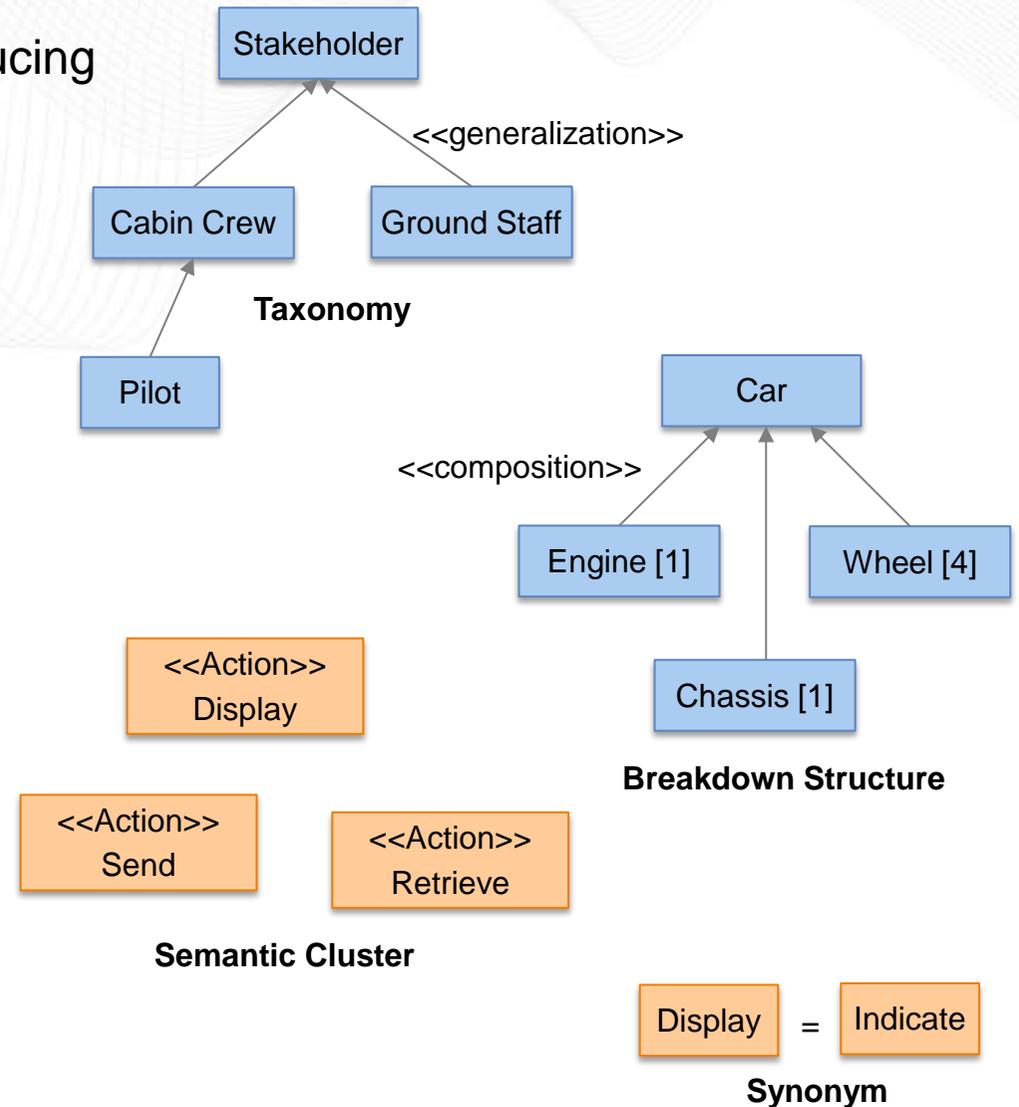
Conceptual models represent knowledge by introducing relationships between concepts in the vocabulary:

- generalization – specialization
- whole – part
- equivalence
- user-defined associations

Everything included in the conceptual model is considered as an axiom.

Allows to...

- Find similar requirements based on terms organized in taxonomies.
- Check completeness or consistency of requirements against breakdown structures.



