Artificial Intelligence for Engineering Design, Analysis and Manufacturing (2016), *30*, 214–216.

doi:10.1017/S0890060416000202

GUEST EDITORIAL

System architecture design

CLAUDIA ECKERT[1] AND MARIJA JANKOVIC[2]

[1]Department of Engineering and Innovation, Open University, Milton Keynes, United Kingdom
[2]Laboratoire de Génie Industriel, Centrale Supéléc, Université de Paris Saclay, Chatenay Malabry, France

All throughout history people have had the sense that products become more complex by incorporating new features or new technologies. Up to the middle of the 20th century, 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 products span a range of traditional 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, such as aircraft, cars, or trains, started off as mechanical systems, but now require a similar, if not greater, effort in the development of the electronic and software systems. Their 20th-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 minimize risk associated with products as well as product and design costs, companies reuse as many subsystems 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 optimized and customized 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 the 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 had let to an increasing interest in system architecture design in many companies. System architecture determines the "arrangement of the functional elements into physical blocks" (Ulrich & 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 & Eppinger, 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 its 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 they were able to carry out fundamental trade-offs between different parts of the system in their minds. Many highly complex products have now reached such a level of complexity and multidisciplinarity that very few engineers have the breadth of knowledge to have an even cursory understanding of the product and its life cycle 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 at 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 remarkably similar over generations of products even if the functional requirements that led 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 subsys-

Reprint requests to: Claudia Eckert, Department of Engineering and Innovation, Open University, Walton Hall, Milton Keynes MK7 6AA, UK. E-mail: claudia.eckert@open.ac.uk

tems. Many products share components not only 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 modeling and mapping system functions, structure, and predicted behavior of a system. The choices made at the 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 (Lee, 2014). 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 (Friendenthalet al., 2009) Thus far, the academic literature from the different fields has not converged and the Special Issue 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. Marija Jankovic and Claudia Eckert are exploring these factors in their article "Architecture Decisions in Different Product Classes for Complex Products," which was reviewed independently of this Special Issue 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 subsystems, the degree of integration of other products, and the degree of modification across the life cycle. From this they distinguish five classes of design that are very different considerations 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; and future flexibility. 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 Anja Schultze in "Developing Products With Set-Based Design: How to Set Up an Idea Portfolio and a Team Organization to Establish Design Feasibility." 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 determine 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 alternatives 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 by Marie-Lise Moullec, Marija Jankovic, and Claudia Eckert, "Selecting System Architecture: What a Single Industrial Experiment Can Tell Us About the Traps to Avoid When Choosing Selection Criteria," 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 focus on the importance of considering downstream issues during system architecture design. "A Maintenance-Focused Approach to Complex System Design," by Bo Yang Yu, Tomonori Honda, Syed Zubair, Mostafa H. Sharqawy, and Maria C. Yang, points out that maintenance is a major cost factor during the life cycle of a complex product that can be affected 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 that allows the product to operate under conditions of uncertainty with minimal cost.

Julia Lindèn, Ulf Sekkgren, and Anders Söderberg argue in their paper on "Model-Based Reliability Analysis" that re-

https://doi.org/10.1017/S0890060416000202 Published online by Cambridge University Press

liability of a system has two aspects: the explicit technical requirements and the subjective requirements such as ergonomics and communicative needs. Failure in either can lead to customer dissatisfaction. They propose a method that explicitly models the sociotechnical 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 ongoing without the researchers 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.

REFERENCES

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

Flanagan, T., Eckert, C., & Clarkson, P.J. (2007). Externalizing tacit overview knowledge: a model-based approach to supporting design teams. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 21(3)*, 227–242.

Friendenthal, S., Steiner, R., & Moore, A. (2009). *A practical Guide to SysML*. Burlington, MA: Elsevier.

Lee, E.A. (2014). Constructive models of discrete and continuous physical phenomena. *Access IEEE 2*, 797–821.

Simpson, T.W., Maier, J.R., & Mistree, F. (2001). Product platform design: method and application. *Research in Engineering Design 13(1)*, 2–22.

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

Wyatt, D.F., Wynn, D.C., Jarrett, J.P., & Clarkson, P.J. (2012). Supporting product architecture design using computational design synthesis with network structure constraints. *Research in Engineering Design 23(1)*, 17–52.

Claudia Eckert is a Professor of design at Open University. She has a longstanding interest in studying and supporting industrial practice in different design domains and has published numerous papers on it. In particular, she has been working on process modeling, engineering change, and functional modeling of complex engineering products.

Marija Jankovic is an Associate Professor at Centrale Supélec, Université de Paris Saclay. Her main domain of interest concerns developing a decision support framework for early design stages. She is interested in developing support methods and tools that will permit design engineers to make more robust decisions. Her research work is also challenged by multidisciplinary design environments that are developing in view of the new world's competition. Dr. Jankovic has working experience in designing complex systems. A majority of her research projects are performed in collaboration with industry or government and with direct implementation and verification of research results. She collaborates with some of the major French and international companies such as Snecma, Thales, EADS, PSA Peugeot Citroen, and Schlumberger.