The challenge of increasing heterogeneity in Systems of Systems for architecting

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***Abstract*—The transition from capabilities provided by traditional physical systems to today's capabilities provided by heterogeneous systems of systems complicates architecting. In this paper, we look at trends in this ongoing transition, especially into the degree of heterogeneity of technologies and the context. We observe in an increase in virtual intangible technologies from the cyber domain, and an increase in human and organization aspects. Main question is how the heterogeneity of concerns, needs, considerations, and technologies impacts architecting and the role of architects.**

***Keywords*—heterogeneity, dynamics, cyber, architecting, trends**

I. Introduction

Companies that used to develop systems as OEM equipment or as stand-alone solutions see an increasing demand for integration into the system context. In practice, many systems today are de facto part of a System of Systems (SoS). A few examples are:

- MRI scanners, which are part of examination rooms, which are part of radiology departments, which in turn are part of hospitals in a health care chain
- Workover systems as part of Subsea Production Systems, as part of oil fields, which in turn fit into an oil production and logistics chain.

One of the consequences of this increasing integration is an increase of heterogeneity of capabilities, technologies, and life cycle dynamics of constituting parts.

The author of this paper teaches in-company courses and courses to (part-time) students working in systems development. In these courses, the participants model their system of interest in the broader context, i.e. the system of systems supersystem. The participants come from many domains, such as defense, maritime, oil and gas, manufacturing, automotive, OEM equipment, and health care. For all these systems, we observe similar ongoing trends:

- Growth of data/information collection
- High expectations from harvesting useful data across systems to improve performance and functionality
- Infrastructure platforms using cloud technology, factoring out common digital functionality
- Ubiquitous use of commodity devices as smart phones, tablets, and laptops
- Focus on trustworthiness and affordability
- More automation and considering autonomy
- Societal pressure for privacy and responsible behavior

The observations in this paper are a generalization of the trends in the variety of domains present in the conceptual modeling courses described in [1]. The courses were among others in the following domains:

- Health care
- Defense
- Maritime
- Oil and gas
- Manufacturing
- OEM equipment for imaging, printing, machining
- Automotive

Consequence of these trends is that the system boundaries for systems architects and designers are blurring. How can they ensure proper performance and functionality of capabilities that depend on so many systems in the SoS? What are their responsibilities in today's SoS context? What aspects do they need to consider during architecting?

In this paper, we briefly discuss the SoS background in literature (Sec II). Sec III discusses the role of architecting. We elaborate the trends some more in Sec IV. Sec V explains the blurring of the system boundaries. Then we elaborate technical heterogeneity (Sec VI), contextual heterogeneity (Sec VII), and the heterogeneous dynamics of the various parts and functions (Sec VII). In Sec VIII, we discuss the heterogeneity and its impact on architecting. Sec IX concludes the paper

II. Systems of Systems Background

There is extensive literature on systems of systems; Fig 1 summarizes some of these models. Boardman and Sauser [2] define the following differentiating characteristics for SoSs: Autonomy, Belonging, Connectivity, Diversity, and Emergence. Maier [3] uses managerial independence, operational independence, geographic separation, emergent behavior. And evolutionary development as typical characteristics. DeLaurentis [4] uses 3 dimensions for a taxonomy of SoSs: Type, Control (or autonomy), and Connectivity. Dahmann and Baldwin [5] describe several types of SoSs: Directed, Acknowledged, Collaborative, and Virtual. These types have a decreasing amount of explicit management and recognition of het SoS.

Boardman and Sauser	Maier	DeLaurentis	Dahmann and Baldwin
Autonomy	Operational independence	Type	Directed
Belonging	Managerial independence	Control (or autonomy)	Acknowledged
Connectivity	Geographic separation		Collaborative
Diversity	Emergent behavior	Connectivity	Virtual
Emergence	Evolutionary development		

Fig. 1. Keywords from some of the SoS models in literature

III. The Role of Architecting

The Helix project lists characteristics for senior systems engineers: paradoxical mindset, effective communications, flexible comfort zone, smart leadership, and self-starter. A crucial role for architects is to connect the context (e.g. the operational, organizational, and life cycle) to the technical design [6], ensuring fitness-for-purpose [7]. Fig 2 shows how technology via the system design enables the system requirements, which in turn enable the customer and business value propositions. The customer and business value propositions require a clear understanding of the operational and life cycle context. The left-hand side of Fig 2 shows the various organizations active in creating, building, and using the system in its context.

