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UAF (Unified Architecture Framework) Based MBSE (UBM) Method to build a System of Systems Model

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Abstract. The system model is defined as the main source of truth for systems engineering. Current MBSE methods are focused mainly on single systems. As per the literature, we lack the MBSE methods to develop the system models of System of Systems (SoS). Systems engineers use architecture frameworks for this purpose, but the huge number of views included within an architecture framework makes it difficult to select the appropriate views and expert knowledge is required to tailor the framework.

The UAF (Unified Architecture Framework) Based MBSE (UBM) method described within this paper addresses this issue. This method uses a selected subset from the UAF domain model and defines a step by step procedure to construct the system model for a complex, System of Systems in a military domain.

Introduction

The system descriptive model which is considered as the main source of truth is described using a modelling language. This language is defined using a Meta-model which is understood and shared by the systems engineers who are involved in system development. The Meta-model is also required to ensure the consistency of the systems engineering data represented by the model elements and their relationships. Systems engineers and architects use architecture frameworks to build and structure the model views presenting the system model from different perspectives. The model views are used also to input the data required to build the system model. In many cases, these views are not compatible and are completely disintegrated to each other. To deal with this challenge, the organization must implement proper practices, where language, method and tool are vital constructs [Chami *et al*.,2018]. Most of the architecture frameworks do not include methods to give a clear guidance on the activities to be performed to build the system model in a consistent manner. Furthermore, the huge number of views included within an architecture framework requires expert knowledge to tailor the framework. The experts knowledgeable in architecture frameworks are however scarce within enterprises.

Some misconceptions exist among system engineers about the applicability of architecture frameworks and MBSE methods. These misconceptions include:

- Architecture frameworks describes the system of systems architectures, but cannot be used for a single system like an aircraft.

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- MBSE concerns only the definition of the architecture starting from the functional analysis of a single system.

These misconceptions are a result of focusing only on a one type of system while defining MBSE approaches. Tirone et al., 2018 discussed this issue and concluded that any entity which can be subject of "Architecture" should be the target of the UAF. The entity whose architecture is defined can be any: enterprise, system of systems, collection of systems, product line, individual system, portion of a system, product, service, individual hardware or software item, any other entity that is amenable to architectural definition (eg, data, doctrine, organization, process, method, technique, policy, facilities, etc) [Martin, 2016]

The works reported within the literature [Tirone *et al*., 2018, Morkevicius *et al.*, 2017] describes the tailoring of UAF to describe the architecture of system of systems. But those works do not describe any step by step method to build a system model necessary to give a clear guidance to system architects.

The six step method for model development, including a problem framing approach [Martin, 2019] provides a structured way of building the right models and getting maximum utility out of them. A similar approach has been applied within our company for several years [Asagiri *et al*, 2017, Abhaya, 2017]. These approaches frame the problem under study within each project, develop a domain Meta model, tailor an architecture framework and define a methodology. The lessons learned from the previous projects show that the most of the time the same view set is chosen as the result of tailoring. Moreover, this phase requires the intervention of expert knowledge in the architecture frameworks and takes some additional time prior to starting modelling. The architects prefer to use a predefined method which leads to the same results, though the problem framing approach can be used complementarily.

The UAF Based MBSE (UBM) method described within this paper uses a selected subset from the UAF domain model and defines a step by step procedure to construct the system model. The tailoring of UAF proposed by Tirone *et al.*, 2018 selects the same perspectives as UBM, but they customize the UAF profile by adding some specific stereotypes as, System of Interest, Actor and Use Case. We use the UAF profile without customizations and provide the mapping between UAF elements and the common terms used by system engineers. This provides advantages for interoperability or the possibility of using existing tools to convert UAF model to NAF.

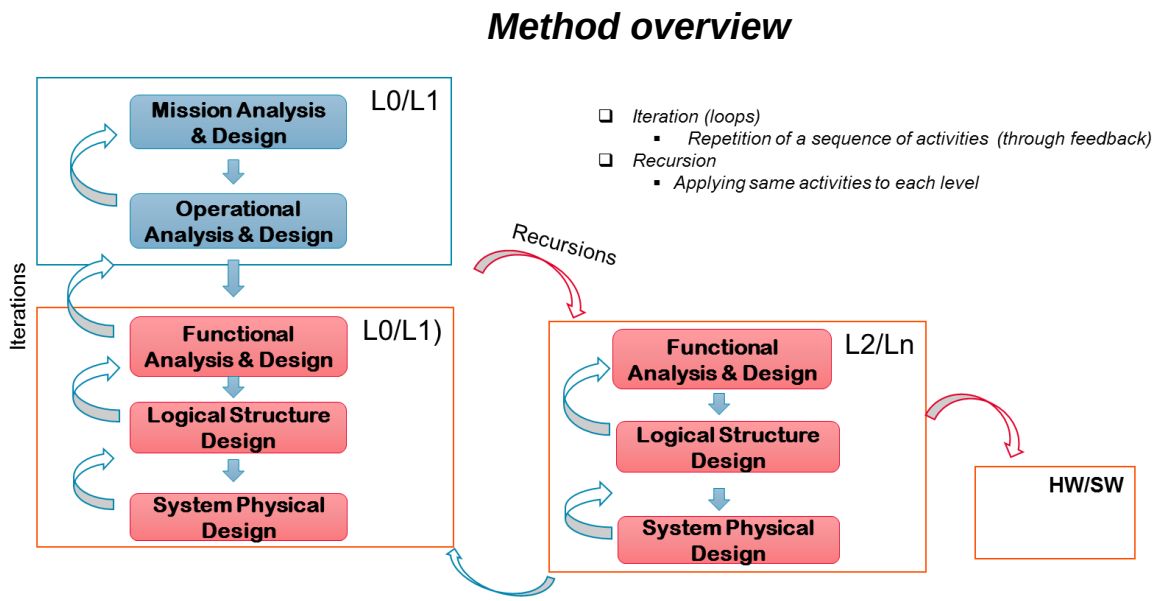

Figure 1. UBM Method Overview

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The method includes five main activities that are aligned with the company systems engineering processes. Though these activities can be applied to the systems at any level of the systems hierarchy, first two activities are mainly applied to the systems found at top levels (Level 0 and 1). These activities are performed through iterations and recursions. Several steps are required to complete each activity which builds the system model through the related model elements.

