TOWARDS A DECISION SUPPORT FRAMEWORK FOR SYSTEM ARCHITECTURE DESIGN

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Abstract
Early phase design phases of more and more complex systems enhance the need for a more interdependent decision-making process across design disciplines and processes. No clear system architecture design process in industry identifies support tools for system architects' need. In this paper, we conducted interviews and workshop with system architects in a major aerospace company in order to understand what system architecture design process is and what decision support tools are needed in this process. The analysis of the collected data has underlined 10 different decision domains that we define and link to the needs expressed by the systems architects interviewed.

Keywords: Decision making, Early design phases, Product architecture

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1 INTRODUCTION

Early phase design phases are critical as they focus on investigating several solutions with regard to multiple objectives like system performances, cost, usability, manufacturing lead-time, etc. It is generally accepted that the decisions in early stages, including conceptual design, affect between 75% and 80 % of overall system life costs (Bellut 1990, Whelton et al. 2002). Moreover, increase in system complexity is enhancing the need for a more interdependent decision-making process across design disciplines and processes (Kreimeyer 2009, Lindemann et al. 2009).

One of the major processes that crystalizes this phase is system architecture design. System architecture encompasses concept design by defining the system design perimeter, the main system functions and the possible system physical or structural architectures. System architecture is linked to several processes and many design issues (design platform, modularity, performances, etc.) (Fixson 2005). In order to have an overview of system architecture design there is a need for specific collaborative working methods as well as involvement of several system design departments. However, in industry although there are best practices as to what is considered in system architecture design, it is not necessarily clear where the system architecture process stops and where conceptual design starts. In particular because system architecture represents also the embodiment of one or several concepts. Moreover, the question is also what are the tools necessary in system architecture design and if these tools are the same or different from support already used in conceptual design. In order to clarify these questions, the aim of this work is to better understand system architecture design process, and the difference with the conceptual design. In addition, it is necessary to understand what tools are needed and what system architects have in practice and what they need.

In order to answer these questions, several data sources have been used, such as interviews with system architects, data gathered during the European project TOICA. These data has been analyzed and compared with extensive literature review in view to identify research methods and tools not necessarily deployed in industry.

In order to answer these questions, we address the background on system architecture and related process in section 2 of this paper. Section 3 details the research methodology. In section 4, we analyze gathered data and discuss needs for a system architecture design DECISIon support Framework (DECISIF). Section 5 presents some of the conclusions and future work.

2 BACKGROUND

The notion of the system architecture relates to the notion of the design concept. In their work Urlich and Eppinger (Ulrich and Eppinger 1995) define the system architecture as “the arrangement of the functional elements into physical blocks”. Urlich refines the definition of the architecture as “(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components”. Crawley defines the system architecture as” the embodiment of concept and the allocation of physical/informational function to elements of form, and definition of interfaces among elements and with the surrounding context” (Crawley 2007).

Several societies have also been working on system architecture. INCOSE is not necessarily addressing directly the definition of an architecture but of a system. A system is a “combination of interacting elements organized one or more stated purposes” (Haskins et al. 2006). IEEE institute defines system architecture as “the fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolutions” (IEEE 2000).

Eppinger further develops the definition proposed by the IEEE society, replacing the word “organization” with “structure” even though the “structure” is also referring to the organization. Furthermore, he proposes to generalize a product-oriented terminology by using the term “elements” for any kinds of “components”. He defines system architecture as “the structure of the system, embodied in its elements, their relationships to each other (and to the system’s environment), and the principles guiding its design and evolution – that give rise to its functions and behaviors” (Eppinger and Browning 2012). Eppinger, as it can be deduced from his definition, integrates not only the product vision, but also the process vision of the system architecture. In general the notion of the “system” can be applied to product, process and organization, or embodiment of the three at the same time.

In his work Simmons (Simmons 2008) investigates different decision support for system architecture. He identified Matrix-Based Decision Support based upon Design Structure Matrix (DSM) approaches, Constraint Graph-Based decision-support, Tree and Directed Graph-Based decision-support. Many support for system architecture exist, however very little research has been looking at the system architecture design process and the methods and tools needed to support this process. In order to address this issue a research protocol has been designed to identify the scope of system architecture design process and necessary methods and tools related to the identified difficulties.

