Collaborative Systems Engineering: Issues & Challenges

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***Abstract*—Today, we live in a society where time and space have been shortened by the introduction of digital technologies. This situation puts a lot of pressure on the market and companies unable to adapt are doomed to extinction. Collaboration is needed. Although the Systems Engineering approach brings many benefits to manage risks and to improve the quality, cost and delay of deliveries; we argue in this paper that we are missing today adapted methods and tools in the Model-Based System Engineering to support this change of paradigm. Based on use cases' observations, 5 collaborative systems engineering challenges are raised to position 2 research tracks.**

***Index Terms*—Systems Engineering, Collaborative Engineering, Model-Based System Engineering, Domain Intention, Controlled Exposition**

I. Introduction

Today, we live in a society where time and space have been shortened by the introduction in our daily lives of digital technologies: mobiles, cyber-physical systems, IoT, social networks, big data, artificial intelligence, etc. Information and goods move ever more easily and quickly. This recent digital shift has been identified as the fourth industrial revolution [1]. This brings a lot of benefits: quicker and safer sharing of information, real-time processing of data to better respond to customers' needs, more customized offers, etc. This has also led to a disruption at several scales: from the geo-strategic perspective down to personal habits. The ever greater exposition of consumers to accessible goods and services fuels their appetence for them in ever shorter delays to satisfy a demand for immediate gratification [2].

This situation puts a lot of pressure on the market and companies unable to adapt are doomed to extinction. Because the adaptation requires new ways of thinking and new ways of working, some companies encounter difficulties. First, some are hindered by the fear of major disruptions to their internal organization. This fear is amplified by the uncertainty as to how to perform such an adaptation. Second, at a larger scale, the digital transformation also impacts the relations between the companies. Indeed, the increasing market pressure requires a more and more intricate collaboration between the companies. Previously, established industrial companies producing complex products have largely relied on hierarchical client-supplier relationships, with them at the top. The current trend for both internal and external cooperations is to reshape the relationships into the form of a collaboration network in which the hierarchy is supposed to fade to give way to fairer relationships based on trust, thus protecting the industrial know-how. This network, largely made possible through the use of digital technologies, is widely conceptualized as the extended enterprise [3].

Although the transformation described above tends to promote more collaborative ways of working at various scale; let's not forget that the collaboration has always been in the genes of the animal kingdom [4]. It has historically existed in engineering practices [5] and has been highlighted in studies: e.g. Ellis' 3C model. From them we can observe the prerequisites for a successful collaboration: 1) A shared objective between involved stakeholders; 2) A synchronization of actions; 3) An exchange of information, between the right people, at the right time; 4) A complementarity between skills.

These seem natural enough. The question is then, how can we facilitate the fulfillment of these prerequisites in order to ease the adaptation of the struggling companies?

This paper is placed in the particular case of industrial companies that produce complex systems such as aircrafts, cars, trains, etc. Such companies have historically heavily invested in their engineering processes, skills and tools. Yet, they are typically struggling to adapt to the more collaborative approaches required by their context. They see themselves vulnerable to new, more agile, market players. This paper then reports on the current issues and challenges that still need to be addressed in order to support a collaborative systems engineering that can be leveraged by these companies. More specifically, this paper looks into the issues and challenges faced by Model-Based System Engineering (MBSE) [6] approaches.

This paper is structured as follows: Section II first presents a typical application scenario for a collaborative MBSE approach. It summarizes the observed issues with these approaches. Then, this example also serves as a base for the current challenges regarding a collaborative MBSE presented in Section III, positioning related works. Later, Section IV presents our position regarding these challenges and how they can be addressed. Finally, Section V draws our conclusion.

II. Scenario

This section presents an example of a collaboration for the production of the braking system of an aircraft's landing gear. The objective of this collaboration is to produce a set of design artifacts for the landing system. The involved stakeholders are:

- The *system architect*, responsible for the management of the system requirements and the operational analysis;
- The *system engineer*, responsible for the design of the system's functional and physical architectures;
- The *safety analyst*, responsible for the Safety Analysis (SA) against the other design artifacts.

The present scenario focuses on: the Operational Analysis (OA), the Functional Architecture (FA), and the Safety Analysis (SA). For example, the FA produced takes the form of a SysML model, as shown in Figure 1.

