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Model-Based Evaluation of the System of Systems Architectures Used to Perform Trade Studies and Sensitivity Analyses

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ABSTRACT Trade studies have become an indispensable engineering activity and are used often in the early stage of system architecture development. Trade studies not only help when choosing the most balanced alternative, but are also essential in highlighting the most influential aspects of the system. Trade studies in highly sophisticated systems are often very complex. Therefore, given these complexities, we proposed a new trade study process for the system of systems architecture developed in Unified Architecture Framework models. This process supports automated methods that allow for greater accuracy, better uncertainty analysis, and accelerated analysis of alternatives. One of the essential and challenging stages of the proposed trade study process is a thorough evaluation of plausible alternatives, referred to as the Deep Check. The goal of this stage is to identify the most balanced alternative by evaluating those that are plausible against established evaluation criteria. This paper introduces a new approach to evaluate the system of systems architectures within a trade study process using automated methods in a model-based system engineering environment. We verified the proposed method by running an experiment on a real-world model to confirm its eligibility.

INDEX TERMS Architecture evaluation, sensitivity analysis, system of systems architecture, trade study, unified architecture framework (UAF).

I. INTRODUCTION

A trade study is an evaluation of alternatives based upon criteria and systematic analysis to select the most balanced alternative to attain the objectives desired. Potential solutions for a trade study are judged by their satisfaction overall with a series of desirable characteristics [2], [3]. In sophisticated systems or system of systems (SoS) design, a trade study is often very complex, with engineering details that approach the actual design process in some areas [4].

Architecture frameworks (AF) and modeling languages help manage the complexity in defining system architectures, particularly if the systems are complex. Several architecture frameworks are used widely for SoS today, such as the NATO Architecture Framework (NAF) [5], [6], Department of Defense Architecture Framework (DoDAF) [7]–[9], or Unified Architecture Framework (UAF) [10]–[13]. However, despite the established standard practices for collecting the data, there is no process that guides the way to perform trade studies.

Given this gap and consistent with the best practices of the existing trade study process, we proposed a new UAF-based trade study process for SoS architecture models [1]. One of the critical stages in the proposed trade study process is to determine the most balanced alternative from a set of alternatives by evaluating the selected alternatives according to established evaluation criteria, referred to as the Deep Check.

Although, trade study methods are well established in system engineering domain, their applicability and automation to SoS architectures described by UAF models in a model-based system engineering (MBSE) environment has not been extensively studied. In addition, as digitalization accelerates and the number of organizations using MBSE increases, there is a lack of science-based analytical methods that can be applied, especially in the MBSE environment [14], [15].

In this paper, we propose a new approach to comprehensively evaluate potential SoS architectures and to perform sensitivity analysis, which is essential for determining

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the robustness of the alternatives. Combining SoS architectures evaluation and sensitivity analysis with MBSE and the fundamental subset for executable UML models (fUML) standard [16] allows us to identify the most balancing SoS architecture, as well as speed up the analysis. This approach is one of the key components of our long-term goal of supporting automated trade study analysis for the SoS architectures. We aim to provide model quality checks, automated methods and techniques, which, along with UAF models, automate and accelerate the analysis of trade study in a MBSE environment.

The proposed approach includes four main components: (1) identification of required data to evaluate alternative SoS architectures; (2) an extension of UAF domain metamodel; (3) the fUML-based algorithm to evaluate SoS architectures according to the selection criteria; (4) the fUML-based algorithm to perform a sensitivity analysis.

The structure of the paper is as follows: Section 2 presents a literature review of related works; Section 3 presents the proposed evaluation approach of SoS architectures; Section 4 describes the experimental evaluation and application of the approach proposed, and Section 5 provides the results and conclusions.

II. LITERATURE REVIEW

This section includes three parts. The first provides an overview of SoS within UAF, a cross-industries oriented standardized architecture framework. The second reviews the architecture evaluation methods used with the trade study process, while the third presents an overview of sensitivity analysis methods.

A. SYSTEM OF SYSTEMS ARCHITECTURE WITHIN UAF

The SoS is a set or arrangement of systems that interact to provide a unique capability that none of the constituent systems can accomplish on its own [17]. While the individual systems that constitute the SoS can be very different and act independently, their interaction reveals important new features. The synergy required between the systems allows a new way of thinking to address critical challenges in which the main determining force is the interaction of technology, policy, and economics [18]–[21]. Organizing and managing information in an SoS is often very complex. In this case, AF helps control highly complex system designs.

DoDAF, MODAF, and NAF are standardized AF for defense architectures that use a standard modeling language, known as the Unified Profile for DoDAF and MODAF (UPDM) [10], [22], [23]. Although they were created originally for military systems, they are used commonly in the private, public, and nonprofit sectors worldwide [24]. In addition, frameworks are designed to support trade studies at different layers (Fig. 1): Operational scenarios can be traded-off against capability requirements, and resources can be traded-off against both operational scenarios and capability requirements [23], [25], [26].

However, to respond to industry demand and address specific AF problems, a new AF referred to as the Unified Architecture System (UAF) has been introduced [27]. The UAF combines the DoDAF and MODAF principles and uses the System Modeling Language (SysML) as a core mechanism. The final version of the UAF 1.0 specification was published in November 2017 [28]. UAF has become a prominent upgrade with both the U.S. Department of Defense (DoD) and commercial organizations. Unlike DoDAF, MODAF, and NAF, UAF is cross-industries oriented.

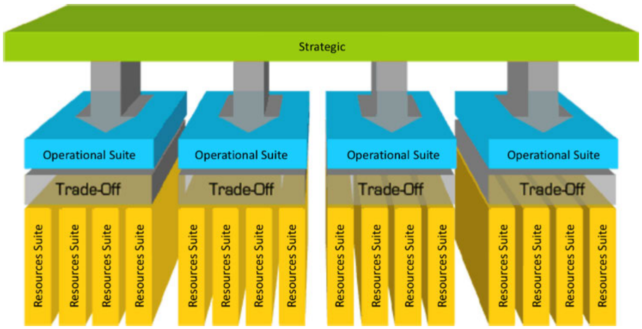


FIGURE 1. Architecture frameworks abstraction layers in the context of the trade study process [1].

DoD research projects that have used SoS modeling revealed that the UAF eliminates the limitations in solving problems [29]. Further, [30] and [24] describe the way a UAF model can be used to influence continued system engineering efforts significantly. The UAF application is exemplified by a series of representative case studies selected from the literature: Airbus Helicopters [11]; UAF for IoT architectures [12]; Space Situational Awareness system [13], and UAF for security systems [31].

B. ARCHITECTURE EVALUATION METHODS IN THE TRADE STUDY PROCESS

An architecture evaluation is a structured process in which one or more architectures are evaluated and take into account the specified evaluation objectives to ensure that the design is consistent with the quality desired [32], [33]. A trade study in system engineering is an evaluation of alternative system architectures to select the most balanced alternative. The systems engineering community worldwide has acknowledged and uses various architecture evaluation methods currently within the trade study process.

In this section we reviewed the most popular methods such as the Utility Theory (UT), Pugh method, Multivariate analysis (MVA), Analytic Hierarchy Process (AHP). Table 1 summarizes these methods [34]–[43], including their essential features, advantages, and limitations.