3 RESEARCH METHODOLOGY

Our work takes root in the project Thermal Overall Integrated Concept Aircraft (TOICA 2013), a 3-year European project coordinated by AIRBUS. This project focuses, during the concept phase, on simulations, multi-disciplinary approach for architecture trade-offs and integrated architectures and capabilities. We also got access to AIRBUS systems architects. Figure 1 describes the process we followed to develop and validate the framework.

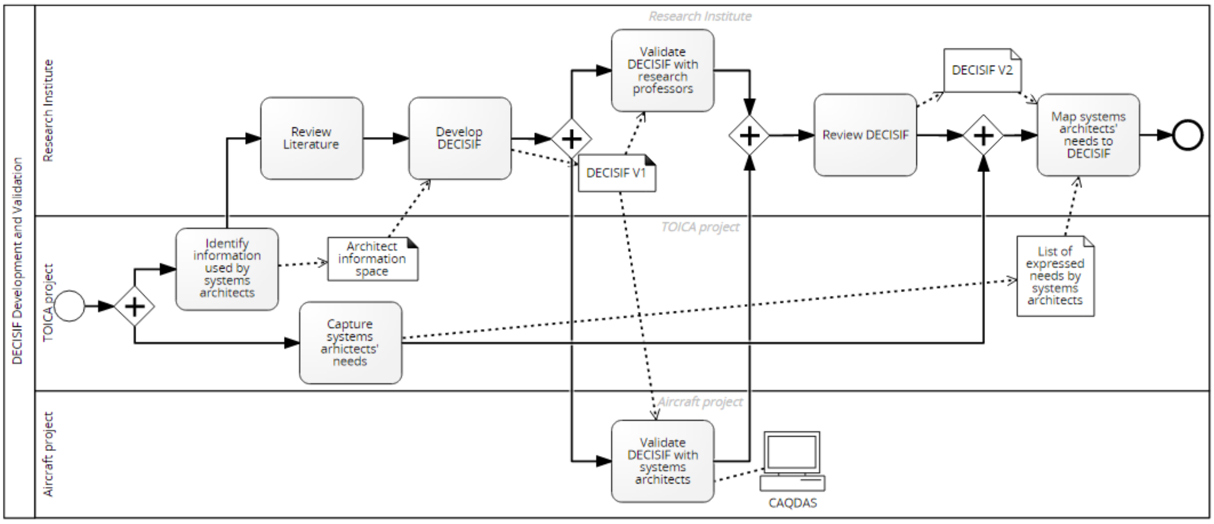

Figure 1. Development and Validation process of the DECISIon support Framework (DECISIF) for system architecture design

Each task is described in detail in Table 1.

Table 1. Tasks to develop and validate the DECISIon support Framework (DECISIF) for system architecture design

Task	Description
Identify information used by systems architects	Input: *Questions for systems architects*: List of 124 questions organized in 10 main topics: Architecture, definition of alternatives, interactions with simulation specialists, collection of study results, verification of data, analysis of the results, design exploration, capture of decisions, synthesis of local or domain specific trade studies, remarks and suggestions. Task: In 2013, interviews of three architects from AIRBUS, Dassault Aviation and Alenia allowed to identify what is discussed as the system architect cockpit, i.e. to define requirements for future system architecture design support. Output: *Architect information space*: view of 7 typical architecture information space in the context of aeronautic industry: Understand value drivers and top program objectives, define architecture concepts, compare and assess architecture concepts, understand status & progress of baselines, alternatives & variants, lead the integration work and technical trade-offs, steer and monitor the design technical processes, understand research portfolio & innovation opportunities.
Capture systems	Input: *List of 25 questions for systems architects* Task: End of 2013, a worskhop of 3 days was orgnised with 18 members of TOICA. Among them, two senior architects from AIRBUS and one from Dassault Aviation.