The stakeholders know they have to produce artifacts that are consistent with each other. Through their experience, they are aware of a set of constraints that have to be verified; although, in practice, the constraints themselves may not be formalized or even made explicit. In particular, the safety analyst is used to a constraint of well-formedness that can be expressed as:

Constraint: The failure mode of a function is consistent if 1) the function realizes a service activated by a scenario in a context and 2) the failure mode is an effect of an accident in the same context.

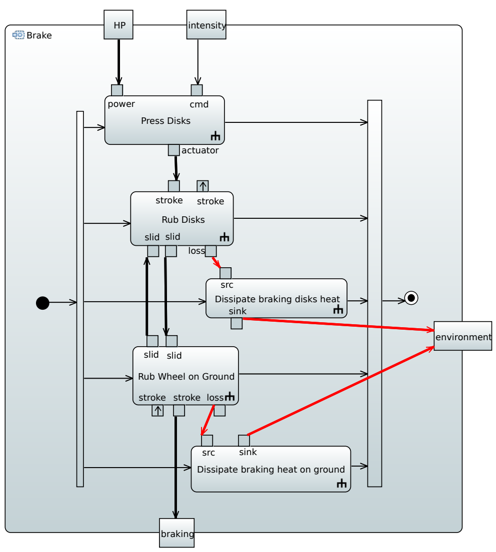

Fig. 1. Excerpt of the functional architecture of the Braking System

A. *Observation 1 - The collaboration needs to rely on consistent data*

An example of inconsistency violating this constraint would be: the failure mode "No Braking" for the "Brake" function on the landing gear is an effect of an accident during the "In Flight" context. Intuitively, the "Brake" function on the landing gear is probably not supposed to be used "In Flight". But no one can determine where the inconsistency is coming from. Yet, *the collaboration need to rely on consistent data*. In a collaborative engineering process, one must ensure that the vision of the different stakeholders are consistent with each other. In the present case, there is probably a mismatch between the visions of the three mentioned stakeholders.

B. *Observation 2 - The stakeholders must share their data*

Furthermore, the presented constraint spans the data from three engineering artifacts: 1) the OA (context and scenario), 2) the FA (functions), and 3) the SA (failure modes and accidents). It means that the stakeholders, in a collaboration, *must share their data* to communicate and effectively align their vision. This is made further necessary by the fact that the kind of holistic consistency required by the collaboration, and shown by the presented constraint itself, requires the data from multiple stakeholders.

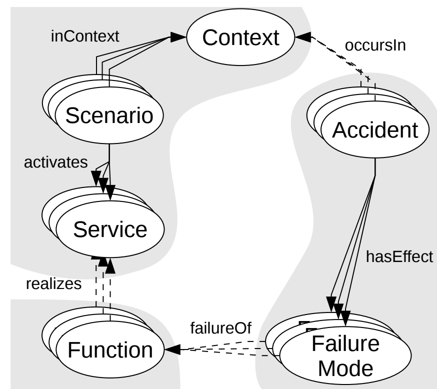

Fig. 2. Concepts used for the collaboration

C. *Observation 3 - Sharing implies an agreed vocabulary*

The data from the different stakeholders take different forms, most usually models. In this scenario, they made explicit the agreed vocabulary in the form of the concepts (and relations) summarized in Figure 2. The elicitation of the shared vocabulary enables the stakeholders to efficiently share meaningful data. The actual sharing of data from one stakeholder to another then entails a mediation. This mediation is required to account for the actual form of the shared data (their modeling language, etc.), but more importantly, for the semantics that the stakeholders projected onto them. A prerequisite for this mediation is then: *The stakeholders have to agree on a set of common concepts and their meaning*. This precise step can be achieved generally through the production of business quality management documents as a preamble to an engineering project. This is especially true for projects that involve stakeholders from different organizations [3].