In this paper, we choose to perform architecture evaluation using the AHP method. This decision was made for three reasons: (1) it considers the relative priorities of factors or alternatives and represents the best alternative; (2) it provides a simple and very flexible model for a particular problem; (3) it provides high level of rating scale granularity.

TABLE 1. Comparison of architecture evaluation methods.

Criteria	UT	Pugh	MVA	AHP
Rating scale	0 - 1	+; -; S	0 - 1	1/9 - 9
Calculation method	Utility function	Total aggregation	Regression equation	Hybrid aggregation
Uncertainty consideration	Allowed	Not Allowed	Not Allowed	Not Allowed
Easy of understanding results	4	5	2	5
Easy of use	3	5	2	5
Limitations	- Treats uncertainty as objective risk. - Difficult to obtain an accurate utility function for each attribute.	- Low granularity of the pairwise scale. - Wrong expertise and insufficient experience in teams can distort results.	- Complex analysis involving high-level mathematics. - Time-consuming process. - Requires many observations for a large number of variables need to be collected.	- Large number of paired comparisons. - Does not consider the correlation between attributes.

Other methods were not chosen for the following reasons: UT – difficulty in determining the accurate utility function; Pugh – low level of rating scale granularity; MVA – requires a large number of observation tasks.

C. SENSITIVITY ANALYSIS METHODS

When the results of the architecture evaluation are summarized, several alternatives may have similar or even equal scores. In this case, a sensitivity analysis (SA) can be carried out to help select the alternative preferred. As weighting factors and some quantified data may have arbitrary aspects, SA becomes essential [44].

SA is a study of the way input uncertainty affects a model's output response [45]–[47]. SA is used to determine a system outcome's robustness and understand the dependency between variables and their relative influence on the system's performance [48], [49]. If there is a difference in output when an input variable is changed within a certain range, the output is sensitive. If the output does not change appreciably, it is insensitive or robust. The SA methods are divided into two main approaches: local and global.

Local SA is a study that evaluates the sensitivity of a single set of input parameters. The input parameters are changed one at a time, while the other parameters are fixed [50]. The local sensitivity methods include the use of these one-at-a-time (OAT) sensitivity measures: partial derivatives (PD) and sensitivity index (SI). PD can be applied in two ways. The first, the sensitivity measure, is determined by calculating the ratio of the output parameter when the input parameter varies by ±20% [51]. The second, the change in output, is examined as each parameter is increased individually by its standard deviation [52]. Another local method is a sensitivity index Hoffman and Gardner introduced in 1983. This method determines parameter sensitivity by calculating the output percent difference when one input parameter varies from its minimum to maximum value [53].

TABLE 2. Comparison of global sensitivity analysis methods.

Criteria	Sobol	FAST	MPSA	PRCC
Discrete inputs	+	+	+	+
Model independence	+	+	-	-
Non- linear, input-output relationship	+	+	+	+
Non- monotonic input-output relationship	+	+	+	-
Robustness	+	+	+	+
Reproducibility	+	+	+	+
Higher-order interaction of parameters	+	+	-	-
Quantitative measure for ranking	+	+	+	+
Computational efficiency	-	-	+	+

Typically, local sensitivity analysis is used when the model output is related linearly to parameters near a specific nominal value [53]. The limitations of local sensitivity analysis are that it examines only a small part of the design space, so it is impossible to evaluate the simultaneous changes in all model parameters.

Global SA is a study of the way model output uncertainties can be divided into different sources of model input uncertainty [54], [55]. In a global sensitivity analysis, all parameters are changed simultaneously throughout the entire parameter space, which allows each parameter's relative contributions, as well as the interactions between parameters, to be evaluated concurrently with the model output variance [50].

There are several methods of global sensitivity analysis, such as the Sobol method, Fourier amplitude sensitivity analysis (FAST), multi-parametric sensitivity analysis (MPSA), and partial rank correlation coefficient (PRCC). Table 2 summarizes these methods [56], [57], [52], including their essential features, advantages, and limitations.

In this paper, we chose to perform the sensitivity analysis in the MBSE using the partial derivatives method of a local sensitivity analysis. This decision was made for two reasons: the model outputs are related linearly to the parameters, and OAT is a very common technique used in the modeling community [58].

III. EVALUATION OF ALTERNATIVE SOS ARCHITECTURES IN THE TRADE STUDY PROCESS

This section includes three parts. The first provides an overview of the UAF-based trade study process and its main activities. The second introduces the method used to evaluate alternative architectures, and also provides the extensions of the UAF domain metamodel required. The third part describes the technique used to conduct a sensitivity analysis in MBSE.

A. BRIEF OVERVIEW OF UAF-BASED TRADE STUDY PROCESS

A new trade study process for the SoS architecture was introduced in [1], which is based strictly upon the principles of the

UAF and is designed to support automated analysis methods. Several problems prompted the emergence of this new process. First, applying the process to MBSE is complex and sometimes requires changes in the process itself. Secondly, existing processes are relatively universal [23], [41] and can be applied to different domains. However, at the same time, they are not focused on any specific problem.

The UAF-based trade study process (Fig. 2) consists of ten main steps and five roles: SoS Engineer; Trade Study Lead; Trade Study Team; Decision Making Authority, and Contractor. Further, the necessary inputs and outputs are provided in each step of the trade study. The process focuses on a trade study when the decision is made to run a competition in the acquisition.

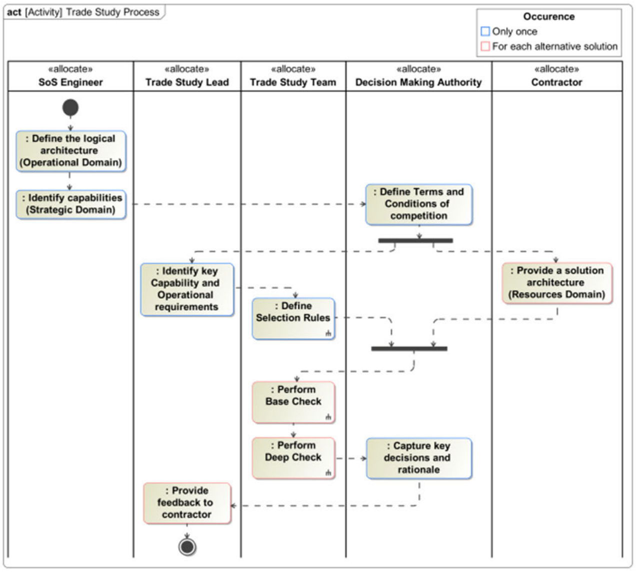


FIGURE 2. Trade study process [1].

The process begins by modeling the UAF Operational Domain (Op) and Strategic Domain (St) views to define the logical architecture and identify capabilities with specific functions and implementations. If it is decided to organize a competition in the acquisition, then the competition's conditions must be defined. This step may be skipped if the acquisition is not made. However, it is recommended to describe the way a specific trade study will be conducted and how the selection of the alternative architecture preferred will be determined.

Typically, the solution preferred encompasses many criteria that must be met to achieve the functionality intended. However, because of limited resources and time, it is necessary to determine the crucial requirements to ensure that the solution preferred includes the most critical functions. After this step, the selection rules are defined, and evaluation criteria with their level of importance and measurement methods are established. In the meantime, contractors model the Resources Domain (Rs) views of UAF to provide a solution architecture. Once they have submitted their solutions, the investigation phase of the architectures begins with the Base Check and Deep Check.

