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ORIGINAL PAPER

Modelling engineering interfaces in big science collaborations at CERN: an interaction-based model

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Abstract
In large engineering projects, the complexity of organizational and decision-making structures is a challenge for efficient management. Middle management plays a crucial and often underestimated role in the daily life of these complex projects. Our goal is to provide theoretical tools to seize the complexity of large engineering projects from the point of view of the human actors. An analysis of the organization of the ATLAS detector within the LHC at CERN was conducted over a period of several years. This contribution presents work on engineering interfaces in collaborative activities by showing how middle managers (mostly engineers) act as interfaces with other stakeholders and deal with complex socio-economic and technical issues. The interface model described is human-centric and aims at reflecting the complexity of engineering management situations. Different types of interactions stem from this model, as well as the exchange spaces established through the interface actor. The potential of application of the model is illustrated through two project case studies, one in the field of big science and the second one in high-tech medical equipment.

Keywords Interface modelling · Design collaboration · Big science · Mediation · Interaction · Middle management · Trading zones · CERN

1 Introduction

CERN is one of the most important representative of big science research infrastructure, whose history is marked with great achievements. And as for any of such endeavors, this is not only the excellence in terms of scientific performance, but also the quality, robustness and efficiency of innovative design and engineering processes that ensure its success. These engineering and innovative processes rely on the skills of thousands of engineers and technicians whose everyday work consists of establishing a constructive collaboration among themselves and with scientists.

> *"Here at CERN, we have a rather 'collegial' hierarchy and not an 'industrial' one with the boss sitting high up and the others far below him. The physicists at CERN can't do any experiment without engineers, designers, technicians & mechanics. On the other hand, the technical staff is of no use for CERN without the physicists. Most times the applied physicists work directly in a 'collegial' manner hand in hand with the technical staff on the experiment. It needs a bit of mutual respect and feeling for the professional proficiency of the others".*

With these words, a CERN group leader illustrated for a project engineer the complex relation between the physicists and the technical staff. The project engineer who belongs to the technical staff is a typical middle manager who has to face this complexity to achieve their daily work. The decision-making process entails thousands of small daily decisions that result of interactions and negotiations between physicists, engineers, technicians and project managers.

The middle managers at CERN are constantly acting at the interface between physicists, top management or sub-contractors but also technicians and operators. They are acting as a prescriber (superordinate) or as an executant (subordinate) depending on the situation. It also need cooperating with peers to achieve his work. These roles are

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deeply interwoven with the daily life of the middle managers who are constantly flipping from one role to another, sometimes experiencing them simultaneously in some meetings. The motivation of the present work is to propose a generic model of the interfaces at the level of the activity of the middle managers. This contributes to the understanding of the dynamics of the interface position of the middle managers. While not being specific to CERN, this question is partly the consequence of the CERN organization and management culture, as highlighted by the introductory quote.

As described here, the middle managers experience an interface position. Boundaries and interfaces have been studied extensively from diverse research perspectives for over 30 years. Indeed, as early as the 1960s, management science explored, analyzed and described in detail the main functions of boundary roles. Aldrich and Herker (1977) showed that, up to a certain extent, organizations can be described by their boundaries and the way in which they manage them together with their relationship to the environment. With a focus on innovation and technology transfer, Howells (2006) stressed the role of intermediation within the innovation process. This is of interest to our research since large engineering projects involve innovation processes. From the point of view of knowledge integration, Carlile (2002) considered boundaries as critical in new product development. This author suggested that innovative problem-solving across functions is both a challenge and a necessity. In their study of Japanese industry, Hong et al. (2009) recognized knowledge flow as an important factor in boundary crossing. Artefacts have also been considered as key contributors to boundary spanning (Lee 2007) (Subrahmanian et al. 2003), as they foster the transformation of processes and organizations by transforming the relationship (cognitive and physical) human actors have between them and with their colleagues (Laureillard and Boujut, 2002). More recently, O'Raghallaigh et al. (2020) showed that an in-depth communication (in terms of knowledge sharing) was facilitated by the presence of richer types of artefacts shared in the project.