The model repository is organized to contain separate models for each main system of the system hierarchy. Each model has shared folders for the elements coming from upstream, as well as those going down stream. The generic model structure is defined based on the Strategy, Operational and Resources perspectives available within UAF.

The model elements produced through the Mission Analysis & Design contribute to building the strategic and operational views of the system model. Operational analysis and design activity complete the operational perspective. Resource perspective includes the model elements resulting from the other activities. The main outcome from the Functional Analysis & Design is functional flows. How the functional architecture is structured is defined during Logical Structure design.

A deliverable model (Figure 2) is defined to describe different outcomes of the modelling activities.

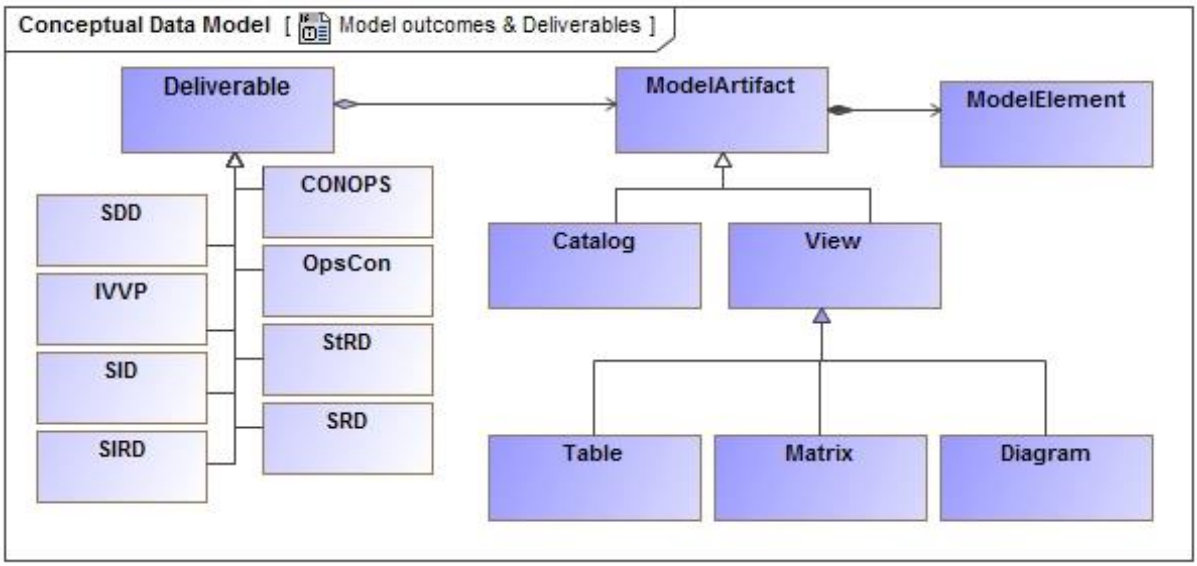

Figure 2. Deliverable Model

A Deliverable is a work product that is contractually specified and in turn formally reviewed, agreed, and signed off by the stakeholders [Harrison, 2013]. A Model Artifact is a work product that describes an aspect of the System of Interest's architecture. A Model Element represents System Engineering Data which are the Instances of Meta-Model elements. Model Artifacts are classified as Catalogs which provides lists of things and Views that can be:

- Diagrams : showing model elements and their relationships;
- Matrices : showing relationships between model elements;
- Table: showing model element details;

The main diagram types provided by the UAF specification are the subtypes of SysML Block Definition Diagram (BDD) or Activity diagrams. Taxonomy, Structure and Connectivity Diagrams are all subtypes of SysML BDD and the UAF specification provides overlapping definitions for each of these diagram types. As a result, the tools allow creation of taxonomy, structure or connectivity in any of these diagram types. The method gives the guidelines to use only correct elements:

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- Taxonomy: Model elements with generalization relationships, or arbitrary connectors
- Structure: Composition/aggregation relationships
- Connectivity: shows the logical exchanges between structural elements.

Structural elements represent “Things” in the architecture and are considered as “elements of definition”. They possess a set of properties: Role considered as “elements of usage”, Measurement, Constraint, Behavioral feature and Port.

A hypothetical case study, considering a Multi-UAV (Unmanned Aerial Vehicles) Forrest Fire Management System of System is used to illustrate the method.