Task	Description
architects' needs	The aim of the workshop was to capture architects' expectations on the architect cockpit. The questions were oriented on today's architects practices and challenges around the topics: modeling, integration, value assessment, uncertainty management, robust analysis. Output: *List of expressed needs by systems architects*
Review Literature	Task: An extensive literature review has been conducted to cover the research streams related to the decisions domains defined in DECISIF, in order to gather the state of the art of research methods and tools. Output: *State-of-the art per decision domain*. Note: the literature review per decision domain is not provided in this article due to page limits.
Develop DECISIF	Input: *Architect information space* Task: We identified and described the 8 following decision domains, see section 4: Value-driven systems engineering, innovation and technology portfolio, system architecture generation, system architecture selection, system architecture exploration, simulation architecting process, product platform and modularity, change propagation analysis. For domain, we identified related scientific field and research, to discuss the different activities identified by the system architects. Output: *DECISIF V1*
Validate DECISIF with research professors	Input: *DECISIF V1, Literature review* Task: We discussed the framework consistency and completeness with two research professors in design. They validated the different decision domains and the literature review. One professor highlighted the importance to work with heuristics, as well as to integrate uncertainty and visualization aspects. Output: *Reviews*
Validate DECISIF with systems architects	Input: *DECISIF V1, Literature review, Questions for systems architects* Task: In order to validate the framework, we set up a one-day workshop in 2014 with three AIRBUS senior system architects who work on an aircraft project. We first presented the framework, and examples of relevant tools from the literature review. We oriented our questions through 3 aspects of system architecture design process and decision support: Decisions, information, timing; Actors and collaboration; Existing and needed methods & tools for decision support. For each decision domain, decisions pertaining to system architecture have been discussed, as well as methods and tools used or needed. All the systems architects agreed on the decisions domains presented. They also highlighted the existence of cross-domains activities. In the afternoon, we modeled and defined a system architecture design process based on their project. Different steps were identified and the difficulties encountered by the architects were discussed towards the framework. Output: *AIRBUS list of 57 needs, Tailored system architecture design process*
Review DECISIF	Input: *AIRBUS list of 57 needs, Reviews, Tailored system architecture design process* Task: The workshop was recorded, transcribed and coded using MAXQDA 11.0, a Computer-assisted qualitative data analysis software (CAQDAS), in order to insure rigorous data gathering and analysis. The architects expressed 57 different types of difficulties related to decision making process in system architecture design. We updated the framework as follows: we added to the decision domain "Simulation architecting process" the need to link the system architecture to 3D models. We added the 3 transverse decision domains and the 'information visualization' capability. See section 4. Output: *DECISIF V2*
Map systems architects' needs to DECISIF	Input: *DECISIF V2, List of expressed needs by systems architects, AIRBUS list of 57 needs* Task: The *List of expressed needs by systems architects* are presented in section 4.9. Note: the *AIRBUS list of 57 needs* is not shared in this article for confidential issues.

4 DEVELOPMENT OF A DECISION SUPPORT FRAMEWORK FOR SYSTEM ARCHITECTURE DESIGN

Seven different design decision domains have been identified that can be related to the system architecture life-cycle, see Figure 2:

- value drivers and requirements understanding,
- innovation and portfolio identification,
- brainstorming and generation of possible system architectures,
- selection of several system architectures,
- exploration of further system architecture performances and necessary trade-offs,
- identification of downstream simulation processes to further explore in depth engineering domain,
- and exploration of the relation to platforms and modularity aspects.

Moreover, 3 decision-making activities are cross-domain:

- change propagation analysis,
- margins management in system architecture,
- and risk and cost estimation.

System architects have found that although they need specific methods and tools to support these activities, they can be part of or embedded in other decisions domains. For instance, systems architects need to analyze change propagation both with regard to innovation and technology portfolio investigation, as well as system architecture selection and exploration. In Figure 2, these transverse decision domains are represented inside the circle to highlight their involvement in other decision domains. We do not presuppose of a specific order to cover the decision domains, as moving from one decision domain to another is tailored by projects' characteristics, e.g. the degree of innovation.

