A Framework for Negotiation-Based Sustainable Interoperability for Space Mission Design

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Abstract. The need to improve the time spent performing space mission feasibility design studies has led the aerospace industry to the adoption of Concurrent Engineering methods. These high-performance concepts parallelise the design tasks, effectively reducing design time, but at the cost of increasing risk and rework. The fragile interoperability in this design environment depends greatly on the seniority of the space domain engineers and their expertise in the space design engineering area. As design studies get more complex, with an increasing number of new domains, systems and applications, terminologies and data dependability, together with growing pressure and need for adaptation, the design interoperability arena becomes extremely hard to manage and control. This paper presents the concept of developing and maintaining strong interoperability nodes between the design domains by providing a framework of cloud-based services dedicated to negotiating and enforcing a sustainable interoperability between high-performance businesses.

Keywords: Sustainable Enterprise Interoperability, Negotiations, Control, Aerospace.

1 Introduction

The development of conceptual design for space-related missions on the European Space Agency – Concurrent Design Facility (ESA-CDF [1]) is a complex process that involves multiple domains (e.g., Mission analysis, Thermal, Power), which match the different views and interests of the mission. In this process, to increase the performance of the studies duration, the design is fast-tracked into a scenario where multidisciplinary teams perform their activities in parallel, applying the concept of Concurrent Engineering [2]. Although each domain design team models its own view of the mission, the teams need to exchange a large set of mission parameters, required to satisfy the mission and to ensure that all views are fully integrated and fit perfectly. As the heterogeneity grows in the various systems and applications used by each design team and mission, and as studies get larger and more complex, interoperability problems are being reported between the design teams, leading to additional rework.

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When the involved parties in a study face a detected interoperability problem, they must solve it. Kaddouci et al. [3] state that in any case of divergence, negotiation is the most appropriate method to solve conflicts. Usually these interoperability conflicts are resolved via one party forcing the other to change, or by reaching consensus towards a midway solution. This paper addresses the need for interoperating enterprises to formally negotiate the interoperability solutions towards reaching the most appropriate decision, one that minimises the effort and time spent regaining interoperability. It proposes a collaborative framework to model and support the interoperability negotiations of businesses towards achieving sustainable Enterprise Interoperability (EI) on organisations acting in the same industrial market.

Section 2 of this paper details interoperability problems commonly found in business-to-business activities derived from the example of the ESA-CDF environment. Section 3 presents research questions and hypotheses. Section 4 enumerates requirements towards enforcing interoperability. Section 5 presents the proposed collaborative negotiation framework. Section 6 presents final statements and future work.

2 Problem Description

The rapid evolution and constant improvement that is required towards companies (particularly SMEs) leads to the need to deliver faster, better and cheaper. This typically means the need to fast-track the activities in a company, or otherwise the need to specialise in a particular business area, delegating the other activities to a network of partners and providers. The proposed framework is suitable for enterprises facing the described interoperability problems, and is being validated in a real business-case on the ESA-CDF department.

In the ESA-CDF environment the design of each future space mission is split into a set of engineering domains. Each domain engineering team performs its design using different tools (e.g., CATIA, STK, Matlab) and is provided and supported by a network of partners and suppliers (large companies and SMEs). Therefore interoperability in this case is defined in two levels: i) The interoperability between each domain and its tools, partners, and suppliers towards the target of defining the domain design or vision of the mission, and ii) The interoperability between the various domains of a mission-related study, where all domains compete for their interests into setting the values for mission-related parameters (e.g., Spacecraft dry mass, Electrical power).

These mission parameters are inter-related (e.g., changes in the structure or in the number of instruments naturally affect the total Dry Mass) and their values are kept under control by the mission requirements. The data exchanges between design domains are performed in a set of closed “war-room” sessions [4] where all involved domains and stakeholders are represented and each domain presents its design solutions and corresponding impact on the mission design. Interoperability in this highly-competitive scenario is assured by the study Team Leader which moderates the discussions and the Systems engineer which provides local support to the engineers.