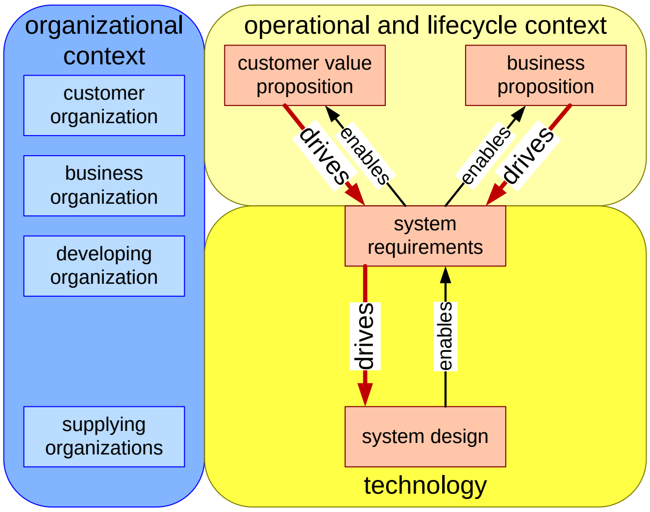

Fig. 2. The architecting playing field

A major task of systems architects of traditional systems is bridging of various contributing engineering disciplines, such as mechanical, electrical, and software engineering. All engineering disciplines and their further specialized subdisciplines use their own language or jargon, formalism, tools, and way of thinking. The contribution of architects is achieving system functionality and performance, which is more than combining the results of the various engineering disciplines. The system discipline is to facilitate developers to let desired functionality and quality attributes emerge from the interaction of the individual parts. This part of the architecting job was already challenging in the traditional world of architecting systems.

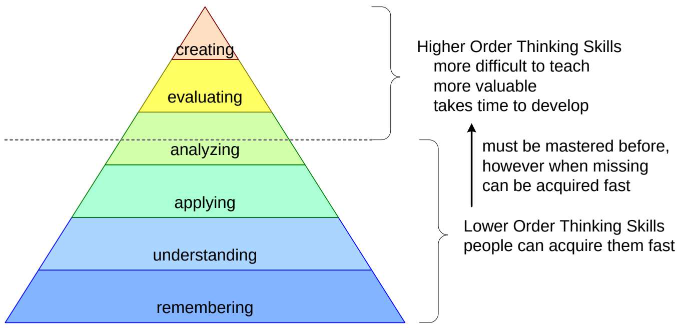

Fig. 3. Lower and higher level thinking skills in Bloom's revised taxonomy.

During the education of architects, we hit the problem of balancing transfer of knowledge in the form of methods, techniques, and concepts versus the development of their abilities and attitude. Bloom's revised taxonomy [8], as shown in Fig 3, provides a useful model for this balancing act. King et al discuss the higher level thinking skills [9], which correspond with the top layers of Bloom's taxonomy analyze, evaluate, and create. Many students and course participants expect to learn the means of the trade being methods, techniques, and concepts. These match with the lower layers of Bloom's taxonomy. Sufficient knowledge and skills at these layers is a prerequisite for the upper layers. However, the upper layers are essential for the architecting competence. These Higher level thinking skills correspond with the Helix characteristics.

All of the Helix characteristics [10] are crucial for the architect role. We assert that the increase in heterogeneity of context and technology makes these characteristics even more important.

IV. Discussion of Observed Trends

Strategy reports[1] discuss the potential impact of the wave of cyber technologies, such as Internet of Things, miniaturized and commoditized sensors, ubiquitous networking, storage and processing resources, Artificial Intelligence ((deep) learning, data mining, data analytics), block chain, microservices, and clouds. Many companies "feel" that there opportunities for them in this wave of cyber technologies. However, for many of them these new cyber technologies are far removed from their current competences. Consequently, they are searching for ways to find and develop these perceived opportunities.

These new technologies with new ways of operations bring new concerns and tensions too. Behere provides a good example of these tensions in [11] in architecting autonomous machines. The traditional systems in automotive focus on determinism and predictability, robot platforms focus on variability and composability, while artificial intelligence in autonomous systems depends on training and learning. These three domains have completely opposite perspectives and related beliefs.