D. *Observation 4 - The collaboration is orchestrated*

The exchanges of data between stakeholders are sequenced. In this scenario, the safety analyst cannot work on a Failure Mode and Effect Analyzis (FMEA) without a first version of the FA produced by the system engineer, as illustrated by the excerpt from the collaboration process in Figure 3. Therefore, another common prerequisite to an engineering project is the agreement on a collaborative process. Indeed, the actual orchestration of a collaboration can take many forms, including free-style point-to-point exchanges. But even in this very liberal case, the stakeholders have to agree on the kind of orchestration beforehand. *The collaboration is orchestrated*. This kind of temporal constraint and organization must be accounted for in an orchestration of the collaboration in order to reduce latency and delays in the engineering cycle. Let's not forget that the adaptation to a collaborative engineering approach in this kind of scenario is most likely to be driven by the market pressure to reduce delays (and thus costs), as presented in Introduction.

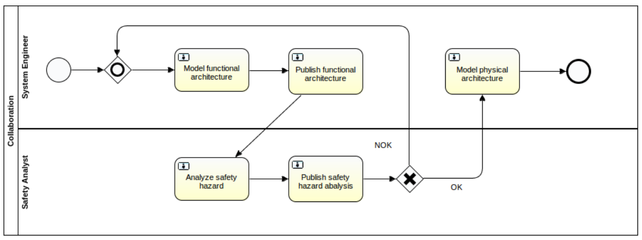

Fig. 3. Extract from the collaboration process

E. Observation 5 - Sharing does not mean expose everything

When the system engineer shares a version of its FA with the safety analyst (Figure 3), he/she may not want to provide all the intricate details of the architecture. On the other side, the safety analyst does not want to be "polluted" either by these details. In the case of an FMEA, the safety analyst only requires the names and the overall hierarchy of the FA. Figure 1 shows the FA produced by the system engineer. But the safety analyst really only need the name of the functions and their organization: "The function Brake is composed of the functions Press, Rub, and Dissipate". The goal of the mediation in the collaboration is to ensure that the right stakeholder has access to the right data at the right time in a comprehensible manner. In other words, in this scenario, the safety analyst shall have access to the functions and their hierarchy (and no more) when it is shared by the system engineer, in the form of a pre-filled FMEA table. The stakeholders need only to *share the necessary and sufficient data* to perform a given activity. In the end, the collaboration answers to an objective, the design of the braking system for the landing gear of an aircraft.

F. Observation 6 - The collaboration has a scope and does not exist in a vacuum

The stakeholders share the necessary and sufficient data so as to complete this objective, but no more. This means that *the collaboration has a scope*, i.e. a precise objective with identified stakeholders. In this scenario, the initial data comes from a set of requirements managed by the system architect. The requirements are not produced in the context of the described collaboration, but are probably an output from another collaboration involving the system architect with the clients and the business strategist. In the same way, the architectures produced by the system architect can be used for the design of the overall aircraft in another collaboration. The FMEA produced will be included in the dossier to be sent to the certification authorities. This means that *the collaboration* presented in this scenario *does not exist in a vacuum*. Over the course of the collaboration, the stakeholders will have exchanges outside its scope. This results in new data coming from and going to other collaborations. For example, the design of the aircraft's hydraulic circuit requires the collaboration of another group of experts. The decisions taken in the hydraulic circuit's collaboration impact the decisions taken in the presented one, and vice versa. Even if we consider that each collaboration can achieve an optimal outcome, there is still a need to achieve a trade-off between collaborations through the exchange of relevant information. The consequence is that, in a collaborative engineering approach, one has to consider not only the orchestration within a collaboration, but also the orchestration between them.

At a larger scale, the building of the complete aircraft requires a network of collaboration involving stakeholders from different organizations. Whereas the organizations used to fit in a hierarchical model, the market pressure forces them to adopt a new decentralized model in which the hierarchy fades to give way to the network of the extended enterprise.

This section presented the scenario of a collaboration for the design of the braking system of the landing gear of an aircraft. This ideal, yet realizable scenario describes a collaborative engineering approach that is based on the MBSE practices. In the course of this scenario, we identified 6 key observations.

III. Challenges

From the 6 observations, this section exposes issues and challenges to be addressed for a collaborative systems engineering. It positions them regarding the current state of the art and brings out current issues faced by the MBSE approaches.