Several interoperability problems were detected and reported in this environment [5]. While some of these relate to problems (e.g., communications, data formats, typos, and syntax) which are frequently discussed in literature and already have some tools for correction (e.g. protocols, check digits, dictionaries and grammars) other less evident grow in abstraction to semantic mismatches, relationships, concepts, methodologies, strategies and hierarchies. With this growth comes a proportional increase in the difficulty to detect these problems, and a proportional increase of their impact. The fact that each domain has its own set of external dependencies to tools, suppliers and partners makes interoperability on the study life cycle even more difficult, as the number of communicating/interoperating channels increases due to their supply chain.

The proposed framework aims to provide support in reaching a sustainable EI (SEI) by providing mechanisms that allow businesses to model and formalise their knowledge (e.g., questionnaires and surveys, modelling of business activities and data), providing services that are dedicated to assisting the interoperation, particularly a mechanism to model and formalise the interoperability negotiations (Fig. 1).

Fig. 1. Application of the proposed framework to the ESA-CDF business

This research worked together with the ESA-CDF team to develop questionnaires and gather information on issues regarding interoperability. The outcomes of this analysis can be mapped into most common problems reported by companies when dealing with business-to-business interactions.

Each domain interoperates with the others and with its supply chain using a heterogeneous set of interfaces which include shared data and tool interfaces, shared workspaces (e.g., shared databases) and shared tools. Heterogeneity in this environment grows with new trends, concepts, platforms, technologies and development methods.

The main difficulty regarding interoperability is related to the lack of a deeper common knowledge of the business concepts, which then leads to misunderstandings and errors caused by simple mistakes e.g., on data meaning, data units, or methods.

The tools that are used to perform the design activities (e.g., Domain-specific tools, STK, CATIA) are standard and not customised to the specific design business needs, which means their concepts and terminology may not be aligned with the business.

Despite its high-performance target, the ESA-CDF environment manages to incorporate several knowledge management tools for capture of design study knowledge like decisions and lessons-learned recording. However the knowledge management on the scope of each domain is very limited. The reuse of each domain's tools and knowledge of these tools itself is very scarce as each study carries its own context, dependability, together with limited available time on the domain engineers' side. This is mostly a habit and cultural problem, as several methodologies like CMMI [6] and six-sigma enforce the benefits of corporate knowledge capture and reuse [7].

This paper enforces that interoperability must comprise a dynamic, recurring and adaptable effort for tackling changes, supported by a strong business knowledge [8]. However, flexibility to submit to all changes is not always desirable. Complying with a new concept may alter the delicate balance of the whole interoperating network. Therefore, it is essential to have a formal negotiation mechanism to deal with interoperability changes and factually support decisions on the best solution for compliance, to state that the benefit/cost ratio needs to support higher investment on a stronger interoperability, or even that interoperability in this case is not feasible or worthy.

3 Research Questions and Hypotheses

Following the performed research, the authors advance the following key open research question addressing the interoperability problems described previously:

- How can negotiations improve business towards achieving a sustainable EI?

Under this consideration, a set of hypotheses is enumerated:

- If businesses are served by dedicated entities that formalise decisions regarding interoperability, it will be easier to detect and correct divergences earlier;
- If business parties detect that changes need to be performed to be able to reach interoperability, negotiation is a good way to ensure success and the adoption of the best solution.

4 Requirements for Interoperability in the Work Environment

Driven by the outcomes of this research, the authors proceed to enumerate requirements considered essential for improving the interoperability between partners in a business-to-business relationship:

- Req#1: Interoperability should be taken into consideration from the very foundations of any business application;
- Req#2: Interoperability regards three logical layers (middleware, coordination and business logic), and all these should be covered;
- Req#3: Each party should clearly define and model its core business so that other interoperating parties can understand it;
- Req#4: The interaction between interoperating parties should be clearly defined and modelled;
- Req#5: Data models for each party should be clearly defined and available to the interoperating parties. These models should be standardised as well as the procedures to access data;

- Req#6: Each party should model its definitions and knowledge into one or more business-related ontologies and share it with the other operating parties;
- Req#7: Systems and applications should be adaptable to accommodate interoperability in businesses.

