The Originating Concept: a Foundation for System of Systems Architecting Decision Making

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Abstract - *The paper describes an approach enabling the development of an artefact that can support the analysis of needs and definition of requirements, and make available, to the Architectural Decision-Making process, a "measurement tool" for the evaluation, based on criteria and performance parameters, of the overall effectiveness of the alternative solutions. The approach encourages the active involvement of the main stakeholders enabling the development of a shared understanding and the building of consensus. The information content of the artefact facilitates the generation of diverse alternative solutions and provides also a sound foundation for all the following development activities of the System of Systems.*

Keywords: Systems Architecting, Decision-Making, Needs Analysis

1 Introduction

In the development process of a System of Systems, the term "systems architecting" is frequently used to refer to the activities of the upper left of the "Vee". At the highest level of synthesis, systems architecting can be seen as comprising three main tasks :

- understanding the problem and needs and translating these into clearly defined requirements, criteria and performance parameters
- generating a set of viable solutions, evolving a system concept of operation that satisfies the needs
- select the preferred solution and define its characteristics to enable its development.

It is well known that the fate of a project is strongly dependent on how well these tasks are performed. While the susbequent phases of the system's development (where the focus shift to requirements flow down, interfaces and configuration management, verification, integration and validation) can rely on well defined and proven processes and methods, those initial task are often regarded as to represent the "art" component of systems engineering.

A SoS, due to its scale and complexity, must be able to address a wide range of functional and non-functional needs, many of these conflicting each other. The identification, through extensive trade-offs, of the best value solution requires a sound decision making process.

The intent of the present paper is to describe an approach to carry out the first of above tasks, having the purpose of providing a solid foundation for the decision process, and, at the same time, to the whole development process of the SoS.

Stated in more detail, the proposed approach has the following goals:

- to stimulate, facilitate, and support a pervasive and comprehensive analysis of needs, requirements and constraints,
- to produce a “workable” structured formalization of the high level requirements, facilitating the definition of alternative candidate solutions,
- to define a "Value Model" suitable to provide the reference for the evaluation of alternatives, enabling the selection of the best balanced solution,
- to facilitate the development of a common understanding and consensus with the stakeholders about the high level requirements.

1.1 Understanding Needs

One of the fundamental tasks of Systems Engineers, as identified by Parnell and Driscoll, is to "Convert customer needs to system functions and requirements." [1] To do that, one has to identify "the stakeholders involved with the system throughout its life cycle, and their needs, expectations, and desires" as the definition of the "Stakeholder Requirements Definition Process" of the ISO/IEC 15288 Standard states. [2] This is not an easy job; for starters, also the needs that are clearly stated must be analysed in depth and refined to be put in the form of proper requirements.

Expectations and desires are intrinsically difficult to discover since they are not well perceived, let alone articulated, by the stakeholders. All too often only when they start interacting with the real, delivered, system, users and the other stakeholders discover needs that they could not anticipate, but that now they perceive as severe deficiencies.

Unstated needs may originate either from really unknown needs or, somewhat surprisingly, from characteristics seen as too obvious to be stated. Unstated needs and requirements are a major cause of costly reworks and delays. Beside preventing these problems, the early discovery of unstated requirements can also inspire

innovative ideas and products.

The "Excited Qualities" ("Delighters") defined by the well known Kano model, are, almost by definition, related to unexpressed, latent needs; the ability of the system's designer to anticipate the features that provide an added benefit to the customer, can result in a significant increase of the perceived value of the SoS.

Lastly, the thorough analysis of needs and requirements can help to limit the extent of the so called "requirements volatility", reducing the causes of confusion and dissatisfaction for customers and designers.

The Originating Concept approach is devised to help guarantee that the ensuing project activities are well rooted in a clear and exhaustive understanding of needs, expectations, desires, conditions and constraints.

1.2 Defining Evaluation Criteria

With reference, again, to Parnell and Driscoll, another fundamental task of the Systems Engineer is to "Define system performance measures to guide design synthesis, system validation, and successful system realization." The need to support and strengthen the design process with quantitative measures to make it successful ("how well") and, at the same time, effective ("good enough") is well known to engineers.

The high level needs and requirements often encountered when dealing with complex, large scale SoSs, does not lend themselves, for their very nature, to be easily related to measurable parameters; on the contrary the level of accomplishment of these needs can often be defined only in qualitative terms. The perceived value of a SoS is, to a large extent, related to its ability to address those high level concerns; to properly guide the development of an effective and successful solution to the customer's problem, the designer must have a "measurement tool" able to account also for there aspects.