In this paper, we aim to address the interfaces and boundaries from the activity perspective. As Paraponaris and Sigal (2015) advocated for a heuristic for creating knowledge through interactions, we propose to address the problem of boundary crossing by modelling interactions at the boundaries. These boundaries are, therefore, considered as the main object of our study. This approach is motivated by our focus on middle managers as a boundary spanner (Carlile 2004) in the context of large engineering projects involving very complex organizations and a large number of actors from very diverse fields of expertise. Particularly in large scientific collaborations such as the ATLAS detector at CERN or high-tech projects such as the MedAustron medical accelerator, which are both analyzed in this paper, the complexity of organizational and decision-making structures often puts the stakeholders in challenging situations. Action is hindered by a number of factors leading to a web of constraints beyond any one individual's control. In such complex decision-making contexts, the decision-making process relies mainly on middle managers whose daily job involves setting up compromises and trade-offs (Badawy 1995). The influence of middle managers is underlined by Floyd and Wooldridge (1997), who especially point out their mediating role and influence within a network. They are yield to turn strategy into reality as they manage diverse technical tasks while juggling with the contradictory forces at work in every organization (Floyd et al. 1992). These constant tensions require them to develop particular skills and strategies. They may have to present high-level strategic views one day and work on very focused technical problems the next one, while making sure they do not offend neither their hierarchy nor their team members. These skills can be referred to as translation or interface skills and are sometimes described in the literature as knowledge broker (Hass 2015). Indeed, most of the time, middle managers act as translators. They translate information from senders to receivers. Those involved may be superiors (superordinates), subordinates or colleagues. Middle manager translations must, therefore, consider the political, social and psychological dimension of the context while tuning the cognitive dimension to the correct level of their interlocutors.

1.1 The paradox of big science engineering projects

As it was underlined at the beginning of the introduction, big science projects in particle physics are based on collaborations rather than on hierarchically structured organizations. At the same time, the hierarchically structured engineering process must be followed for technical devices to be developed. As Knorr-Cetina (1995) points out, the decision-making process in large collaborations such as CERN is based on a consensually based agreement that is reached progressively as the object design and development process unfolds.

Engineering requires specific management rules: internal rules for participants and external rules for suppliers. It also calls for process management and information systems, all of which must be hierarchically structured. There is a considerable amount of literature in the field of engineering design dedicated to process modelling and management in industry. However, little research has been published on big science engineering projects (Minier et al. 2017). The organization of scientific collaborations and big projects generally requires on one hand a system engineering approach and a cross-disciplinary approach based on an "integrative theoretical framework" that describes the non-deterministic dimension of engineering on the other. This is especially true for large complex projects. Some research (Haque et al. 2003) highlighted that most modelling tools (e.g., BPMN or IDEF0) fail to cover concurrent engineering or integrated product development due to their lack of interest in human behavior issues or problems arising at the inter-individual and task level. Browning and Ramaseesh (2007) carried out a survey on the main process modelling tools and found that one improvement would be to focus more on activity interactions rather than on activities themselves. Sitton and Reich (2018) also underlined the importance of considering operational processes effectiveness in cross-enterprise collaboration in large engineering projects. Additionally, Clarkson and Hamilton (2000) recalled that process management relies on meta-knowledge related to task execution and the context of the task, which is seldom considered in classical modelling frameworks. The need to integrate actors in the modelling process has been raised by Hassannezhad and Cantamessa (2014). More recently, a simulation model proposed by Abdoli and Kara (2019) allowed to highlight the risk of design failures if the decisions are taken on an individual basis. This brings us back to the actor-based approaches supported by the actor-network theory: Kaghan and Bowker (2001) emphasized the complex interdependencies between actors and technical systems.

Although big science has succeeded in developing suitable and original political governance at high levels (Knorr-Cetina, 1995), the articulation between the worlds of physicists and engineers suffers from an apparent mismatch. Practices, management and modelling tools are all based on industrial requirements and the deterministic and somewhat rigid nature of the modelling tools used in industry does not meet the collaborative requirements of, for instance, large-scale particle physics experiments. Hence, there is a need to create a modelling approach to bridge the gap between the systematic modelling needed to ensure information consistency and process quality, on one hand, and the collective, consensual and collaborative nature of the scientific collaborations, on the other. This is the reason why our actor-centric approach focuses on modelling interactions.

The aim of this paper is, therefore, to present a model for the interface actor in engineering design situations at scientific facilities. We borrow concepts from management sciences, sociology and psychology and aim to explore and draw together the relevant concepts on which our conceptual baseline is built. Stemming from these ambitions, the model we have developed aims to be generic enough to be of potential use to stakeholders involved in any kind of large engineering project. This paper contributes to design science by providing an actor-centric model with a multi-scale approach for boundary spanning engineering activities for engineering activities spanning over boundaries and cooperation activities in large engineering projects.