The purpose of the Base Check is to determine the alternative solutions' quality. This stage is intended to narrow the set of solutions submitted so that only plausible alternatives of sufficient quality are selected. Article [59] introduces a set of UAF-based validation rules together with automated methods that apply to the initial architecture evaluation.

The Deep Check stage (Fig. 3) is intended to evaluate the alternatives selected against the established selection criteria to identify the most preferable alternative. Once potential solutions are judged according to their overall satisfaction of a series of desirable characteristics, the score for each alternative overall should be calculated. Sometimes, several alternatives can have similar or even equal scores. In this case, a sensitivity analysis is carried out to facilitate the choice of the alternative preferred. When the preferred solution is selected, a sanity check is recommended. This is an engineering judgment to ensure that the right decision is made.

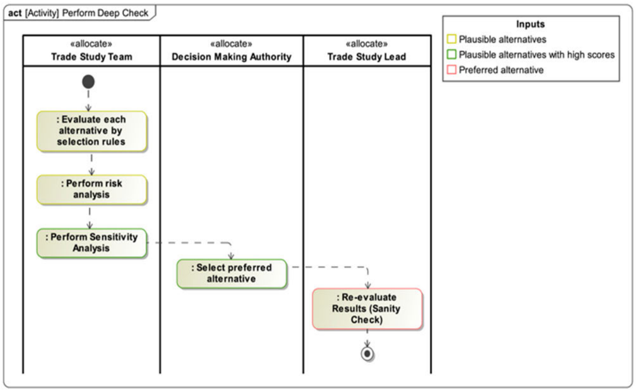


FIGURE 3. Trade study process – deep check [1].

Finally, based upon the results, the decision-making authority selects the most appropriate alternative that meets the critical requirements. Contractors should be informed of the status of the competition.

B. TRADE STUDY ANALYSIS IN MBSE

This section consists of two parts. The first provides a set of data needed to conduct a trade study, as well as the UAF domain metamodel extensions. The second describes the evaluation algorithm designed according to MBSE principles.

1) INITIAL DATA FOR THE EVALUATION OF ALTERNATIVE SOS ARCHITECTURES

To begin an evaluation of alternative SoS architectures, it is necessary to ensure first that all required data are specified and available. The following list provides the set of data that should be prepared before architectures are evaluated (Fig. 4):

- Selection criteria with specified importance level
- Desired architecture with limiting values of criteria (optional)
- Weighting factors
- The set of configurations achieved

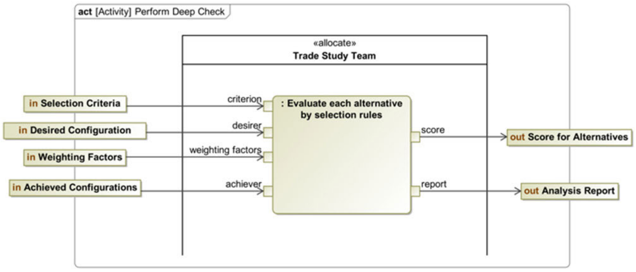


FIGURE 4. Initial data for the evaluation of alternatives.

Selection criteria: Measures of effectiveness (moe) are measures designed to correspond to the accomplishment of mission objectives and achievement of desired results [60]. They quantify the results a system obtained and can be used as criteria in a trade study. The criteria define the critical measurements that an ideal alternative architecture must have.

From the UAF perspective: CapabiltityConfiguration contains a set of *measurements* that reflect a particular *Capability*'s moe. *CapabiltityConfiguration* is indicated to be able to meet a particular *Capability* using the *Exhibits* relation. The *Criterion* is the stereotype introduced that extends the UAF domain metamodel (Fig. 5). The *Criterion* stereotype is applied to *measurement* to indicate that a particular *measurement* will be used as a criterion in a trade study. The *target* attribute of the *Criterion* stereotype is used to determine whether the higher or lower value of a particular criterion is the best.

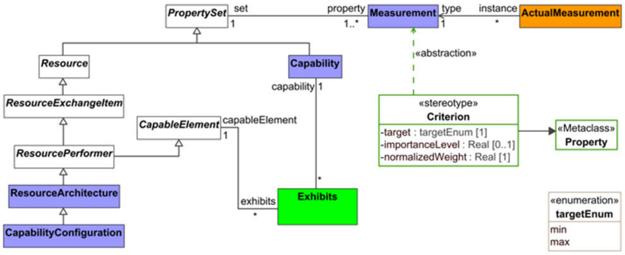


FIGURE 5. Extended UAF domain metamodel with criterion stereotype.

Configuration desired within limiting values of criteria: The configuration desired corresponds to the accomplishment of mission objectives and the achievement of the results desired. It contains measurements with the desired values that the preferred system has to obtain. These desired values can be used as limiting values of criteria.

Some criteria may have a defined specific value or potential ranges of value that must be met. Such criteria are very sensitive in most cases, so it is important to ensure that alternative architectures meet the set threshold. Otherwise, the alternative is excluded from the set of alternatives compared to find the best alternative, as these limit values are unsatisfactory.

From the UAF perspective: FieldedCapability typed by a *CapabilityConfiguration* defines the *measurement* values desired. *FieldedCapability* is indicated as the results of *Capability* desired using the *DesiredEffect* relation (Fig. 6).

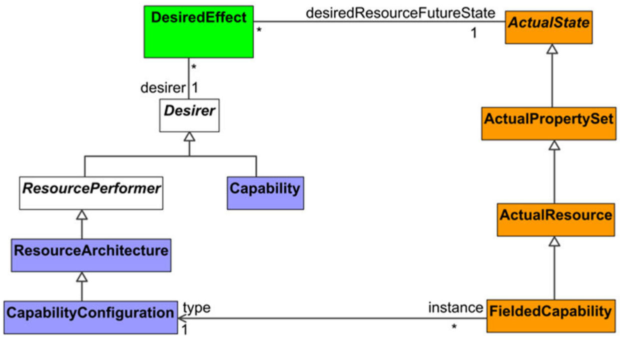


FIGURE 6. UAF domain metamodel part of defining configuration desired [61].

Weighting factors: Once a set of criteria is established, the weighting factors for each criterion are assigned according to each criterion's relative importance. Weights determine how strongly a criterion contributes to the score overall. There are several ways to determine the level of importance: linear, pairwise, and AHP.

Linear: The level of importance is assigned to each criterion using a predefined scale (e.g., a scale of one to five, where one is the least important and five is the most important). The importance scale can be selected freely. When importance levels are established, the values are normalized using (1) so that the sum of the importance levels is equal to 1. Normalized values become weighting factors.

$$n_i = \frac{v_i}{\sum v} \tag{1}$$

where:

n_i – normalized value of the i^{th}

v_i – i^{th} value

Σv – sum of every criterion

Pairwise: Pairwise comparison compares candidates in pairs to judge which of the candidates is preferred [62]. The pairwise weighting method begins by constructing a matrix in which the criteria are presented in rows and columns.

There are two ways to fill in a matrix: specifying only a more important criterion or specifying a more important criterion and identifying its level of importance (Table 3). The second method provides a more accurate way to determine which criterion is more important and how important it is.

TABLE 3. The example scale for comparison [63].