Indeed, this work focuses on the challenges of a collaborative engineering in the context MBSE approaches to the design of a product. The hypothesis of this work is that a collaboration is specifically tailored to address a defined engineering objective. While the boundary of a collaboration is defined by its stakeholders, its objective can take many forms, from a short-term need to take a decision, to an overarching engineering work spanning the complete life-cycle of the product.

A. Challenge 1 - Building the Collaboration, Shared Vocabulary

A collaboration in the context of a MBSE approach will most likely involve experts from several domains ranging from the specialty engineering domains (mechanical, thermal, electrical, software, etc.) to the safety, security, reliability domains, without forgetting the legal, certification and business strategy domains. During the span of the collaboration, the diverse stakeholders are expected to communicate the required domain-specific data. They must do so in a form that is comprehensible to the other stakeholders, as identified by **Observation 2** and **Observation 3**. A key point is that the purpose of the shared vocabulary in a collaboration is to help mediate the necessary data between the stakeholders.

This very challenge has been identified in various scientific communities. In the Model-Driven Engineering (MDE) community, this challenge takes the form of the heterogeneous modeling problem [7] [8] [9]. It can be addressed through various means, such as the federation of models [10]. In the semantic web community, the challenge takes the form of the semantic alignment of ontologies [11]. However, the challenge cannot be reduced to an integration problem of heterogeneous data. A necessary step in the construction of a collaboration is the identification of the vocabulary used by the stakeholders [12]. Indeed, to point out the simplest cases, different stakeholders may use different words to refer to the same concept; or conversely, use the same word to refer to different concepts [12]. A prerequisite for the collaboration is the identification of the common concepts, their meaning, their relations and how they are used by the stakeholders in their local vocabularies. This is referred to as the "integration of data" in [13]. In the specific context of MBSE, one has to be careful as to what are the concepts manipulated by the stakeholders in their local domain-specific models. For example, if an engineer uses SysML to represents the FA of the system under study, he/she most likely manipulates the domain concept of "Function", not the concept of "SysML::Block" defined by the SysML language; even though a "Function" may be represented by a "SysML::Block" in the actual model. Conversely, some standard try to provide a common vocabulary for a domain. This is the case for the STandard for the Exchange of Product model data (STEP - ISO 10303) and its application protocols, or OSCL[1] which is more focused on immediate tool integration. However, this often leads to standard misuses and conformity issues.

The MBSE community has followed the trend of the standardization of a common vocabulary (meta-model) for all stakeholders of the collaboration; stating that their data have to be integrated into a single technical space and a single repository [14]. Some technological solutions has been produced in this regard, following a meta-model-centric approach (e.g. Capella[2]), or a PLM driven one (e.g. 3DExperience/Enovia[3]) to name a few. One downside of this vision is the unavoidable mis-representation, mis-alignment of the stakeholders' domain-specific concepts, which can lead to its pauperization. In essence, the problem addressed by these technologies is purely technical. They fail to address the human aspect of the collaboration, i.e. the meaning projected by the stakeholders onto their data.

B. Challenge 2 - Building the Collaboration, Orchestration

The second challenge to solve for the setup of a collaboration is the negotiation between the stakeholders and the specification of a collaboration method, as identified by **Observation 4**. This primarily resides in the decision making process of settling on a collaboration method.

The collaboration method can indeed take multiple forms. In some form of collaboration, the stakeholders may work simultaneously on a single artifact. In this case, the co-edition (multiple stakeholders) of this artifact is a possible method as in [15] and [16]. Otherwise, an approach to the design of collaborative processes is referred to as the "collaboration engineering" [17]. The expression of the orchestration of collaborative activities can take multiple forms, from ORCHESTRA [13] to BPMN extensions for highly collaborative processes [18]. In a collaboration engineering approach, the design of collaborative processes can be facilitated by the use of ThinkLets as abstract building blocks [19].

The systems engineering domain (and MBSE) has been driven by norms and standard for a long time. In this context, standards such as the EIA-632 and the ISO/IEC/IEEE-15288 present global system engineering processes spanning the design or complete life-cycle of a system. The issue faced by the MBSE community is to differentiate between those overarching processes and the collaborative processes that must take place between the stakeholders of a single collaboration. The traditional system engineering processes presented by the standards do not concern themselves with the actual collaboration between human stakeholders for a precise objective. They instead focus on the high-level description of engineering activities that may take place, instead of the necessary collaboration within and between the activities.