2 The Originating Concept

The adjective "originating" was chosen to underline that the artefact produced with this approach is intended to be the true origin that underlies the whole system's development; this choice is also intended to differentiate it from the other "concepts" that are widely referenced in the literature (e.g. Operational Concept, Concept of Operations, Con-Ops, etc.). That does no mean that the originating concept approach is a total departure from the concepts at the basis of artefacts like the "Operational Concept Document" as defined by the AIAA "Guide to the Preparation of Operational Concept Documents", or by the IEEE "Guide for Information Technology-System Definition-Concept of Operations Document". On the contrary, it builds on the basis of these authoritative references with the addition of components able to support the decision process for the selection of the preferred architectural solution, and also to provide a guiding reference for the generation of alternative solutions. In fact, the IEEE documents states that "Classifying the desired changes and new features into essential, desirable, and optional categories is important to guide the decision making process during development of the proposed system."[3] The AIAA document suggest to include a subsection to "describe the system's goals and the objectives and expectations for it, quantified where possible, and the key performance attributes for the system." [4] The method to be applied to define and prioritize goals and objective is not, however, dealt in detail by either of the documents.

The Origination Concept approach provides a way to integrate the analysis of mission needs, goals and objectives on one side, with the development of a Value Model that defines their relation and relative importance on the other. This way, not only a better coherence of the end result can be achieved, but also a better overall effectiveness of the process, exploiting the synergies and overlapping existing between the two activities.

2.1 Methods and constructs

The Originating Concept makes use ad integrates some well known methods and constructs. A brief description of these is provided in the following, mainly to highlight the aspects that the approach take advantage of.

2.1.1 Mission Analysis method

The "Mission Analysis" method has been developed by the military "to provide an audit trail from the broadest national objectives down to operational activities at the tactical engagement level".[5] Through a series of subsequent steps, the method leads to the development a hierarchy of objectives linking the high level to the low level ones. The hierarchy structure provides an explicit description of the relations between the objectives. The lower level of the hierarchy contains the "Operational Tasks"; these are defined as: what "force elements are to accomplish in order to achieve an Operational Objective"[5] Operational tasks have associated measures and criteria; measures provide for the quantification of levels of performance, and criteria define acceptable levels of performance.

2.1.2 Value Focused Thinking

Value Focused Thinking (VFT) is a decision making methodology developed by Ralph L. Keeney; he defines the methodology as "a philosophical approach and methodological help to understand and articulate values and to use them to identify decision opportunities and to create alternatives." [6] The methodology is contrasted with the more usual alternative-based approach, that starts with a set of alternatives and then defines the selection criteria. The VFT methodology involves the development of a Value Model comprising two elements:

- The Qualitative Value Model: a structured objectives hierarchy built following a top-down recursive approach.
- The Qualitative Value Model: a means for the evaluation of how well each of the alternative solutions achieves the fundamental objective

The Qualitative Value Model comprises two elements:

- the Objectives Hierarchy
- a set of Value Measures / Measures of Effectiveness

The starting point for the development of the Objectives Hierarchy is the "Overall Fundamental Objective" that defines the highest level goal. It is decomposed into a first layer of objectives; each of these are then decomposed in further layers, until a level is reached where for each objective can be defined one or more metrics (Value Measures/Measures of Effectiveness); these enable the assessment of how well the objective is attained by a specific solution. Building the objectives hierarchy promotes an in-depth analysis of values, since defining lower level objectives add to the definition and understanding of the higher level ones. As the hierarchy defines the relations between objectives at different layers, the attainment of each higher level objective can be evaluated on the basis of the attainment of corresponding lower level ones. This can be carried on down to the lowest level objectives whose attainment can be assessed on the basis of measurable criteria. Sources of goals and objectives can be: approved documents, the actual stakeholders or Subject Matter Experts acting as "surrogates".

To result in a proper Qualitative Value Model, the methodology requires that the decomposition process results in an objective hierarchy that is:

- complete (the objectives and value measures must cover all the aspects needed for the evaluation of the overall objective),
- non-redundant (objectives and value measures on the same layer should not overlap),
- decomposable (the grade attained in a specific value measure must be independent from the grades of all the other measures at the same level),
- operable (understood in the same way by all the concerned parties),
- small in size (easier evaluation of alternatives, focus on most important aspects).