The observed trends are full of similar challenges. Trustworthiness may be in conflict with autonomy, large-scale data collection may conflict with privacy, security often conflicts with usability, heterogeneous data sources and data processing may endanger data integrity, etc. These trends open a field of heterogeneous needs, concerns, and tensions.

V. Disappearing Boundaries?

Fig 4 shows a generalized sketch of a system and its context; a sketch to facilitate discussion between stakeholders. In many cases, architects used to focus on the physical system they are working on, e.g. the MRI scanner, the workover system, the crane, etc.; that is the bottom right-hand side of this figure. Quickly, other physical systems pop up that interact with the system-of-interest. When we add control and human interaction, then we see ICT infrastructure appearing for communication, and user interface devices for interaction. In today's world, (micro)services run on cloud infrastructure making their resources entirely scalable. The developing company can develop and operate their own services (in blue in the middle of Fig 4). However, the capability may use various third party services as well, such as maps, traffic information, and weather forecasting (in pink in top left-hand side of Fig 4).

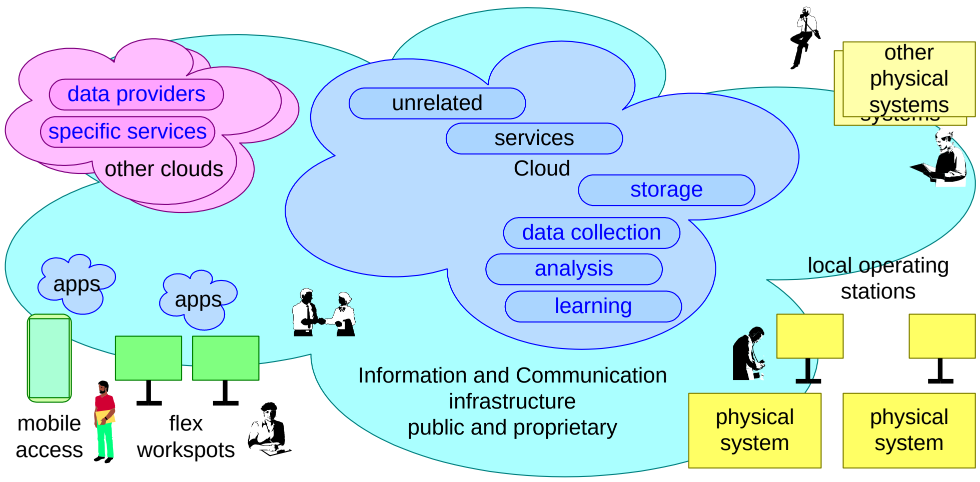

Fig. 4. The challenge of defining system boundaries

A challenging question for a systems architect working on one of the traditional systems is what is the boundary of your system of interest? The problem here is that capabilities that the system provider offers to their customers typically depend on the entire system of systems.

[1] Such as Digitally-enabled automation and artificial intelligence: Shaping the future of work in Europe's digital front-runners by McKinsey October 2017

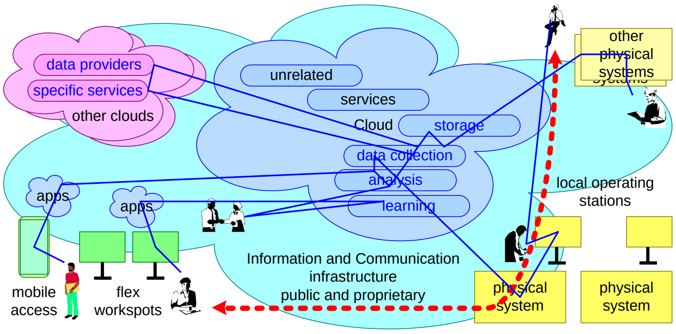

Fig. 5. The red dotted line indicates the perceived end-to-end function, the blue line shows the active communication paths.

Fig 5 illustrates this by showing on the one hand the customer perceived function, as the red dotted arrow, and on the other hand in blue the communication that is taking place within the system of systems.

VI. TECHNICAL HETEROGENEITY

The SoS transition extends the technical breadth that architects need to cover. In traditional systems, there are often a few dominating technologies and disciplines. For example, in MRI, magnets, gradients, and RF are core for system performance. In workover systems in the oil and gas domain, mechanical engineering is crucial. Systems architects often had their root in one of the dominating technologies.