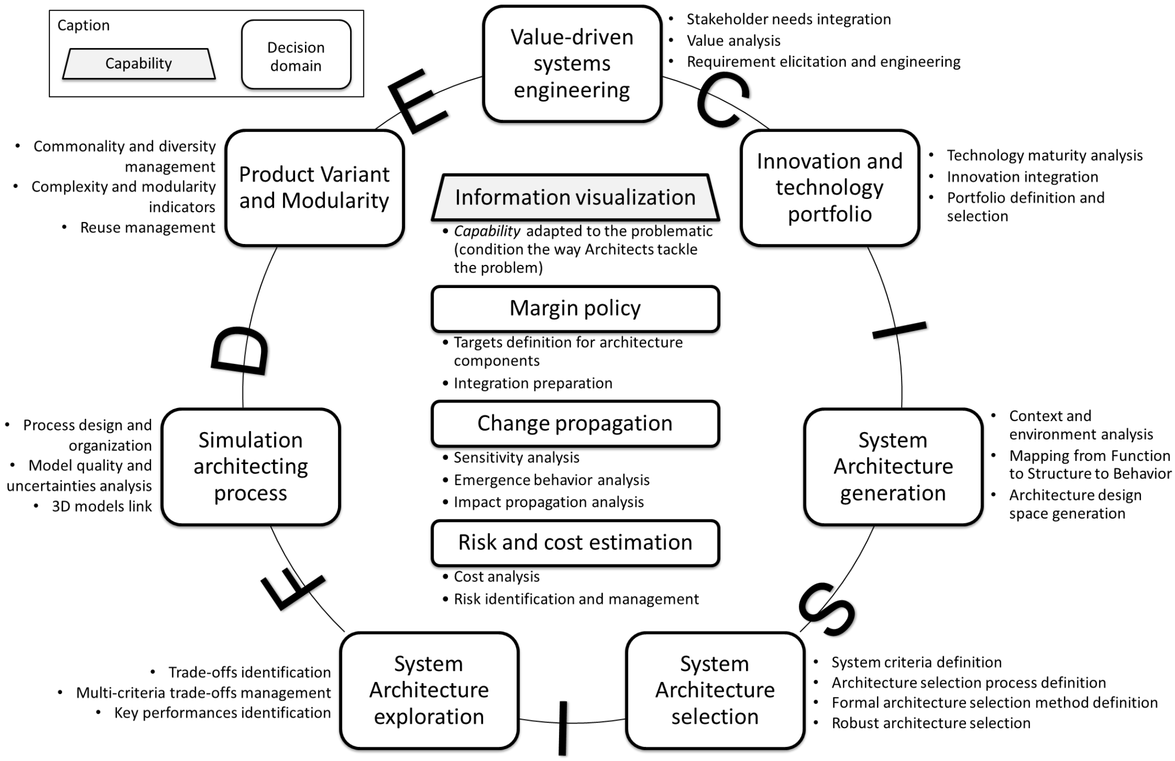

Figure 2. DECISIon support Framework (DECISIF) for System architecture design

The next sub-sections describe the needs expressed by the systems architect gathered through the interviews, for each decision domain.

4.1 Value-driven systems engineering

Systems architects need to have a view over the different stakeholder's expectations including customers, users, but also internal stakeholders such as manufacturing, installation, and support in operations. In early stages, especially for complex systems, these needs are very hard to define for several reasons: multitude of stakeholders, conflicting objectives, uncertainties related to the project span. The interviewed system architects have expressed the need to define adequate methodology and tools to support collecting, analyzing and prioritizing the needs through values drivers stemming from different stakeholders. They need:

- To capture, model and understand stakeholders' needs,
- To resolve conflicting high-level customer requirements,
- To establish a set of requirements, underlying in precise and measurable detail what the system has to do,
- To identify criteria and indicators that can be used in preliminary design studies that affect other stakeholders perceived values,
- To incorporate the value dimension into preliminary design in the context of virtual extended enterprise.

Although it is not necessarily seen as the same research domain, this activity also pertains to requirement elicitation and negotiation. Often understanding value drivers is interlinked to requirements, as well as supporting requirements' negotiation with different stakeholders.