Patterns and Formalization

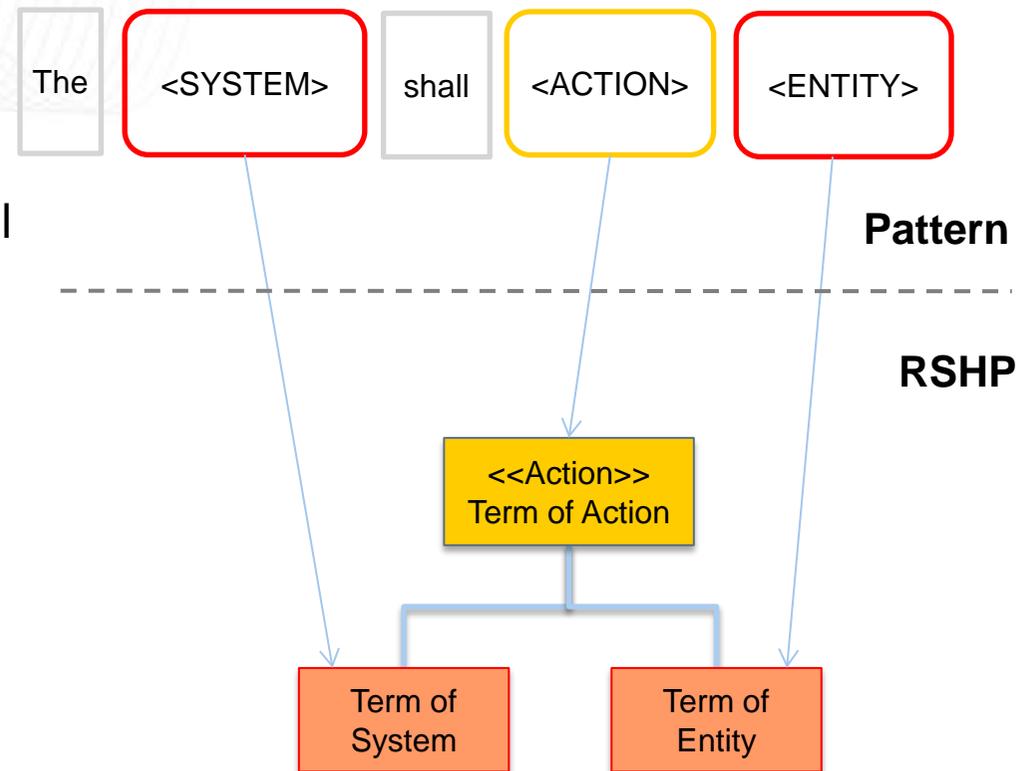
How can we Transform Text into Knowledge Statements?

Pattern constraints

- Patterns are sequential lists of restrictions, e.g. term, semantic cluster, syntactic tag.
- Patterns can be matched from natural language text based on terminology in the conceptual model.
- Patterns establish the rules of writing meaningful knowledge statements of a particular kind.