Value	Description
1	Equal importance
3	Moderately importance
5	Strong or essential importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

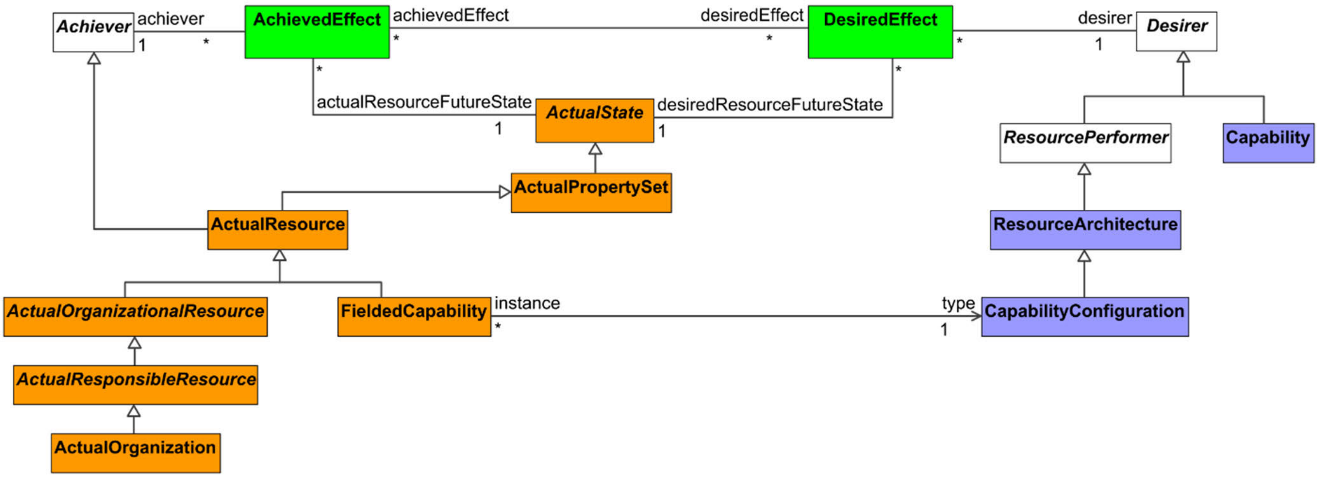


FIGURE 7. **UAF domain metamodel part of defining configuration achieved [61].**

After filling in the pairwise matrix, the weighting factors are calculated. First, (2) is used to calculate the geometric mean of each row in the matrix. Next, the values are normalized using (1).

$$\mu G = \sqrt[n]{\prod\nolimits_{i=1}^{n} x_i} \qquad (2)$$

where:

μG – geometric mean
n – number of criteria in a row
xi – i$^{\text{th}}$ criterion value
i – criterion value index

AHP: AHP is a multi-attribute method that provides proven means to identify and weigh selection criteria and analyze data [41], [42]. AHP begins by constructing a pairwise matrix and setting criteria priorities (Table 3). Once the matrix is complete, each column entry is divided by the sum of the column to obtain a normalized result. Lastly, each row of the resulting matrix is summed and then normalized using (1) to obtain the final weighting factors.

From the UAF perspective: The *Criterion* stereotype has attributes (Fig. 5): *importanceLevel* and *normalizedWeight*. The *importanceLevel* attribute is used to determine a criterion's importance when determined by the linear method. The *normalizedWeight* attribute is used to store values of normalized criteria that are calculated using (1).

Configurations achieved: The configuration achieved reflects the actual resource that can deliver the configuration desired, and contains measurements with their actual values. Contractors have to provide all specified measurements using formal techniques, such as simulation, mathematical calculations, and various analyses.

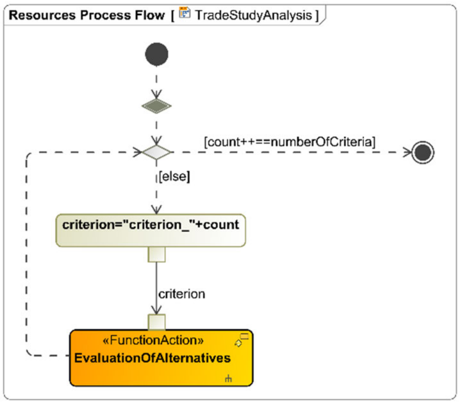


FIGURE 8. **"TradeStudyAnalysis" resource process flow diagram.**

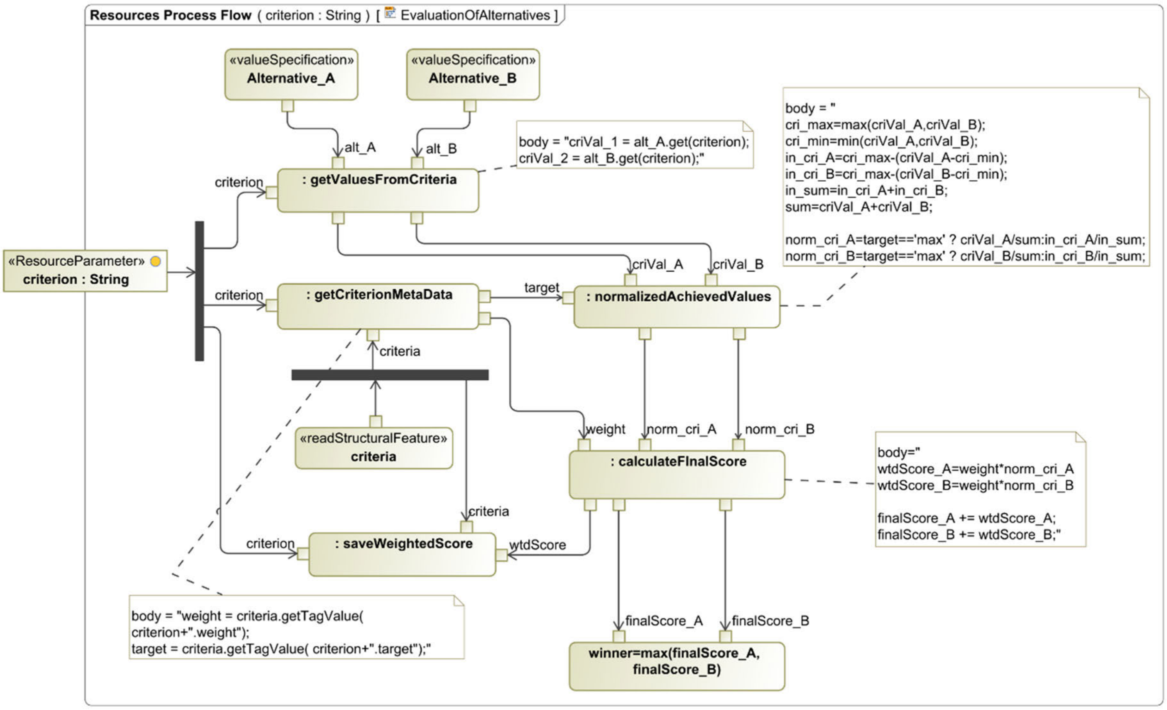
The set of configurations achieved is a filtered set of architectures the contractors provided. The selection of plausible architectures excludes alternative architectures that are of poor quality or do not meet critical requirements. Because of the architecture's insufficient quality, further analysis may lead to misleading conclusions.