4.2 Innovation and technology portfolio

System Architects often decide what technology to integrate and how the system is positioned globally with regard to the company's strategy. Therefore, they need support to identify the most promising technologies and innovations, and to assess costs and benefits. This is done conjointly between the research & technology department and the program department which look at the evaluation of the technology and possible integration within a system architecture. They need:

- To decide during the Technology Readiness Level (TRL) reviews the internal research & development projects pertaining to their domain
- To assess different technology integration in terms of future costs and benefits
- To compare them to decide the set of candidate technologies for the product to be developed

4.3 System architecture generation

System architects need to define set of functions (functional architecture), to identify sub-systems, components or modules (physical architecture) and to estimate future behavior (targets) of the system (behavioral architecture). These elements belong to different design spaces. System architects need methods and tools that will support mapping between the design spaces - Function, Structure, and Behavior. The needed support identified by system architects are:

- To define system operations,
- To define system functions,
- To define system subsystems/modules/components and interfaces between components,
- To estimate system performances (mass , cost, …),
- To generate architectures alternatives.

4.4 System architecture selection

System Architect needs to select a set of feasible promising architectures with regard to wanted system performances (overall costs, mass, performance, operability, manufacturing risks, etc.) for further investigations. This difficulty is also linked to a number of performances that are important to consider but also the need to follow the Set-Based design principles, i.e. manage progressive convergence of the design space. It was identified that the needs are:

- To identify architecture selection criteria,
- To define analyze and compare architectures,
- To define a set of promising architectures with regard to requirements,
- To consolidate requirements.

Several difficulties have been identified in system architecture selection process with regard to existing methodology (Moullec et al. 2014) such as the difficulty to identify and quantify criteria in early design stages, interdependence of all those criteria which is not necessarily the underlying hypothesis in many decision support tools, etc.

4.5 System architecture exploration

To perform system architecture exploration, the use of mathematical models or series of models of the system is required. These models are either already developed or need to be developed, where in this case the definition of the key parameters should trigger the necessary system modeling activities. System architects identified the need:

- To identify possible trade-offs,
- To identify and define key system performances,
- To identify critical system performances,
- To analyze architectures with regard to system performances (MDO, Pareto optimum, etc.),
- To compare architectures with regards to multiple system performances (Pareto optimum, etc.).

Before the analytical part of the trade-off study can be performed two prerequisites have to be performed, as taken from the NASA Systems Engineering (NASA 2007): definition of goals, objectives and constraints and a functional analysis of the system.

4.6 Simulation architecting process

In order to support system architecture design, different simulation capabilities are used for system behavior simulation and prediction. This process is not necessarily formalized and organized for the time being. Different roles are starting to emerge, like the role of model architect, i.e. system architecture behavior modelling and simulation. This process is also impacted by uncertainty modeling and integration, as well as management of modeling adequacy and accuracy. With regard to this part, several decision support methods and tools are needed: support for management and scheduling of this process, support for integrating uncertainties, support to modelling perimeter definition, etc. The needs identified are:

- To define a multidisciplinary simulation process,
- To specify what is the simulation intent,
- To determine the model quality and fidelity level requested taking into account uncertainties propagation

4.7 Product variant and modularity

Although product platforms and product variants are notions relatively close, they have a considerably different impact onto system design process. When designing system architectures it is necessary to understand if there is a product platform and to what extent it is possible to change it. Product platforms are key in design-to-cost and managing costs in life cycle. As for product variants, it is essential to consider them for some possible evolutions. The product platform is of course underlying issue but the question related to product variants is what is differentiating characteristics and possible differentiations with regard to different market segments. These questions are often considered independently of system architecture design and sometimes their constraints can be integrated into system architecture design late in process. Therefore, system architects need support understanding the relation between these issues on commonality and diversity.

4.8 Transverse decision domains

We identified transverse decision domains that may be integrated in other decision domains. They are mostly related to the analysis of different impacts regarding risk and cost, margin, and change propagation.

4.8.1 Risk and cost estimation

Risk and cost estimation occurs all along the design process and concerns all domains. The candidate architectures need to be assessed at all times in terms of costs while ensuring performance.

4.8.2 Margin policy

From (Eckert et al. 2014), a design margin is defined as “the extent to which a parameter value exceeds what it needs to meet its functional requirements regardless of the motivation for which the margin was included”. It is important to understand the complex multidisciplinary system being analysed to determine which parameters are tradable and truly important in satisfying the requirements.