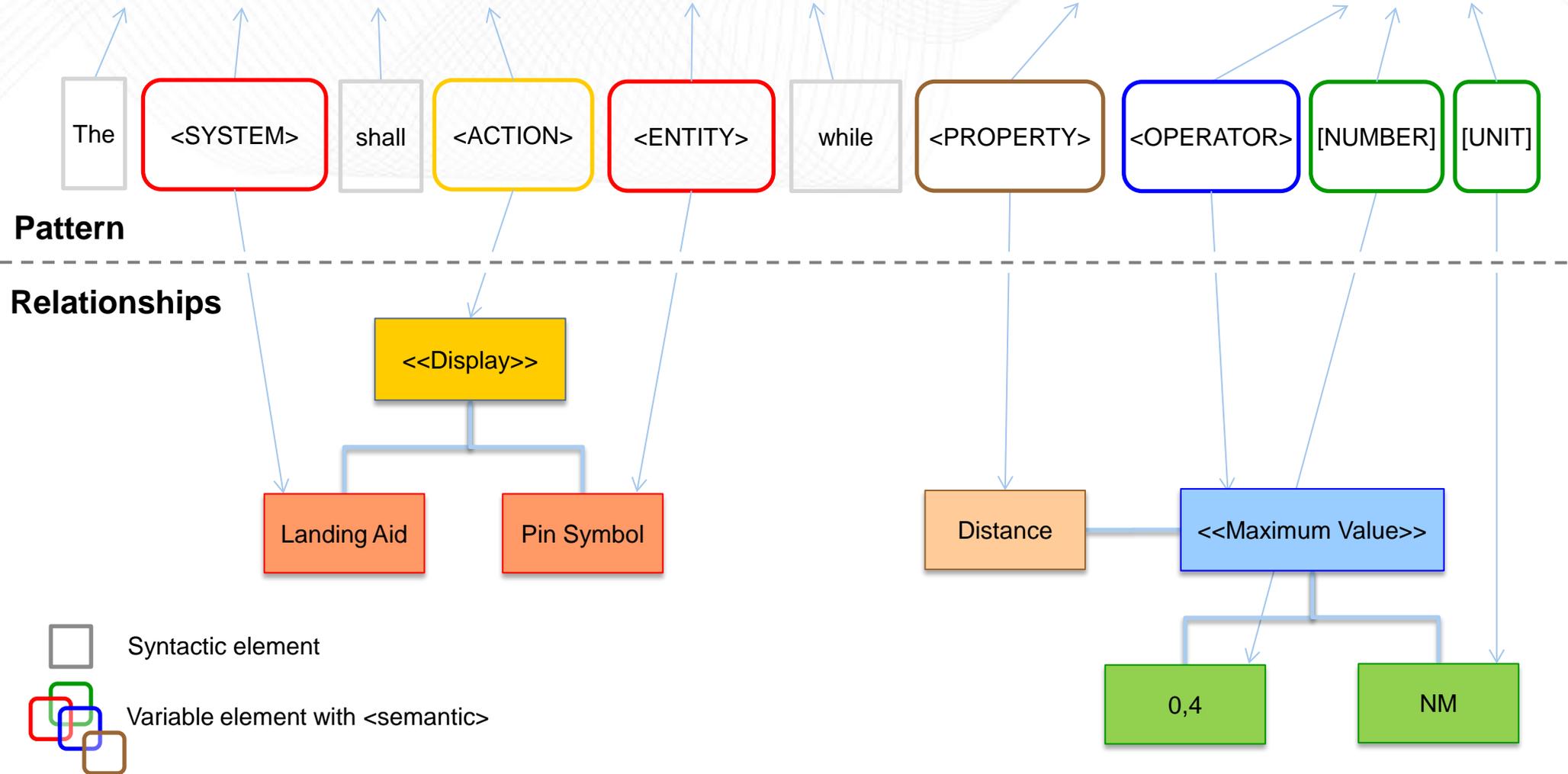
Formalization: RSHPs and Relationships

- Patterns can produce formal representations of text.
- RSHPs are schemas that will be matched by a text to form a relationship between terms.
- Relationships are knowledge statements that depict a connection between two existing terms.



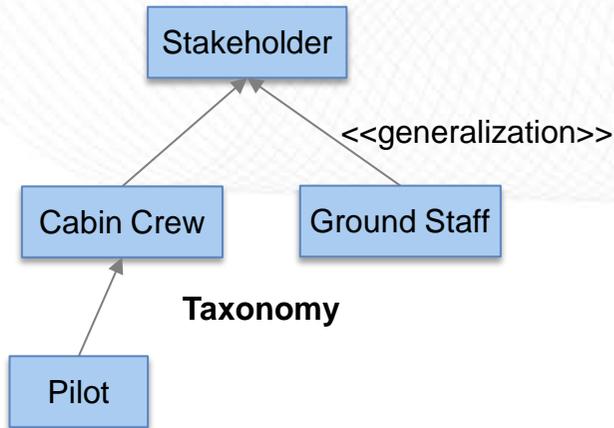
Example: Patterns and Formalization

SR-65: The Landing Aid shall display the pin symbol while the distance to the landing position < 0,4 NM



Semantic Analysis: Completeness

Requirement statements can be checked against the conceptual model.



What is the proportion of the selected terms from the terminology that is not covered by a given specification?

Which patterns of a selected pattern group are not covered by a given specification?

