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## System architecture design

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## Editorial: System Architecture Design

### **Claudia Eckert**

Department of Engineering and Innovation

The Open University

Walton Hall, Milton Keynes,

MK7 6AA United Kingdom

e-mail: [claudia.eckert@open.ac.uk](mailto:claudia.eckert@open.ac.uk)

### **Marija Jankovic,**

Laboratoire de Génie Industriel

CentraleSupélec, Université de Paris Saclay

Grande Voie des Vignes, 92290 Chatenay Malabry

Phone: +33 1 41 13 14 27

e-mail: [marija.jankovic@centralesupelec.fr](mailto:marija.jankovic@centralesupelec.fr)

All throughout history people had the sense that products become more complex incorporating new features or new technologies. Up to the middle of the 20<sup>th</sup> centuries most products remained sufficiently simple that single people could design them. Now all but the simplest products are designed by teams of people with different skills and expertise. Modern product span a range of traditionally engineering disciplines incorporating mechanical and electrical elements as well as software to control them. Many of the products that we now think of as complex products, like aircraft, cars or trains have started off as mechanical systems, but now required a similar, if not greater effort in the development of the electronic and software systems. Their 20<sup>th</sup> century predecessors were designed to withstand many situations by overdesigning many parts of the systems, while other parts of the system needed to be replaced frequently. To minimise risk associated with products as well as product and design costs, companies reuse as many sub systems

or components as they can, so that all products are a mixture of old and new elements. Modern products are to a much larger extent optimised and customised for particular uses, while overall being far more reliable during their intended life span. The products are now designed together with the service and maintenance processes that support them; and assure their safety during the product life cycle. This integration of services with products has reached a point that many companies are now selling capabilities, rather than products keeping the product in the company over its life span.

All of these issues need be considered from the beginning of product development process, as early decisions lock the product and service development in; and determine many of the costs over the product life cycle. This has led to an increasing interest in system architecture design in many companies. System architecture determines the “arrangement of the functional elements into physical blocks” (Ulrich and Eppinger (1995). This involves the arrangement of functional elements; the mapping from functional elements to physical components and the specification of the interfaces among interacting physical components (Ulrich, 1995) as well as the interface surrounding context (Crawley (2007). The system architecture requires an understanding of the product in its entirety and across its life cycle; and use at a time in the process when many requirements and constraints are still unknown. This involves many trade-off decisions between conflicting constraints and requirements, as different solution principles within the system on many levels of detail. System architecture is at the same time subject to this uncertainty but also determines, through the decisions that are being taken, which uncertainties affect the product.

When products were simpler, individual engineers retained an overview of the entire product (see Flanagan et al. 2007); and were able to carry out fundamental trade-offs between different parts of the system in their minds. Many highly complex products have now reached a level of complexity and multi disciplinarity that very few engineers have the breadth of knowledge to have an even cursory understanding of the product and its lifecycle in its entirety. Companies are therefore

demanding from the academic community both the training of general design experts who can support the early phases of design processes and tools to support the experts in the system architecture phase. This special issue is responding to this demand, by attempting to bring together some of the current thinking and research on system architecture design.

The research on system architecture design is dispersed across multiple communities. The interest in the design and product development community in idea generation and early phases of design has grown into addressing system architecture of complex products as the point where fundamental decisions are being made (e.g. Wyatt et al., 2012). New system architectures are rarely designed from scratch, Many inherit the system architecture from a predecessor, so that the architectures can be remarkable similar over generations of products even if the functional requirements that lead to the original architecture no longer exist. The reuse of components or subsystems also leads to a persistence of the architecture both the overall architecture and the architecture of sub systems. Many products do not only share components with their predecessor designs, but also with other products in a family of products or the manufacturers offering. This has led to research on product platform design, which attempts to optimize the communality of elements across groups of products (see e.g. Simpson et al. 2001).