C. Challenge 3 - Controlled Exposition

The stakeholders in a collaboration must be able to control the information they share with others in order to expose only the necessary and sufficient data, as identified by **Observation 5**. In the scenario from Section II, the reason was that all the data produced by a stakeholder may not be of use by another. Another reason may be that multiple companies may collaborate to tender for a single contract; but they are otherwise in competition on other markets. The companies want to expose only the minimal amount of information to the other stakeholders in the collaboration (industrial know-how protection). This is why the challenge to be addressed is the "*controlled exposition*" of the data. It means that the data to be shared must be necessary, yet sufficient and what shall be shared is left to the choice of the sharing stakeholder. A collaboration support system may mediate the shared data, but the sharing stakeholder must be able to choose what to expose and to withhold. In a security conscious system, the choice would be made before the data even reach the collaboration support system to be mediated.

As explained in **Challenge 1** the current technological solutions from the MBSE community do not properly address the shared vocabulary challenge. Instead, they force a standardized vocabulary integrating all possible domains with a vision of a be-all end-all central repository of all engineering data. By definition, they also forsake their ability to properly address the controlled exposition challenge. The vision where all stakeholders must, in the end, use the same global tool to collaborate cannot account for the will of the human stakeholders to only share meaningful data. Conversely, the OSLC approach with its publication of data and services on objects from standardized domains partially tackles the problem, addressing it only at the definition level. Finally,

[1]http://open-services.net/
[2]https://www.polarsys.org/capella/
[3]http://www.3ds.com/products-services/enovia/

People & Organization (P&O) management provided by many tools, which is another part of the answer, must shift from a cooperation context to a decentralized collaboration one.

D. Challenge 4 - Consistency with Domain Rules

The collaboration must rely on consistent data, i.e. the data shared by the stakeholders must be consistent, as identified in **Observation 1**. In the context of a collaboration, the consistency refers specifically to the consistency of the exposed data: a collective consistency across technological spaces. This excludes the "internal" consistency of the original data managed by the stakeholders outside the scope of the collaboration. In the scenario described in Section II, the constraint is not interested in the consistency of the FA in itself, or the consistency of the FMEA alone; but in the holistic consistency of these where they intersect. The challenge at hand is then twofold: First, the stakeholders of the collaboration must be able to express their inter-domain constraints (i.e. domain rules) based on the shared vocabulary discussed in **Challenge 1**. Second, the collaboration must be able to check holistic constraints spanning all the data shared by the stakeholders.

The expression of constraints, or domain rules, is a challenge addressed in several communities depending on their requirements. In the Model-Driven Engineering community, one can rely on the Object Constraint Language (OCL) [20]. In the semantic web community, domain rules can be expressed using the Semantic Web Rule Language (SWRL) [21]. However, one must not forget that the challenge at hand is the expression of domain rules spanning heterogeneous shared data. How this challenge is address will heavily depend on how **Challenge 1** is addressed.

From an industrial perspective, the late detection of inconsistencies between domains is very costly because it leads to rework that could have been avoided. Consistency checking is then a huge resource sink in the industry. For instance, it has been observed that the conformance to norms like the DO-178B in the aircraft domain generally imposes an overhead expense of several factors [22].

E. Challenge 5 - Network of Collaborations

The scenario presented in Section II outlined a single collaboration, but it was clear from **Observation 6** that this collaboration does not live alone. In fact, a collaboration has to be integrated in a greater network of collaborations. This is especially true in the context of the design of complex systems such as an aircraft. Each collaboration focuses on a specific objective, the resolution of a problem. The design and implementation of a system can then be seen as a path between nodes in a network of collaborations. The challenge at hand is then the identification, management and orchestration of the flows between the collaborations.

The concept of network of collaborations, its implication regarding the stakeholders and their integration in a big picture is explored in [23]. In the manufacturing domain, the same idea has emerged as the Dynamic Manufacturing Network (DMN) [24]. The DMN is composed of independent companies that have complementary strengths and are organized in the form of a network with flows of different natures (information, financial, material, etc.). As observed in [25], the introduction of the DMN is a consequence of the need for more flexible and responsive collaborations stemming from the market pressure generated by the undergoing digital transformation discussed in Introduction.