The development process of the Qualitative Value Model helps the "hard thinking" needed to discover and analyse not just needs, but also undesired effects and consequences. The ordered hierarchy building approach greatly facilitates the discovery of hidden objectives and unstated needs. An additional benefit provided by the adoption of the values-first VFT approach is to broaden the range of alternatives considered, thanks to the reduction of the anchoring effect of already identified alternatives usually affecting the alternative-based approach.

The Quantitative Value Model makes the Value Model actionable, providing a means for the evaluation of how well each of the alternative solutions achieves the fundamental objective, elaborated on the basis of the degree to which the alternative solution meets the lowest level objectives of the hierarchy. To this purpose, the Quantitative Value Model complements the objectives hierarchy and Measures of Effectiveness of the Qualitative model with some additional features: Utility Functions, Weights of relative importance, and Mathematical Expression.

The Measures of Effectiveness (MoEs) give a quantitative evaluation of how well each alternative solution attains the lowest level objectives. The performance data of MoEs are measured each with specific units and ranges, so they can not be directly combined.

The Utility Functions first purpose is to transform these data into normalized and dimensionless "utility" figures. Since the utility refers to the value perceived by the stakeholders, a further feature is the ability to take into account their "preferences"; these are usually based not only on objective criteria, but also on subjective, judgmental ones.

The Weights provide the means to prioritize objectives, on the basis of their relative importance for the stakeholders, or their ability to concur to higher level objectives.

Finally, the Mathematical Expression enable the calculation of one overall evaluation figure (Overall Figure of Merit) for each of the alternative solutions.

The method guarantees that all the solution are evaluated in a consistent "fair" way, reducing the effects of the human innate judgmental bias.

A wide choice of methods can be applied to define the elements of the Quantitative Value Model; a large body of literature is available on the topic.

The attainment of a higher level objective is computed combining with the mathematical expression the results of its lower level elements; this is repeated layer by layer from the lowest to the highest.

2.1.3 A triad of constructs: "Rosetta stone"

The main groups of stakeholders involved in the development of a SoS are the customers, the users and the developers. While they are well entitled to hold different perspectives on the SoS, to enable a fruitful cooperation these must be reconciled to provide a common ground of understanding. To that purpose, the Originating Concept approach exploits the affinity between three constructs: Capability, Operational Thread and Use Case.

Capability is a construct coined in the last years by the military to support the Capability Based Planning

approach. It is defined by the "Joint Capabilities Integration and Development System" as: "the ability to achieve a desired effect under specified standards and conditions through combinations of means and ways across the doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) to perform a set of tasks to execute a specified course of action." [7]

The Operational Thread construct is widely used by the military. It is defined by the "NATO Architecture Framework" as: "a set of operational activities, with sequence and timing attributes of the activities, and includes the information needed to accomplish the activities." The same document further elaborates: "A particular operational thread may be used to depict a military capability. In this manner, a capability is defined in terms of the attributes required to accomplish a given mission objective by modelling the set of activities and their attributes. The sequence of activities forms the basis for defining and understanding the many factors that impact on the overall military capability." [8]

The Use Case construct is mostly used for the specification of functional requirements in Software Engineering, but it is also widely applied to the same purpose in Systems Engineering, and to the description of business processes (Business Use Case). One of the most cited definition of the Use Case is the one from Ivar Jacobson: "a sequence of transactions performed by a system, which yields an observable result of value for a particular actor". [9] One of the reason of the effectiveness of the Use Case construct is the combination of the a description using the natural language, with a strong structuration and formalization; the use of natural language allows "non-technical" stakeholders to fully understand and get effectively involved in the definition of the functionalities. On the other hand, just thanks to its structuration and formalization, the resulting information is in a format well suited to be used by the developers as the basis of their activity.

If the three constructs are analysed together, it becomes apparent that they show a strong affinity; more specifically, it can be pointed out that all of them make reference to two main features:

- a desired effect (result, objective)
- a set of tasks (activities,transactions)

On the other hand, the constructs were originated, and are mainly used, in different contexts:

- The Capability belongs mostly to the field of high level planning and acquisition ("customer")
- The Operational Thread is mainly used by operatives: users and Subject Matter Experts.
- The use case one is one of the main components of the "toolbox" of developers.

The conjoined use of the three constructs also helps in "bridging" the divide between the mindsets and languages of the groups, providing for a powerful means of information exchange, knowledge sharing, and consensus building. To state this in a more suggestive way, one can see the three constructs as forming together a sort of "Rosetta Stone" enabling effective communication between users and developers.