5 Framework towards Sustainability of the EI Environment

This paper proposes a collaborative framework for achieving a sustainable interoperability in a distributed environment, together with a methodology, in this case as it was submitted to the ESA-CDF business case (see Fig. 1). This framework is supported by a set of service tools that enhance collaboration and promote negotiations.

Literature refers several examples of methodologies to enhance interoperability, most focusing on the development of adapters, translators, even also using MDI [9]. While this approach is valid as it pertains acting solely in translating the interaction between two different entities, there are times the changes are too many and too profound, leading to the inability of maintaining interoperability.

The proposed approach aims to work in an earlier stage, determining the best solution to handle the existing problems, which means analysing and formalising the required changes, determining the pros and cons of each solution and then maturely and factually selecting the solution that best suits the purpose. Negotiations favour the analysis of alternative solutions, the adoption of new methodologies, models, semantics, or instead the creation of adaptors and translators, but especially, they motivate decisions supported by consensus of the involved parties.

The framework bases its interaction in the definition of a set of negotiation rules, supported by a negotiation model to formalise and register the negotiation interactions in a set of declarative rules, implemented in Java Expert System Shell (JESS, [10]).

5.1 Negotiation Model

Negotiations are sets of complex actions, some of which may occur in parallel, where multiple participants exchange and take decisions in multiple phases over a set of multiple attributes [11], [12]. The participants to a negotiation may define proposals, and each participant can decide autonomously to end a negotiation, either by accepting or rejecting the received proposal. Depending on its role in a negotiation, a participant may invite new participants to the negotiation. The negotiation services make use of negotiation techniques and negotiation model to determine the best alternatives for the negotiation.

The Negotiation Model is defined as a quintuplet $M = <T, P, N, R, O>$ where:

- T represents the time of the system, assumed to be discrete, linear, and uniform;
- P denotes the set of participants in the negotiation framework. The participants may be involved in one or many negotiations;
- N is the set of negotiations that take place within the negotiation framework;

- *R* characterises the set of coordination rules among negotiations that take place within the negotiation framework;
- *O* represents the common reference ontology. This ontology consists on the set of definitions of the attributes that are used in a negotiation.

A negotiation is defined at a determined time instance through a set of sequences: Let $Sq = \{si \mid i \in \mathbb{N}\}$ represent the set of sequences, such that $\forall si, sj \in Sq,\ i \neq j$ implies $si \neq sj$. A negotiation sequence $si \in Sq$ where $si \in N(t)$ is a succession of negotiation graphs that describe the negotiation *N* from its initiation up to the time instance *t*. The negotiation graph produced at a time instance is an oriented graph where the nodes describe negotiation phases present at that time instance (i.e., the negotiation proposals sent until that moment in terms of status and negotiated attributes) and edges express precedence relationships between negotiation phases.

This model covers formal and non-formal aspects of the interoperability, as they may be qualified and hence modelled in the framework in order to be able to be included in the negotiation.

5.2 Framework Architecture

The architecture that supports the negotiation framework performs the actions described on Fig. 2, satisfying Req#2. These actions, described as negotiation levels, are implemented by services as described on Fig. 4.