IV. Research Tracks

The previous section presented issues and challenges and positioned them regarding the current state the art. This section presents some possible research tracks for 2 of these challenges.

A. Capture the Domain Intentions

Challenge 1 presented above showed that for the realization of a collaboration in a system engineering approach, the identification of a shared vocabulary between the collaboration's stakeholders was necessary. The difficulty of doing so does not primarily resides in the identification of the shared vocabulary itself, as shown by the associated state of the art. The difficulty resides in the identification of the meaning projected by each stakeholder on his data. One has to be careful to not mix up the tangible representation of a stakeholder's data and the meaning projected upon them by him. In the given example, the "SysML::Block" is the tangible representation used by the system engineer to represent "Functions". A research track to pursue is then how can the meaning projected by a stakeholder be captured. In this example, it is not sufficient to consider the stakeholder's data in the form of "SysML::Block", because this is only the tangible representation. One has to determine and capture the fact that the projected meaning is indeed "Function". In addition, it is not sufficient to capture the fact that the system engineer projects the concept of "Function". The safety analyzis in a FMEA also projects the concept of "Function". One has to determine that the nature of the relation between the system engineer's "Function" and the safety analyst's "Function", or the meaning variance as presented in [12]. The identification and capture of the meaning projected by a stakeholder onto his data is referred to here as the *capture of the domain's intentions*. This goes beyond the scope of the simple identification of the domain's concept because we also aim at the capture of their operational (behavioral) aspects: How do these concepts are intended to behave from the stakeholder's perspective. The capture of the domain intentions for all stakeholders can then be leveraged for the identification and specification of the shared vocabulary. In this case, the shared vocabulary is really more than just a simple list of concepts and relations. It is a complete ontology that provides the semantic alignment of the stakeholder's domain intentions, including their behavioral aspects. For this purpose, we propose to rely on the extension of the OWL2 language for the expression of behavioral elements [26].

B. Controlled Exposition

The controlled exposition, as presented in **Challenge 3**, is to be related to the capture of the domains' intentions.

For the support of a semantically sound collaboration, the identification and specification of the shared vocabulary is necessary. The controlled exposition is then for one part the specification of which domain intentions a stakeholder is ready to share. In the scenario in Section II, the collaboration requires the system engineer to share "Functions", but probably not the other domain concepts. In this regard, a research track is the automatic operationalization of the captured domains' intentions in the form of a mediation between them, e.g. the mediation between the system engineer's FA and the safety analyst's FMEA. Can this mediation be automatically implemented? What would be the form for such mediation? The MDE community proposed model transformation techniques, which can be seen as a form of mediation. Are they relevant to this context?

The controlled exposition does not stop at the level of the domains' concepts. As presented in **Challenge 3**, the controlled exposition is also for a second part about the selection of which data to expose and which data to withhold. This is orthogonal to the selection of the domains' concept to be shared. This can be seen in the fact that the system engineer may not want to share all the "Functions" in his/her architecture. Despite all elements to be shared being "Functions", there can be a selection as to the precise elements to actually share. This is especially true in the context of a collaboration with stakeholders from different organizations. As presented in Introduction, this concern is becoming ever more relevant.

V. Conclusion

This paper first presented in Section II a simple yet realistic scenario of collaboration for the MBSE of the braking system of an aircraft's landing gear. From this scenario, we derived 6 observations about the collaborative system engineering process. In Section III, the paper relied on the 6 observations to present 5 current challenges to the support of a collaborative system engineering process. The challenges, positioned with regards to their relevant state of the art, are supplemented by the identification of some issues found in the current technologies used for the support of MBSE. Future research tracks for addressing the challenges were then presented in Section IV.

The challenges presented in this paper are our keys to the successful support of a collaborative engineering process. The answers to these challenges must not entail the rejection of the current system engineering practices, processes, skills and assets. To the contrary, the objective should be to support the gradual adaptation of a company by enabling new ways of working and still support the existing practices until they naturally die. In this way, a company will be able to naturally adapt to the digitalization of the economy and its consequence as the increase pressure of the market for better, cheaper, more complex products in shorter delays.

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