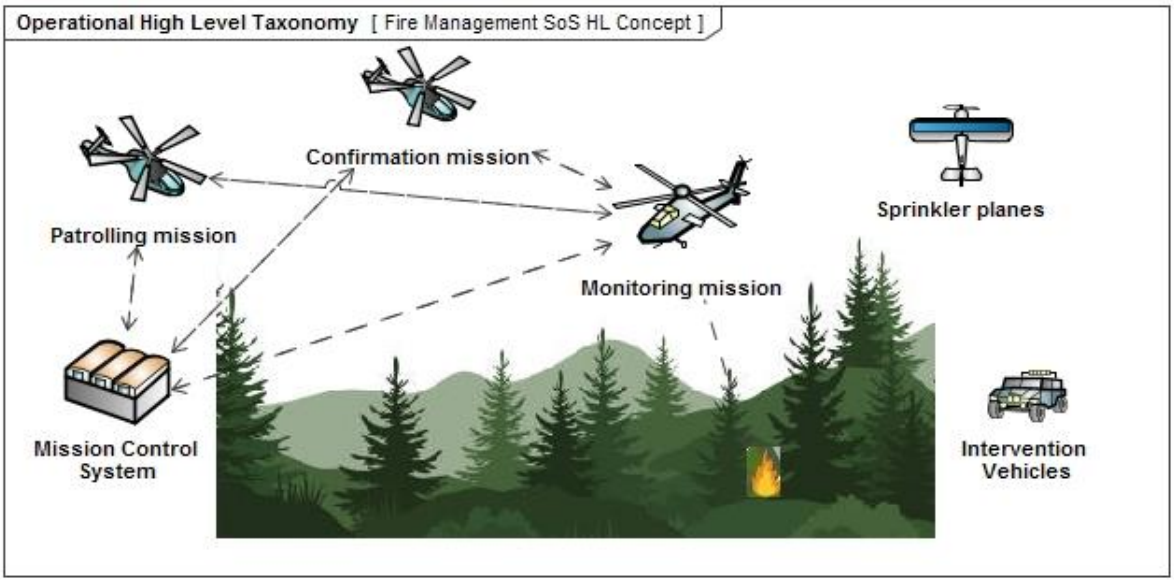

Figure 3. Multi-UAV Forrest Fire Management SoS

When patrolling a UAV suspects or detects a fire, a confirmation mission is assigned to another UAV. One UAV with sufficient loitering capabilities monitors the fire. Several challenges exist due to the nature of the mission and environment conditions, such as:

- Collison avoidance if path changes happens to avoid damage from fire
- Locating Operators at sufficient distances for safety
- Losing visibility due to smoke
- Poor communication means in forest areas

Description of the main activities and steps

Mission Analysis & Design

The purpose of the Business/Mission analysis is to define the problem or opportunity, characterize the solution space, and determine potential technical solutions class(es) that could address a problem or take advantage of an opportunity. The business or mission analysis for a System of Systems (SoS) should address [ISO 21840, 2019]:

- Definition of the SoS objectives and SoS target states(s), noting that these could be defined at multiple future times with varying fidelity;

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- Analysis of the priorities to address capability gaps;
- Analysis of potential alternatives and courses of action to address SoS operational needs, taking into account known plans for individual constituent systems;
- Evaluation of the SoS capacity to satisfy stakeholders.

The Mission is defined as a task, together with the purpose, that clearly indicates the action to be taken and the reason therefore (DoD. 2017). Mission is the answer to the question "What should be done?" to achieve a goal.

This activity consists of five main steps during which the system model is developed from the strategic and operational viewpoints. The following figure presents the Meta-Model elements and UAF views used to build the strategic perspective of the model during first two steps.

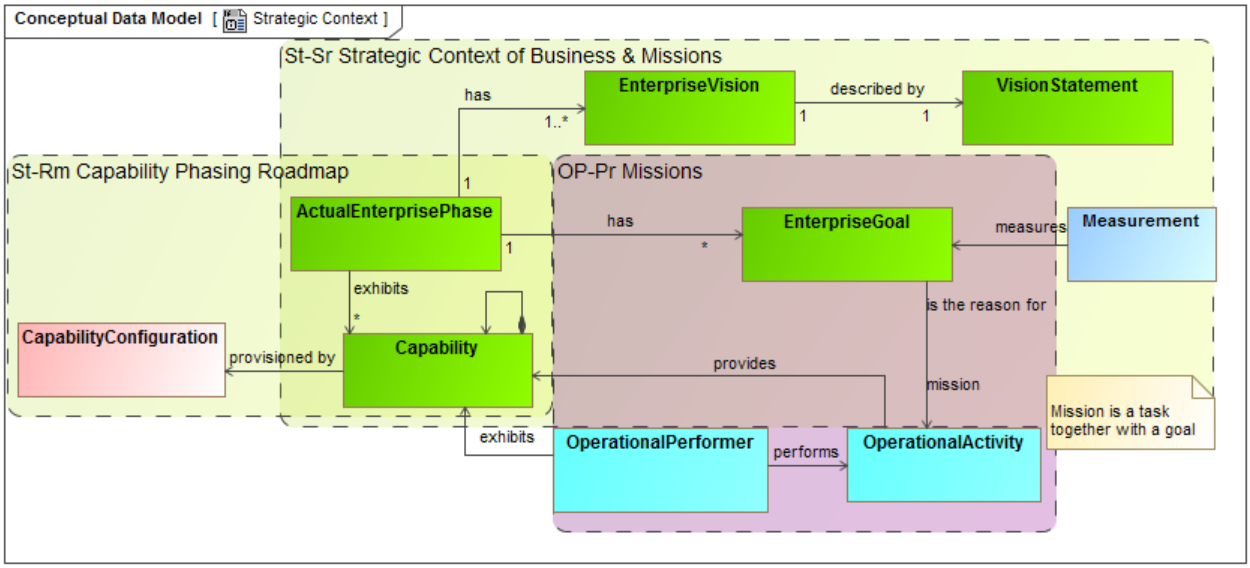

Figure 4. Meta-Model for the Strategic perspective

STEP#1 - Define the Vision, goals & objectives of the Enterprise with associated benefits. The Enterprise is defined as one or more organizations sharing a definite mission, goals, and objectives to offer an output such as a product or service [ISO 15704:2019]. The enterprise summarizes their goals and objectives in mission and vision statements. While a mission statement describes what an enterprise wants to do now, a vision statement outlines what it wants to be in the future. The goals and objectives, both describe the things that an organization wants to achieve.

The customer enterprise is the one which is analyzed at this step. The Enterprise Goal element is used to model goals and their decomposition to measurable objectives. These model elements including Enterprise Vision are depicted using a Strategic Structure Diagram. The success criteria to measure the objectives are defined using the Measurements model element.