It must be noted that, even though two of the constructs are part of the military lexicon, they are suitable to be applied in any operational context, where processes (sequences of actions) are used to produce results.

2.2 Expanded Operational Effectiveness Model

The basic definition of Operational Effectiveness from the DAU Systems Engineering Fundamentals Guide reads: "Operational effectiveness is the overall degree of a system's capability to achieve mission success considering the total operational environment." [10] In a more articulated way, the Defense Acquisition Guidebook [11] defines the "Affordable System Operational Effectiveness" as the combination of Mission Effectiveness with Life Cycle Cost/Total Ownership Cost. Mission Effectiveness is, defined as the combination of Design Effectiveness and Process Efficiency; Design Effectiveness is, finally, defined as the combination of Technical Performance and Supportability. Process Efficiency includes: production maintenance, logistics and operations. Supportability includes: reliability, maintainability, and support features Technical Performance includes functions and performances. This last term refers to the functional needs; all the other needs can be classified as non-functional needs.

The "Expanded" Operational Effectiveness further broadens the scope of the concept to include additional non-functional elements that play a role in the SoS ability to achieve customers' satisfaction, like: modularity, scalability, flexibility, adaptability and robustness. This includes also new concepts, like sustainability (the use of resources without depletion or damage) and socio-economic return. These last require to take into account the interaction of the SoS with a wider context (not just technical, but also environmental and socio-economical).

The Expanded Operational Effectiveness Model intent is to provide a holistic description of the complete set of high level requirements that the candidate SoS solutions must address. The analysis of the functional needs requires a focus on the operational aspects, processes, services and functions that the SoS must perform; on the other hand, non-functional needs are related to qualities, constrains and limitation that are global, in the sense that apply to all the constituents of the SoS. Therefore it seems preferable, when proceeding to develop the Expanded Operational Effectiveness Model, to address separately the functional and non-functional needs,

obtaining two distinct models, to be later integrated in an overall model.

2.2.1 Functional Needs Model

The needs and expectations for complex, large scale SoSs are, usually, expressed by high level objectives and strategies. The level of abstraction of this kind of reference makes it not suited to directly support the development of the SoS. For the guidance of the generation of alternative solutions and of their evaluation, are required concrete, low level objectives and measurable criteria. These can be obtained by means of the analysis and decomposition of the high level needs.

The Originating Concept method for the development of the Functional Needs Model combines the Mission Analysis method with the synthesis of the Capability, Thread and Use Case constructs. The top-down decomposition procedure of the Mission Analysis starts from the high level objectives and develops a hierarchical structure. The clear and easily understandable form of the objectives hierarchy facilitates communication and consensus building between the customers', users' and developers' communities. The decomposition is carried out until a level of resolution is reached where two conditions are met:

- a clear effect resulting from the achievement of the objective can be identified,
- one, or a set of, measures of performance that define how well the effect is attained, can be identified.

It is apparent how he lowest level elements of the hierarchy of objectives, defined this way, satisfy the formal definition of Capability seen before. Each of the identified Capabilities, can then be analysed in further detail in order to define an associated Thread. This can be done with the support of operatives (users or Subject Matter Experts) that define a suitable Course of Action to attain the desired effect. This activity provides an excellent opportunity to actively involve the users. The definition of threads and Courses of Action is preferably supported by the definition of scenarios; an extensive coverage of this specific topic is provided by [4].

In a last step, the Capabilities and Threads descriptions are refined to comply with the Use Case format. The adoption of this more formal description goes in the direction of the developers' perspective, making it ready to be applied for the generation of alternative solution and for the further development activities, greatly reducing the risk of misunderstanding and wrong assumptions. Nonetheless, as seen, the Use Case construct allows the operatives to continue to be involved, thus they can validate the end result.

The Originating Concept model of the functional needs produced following the above approach, comprises:

- a hierarchy of objectives defining the interrelations between the high level objectives and lowest level ones (Capabilities)
- a set of Use Cases, one for each of the Capabilities, that defines the high level requirements for the SoS and is completed with the reference for the evaluation of their fulfilment.