1.2 Structure of the paper

This paper draws on a conceptual framework, presented in Sect. 2, which considers the boundaries and interfaces within organizations as key to understanding the collaboration dynamics at work in large engineering projects. Organizational science provides some very useful concepts for understanding boundary roles and boundary spanning mechanisms, while activity theory provides a modelling approach to activity systems taking into account the articulation between subjects and objects in collaborative activities. Based on these different approaches, we formulate our research question. Section 3 presents the basic theoretical components of the interface actor model, focusing especially on its elementary structure while, at the same time, linking it to the theoretical background upon which it is based. Complexity principles and the notion of interface play an important role in our model, together with the latest developments in activity theory and system thinking. Section 4 introduces our research approach on the CERN field and the overall empirical research process. As we adopted an inductive approach on a longstanding period, we have clarified the whole process. Section 5 introduces a case study to illustrate the complexity of the daily work of a middle manager and concludes by the implementation of one interface type in this configuration. From this, in Section 6, we have systematically and logically unfolded the model and discussed each possible interaction and the detail of the so-called "tripolar interface model" itself and the set of basic logical operations (transactions and translations) covered by it. This section also presents an analysis of the potential combinations of the model components. Section 7 comes back to the field and explores the implementation of the model in real industrial practice in the MedAustron accelerator project and provides a second test and validation case study. In this section, we show how the model was used by the project manager (one of the authors) to identify and deal with the organizational issues of his team. The conclusion explores the practical and theoretical implications of this work and suggests some follow-up research.

2 Conceptual framework and underlying concepts

Collaboration throughout the engineering design process has been studied extensively. As stated above, our focus here is on middle management issues arising when collaboration between heterogeneous actors is required. This work draws considerable inspiration from authors having underlined the importance of boundaries, interfaces and interface actors (Sect. 2.1). Indeed, the middle manager can be seen as a node in a network of interactions. Our approach to the concept of interaction stems from activity theory and the work done on the design of complex systems (Sect. 2.2). Since activity theory considers the interconnections between artefacts and humans or between humans through artefacts, it recognizes the need for interfaces to create shared understanding between stakeholders. Section 2.3 introduces our research question.

2.1 Interfaces, boundaries and the interface actors

In 1995, Finger et al. presented the concept of the interface as key to the integration of both the technical and organizational dimensions of concurrent engineering. Although, today, research and practice have gone far beyond concurrent engineering principles, it is important to remember that as early as the late 1990s researchers were aware of these issues and proposed solutions to improve design environments.

The notion of boundary in organizational science has long been explored. In the late 1970s, researchers pointed out the importance of this notion as a characteristic of organizations. Aldrich and Herker (1977) highlighted that the role of boundaries is to prevent information overload and facilitate information filtering and transmission but also to absorb the uncertainty of environmental constraints. Later, authors focused more on boundary crossing (Tushman and Scanlan, 1981). Individuals seen as boundary spanners were studied and their perceived competence or communication skills were considered to be more powerful predictors of their ability to cross-boundaries than their formal status. Floyd and Wooldridge (1997) highlighted that translation strategies are a mean for middle managers to engage in strategic influence activities. Carlile (2002) considered boundaries from the knowledge point of view and adopts a pragmatic approach from empirical observations. He stressed that knowledge is also embedded into technology and objects as well as into practices. But more importantly, his three-level model emphasizes the complexity of the boundary crossing mechanisms (Carlile 2004). The pragmatic level considers the cultural dimensions of knowledge (technical or scientific cultures, working routines, etc.) highlighted in the quotes above; the semantic level addresses the translation issues that make the message sometimes ambiguous or unclear to the different stakeholders; and finally, the syntactic level of knowledge transmission considers the vehicle of the message itself (i.e., the form and syntax). Eventually, McGowan et al. (2013) calls for the creation of a dedicated "interface dynamics engineer" whose interface role is clearly dedicated to deal with social, political and technical dimensions of the complex engineering interfaces. The middle manager in large engineering projects is typically an interface actor that acts as a boundary crossing facilitator.