STEP#2 - Identify the Capabilities required to achieve objectives. A capability is defined as the ability to achieve a desired effect under specified standards and conditions through combinations of ways and means to perform a set of tasks [Dahmann *et al.*, 2008]. The enterprise requires the capabilities to achieve its goals. These capabilities are acquired by the enterprise at different time periods by means of different System increments. The capability phases are time bounded and linked to the organization's vision and goals. The capability roadmap depicts the capability provision at different phases as capability configurations and serves as a tool to analyze capability gaps.

Next steps describe the development of the operational perspective during mission analysis. The Meta-Model elements used to build the operational context are presented by the following figure.

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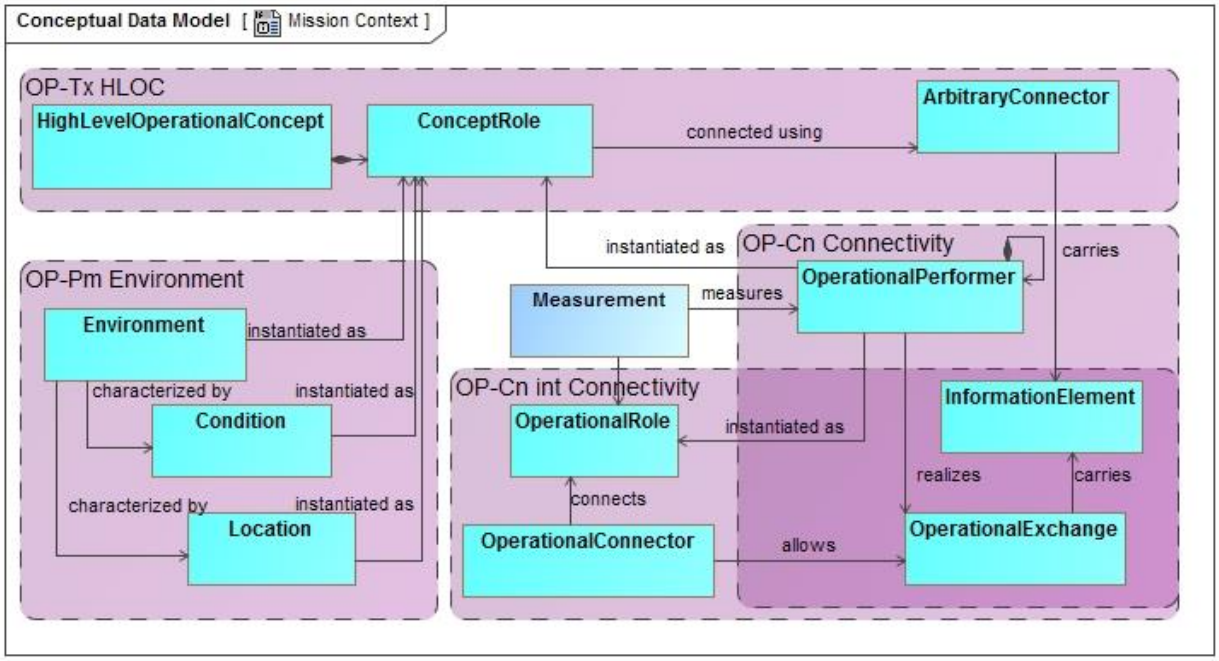

Figure 5. Meta-Model for the Operational context of the mission

STEP#3 - - Identify Operational Missions and Involved Stakeholders related to the defined Capabilities. A Stakeholder is defined as any individual or organization having a legitimate interest in the system [Walden, 2015]. Users, operators, end user organizations, supporters, developers, producers, trainers, maintainers, disposers, acquirers, supplier organizations, parties responsible for external interfacing entities, regulatory bodies are examples of stakeholders. Some stakeholders can have interests that oppose each other or oppose the system. The stakeholders and their concerns are identified using questions like:

- Who will be the users?
- Who impose constraints?
- Who will be impacted?
- At which milestones they intervene?

Missions are related to the tactical, logistical, support operations and maintenance, training, test, and development operations. While analyzing combat systems, the perceived enemy missions are also modelled.

A mission is captured using an Operational Activity element while Stakeholders are instantiated as Operational Performers. An Operational Activity is defined as an activity that captures a logical process, specified independently of how the process is carried out [OMG, 2017].

STEP#4 - Define Mission Contexts Including System of Interest and its environment. The system or mission context includes the System of Interest delineated by its boundary and the surrounding environment. The boundary of a SoS is blurred as assets are dispersed within the environment. The context where a mission scenario takes place is defined by a vignette.

A mission vignette describes the overall environmental factors that may be architecturally significant--that is, they impose a constraint on the architecture that would not exist in the absence of these environmental factors. These factors are related to the geography, organizational structure and mission, as well as strategies, tactics, timing and information on any protagonists.

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The environment is modelled to represent those factors, the external actors and systems interacting with the system of interest. These interactions can be events (e.g. Commands) or flow of material, energy or information. The mission vignette, or the SoS within its context is modelled as an internal connectivity diagram. Environment (e.g. Forrest Fire), Location (e.g. High altitude) and Condition (e.g. High wind velocity) are the elements used to model the environment. All the possible environment conditions are not presented in the following example diagram to keep it simple.