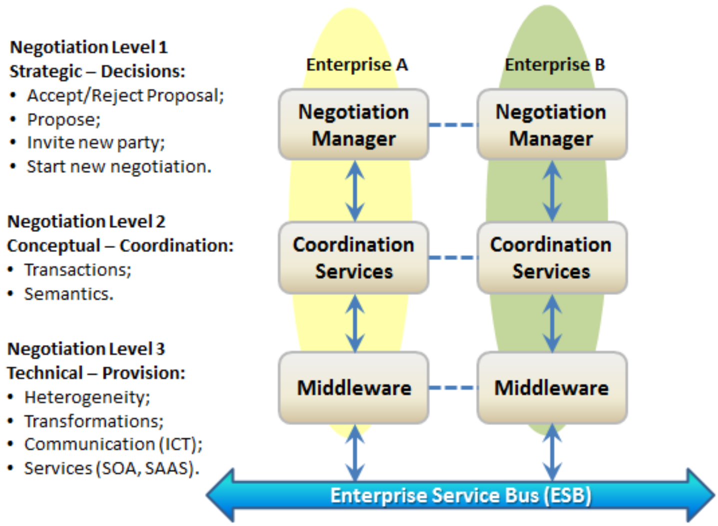

Fig. 2. Negotiation modules of the proposed framework

The proposed methodology started by filling a set of questionnaires that defined a qualitative classification of the business, as well as conducting interviews with stakeholders, to capture the business knowledge of each engineering domain. This knowledge was then modelled into a Model Driven Architecture (MDA) Computation-Independent Model (CIM), describing the business strategies, objectives and visions of each domain. This CIM layer can be split into two layers [13]: a Top CIM layer handles the strategic business functionalities, that are stable and conformant to requirements and needs ("as-is"), which include the interoperability needs towards other existing partners. The Bottom CIM layer handles the operational transients and the proposed changes towards new partners, additional self-improvements (due to e.g., adoption of new technologies, supported platforms, lessons learned and best practices) and new interoperability challenges [14]. This satisfies Req#1 and Req#3.

This model was then transformed into a Platform-Independent Model (PIM), which defined the flows and algorithms that rule each domain, while still maintaining platform independence, and defined specific domain ontologies. Finally, the PIM was transformed into a Platform-Specific Model (PSM), rules and code that implement the domain functionalities [15].

Similarly to the vertical transformations that are processed within the MDA approach, Model-Driven Interoperability (MDI [16–18]) operated at each MDA level performing horizontal transformations to allow the interoperability at each level, and where negotiations are settled, which complies with Req#4, as can be seen on Fig. 3.

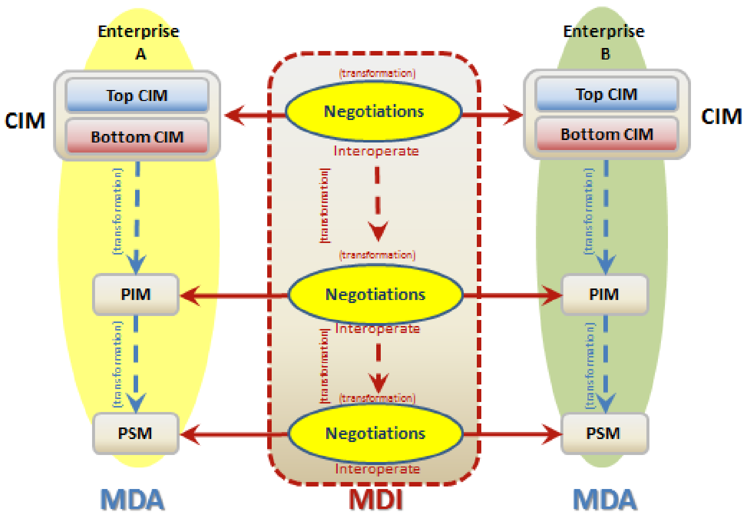

Fig. 3. MDA and MDI including negotiations

At CIM level the purpose was to harmonise the visions of each domain towards the common space mission purpose, defining policies, design strategies and hierarchies.

Then at PIM level, MDI performed black-box test specifications, negotiated and defined the common data model based on standards ISO 10303 STEP [19] and EXPRESS (ESA-SEIM [20]). It also performed negotiations towards the definition of a harmonised reference space ontology (ESA-SERDL [21]), implementing Req#5 and Req#6. These data models and definitions were then implemented in a virtual cloud infrastructure (Infrastructure as a Service – IaaS [22]) to deal with scalability issues regarding the data structure. Finally, at PSM level, negotiations are carried towards setting the middleware convergence and session handling.