Each architecture's quality is determined by running a set of predefined rules introduced in [59]. Rules verify the existence of the required traceability links between three domains: Strategic, Operational, and Resources [59]. The validation-based metric definition method allows these rules to be executed and sets the architecture's quality index automatically.

From the UAF perspective: FieldedCapability typed by a *CapabilityConfiguration* defines the *measurement* values obtained. *FieldedCapability* is indicated as the architecture of *ActualOrganization* achieved using the *AchievedEffect* relation (Fig. 7). *AchievedEffect* is linked within *DesiredEffect*.

2) EVALUATION ALGORITHM FOR TRADE STUDY ANALYSIS

A trade study is an iterative analysis in which the scores of each pair of criteria and the values of the alternative obtained are calculated separately.



```
body = "criVal_1 = alt_A.get(criterion);
criVal_2 = alt_B.get(criterion);"
```

```
body = "
cri_max=max(criVal_A,criVal_B);
cri_min=min(criVal_A,criVal_B);
in_cri_A=cri_max-(criVal_A-cri_min);
in_cri_B=cri_max-(criVal_B-cri_min);
in_sum=in_cri_A+in_cri_B;
sum=criVal_A+criVal_B;

norm_cri_A=target=='max' ? criVal_A/sum:in_cri_A/in_sum;
norm_cri_B=target=='max' ? criVal_B/sum:in_cri_B/in_sum;
```

```
body="
wtdScore_A=weight*norm_cri_A
wtdScore_B=weight*norm_cri_B

finalScore_A += wtdScore_A;
finalScore_B += wtdScore_B;"
```

```
body = "weight = criteria.getTagValue(
criterion+".weight");
target = criteria.getTagValue( criterion+".target");"
```

FIGURE 9. **"EvaluationOfAlternatives" resource process flow diagram.**

The number of iterations depends upon the number of criteria (Fig. 8).

Fig. 9 illustrates the algorithm used to evaluate alternative architectures and find the "winning" alternative. The evaluation begins by collecting the values obtained, criteria, weights, and target values to calculate each alternative's final score.

When the data required are collected, the values obtained are normalized according to the criterion. Normalization calculation varies depending upon the target value given by the criterion: min or max. If a criterion specifies a maximum target, normalization is calculated according to (1). If a criterion specifies a minimum target, the intermediate inverse value is calculated first using (3) and then normalized according to (1).

$$V_{invr} = V_{max} - (V_{actual} - V_{min}) \tag{3}$$

where:

V_{invr} – Inversed value
V_{min}– Minimum achieved value of alternative
V_{max}– Maximum achieved value of alternative
V_{actual} – Achieved value of alternative

The next step is to calculate the weighted score. This is calculated by multiplying the normalized alternative value by the relevant criterion's weighting factor (4).

$$WS = \prod_{i=1} x_i y_i \tag{4}$$

where:

WS – Weighted score
x_i– i^{th} criterion normalized weighting factor
y_i– i^{th} alternative normalized valu

Then, the score overall is calculated by summing the weighted scores for each alternative (5). Optionally, the weighted score can be converted to a scale of 100 to highlight the alternatives that have scored the most points. The highest scoring alternative is rated 100, and all other alternatives have a correspondingly lower score.

$$S = \sum_{i=1}^{n} x_i \tag{5}$$

where:

S – Sum of weighted scores per alternative
x_i– i^{th} criterion weighted scor
n – Number of criteri

Finally, all scores are compared and the alternative with the highest score is chosen as the "winning" alternative architecture. However, the scores should be reviewed and if there are very similar results compared to the winning alternative, a sensitivity analysis should be carried out.

C. SENSITIVITY ANALYSIS

In summarizing the trade study analysis results, several alternatives' scores may be found to be similar or even the same. To facilitate selecting the alternative architecture preferred, a sensitivity analysis should be carried out. During the analysis, the values obtained are modified to see how sensitive the results are to the changed values. This allows the criteria that are most sensitive to be determined and then compared to the values of those criteria met to choose the best alternative.

Fig. 10 and 11 show the design of the one-at-a-time (OAT) sensitivity analysis algorithm in the MBSE. The OAT method evaluates changes in model output based upon input changes for a single parameter. The input parameters are changed one at a time while the other parameters are held constant.

The value of a particular alternative obtained is modified by a specified variable (e.g., +–20%), and then the recalculated value is normalized according to the criterion. The final score is then recalculated by replacing the recalculated value of a specific criterion.

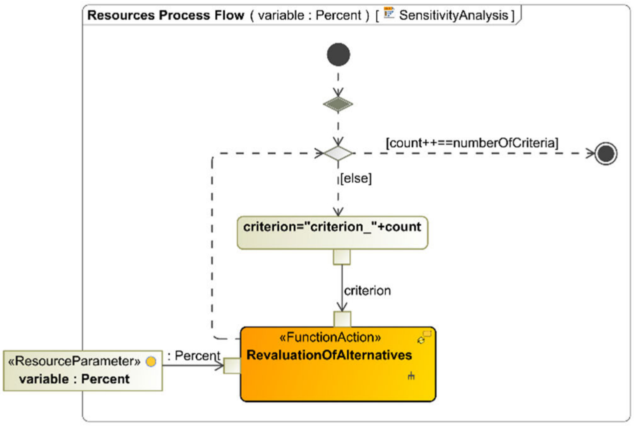


FIGURE 10. "SensitivityAnalysis" resource process flow diagram.

Equation (6) is used to calculate how sensitive the results are to changes in the values obtained. The higher the result, the more sensitive the criterion.

$$Sens_i = \frac{\Delta Y}{\Delta X_i} \tag{6}$$

where:

Sens – sensitivity index

Y – total score

x_i–i^{th} achieved value

Sensitivity analysis provides a list of sorted criteria based upon the sensitivity index. The sensitivity of the criteria for different alternatives may vary because of differences in the value obtained.

IV. EXPERIMENTAL EVALUATION

To confirm the suitability of the proposed trade study approach, it was adapted to a project based upon an industrial example of an electric road [24], [64], [65]. We used the Magic Systems of Systems Architecture (MSoSA) CASE tool to conduct the experimental evaluation.

The primary goal of the trade study example was to select the most balanced alternative among three possible alternatives in the electric road configuration. To conduct a trade study, the selection criteria must be defined first. Selection criteria are specified by applying the Criterion stereotype to the measurements of the *CapabilityConfiguration* (Fig. 12).

In addition, for each criterion identified, the target attribute of the Criterion stereotype is specified. The target value indicates whether the lower, higher, or exact value is the best value for the selection criteria.

Some selection criteria may define values or ranges that the alternatives being evaluated should meet. To determine the specific limiting value for the selection criterion, the configuration desired with its specified limiting values is defined (Fig. 12). In addition, the criteria that determine the limiting values satisfy the system requirements that refine the configuration desired. This ensures that there are traceability links between requirements, measurements, and the configuration desired.

Once a set of criteria with limiting values is established, the weighting factors for each criterion are assigned according to each criterion's relative importance. In this case study, the AHP method was applied to calculate the criteria's weighting factors, as it is used widely in MCDA. Thus, a pairwise matrix was constructed and each criterion's level of importance was determined by judging the criteria pairs (Table 4). The criteria in Table 4 are listed in the same order as in the "Total Swedish ER road configuration" *Capability-Configuration* (Fig. 12).

TABLE 4. Pairwise matrix of electric road trade study.