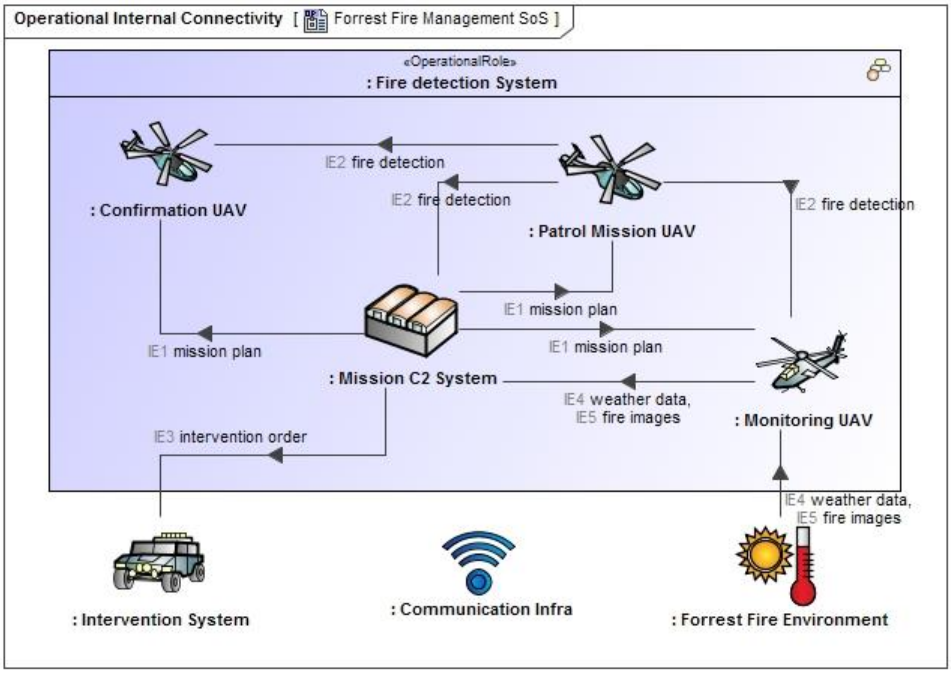

Figure 6. Mission context for the Fire management SoS example

STEP#5 - Develop Mission scenarios & mission success criteria. A mission scenario is a sequence of end-to-end activities and events presented as a series of actions that accomplish the execution of one or more capabilities that the system of interest supports. It describes how these actions are related to each other and what they exchange (see Figure 8 for an example mission scenario). Mission scenarios serve as drivers for developing the architecture and as the basis for test cases during verification. The environment elements from mission vignette can act as participants in a scenario depending on the context.

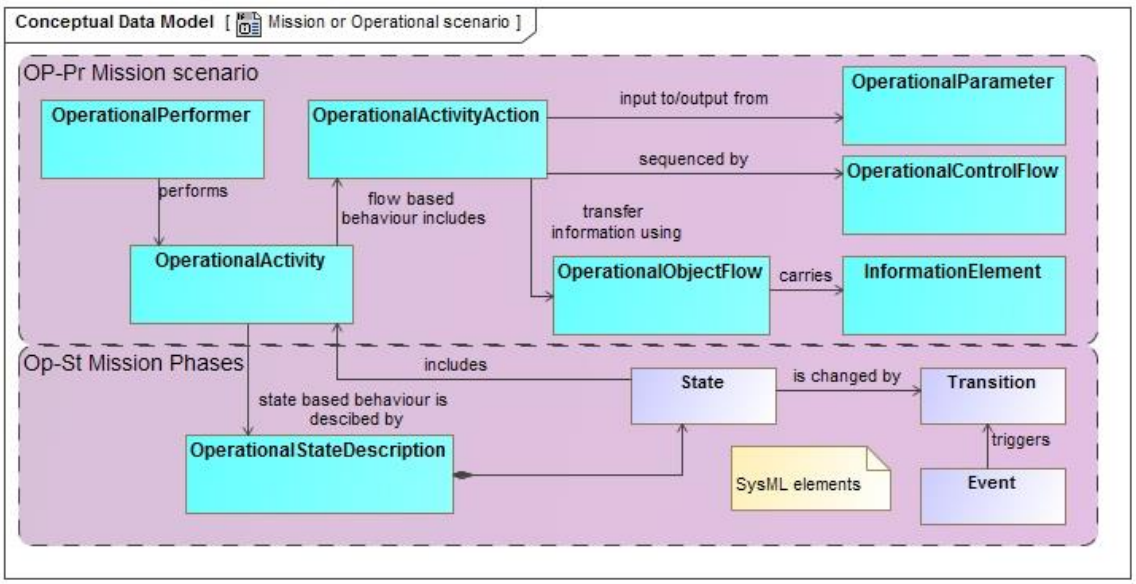

Figure 7. Meta-Model for the Mission/Operational scenario

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The Operational Flow Diagrams are created for each Mission to describe the mission scenarios. The Operational exchanges between the actions are created or reused from the operational context model elements, from STEP#3. The Meta-Model elements used to describe mission scenarios and operational scenarios are depicted within following diagram. The UAF does not provide the time line diagrams, but the Operational Interaction Scenario diagrams can be used to depict time lines with the help of duration constraints.