In Fig 4, we see information and communication infrastructure as core technologies (which in fact is already the case for decades). Commodity devices as smartphones, tablets, and laptops add the technologies of Android, iOS and Windows. The cloud infrastructure adds new technologies for deployment and business models. In the cloud, many services with new technologies, such as artificial intelligence and (deep) learning, appear. All these cyber technologies require security technology.

Each technology area brings its own set of considerations and technical aspects that impacts the end-to-end capability. For instance, the information and communication infrastructure and the cloud have dominant concerns related to security, information integrity, and service scalability. The commodity devices bring concerns related to variability of the devices, operating systems, and apps, translating into configuration, version, and release management.

Finally, there may be domain specific technologies that expand when the boundaries expand. For instance, in case of MRI scanners, clinical knowledge related to diagnostics, and treatment. may start playing a larger role. Apps and services typically bridge technology and domain by capturing domain specific knowledge.

VII. CONTEXTUAL HETEROGENEITY

Systems architects should already be aware of the physical context (nature) impacting their system, since that used to be a major factor n traditional architecting. The blurring of the system boundary also increases the amount of system context that plays a role. This expanded system context consists partially of other technical systems with their physical context. More challenging is that various humans and their organizations and processes impact the capability-of-interest. In addition, with the human and organization dimension, we get many non-technical considerations, such as economical, ecological, legal, social, political, psychological, and criminal.

The heterogeneity of humans, organizations, and processes shows in the operational and managerial independence coined by DeLaurentis. Most of these SoSs are rather heterogeneous in the Dahmann and Baldwin types; part of the SoS may be virtual, while other parts may be directed or collaborative.

The dynamic interaction of the systems in the context, the underlying infrastructure, and the people and organizations together will result in the capability-of-interest and its quality attributes. In other words, systems architects need sufficient understanding of the blue lines in Fig 5 when architecting their system-of-interest.

These blue lines in Fig 5, in the context of the system-of-interest, are largely cyber or in nature. Cyber interactions are virtual, intangible, and abstract; cyber interactions are difficult to grasp when working from a physical perspective. Human interactions suffer from psychological, social, and political factors. Emotion, social pressure, political gains may trigger unexpected behavior.

VIII. HETEROGENEOUS DYNAMICS OF PARTS AND FUNCTIONS

Sec III and IV show the breadth of entities and technologies determining the capability-of-interest. All these entities have varying lifecycle heartbeats. Traditional physical systems typically have heartbeats in the range of year to decade, determined by development and goods flow properties.

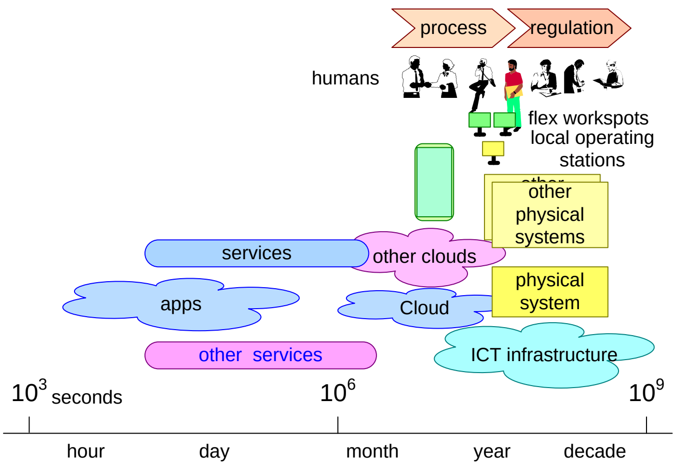

Fig. 6. The lifecycle dynamics of various parts and functions mapped on a logarithmic time axis with a time scale in seconds

Fig 6 shows the various parts and functions and their lifecycle heartbeats. Both the worlds of apps and services are moving fast to extremely fast, from traditional architecting perspective. Modern deployment technologies allow providers to deploy or update new apps and services in hours. Not only can the infrastructure deploy the apps and services fast, it also allows deployment of many variants simultaneously.

Infrastructural parts, such as cloud and ICT infrastructure, evolve somewhat slower, although they may evolve faster with a heartbeat rate of few months to few year years than traditional physical systems.

The world of commodity devices, smart phones, tablets, and laptops, and their related operating systems has heartbeats in the range of half to two years.

The humans, processes, and organizations evolve gradually. Processes may change in months. Regulations typically are relatively slow with heartbeats of many years.