#	1	2	3	4	5	6	7	8	9	10	11
1	1	6.00	0.12	0.12	3.00	0.25	0.12	0.14	0.20	0.50	1.00
2	0.17	1	0.11	0.11	0.25	0.12	0.11	0.12	0.12	0.12	0.14
3	8.00	9.00	1	1.00	6.00	3.00	0.33	3.00	4.00	5.00	4.00
4	8.00	9.00	1.00	1	4.00	4.00	0.50	1.00	4.00	4.00	4.00
5	0.33	4.00	0.17	0.25	1	0.17	0.12	0.12	0.17	0.17	0.17
6	4.00	8.00	0.33	0.25	6.00	1	0.20	0.20	1.00	4.00	1.00
7	8.00	9.00	3.00	2.00	8.00	5.00	1	3.00	7.00	7.00	5.00
8	7.00	8.00	0.33	1.00	8.00	5.00	0.33	1	4.00	4.00	3.00
9	5.00	8.00	0.25	0.25	6.00	1.00	0.14	0.25	1	2.00	0.50
10	2.00	8.00	0.20	0.25	6.00	0.25	0.14	0.25	0.50	1	0.25
11	1.00	7.00	0.25	0.25	6.00	1.00	0.20	0.33	2.00	2.00	1
Total	**44.50**	**77.00**	**6.76**	**6.48**	**54.25**	**20.79**	**3.19**	**9.41**	**23.99**	**29.79**	**20.06**

The next step is to normalize the weights. First, each column entry is divided by the sum of the column to obtain a normalized result (Table 5). Then, each row of the resulting matrix is summed. Finally, the sums of the criteria are normalized to obtain the final weighting factor. Equations (7) and (8) show the weight normalization of the "electric road noise disturbance" criterion.

$$n_1 = \frac{v_1}{\sum_{i=1}^{1} v_i} = \frac{1}{44.5} = 0.02 \tag{7}$$

$$nw_1 = \frac{trv_1}{\sum_{i=1}^{11} trv_i} = \frac{0.33}{11} = 0.0301 \tag{8}$$

where:

n_1 – 1st criterion normalized value by column

nw_1 – 1st normalized weighting factor

trv_1 – 1st total rows values

A set of configurations obtained that the trade study identified as alternatives was associated with the "Electric Road Installer" ActualOrganization using the AchievedEffect relation (Fig. 13). In addition, the configurations obtained (Alternative_A, Alternative_B, Alternative_C) were related to the expected configuration desired by specifying the achievedEffect tag of the DesiredEffect relation.

To automize the trade study, we executed a model that normalizes the values obtained, and calculates each alternative's weighted score and final score. The following calculations

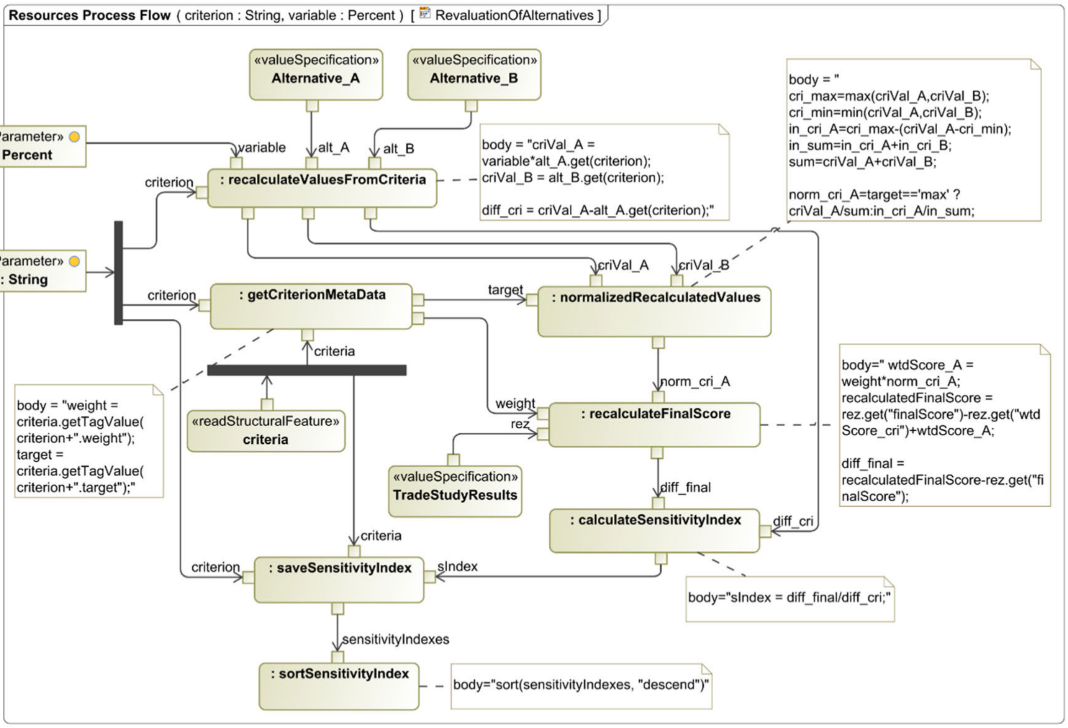


FIGURE 11. "RevaluationOfAlternatives" resource process flow diagram.

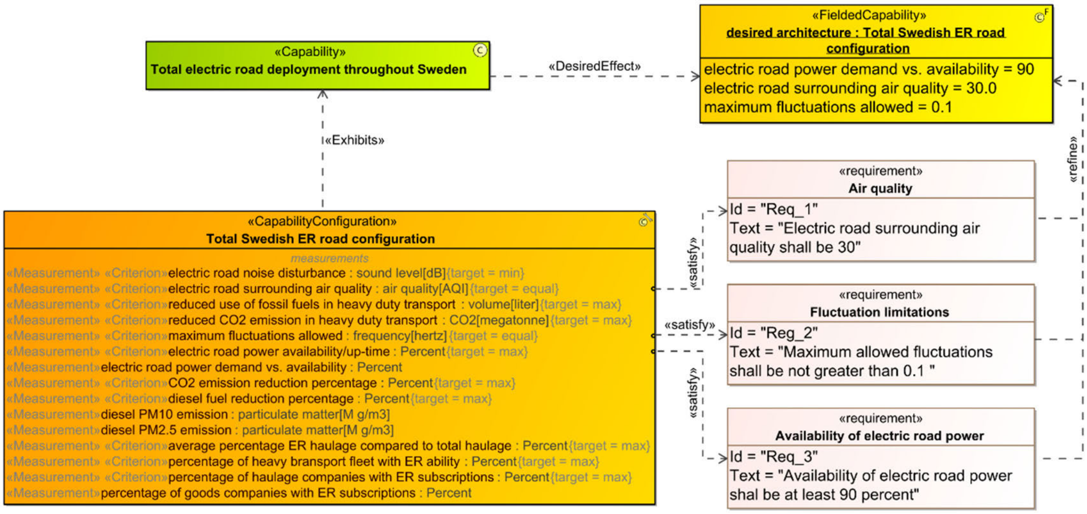


FIGURE 12. Desired configuration with limiting values of criteria.

were performed by running the model using the algorithm shown in Fig. 9.