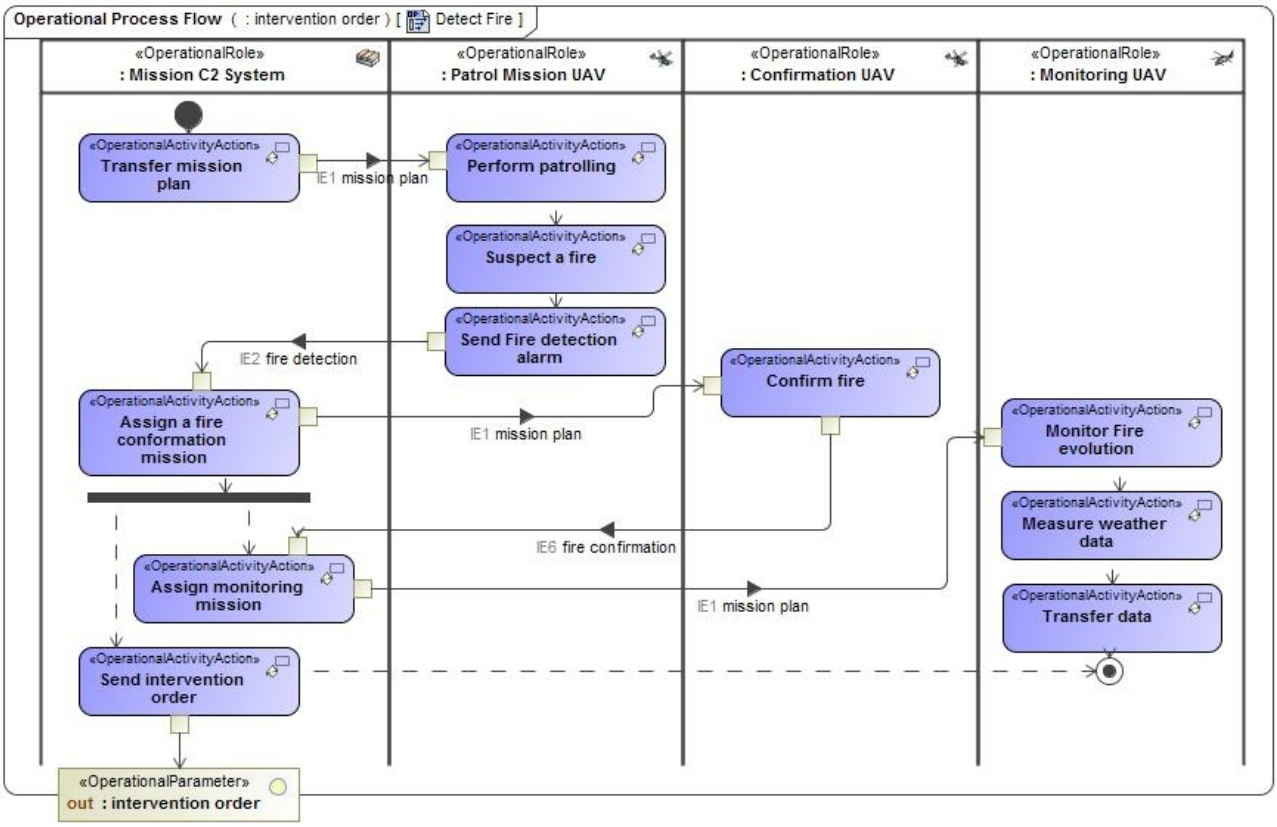

Figure 8. Example Mission scenario

STEP#6 - Define the Mission Requirements & the performances expected by the stakeholders. The mission requirements are either captured or generated from the model using requirement patterns. The requirement is not included as an element of the UAF Meta-model, but the SysML defined Requirement element is used. Model elements used in requirement generation are the Mission scenarios and related environment conditions, Operational exchanges, Constraints and Measurements.

Operational Analysis & Design

The goal of the operational analysis is to define the Operational Concept which is prepared initially to support the concept and development stages of the system life cycle and then maintained throughout the Program to support the production, utilization, support, and retirement stages. The operational concept is defined as the user definition of how a specific system will be utilized within the organization [ANSI/AIAA G-043A-2012].

The Use Case analysis is a term originated from software domain and widely used by system engineers to designate operational analysis. Use Case is defined as a description of the expected use of a system of interest seen by the user's point of view which describes "who" can do "what" with the system of interest.

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The operational analysis is not intended to describe the solution or the functions but the usage of functions offered by the system of interest. The operations performed by the mission participants, identified and modelled within mission scenarios are further analyzed and detailed during operational analysis & design.

STEP#1 - Define Operational Context for the SoI. This activity is performed for each individual system contributing to the SoS, when these individual systems are identified as new or required to be modified. The contexts are modelled for important life cycle stages of the system, similar to the mission context model views. The Operational Performers identified within contexts participate in operational scenarios developed in next step.

STEP#2 - Develop Operational scenarios & measures of effectiveness (MoE). The operational scenario is defined as an imagined sequence of actions/events describing the interaction of the system with its environment and users to achieve a mission or a service. A scenario represents a single path through the use case. So, a use case contains a main flow and other scenarios for each possible variation of flow through the use case (e.g., triggered by options, error conditions, security breaches).

Then the operations are captured using the Operational Activity elements and the scenarios are developed as Operational Flow Diagrams. A Measurement Set which is composed of Measurements representing MoE is attributed to each Operational scenario.

The operational scenarios are complemented by providing operational modes (Operational State Diagram) within which the system performs specific scenarios. Operational Mode is defined as an operational situation or configuration of a system characterized by its active functions.

STEP#3 - Perform a trade study of the alternatives. The tradeoff methodology is applied within each main activity when alternatives exist. The methodology includes the following steps:

- Establish the Study/problem Statement;
- Review inputs, requirements, constraints and assumptions;
- Develop and quantify criteria including weights (relative importance);
- Develop/refine alternative models and measurements of merit;
- Evaluate alternatives and analyze results;
- Document process and results.

STEP#4 - Capture/Generate Stakeholder requirements. The stakeholder requirements are formal structured statements that can be verified and validated. The needs are often capabilities or things that are lacking but wanted or desired by one or more stakeholders, which are formulated as requirements.

Model elements used for Stakeholder requirement generation are Operational scenarios, Operational exchanges, Operational constraints, Conditions and Measurements.

STEP#5 - Trace Operational scenarios to requirements. Mission scenarios are traced to Mission Requirements while other Operational scenarios are traced to the other stakeholder requirements.

STEP#6 – Perform early validation using models. The models are used for early validation of the operational behavior with the stakeholders. Moreover validation artifacts are generated using models. This step includes:

- verifying the models for correctness by automatic checking against modelling rules & reviews using checklists

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- Developing simulation models and simulate behavior within simulated operational environment to observe performances
- Refine & Validate models with operational experts
- Generate System validation plans from Operational scenarios, validation scenarios and requirements

Functional Analysis & Design

The objective of this activity is to analyze and identify the required functions to be provided by the system to fulfil Operational Activities. The operational scenarios already realized show the usage of functions offered by the system of interest which is seen as a "Black Box". These functions are triggered by the actions performed by the environment and considered as high level system functions. The identification of the high level functions can be considered complete if all the Operational Scenarios are covered. An operational scenario may use several high level functions. The Meta-Model elements used to model functions, functional flows including the function performers (Resource Performer) are presented within following Figure. A Resource Performer is an abstract model element which is instantiated as an Organization, Post, System, or a Resource Artifact.