The resulting PSM was then implemented as a set of flexible and dynamic services within the governance of a SOA [23], which were deployed as cloud-based services (Software as a Service – SaaS [24]). The whole infrastructure can be seen on Fig. 4.

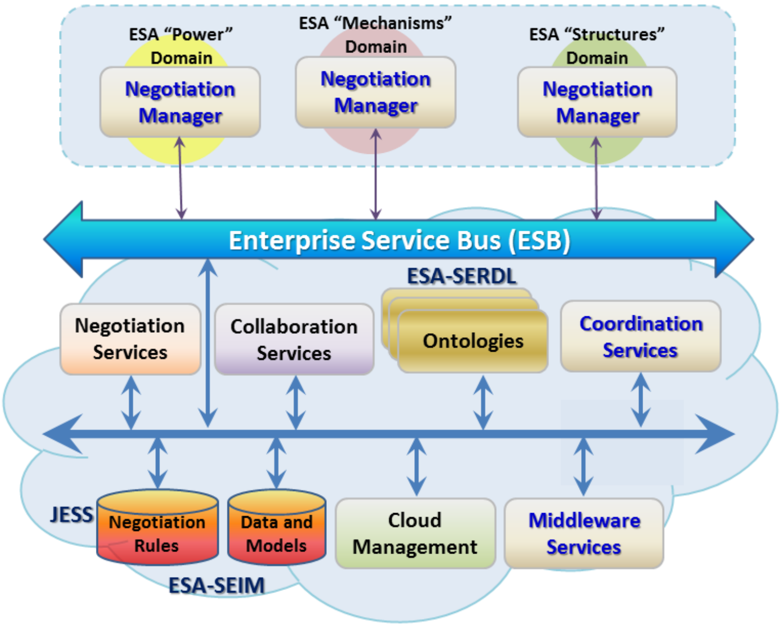

Fig. 4. Framework architecture applied to the ESA-CDF

The services that support the negotiations and the collaboration for interoperability have the same consistence and reasoning of the negotiation levels (Fig. 1), although the support for each MDA/MDI level is implemented in different abstraction levels.

The negotiation rules, as stated previously, were implemented in JESS and were inferred using the platform SWRLJessTab [25], [26]. The decision to implement these in a rule is justified by the need of flexibility and adaptability of the negotiation rules, criteria and evaluation methods, thus responding to Req#7.

6 Final Considerations and Future Work

Driven by the stated research question and the formulated hypotheses, the conclusions are that business interoperability is often developed over tacit knowledge, which in time gets fragile and has a large probability of breaking apart. The integration of a framework that provides formal procedures for modelling, storing and documenting the business activities and data contributed a great deal into achieving a stronger and sustainable interoperability. Furthermore, the adoption of formal methods for capturing corporate knowledge at domain level lead to an increase on the internal knowledge of each domain, and promoted reuse and establishment of best-practices.

Using the proposed framework, the detection of interoperability changes triggers the negotiation services to handle the reestablishment solutions, allowing the selection of the best solution by consensus of all parties. Hence, the authors conclude that negotiations when supported by a knowledge-enabled framework improve SEI. Particularly for ESA-CDF this led to less rework and fewer errors as the data is seamlessly interchanged between domains in a formal well-known and controlled environment.

The development of this framework is still conditioned to the improvement of issues that are still under research on MDI concerning the horizontal transformations in the various abstraction levels, and SOA, with issues still rising against service discovery and service composition and orchestration. Also a step must be taken towards the adoption of Cloud federation and improvements on the negotiation processes to avoid negotiation deadlocks.

Future work regards the assembly of the framework environment in the ESA-CDF facility, the comparison of business metrics before and after the change, and in the negotiation field, provision for each negotiating agent of a library of protocols.

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