The affinity of the composition of the above model with the Qualitative Value Model of VFT seen before is quite apparent. Indeed the VFT method has been demonstrated suitable for the analysis of functional needs of systems [1]. However, specially when dealing with SoSs where the dominant perspective is more often operational than functional, the Mission Analysis approach is preferable as it is already familiar to many stakeholders, and it is well aligned with their perspective of the SoS. In view of a later integration with the non-functional needs model, when developing the objective hierarchy with the Mission Analysis, one has to take care to make it also compliant with the characteristics required for a proper Qualitative Value Model. The limited additional effort is rewarded also by the better quality of the end result and by the facilitated detection of missing, or redundant, elements.

The set of Use Cases, notably when related to suitable scenarios, provides also a good reference for the Validation and Verification processes.

2.2.2 Non-functional Needs Model

Probably due to the fact that the functional needs are related to what the SoS is expected to provide, in term of functionalities and services, all stakeholders tend to focus on them and to give a low priority to the analysis of the non-functional needs. This is a major shortcoming, since failing to properly address non-functional needs can typically lead to an unsatisfied customer or, worse, cause the product to be not accepted.

Typically non-functional needs are defined as general goals, often high level ones. As a remarkable example, let just be cited the definition of sustainability of the National Environmental Policy Act: "To create and maintain conditions under which humans and nature can exist in productive harmony and that permit fulfilling social, economic, and other requirements of present and future generations." Also the concerns about the potential interactions of the SoS with its operating context, are usually defined as general goals (e.g. the need, for security systems, to "minimize the interference with the operation of other systems"). The non-functional needs model includes also the cost goals (e.g. Life Cycle Cost, Total Ownership Cost), thus providing a complete reference.

To be useful in guiding the generation and evaluation of alternatives, these high level goals must be articulated into lower level objectives with the final intent of identifying measurable characteristics. The development approach of the VFT Qualitative Value Model is optimally suited to define the objectives hierarchy of the non-

functional needs. The Non-functional Needs Model that is developed this way, has the same characteristics and is fully compatible and integrable with the Functional Needs Model seen before.

The product of the integration of the two models is the Expanded Operational Effectiveness Model that provides a comprehensive view of all the needs, expectation and desires of the stakeholders and, also, of the constraints and expected qualities.

2.3 Expanded Operational Effectiveness Evaluation

The Expanded Operational Effectiveness Model is a Qualitative Value Model; to support the evaluation of the effectiveness of the candidate solutions, it must be complemented by a corresponding Quantitative value Model. The end result is the Originating Concept. The Qualitative Value Model comprises the information about the relative importance of the objectives, in terms of their contribution to the achievement of the highest level goal. This information is quantified and recorded by the Utility Functions and the Weights. Some of these parameters can be defined using "hard" techniques, based on quantitative models and mathematical formulations (sometimes just "back of the envelope" calculations). In many cases this approach proves not practical or feasible; an alternative approach is to revert to "soft" techniques, that rely on judgments, based on experience, of knowledgeable individuals. The best option is to involve in this activity the stakeholders, to elicit and capture their knowledge about the problem and its operational context. If the stakeholder are not available, Subject Matter Experts can act as "surrogates"; in this case, the end result must be reviewed and agreed upon by the stakeholders. While the results obtained with hard techniques are more repeatable and unbiased, the soft techniques have a superior capability to accurately represent the stakeholders' appraisal and perception of the value of the objectives in the hierarchy.

To support and facilitate the elicitation of the information from the stakeholders, many methods are available. One of the main advantages of these methods is to make explicit and document also the subjective component of the judgments. This allows for the review, validation and refinement of the model, thus making it more dependable and trustworthy. Since the quantitative model is associated with the complete effectiveness model, it is assured that the priorities are assigned to all the objectives in a uniform and consistent way; this is an essential condition to be able to identify the best balanced solution.

The ultimate result is a "measurement tool" that provides, for each candidate solution, an overall evaluation of the effectiveness that is the best approximation of the customer own evaluation.

To evaluate the effectiveness of a candidate solution, it must be defined and modeled to a level that enables to estimate its score in each of the Measure of Effectiveness / Value Measures of the Expanded Operational Effectiveness Model; these are then elaborated with the quantitative model relations and parameters.

3 Conclusions

The Originating Concept approach shows promise to enable the development of an artefact that can provide the needed support to the Architectural Decision-Making process for a SoS. The set of models that form the artefact provide also the reference for the generation of alternative solutions and contains most of the information required to support the development of the preferred solution, its validation and verification. All the components of the Originating Concept are defined in formats that enable all stakeholders (customer, users, developers) to get an in-depth understanding and to effectively participate in their development, refinement and validation.

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