4.8.3 Change propagation

Designing an architecture in the early phases is an iterative process. Some decisions can be impacted by a change in the stakeholders' requirements, an evolution of the company business model, an unexpected emergent behaviour discovered during architecture exploration.

4.8.4 Information visualization

One of the aspects that is not considered to be a decision domain but that has been constantly underlined but system architects are visualization capabilities related to different decision support tools. This is in particular related to understanding the interdependencies and large amount of data.

4.9 Discussion and Findings

The preliminary analysis of the workshop showed 53 different types of difficulties mentioned by the experts that are related to decision making process in system architecture design. Some of them concern innovation and technology integration, management of flexibility, required design processes to generate the product, etc. In addition we analyzed which difficulties were discussed together. For instance, the difficulties of cost optimization are often discussed in correlation of managing cash-flow in one project, but also related to the estimation of cost in architecture generation. Two of the most discussed issues are Innovation and Technology integration in relation to system architecture design, where system architects pointing out the need to analyze different possible impacts on the overall product development process. Through the analysis of gap between literature review and expressed needs, a set of needs is proposed in Figure 3 to direct future development of decision support systems for system architecture design. These needs are mapped with the decision support framework domains.

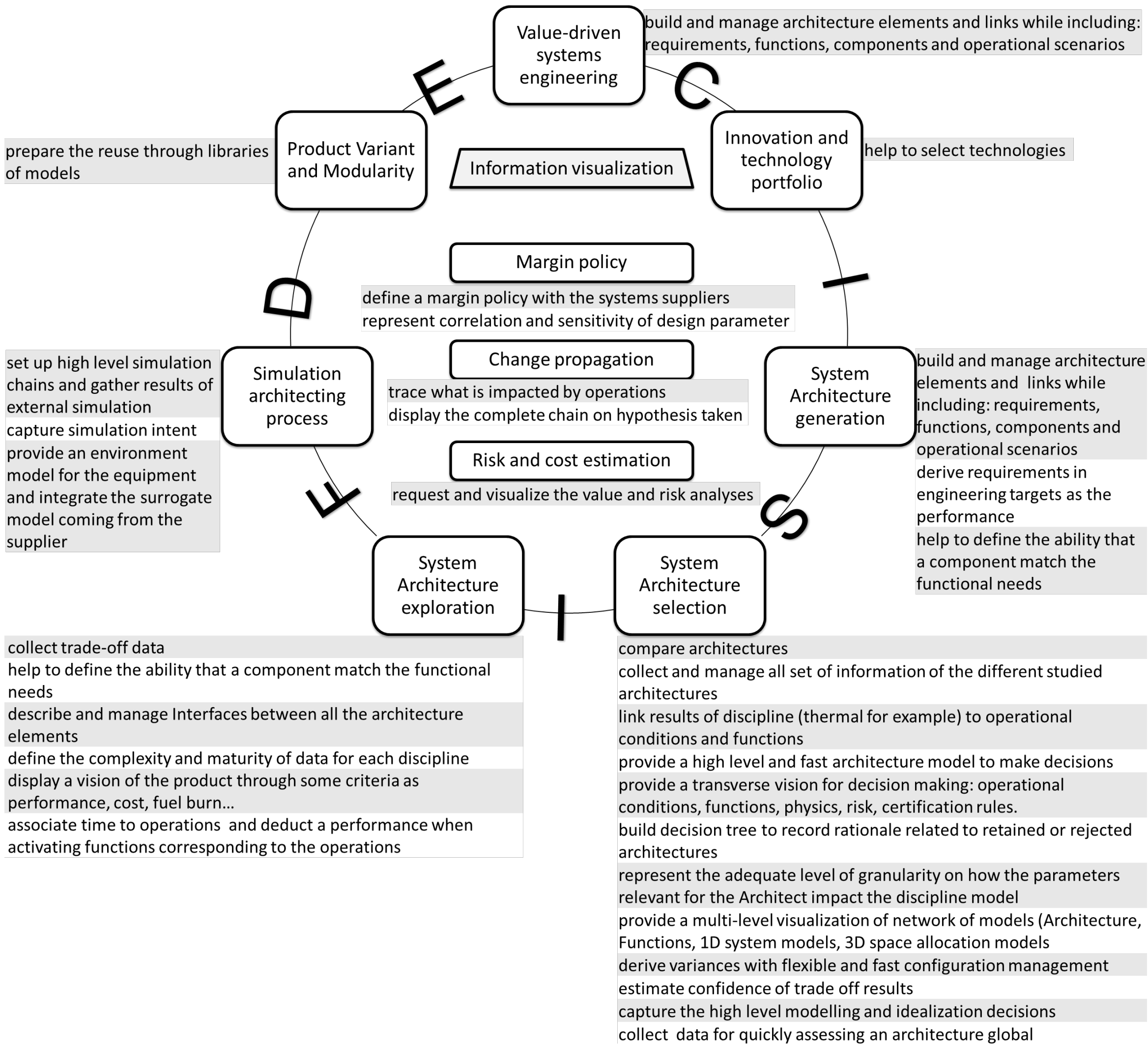

Figure 3. Systems Architects expressed needs on decision support for architecture design

5 CONCLUSIONS AND FUTURE WORK

System architecture design process is a critical process. In this study, we have used several data streams regarding some of the major companies in aerospace in order to understand what system architecture design process is and what decision support tools are needed in this process. The analysis of the collected data have underlined 10 different decision domains that are coherent with the decision making process and needs expressed by system architects. This framework has been validated by the architects in terms of activities where there is a decision taken, with an insistence on the visualization aspects. Although the needs have been discussed for each of decision