Pattern group



Functional requirement



Interface requirement



Performance requirement



Safety requirement

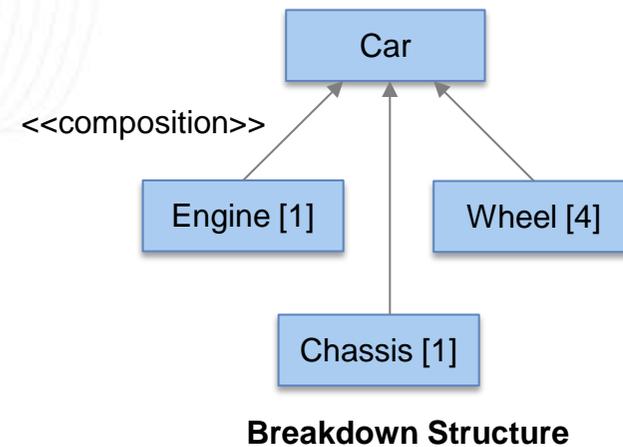
Semantic Analysis: Consistency

Requirement statements can be checked against the conceptual model.

Is the specification consistent with the product breakdown structure? No, since the accumulated weight of the parts exceeds the weight of the whole car.

Other examples are:

- *Are there any overlapping or contradictory requirements?*
- *Are the units of measurement used consistently?*



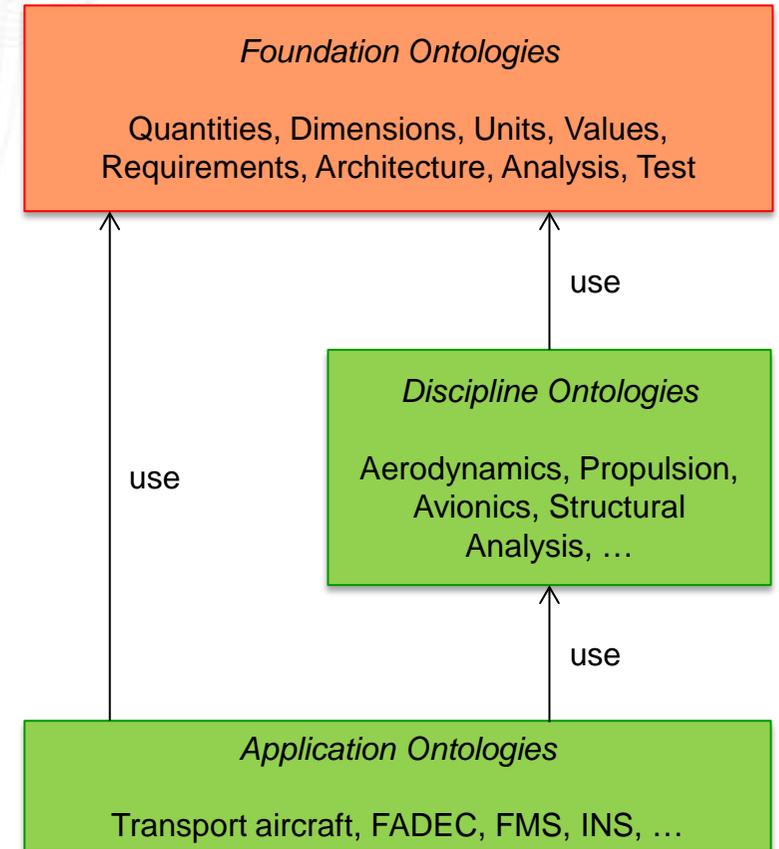
The weight of the car shall be less than 1500 kg.
The weight of the engine shall be less than 500 kg.
The weight of the chassis shall be less than 1000 kg.
The weight of the wheel shall be less than 25 kg.

Specification

Generalization of the Approach

Indexing Systems Engineering Artefacts

- System specifications are often a mix of natural language sentences and semi-formal modelling languages.
- Ontologies help to advance formalization of systems engineering artefacts and resolve ambiguities.
- Based on ontologies, it should be possible to index different kinds of systems engineering artefacts.
- Reasoning services allow to check for consistency and completeness issues, discover missing traces and a lot more...



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Challenge

- We need to advance systems engineering in order to cope the increasing complexity of products.

Adopt linked data principle

- Systems engineering data must be easily accessible using open, linked data standards.
- Advanced search and query capabilities are indispensable for reporting and analysing data.
- Seamless visualization and navigation through data is vital for accelerating the acceptance.

Introduce ontology-based systems engineering

- Ontologies allow improving the accuracy and expressiveness system specifications.
- Indexing should be made available to both text-based and model-based artefacts.
- Semantic services based on knowledge representations assist in assuring the quality of system specifications.



The growing complexity of products requires the convergence of systems engineering and knowledge engineering techniques.

Thank you for your attention!

Dr. Ralf Bogusch
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