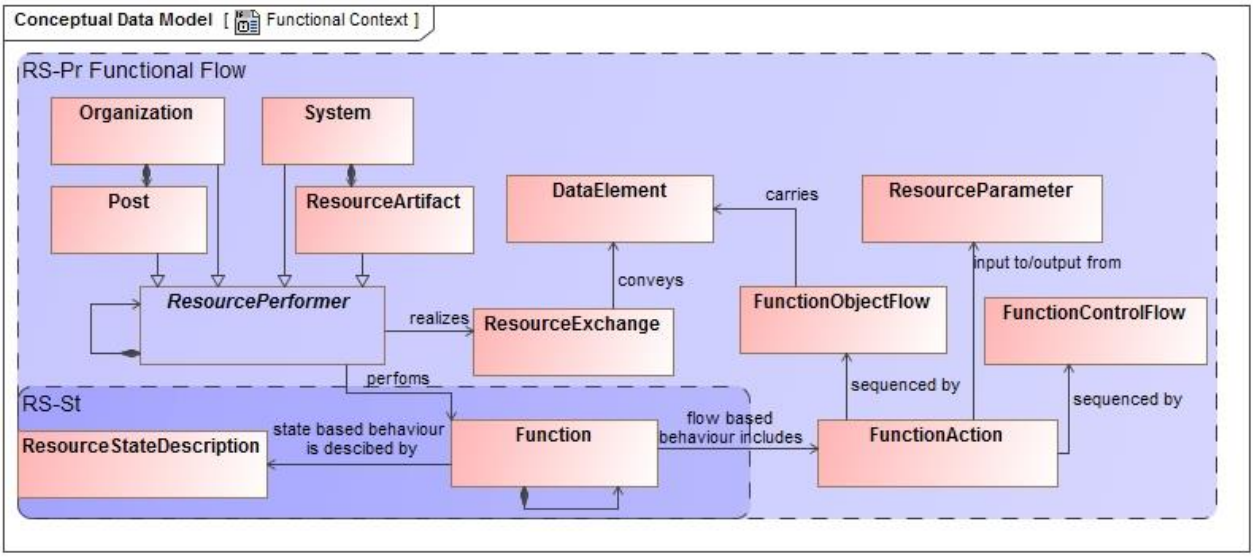

Figure 9. Meta-Model for Functional Behavior

STEP#1 - Identify and decompose Functions. A Function is defined as an action that transforms inputs and generates outputs as materials, energies or information or a combination of them [Faisandier, 2013].The high level functions are decomposed into the low level functions using popular techniques like FAST (Functional Analysis System Technique). Functional decompositions are visualized as Resources Processes diagrams. The best practices used while defining functions are not described within this paper.

STEP#2 - Develop Functional Flows and Measures of Performances (MoP). Functional Flows which are modelled as Resources Process Flow diagrams are initiated by the input coming from the environment. These inputs are modelled as Resource Parameters, while other main model elements used to describe functional flows are, Function Action, Resource Performer, and Data Element. Data Elements are exchanged between functions through Resource Exchanges.

Measurement Set and Measurements representing MoPs and Resource Constraints are attributed to Functional Flows.

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System states and the functions performed within those states are identified at this step and modelled as Resource State diagrams.

STEP#3 - Trace Operational activity to Functions. The coverage of operational scenarios by high level functions is ensured by a traceability matrix between Operational Activities and Functions.

Logical Structure Design

Some system elements are identified during Functional Flow development as Resource Performers. During logical structure design, the structuring of system elements and their interfaces are developed. The functions are allocated to system elements and the interactions between system elements through interfaces are defined. The same Meta-Model elements are used to model Logical and Physical Structures (Figure 8).

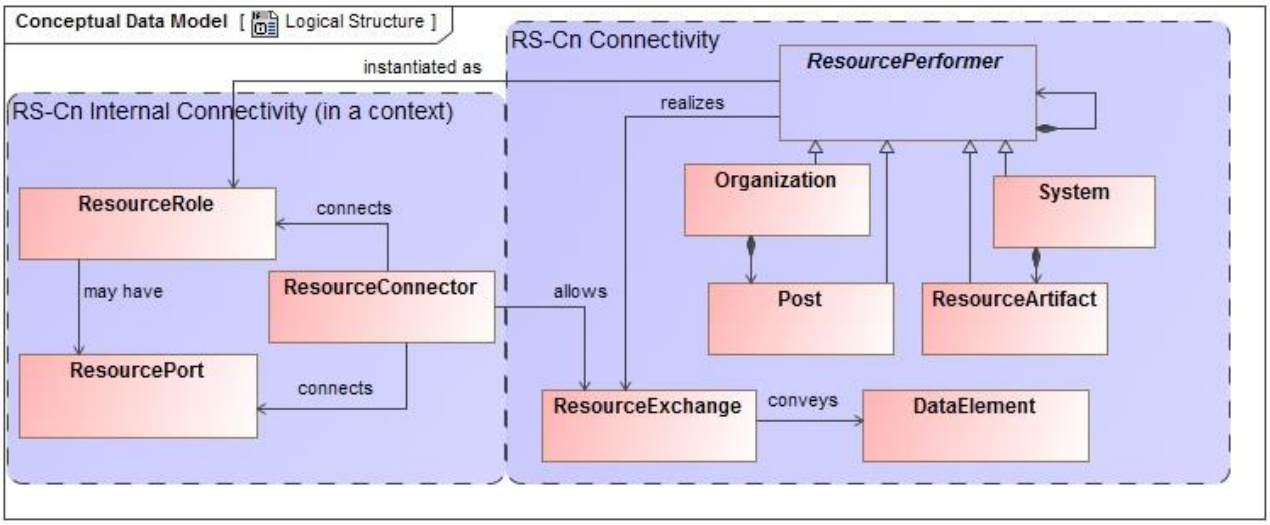

Figure 10. Meta-Model for Logical/Physical Structures

STEP#1 - Realize System decomposition (SBS). The System breakdown structure is realized using model elements “System” and “Resource Artifact”. Resource artifacts represent the leaves of the system tree which are not further decomposed. These structures are modelled as Resource Structure Diagrams.