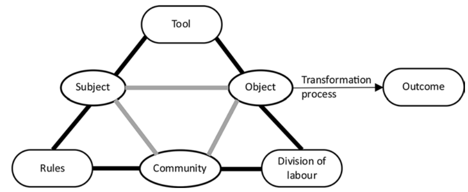


Fig. 1 Basic structure of an activity system (Engström 2000)

2.2 Activity theory

Activity theory introduces the concept of mediation between the subject (person) and the object (the task being performed). Engeström's model (Engeström et al. 1999) depicts the activity as a structure (activity system) based on the mediated action of a subject (the designer, in our case) directed towards an object (the aim of the action). The result is an outcome, which here may be a decision, a CAD (Computer Aided Design) model, a simulation result or any other artefact. In a revised version, Engeström (2000) enriches his previous model by introducing the notion of community. Furthermore, activity theory considers an activity to be part of a process that is highly dependent on the context. Based on the notion of activity system, Engeström's 2000 model has become a classical reference (Fig. 1).

An activity system is considered to be the minimal meaningful context needed to understand an action (Kuutti 1995). The approach, therefore, focuses on individual actions or, more precisely, adopts an actor-centric vision of activity. This means that the collaborative dimension of interactions cannot be easily identified with this kind of model. Yet, interactions are of prime importance if we are to understand the relationship between the actor, the object of the activity and the tool (or instrument) being used. In this paper, the authors focused on the link between subjects and communities. In our model, the community is regarded as a set of subjects mutually interacting (e.g., subordinates, superordinates and peers). One of our aims is to depict typical interaction patterns in the case of large system design projects. In our interaction-based model, the studied interactions happen between subjects in a community where the division of labor is complex and highly dynamic, as reflected in the design and integration activities described in the case study sections (Sects. 5, 6).

In his attempt to model system thinking, Moser (2014) proposes an interesting approach in which Engström's activity models are projected into an activity system network. In chapter 3 of his book, the author adds a multi-scale dimension to the activity hence introducing layers (or levels) of action (e.g., individual, team, etc.). This approach is very helpful when attempting to grasp the complexity of large engineering projects. More specifically, it addresses the same kind of research questions as those presented in the

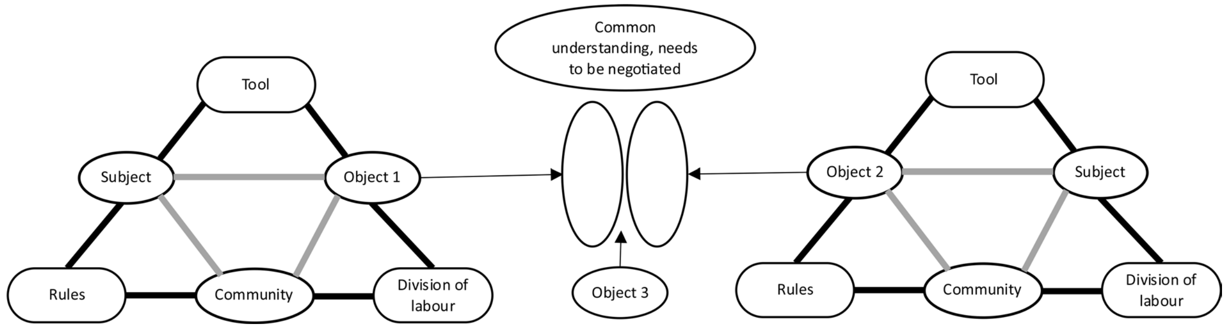


Fig. 2 Activity system interaction at a boundary zone (Moser 2014)

next section. Additionally, the model highlights boundary zones between activity subsystems (Fig. 2).

2.3 Research question

As highlighted by Moser (2014), when there is a contradiction inside an activity system, between elements of an activity system or between different activity systems, a boundary appears (Fig. 2). We propose to focus primarily on the boundary and to model interactions starting from these boundaries.

Activity theory also concentrates on the triadic relationship between a subject, an object and a tool. As already mentioned, in their seminal research work, Kuutti (1995) and Engestrom (1987) carefully document the relations between the subject and the object of an action mediated by a tool. Interactions between several subjects are considered to occur through mediations and the creation of a shared understanding of the context, task and object of the task (Carlile 2004). This point of view is supported by the team mental model developed by Badke-Schaub et al. (2007).

However, these models do not account for the dynamics of the creation or evolution of the boundaries, as defined by Moser (2014) or described by Carlile (2002). Our observations show that a particular role (or position) emerges in these situations to bridge the two sides of the boundaries. This role is played by an actor (mostly a middle manager) who temporarily adopts an interface position (McGowan et al. 2013).