domains, system architects see this support as the integration of different "pluggable" models that can be used flexibly in their decision making process. Furthermore, there is a necessity to continue to validate this framework and identify existing methods and tools. Extensive literature review has underlined different methods and tools that address some decision domains. The idea of integrating several identified research approaches is something that is also currently under consideration.

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REFERENCES

Bellut, S. (1990) La compétitivité par la maîtrise des coûts. Conception à coût objectif et analyse de la valeur, AFNOR/GESTION ed.

Crawley, E. F. (2007) ESD.34 Systems Architecting—Lecture Notes, MIT Engineering Systems Division.

Eckert, C. M., Isaksson, O. and Earl, C. F. (2014) Design Margins as a Key to Understanding Design Iteration, translated by American Society of Mechanical Engineers, V007T07A022–V007T07A022.

Eppinger, S. D. and Browning, T. R. (2012) Design Structure Matrix Methods and Applications, Cambridge: MIT Press.

Fixson, S. K. (2005) 'Product architecture assessment: a tool to link product, process, and supply chain design decisions', Journal of Operations Management, 23(3-4), 345-369.

Haskins, C., Forsberg, K., Krueger, M., Walden, D. and Hamelin, D. (2006) 'Systems engineering handbook',

IEEE (2000) 'IEEE Recommended Practice for Architectural Description of Software-Intensive Systems', IEEE Std 1471-2000, i-23.

Kreimeyer, M. F. (2009) A Structural Measurement System for Engineering Design Processes, unpublished thesis Technical University of Munich.

Lindemann, U., Maurer, M. S. and Braun, T. (2009) Structural Complexity Management, Berlin Heilderberg: Springer Verlag.

Moullec, M.-L., Jankovic, M. and Eckert, C. (2014) 'Investigating the Importance of Criteria Selection in System Architecture: Observations from Industrial Experiment', Research in Engineering Design, Under submission.

NASA (2007) NASA Systems Engineering Handbook, National Aeronautics and Space Administration.

Simmons, W. L. (2008) A Framework for Decision Support in System Architecting, unpublished thesis Massachusetts Institute of Technology.

TOICA (2013) 'TOICA Website', [online], available: http://www.toica-fp7.eu/ [accessed

Ulrich, K. T. and Eppinger, S. D. (1995) Product Design and Development, New York: Irwin McGraw-Hill.

Whelton, M., Ballard, G. and Tommelein, I. D. (2002) 'A Knowledge Management Framework for Project Definition', Electronic Journal of Information Technology in Construction -ITcon, 7, 197-212.