First, the values of each configuration obtained were normalized according to the criterion. Normalization calculation varies depending upon the *target* value given by the criterion: *min* or *max*. Equation (9) shows Alternative A normalization of the "reduced use of fossil fuels in heavy duty transport" criterion for which the *target* was *max*.

$$n_3 = \frac{v_3}{\sum_{i=1}^{3} v_i} = \frac{240000}{240000 + 220000 + 190000} = 0.369 \quad (9)$$

Table 6 shows the Alternative A normalization of the "electric road noise disturbance" criterion for which the target was *min*.

The next step is to calculate the weighted score (Table 7). This is calculated by multiplying the normalized alternative values by the weighting factor of the relevant criteria (4). Finally, the score overall is calculated by summing the weighted scores for each alternative using (5).

Figure 14 shows the results that is filled in after the trade study analysis simulation was completed. The Score column shows the score of the "winning" alternative overall. The Winner column indicates the alternative that has achieved the

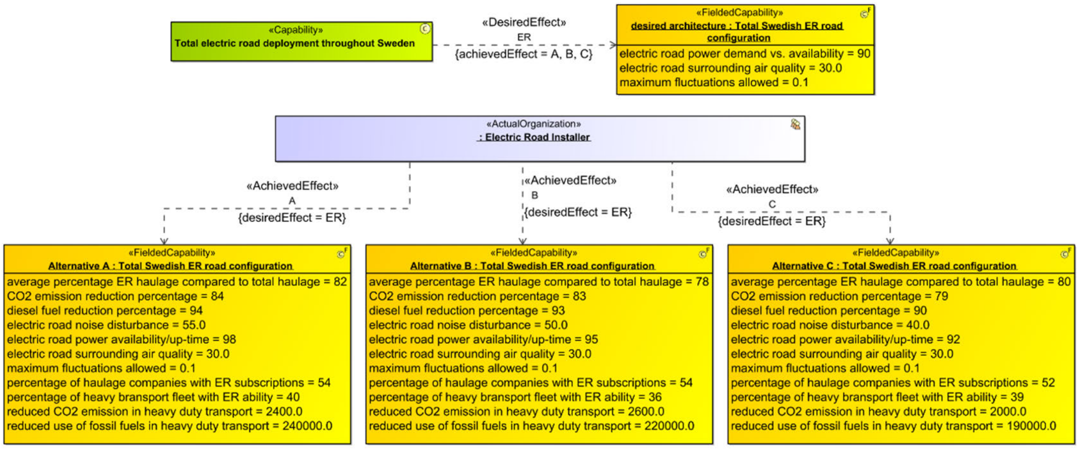
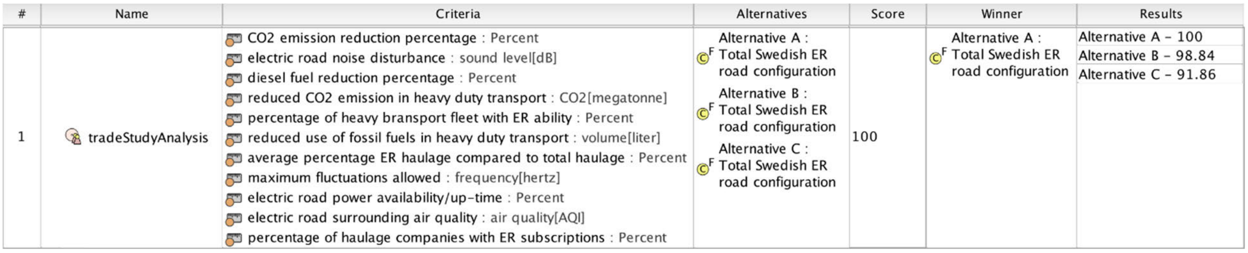


FIGURE 13. Achieved configurations of trade study.



#	Name	Criteria	Alternatives	Score	Winner	Results
1	tradeStudyAnalysis	CO2 emission reduction percentage : Percent electric road noise disturbance : sound level[dB] diesel fuel reduction percentage : Percent reduced CO2 emission in heavy duty transport : CO2[megatonne] percentage of heavy bransport fleet with ER ability : Percent reduced use of fossil fuels in heavy duty transport : volume[liter] average percentage ER haulage compared to total haulage : Percent maximum fluctuations allowed : frequency[hertz] electric road power availability/up-time : Percent electric road surrounding air quality : air quality[AQI] percentage of haulage companies with ER subscriptions : Percent	Alternative A : Total Swedish ER road configuration Alternative B : Total Swedish ER road configuration Alternative C : Total Swedish ER road configuration	100	Alternative A : Total Swedish ER road configuration	Alternative A - 100 Alternative B - 98.84 Alternative C - 91.86

FIGURE 14. Results of a trade study analysis in the MSoSA tool.

TABLE 5. Normalized weights of a pairwise matrix using the AHP method.

#	1	2	3	4	5	6	7	8	9	10	11	Total	Weighting factor
1	0.02	0.08	0.02	0.02	0.06	0.01	0.04	0.01	0.01	0.02	0.05	**0.33**	**0.0301**
2	0.00	0.01	0.02	0.02	0.00	0.01	0.03	0.01	0.01	0.00	0.01	**0.12**	**0.0112**
3	0.18	0.12	0.15	0.15	0.11	0.14	0.10	0.32	0.17	0.17	0.20	**1.81**	**0.1645**
4	0.18	0.12	0.15	0.15	0.07	0.19	0.16	0.11	0.17	0.13	0.20	**1.63**	**0.1480**
5	0.01	0.05	0.03	0.04	0.02	0.01	0.04	0.01	0.01	0.01	0.01	**0.22**	**0.0201**
6	0.09	0.10	0.05	0.04	0.11	0.05	0.06	0.02	0.04	0.13	0.05	**0.75**	**0.0681**
7	0.18	0.12	0.44	0.31	0.15	0.24	0.31	0.32	0.29	0.23	0.25	**2.85**	**0.2587**
8	0.16	0.10	0.05	0.15	0.15	0.24	0.10	0.11	0.17	0.13	0.15	**1.51**	**0.1375**
9	0.11	0.10	0.04	0.04	0.11	0.05	0.04	0.03	0.04	0.07	0.02	**0.65**	**0.0595**
10	0.04	0.10	0.03	0.04	0.11	0.01	0.04	0.03	0.02	0.03	0.01	**0.48**	**0.0434**
11	0.02	0.09	0.04	0.04	0.11	0.05	0.06	0.04	0.08	0.07	0.05	**0.65**	**0.0587**
Total												**11.00**	**1.00**

TABLE 6. Normalized weight of minimum criteria "electric road noise disturbance".

	Achieved Value	Inversed Value	Normalized Value
Alternative A	55	40	0.286
Alternative B	50	45	0.321
Alternative C	40	55	0.393
Total		**140**	**1.00**

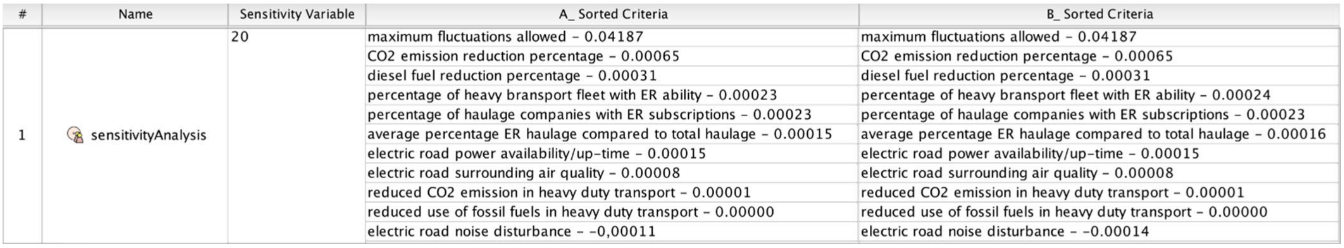
TABLE 7. Score calculation.