STEP#2 - Define communications between system elements & logical interfaces. The candidate system structures are defined and modelled as Resources Internal Connectivity diagrams. The interactions at interfaces are described using Resources Interaction Diagrams when needed.

STEP#3 - Realize trade-offs to evaluate alternatives. The trade-off methodology, described under Operational Analysis & Design activity is applied to this step.

STEP#4 – Capture/Generate System Requirements. This step reuse the same mechanism described for requirement generation. The system requirements are generated from Functional Flows, System states, System elements and associated Constraints and Measurements.

STEP#5 - Trace System Requirements to Stakeholder Requirements. The System Requirements are traced to Stakeholder requirements to ensure the completeness and consistency of the model.

STEP#6 - Support V&V activities. The models are used for the verification of functional behavior of the system and to generate verification plans. This step includes:

- Verifying the models for correctness by automatic checking against modelling rules & reviews using checklists;

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- Developing test cases as operational or resource flows, simulating models within simulated operational environment to observe performances;
- Refining & Validating models with operational experts;
- Generating System verification plans from Functional flows, test cases and requirements.

System Physical Design

STEP#1 - Define PBS. The products (leaf elements) from the system breakdown structure are used as inputs to create product breakdown structure which is made of Resource Artifact model element.

STEP#2 - Identify alternatives & Realize trade-offs. The alternative products are identified at this step and trade-offs are realized according to the methodology described earlier.

STEP#3 - Define physical structures and interfaces implementing logical systems. The physical structures are defined and modelled as Resources Internal Connectivity diagrams. The interactions at interfaces are described using Resources Interactions Diagrams when needed.

STEP#4 - Trace logical elements to physical. The logical system elements are traced to physical elements and traceability matrixes are created to analyses completeness.

Table 1: Mapping of main SE data to Meta-Model elements

System engineering data	UAF 1.0
Vision	Enterprise Vision
Goal, Objective	Enterprise Goal
Stakeholder	Operational Performer
Capability	Capability
System Increment (deployment Version)	Capability Configuration
Operational Node (or Entity)	Operational Performer
KPI, MoE, MoP	Measurement
Mission, Operation, Use Case	Operational Activity
Big Picture	High Level Operational Concept
Mission Context	Operational Performer (and Op-Cn int)
Operational Context	Operational Performer (and Op-Cn int)
Function	Function
System/System Element	System, Resource Artefact
System Operator/User	Post, Organisation
Exchange Items	Information Element, Data Element

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Table 2: Mapping of main UBM model artifacts to diagrams

Model Artefact	UAF 1.0	NAF 3.1	NAF V4	SysML
Goals & Capability decompositions	St-Sr	NCV-1 NCV-2	C1 C2	Block Diagram (BDD)
Mission/Operational Contexts	Op-Cn int	NOV-2	L2	Internal Block Diagram (IBD)
Mission Scenario, Operational Scenario	Op-Pr flow	NOV-5	L4	Activity Diagram
Operational Modes	Op-St	NOV-6b	L5	State Machine
Time Lines	Op-Is	NOV-6c	L6	
Measurements/Constraints	Pm-Me	NSV-7	P1	Parametric Diagram
Functional Flow	Rs-Pr	NSV-4	P4	Activity Diagram
System States	Rs-St	NSV-10b	P5	State Machine
SBS/PBS	Rs-Sr	NSV-2	P1	BDD
Logical/Physical Structure	Rs-Cn	NSV-1, NSV-2	P2	IBD

Conclusion

The MBSE method proposed in this paper is applicable to any type of system within the system hierarchy. It is based on the most used elements from the UAF Meta-Model which is itself an industry recognized standard. Tailoring of an architecture framework requires specific skills as well as adding some overhead to a project. Furthermore the systems engineers have a tendency to produce a set of non-related views. Use of this method negates systems engineers and architects from the need to tailor a framework.

Some issues related to the UAF are also identified during methodology development. The choice between the elements of definition and usage, the use of service description elements are some of challenges faced during the methodology development. Service elements are duplicating “Operational” or “Resource” elements depending on the modelling point of view. But some constraints as customer requirements or the practices of systems engineers require the use of service description elements within models.

Due to the experiences in different domains and practices, most engineers think that is not possible to use the same approach for different types of systems (i.e. SoS or a System like Aircraft). This leads to use of a diversity of approaches within the same project which adds complexity and effort to managing models. This is observed within very complex SoS as those SoS are composed of other SoS, distributed service clouds and product systems as aircrafts. The method described in this paper also negates the need to use different Meta-models and approaches for different types of systems. Finally, these advantages lead to the increase in the productivity of the system engineering effort.

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Biography

Lalitha Abhaya is a Model-Based Systems Engineering expert and a project leader in PMT (process methods and tools) at Airbus Defense and Space. She is a MBSE trainer and has been in charge of MBSE training development within Airbus group. She is an INCOSE ESEP and a key author of the ongoing ISO 24641 standard on MBSE. For several years she has been co lead of the AFIS MBSE working group as well as the projects related to the Meta-Models and methodologies within AFIS.

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