The consequence for the system-of-interest is that its surroundings are changing all the time. It needs to be robust for this dynamic context. Question for the architects is how they can ensure that the capability-of-interest keeps functioning and performing as desired.

IX. Discussion

The consequence of capabilities that depend on dynamic interoperability of many systems is that these capabilities at the same time are a result of a rather heterogeneous set of systems, functions, and technologies. In terms of governance, development, and maintenance, there is similar heterogeneity of persons and organizations contributing to these constituent systems.

There is a clear tension between most of the SoS properties in Fig 1, such as autonomy of systems, and operational and managerial independence, and the need to achieve well behaving and performing capabilities across these systems. The heterogeneity in many dimensions makes development and operation of capabilities more complex.

Many of the trends run parallel with more cyber technology and more human (and organization) interactions. The traditional physical design and local controls still evolve, so these still need full attention of architects.

We have seen that the technical and context heterogeneity increases across domains. This increase can be linked to the characteristics of SoSs as given in the literature.

We see an increase in autonomy, connectivity, diversity, and emergence, as well as an increase in the heterogeneity of these characteristics; these are the SoS characteristics described by Boardman and Sauser [2].

We observe significant independence in management and operations (as described by Maier [3]). Here we also see an increase in the heterogeneity of management and operations.

The emerging SoSs tend to be a mix of the types of SoSs (Directed, Acknowledged, Collaborative, and Virtual, as described by Dahmann and Baldwin [5]). The scope increase of SoSs increases the diversity of types within the SoS.

The taxonomy by Laurentis [4] overlaps with the above SoS characterizations. We see an increase in the heterogeneity of all three dimensions of this taxonomy.

The challenge for architects in architecting is that the increase of heterogeneity of technology requires some depth knowledge and skills over a broad set of technologies. At the same time, the increase of heterogeneity of the context requires a significant breadth in knowledge and skills. Major challenge is the breadth in perspectives (physical, cyber, human) that architects need. Their main role is to synthesize and integrate, taking the holistic perspective. Therefore, crucial for architects are the higher-level thinking skills, which correspond with the characteristics found by the Helix project [10].

X. Conclusions

Via teaching architecting in a rich variety of domains, we see a common trend of capabilities that depend on heterogeneous SoSs. The heterogeneity has many dimensions, running in parallel with SoS literature. Challenge for architects is to achieve the mental breadth to cope with physical, cyber, and human aspects.

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References

[1] G. Muller, "Challenges in Teaching Conceptual Modeling for Systems Architecting," in *Advances in Conceptual Modeling Volume 9382 of the series Lecture Notes in Computer Science*, Stockholm, 2015.

[2] J. Boardman and B. Sauser, "System of Systems – the meaning of of," in *CSER*, Los Angeles, 2006.

[3] M. Maier, "Architecting principles for systems- of-systems," *Systems Engineering*, vol. 1, no. 4, pp. 267-284, 1999.

[4] D. DeLaurentis, "A Taxonomy-based Perspective for Systems of Systems Design Methods," in *IEEE Systems, Man and Cybernetics*, Waikoloa, 2005.

[5] J. Dahmann and K. Baldwin, "Understanding the Current State of US Defense Systems of Systems and the Implications for Systems Engineering," in *IEEE Systems Conference*, Montreal, 2008.

[6] G. Muller, Systems Architecting: A Business Perspective, CRC Press, 2011.

[7] M. Wilkinson, "An Architect's Manifesto for the Development of Systems Engineering," INCOSE Whitepaper, 2016.

[8] J.S.Atherton, "Learning and Teaching; Bloom's taxonomy," retrieved 4 February 2016 from http://www.learningandteaching.info/learning/bloomtax.htm, 2013.

[9] L. G. a. F. F.J. King, " Higher order thinking skills,," Center for Advancement of Learning and Assessment, retrieved 4 February 2016 from http://www.cala.fsu.edu/files/higher_order_thinking_skills.pdf.

[10] N. Hutchison, D. Henry, A. Pyster and R. Pineda, "Early Findings from Interviewing Systems Engineers

who Support the U.S. Department of Defense," in *INCOSE*, Las Vegas, 2014.

[11] S. Behere, F. Asplund, A. Söderberg and M. Törngren, "Architecture challenges for intelligent autonomous machines: An industrial," in *Proceedings of the 13th International Conference on Intelligent Autonomous*, Padua, 2015.