#	Weight	Alternative A		Alternative B		Alternative C	
		Nrml. Value	Wtd. Score	Nrml. Value	Wtd. Score	Nrml. Value	Wtd. Score
1	3.01%	0.286	0.009	0.321	0.010	0.393	0.012
2	1.12%	0.333	0.004	0.333	0.004	0.333	0.004
3	16.45%	0.369	0.061	0.338	0.056	0.292	0.048
4	14.80%	0.343	0.051	0.371	0.055	0.286	0.042
5	2.01%	0.333	0.007	0.333	0.007	0.333	0.007
6	6.81%	0.344	0.023	0.333	0.023	0.323	0.022
7	25.87%	0.341	0.088	0.337	0.087	0.321	0.083
8	13.75%	0.339	0.047	0.336	0.046	0.325	0.045
9	5.95%	0.342	0.020	0.325	0.019	0.333	0.020
10	4.34%	0.348	0.015	0.313	0.014	0.339	0.015
11	5.87%	0.338	0.020	0.338	0.020	0.325	0.019
Sum:			**0.344**		**0.340**		**0.316**
Final Score			**100**		**98.84**		**91.86**

highest score among other alternatives. The Results column displays the scores for all alternatives evaluate.

The winner is Alternative A, but Alternative B had a very similar score. A sensitivity analysis was carried to ensure that the alternative that had the highest score was truly the winner. Table 8 presents the sensitivity analysis calculations obtained by running the model with the algorithm introduced in Fig. 11.

Figure 15 shows the sensitivity analysis results when the criteria were increased by 20% and the sensitivity index was calculated according to (6). The sensitivity analysis revealed that the most sensitive criteria were the "maximum fluctuations allowed", "CO2 emission reduction percentage", and "diesel fuel reduction percentage".



#	Name	Sensitivity Variable	A_ Sorted Criteria	B_ Sorted Criteria
1	sensitivityAnalysis	20	maximum fluctuations allowed - 0.04187	maximum fluctuations allowed - 0.04187
			CO2 emission reduction percentage - 0.00065	CO2 emission reduction percentage - 0.00065
			diesel fuel reduction percentage - 0.00031	diesel fuel reduction percentage - 0.00031
			percentage of heavy bransport fleet with ER ability - 0.00023	percentage of heavy bransport fleet with ER ability - 0.00024
			percentage of haulage companies with ER subscriptions - 0.00023	percentage of haulage companies with ER subscriptions - 0.00023
			average percentage ER haulage compared to total haulage - 0.00015	average percentage ER haulage compared to total haulage - 0.00016
			electric road power availability/up-time - 0.00015	electric road power availability/up-time - 0.00015
			electric road surrounding air quality - 0.00008	electric road surrounding air quality - 0.00008
			reduced CO2 emission in heavy duty transport - 0.00001	reduced CO2 emission in heavy duty transport - 0.00001
			reduced use of fossil fuels in heavy duty transport - 0.00000	reduced use of fossil fuels in heavy duty transport - 0.00000
			electric road noise disturbance - -0,00011	electric road noise disturbance - -0.00014

FIGURE 15. **Results of a sensitivity analysis in the MSoSA tool.**

TABLE 8. **Sensitivity index calculation.**

#	Alternative A			Alternative B		
	Δx	ΔY	S index	Δx	ΔY	S index
1	11	-1.17E-03	**-1.06E-04**	10	-1,37E-03	**-1,37E-04**
2	6	4.67E-04	7.78E-05	6	4,67E-04	7,78E-05
3	48000	7.14E-03	1.49E-07	44000	6,90E-03	1,57E-07
4	480	6.24E-03	1.30E-05	520	6,43E-03	1,24E-05
5	0.02	8.37E-04	**4.19E-02**	0.02	8,37E-04	**4,19E-02**
6	19.6	2.88E-03	1.47E-04	19	2,84E-03	1,49E-04
7	16.8	1.09E-02	6.48E-04	16.6	1,08E-02	6,53E-04
8	18.8	5.77E-03	3.07E-04	18.6	5,75E-03	3,09E-04
9	16.4	2.51E-03	1.53E-04	15.6	2.45E-03	1.57E-04
10	8	1.84E-03	2.30E-04	7.2	1.76E-03	2.44E-04
11	10.8	2.46E-03	2.28E-04	10.8	2.46E-03	2.28E-04

The values of the most sensitive criterion met were reviewed, and Alternative A still had higher values for these criteria. Therefore, the final verdict was that Alternative A was the "winner".

V. CONCLUSION

An analysis of architecture evaluation and sensitivity analysis methods led us to choose the AHP method to evaluate alternative system architectures and the partial derivatives method of local sensitivity analysis to determine the most sensitive selection criteria. AHP was chosen for the following reasons: (1) it considers the relative priorities of factors or alternatives and represents the best alternative, and (2) it provides a simple and very flexible model for a particular problem. Meanwhile, the partial derivatives sensitivity method was chosen for the following reasons: (1) our approach covers only model outputs that are related linearly to parameters, and (2) it is powerful and at the same time documented well and adaptable.

To perform an automated trade study analysis in the MBSE environment, first we determined the scope of the required data. Second, we provided specific guidance on UAF modelling, which should be carried out in order to develop an executable model for evaluation. Third, we designed two algorithms according to the semantic rules of fUML standard that allows us to perform analysis using simulation in MBSE environment. The first algorithm is devoted to the evaluation of SoS architectures according to a set of selection criteria. In this algorithm the evaluation is performed iteratively on the basis of the number of selection criteria. During the evaluation, calculations based on AHP method are carried out. The result of this evaluation is that all alternatives are scored according to their compliance with the selection criteria.

The second algorithm is designed to perform sensitivity analysis by allowing the percentage by which the achieved alternative values would be changed to be specified. At the end of the sensitivity analysis, a sorted list of criteria with a sensitivity index is obtained. The sensitivity index allows the criteria that are most sensitive to be determined and then compared the values of those criteria obtained to choose the best alternative. In addition, the UAF domain metamodel is extended to store additional selection criteria data that are used to calculate the final score.

The proposed approach is implemented in the Magic Systems of Systems Architecture CASE tool. To confirm the suitability of the proposed trade study method, it is applied to a real-world industrial UAF-based project. The application of the approach disclosed the following:

1. Complex trade study analysis can be performed in the MBSE environment. However, to automate the analysis, the model should use an executable evaluation algorithm, which accelerates the analysis.
2. The UAF profile lacks of semantical description of how to execute models. Therefore, the fUML standard is essential to automate trade studies and sensitivity analyses.
3. The UAF domain metamodel does not provide the ability to define the importance level of the selection criteria. Therefore, we extended the UAF domain metamodel by the Criterion stereotype. This stereotype has attributes to specify the level of importance, as well as store the values of the normalized criterion. Extensions was proposed to the UAF working group.

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