INCOSE has defined "Systems Engineering as an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs." System Architecture design is a subprocess that draws on the same principles but is focused on modelling and mapping system functions, structure and predicted behavior of a system. The choices made at system architecture

level significantly determine both the product and the design cost. As system architecture arises from multiple disciplines, there is a considerable literature and work stemming from embedded systems and cyber physical systems (ref Lee). Some research is also integrating business and process related parameters in their research.

While most complex products are interdisciplinary requiring the integration of mechanical systems, software and electronics, many system architecture processes and methodologies stem from the disciplinary traditions that have been following a given product evolution. The difficulty is that the disciplines have their own traditions of design methodology. In particular software engineering has a long standing tradition of system architecture with its own systematic methods, such as SysML (Friendenthal, Steiner et al. 2009) So far the academic literature from the different fields has not converged yet and the special issues did not receive submissions from these communities.

How system architecture can be understood and supported depends on many factors arising from the product and organizational characteristics. Jankovic and Eckert are exploring these factors in their article "Architecture decisions in different product classes for complex products", which was reviewed independently of this special issues, but included here to set a context for the system architecture. They review some of the literature on system architecture design and argue that system architecture is affected profoundly by the degree of innovation on a system level, the degree of reuse of components and sub-systems, the degree of integration of other products and the degree of modification across the life cycle. From this they distinguish five classes of design which vary in their consideration of system architecture: ab initio design; incremental design, where the majority of the components are reused; the reuse of solution principles, where the detailed components are different, but the architecture or parts of the architecture are reused; product platforms, where several products are designed at least in part as a group and designs that are created with future upgrades in mind. They suggest that research on system architecture needs to clearly state the intended scope and application problem.

The impact of the set based design on system architecture design has been investigated by Schultze. Several cross-industry cases have been investigated to understand the advantages of organizing early design based on the set based principles focusing on how the firms determines the number of system architecture alternatives and how the firms assign the design teams to these alternatives. The analysis of the case studies highlights that the number of system architecture alternative is not determined by cost-benefit calculation but rather by the number of initially proposed ideas. As for the resource assignment, in general one team is assigned to each alternative or one team pursued all alternatives. This is highly dependent on the product's complexity, innovativeness and criticality of the time to market. This paper also investigates the relationship between system architecture design, design process and design organization.

The paper of Moullec et al. investigates how system architectures are selected in a company environment and what are the constraints of this process that should be looked at. In particular, the impact of the system architecture criteria in the selection process is underlined. Two characteristics influence this process strongly: the interdependence of the selection criteria and the lack of information rendering the definition of an exhaustive set of criteria extremely difficult. The conclusions highlight the need to identify an ontology of decisions related to system architectures, as well as associated criteria that can depend on different product development stages.

Two papers focused on the importance to consider down stream issues during system architecture design. The article on "A Maintenance Focused Approach to Complex System Design" by Yu, Honda, Zubair, Sharqawy and Yang points out that maintenance is a major cost factor during the life cycle of a complex product which can be affect through the system architecture designs. They propose a framework that captures the interaction between maintenance strategies and system-level design parameters, so that designers can choose a system architecture and maintenance strategy together which allows the product to operate under conditions of uncertainty with minimal cost.

Lindèn, Sekkgren and Söderberg argue in their paper on “Model Based Reliability Analysis” that reliability of a system has two aspects: the explicit technical requirements and subjective requirements such as ergonomics and communicative needs. Failure in either can lead to customer dissatisfaction. They propose a method that explicitly models the socio-technical interface in a system through a combination of Function-means trees and Design Structure Matrices to consider these issues in the system architecture phase of the product.

In spite of the considerable interest from industry, the academic research in this field is still in early stages and much of the research is on-going without the researcher feeling able to submit papers in time for the special issue. This is also a reflection of the fact that system architecture is rarely the main focus of the research, but becomes relevant when other areas are addressed. However it is exactly that specific support and understanding of system architecture that is required.

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