Our research question can be formulated as follows: *how do interactions occur between middle managers and other actors involved in engineering subprojects in the field of particle physics?*

In other words, is there a generic model that could describe the interface position of the middle manager that allows to embrace all the complex interactions that occur during the course of a large engineering project in the context of CERN?

Furthermore, the three levels model defined by Moser (2014) that shows discontinuities between the levels (individual vs. team) can be replaced by a model introducing some continuity between individual, team, corporate and inter-organizational levels. Our actor-centric model, where the actor can be an individual, a department or a company, intends to capture these different levels. In what follows our tripolar interface model shall be presented and shall be documented through two case studies where it was used as a management tool.

3 Building the tripolar interface model

3.1 A theoretical model of the interface actor

In any design process, an interface may occur between two actors (Fig. 3). Each actor is a subject (in the activity theory sense), holding specific knowledge and skills (community of practice), belonging to an organization (team, department, company, etc.) and working on a given subsystem. Activity theory considers that, inside an activity system (Moser, 2014, p. 131), when a contradiction occurs, this contradiction is resolved through direct interaction between the two actors. This interaction creates a common shared object (and by extension a shared representation), which is different from the original individuals' objects. A boundary appears when there is a disjunction (or a contradiction) inside the system or between systems (Fig. 2). Our observations reveal that

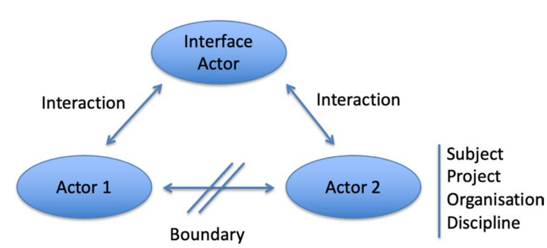


Fig. 3 General configuration of an interface

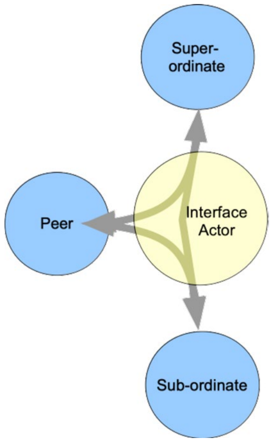


Fig. 4 The three ways of interacting: up, down, and middle out

frequently a third actor acts as an interface to solve this disjunction; this was also shown by previous works described in Sect. 2.1. Thus, a triad is formed involving complex translations between actors. This is also underlined by Moser (2014, pp. 223–224) when he reports a discussion involving three persons, one acting as a facilitator who is aware of the conceptual framework of the other two actors and who helps creating a shared understanding of the context. Our approach to design interfaces (as a proposal to solve our research question) is thus tripolar and shall be described in detail in what follows.

3.2 Three ways of interacting

Based on these premises, whatever the point of view adopted with respect to the organization or regardless of the focus on any actor or group of actors considered, it can be assumed that any actor may *interact in only three ways* (Fig. 4): "what I am asked to do" (up); "what I actually do" (middle); and "what I request to be done" (down).

(The generic verb "to do" is being employed here on purpose since the type of action considered is not specified at this stage).

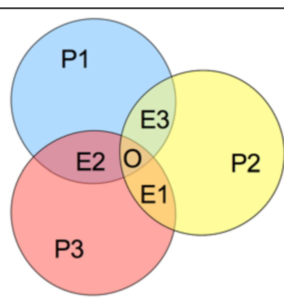
These terms correspond to the three categories of identified stakeholders: those who ask me to do (e.g., superiors, superordinates, supervisors, project managers or clients); those with whom I do (e.g., peer companies or organizations, peers, colleagues or partners); and those to whom I request to do (e.g., subcontractors, operational subordinates, performers or suppliers). Within the context of professional action, these three elementary ways of interacting are here considered to encompass all the other more complex interaction models found in the literature (Sect. 5).

3.2.1 Basic description of the tripolar cell

Now that the underlying concepts have been exposed, let us now address the question of interaction modelling. Is it possible to treat the three directions (up, down, middle out) in a generic way and if so, how? To answer this question, we propose to define the two elementary interaction components, *translation* and *transaction* and to implement these in a structured way.

Assuming any actor can be represented by a tripolar cell. This cell is basically composed of three poles that represent the three elementary ways of interacting previously introduced: "what I am asked to do" (up); "what I actually do" (middle out); and "what I request to be done" (down). This model or elementary cell takes the basic topological form displayed in Fig. 5.

In addition to the three initial areas represented by the circles, their interpenetration forms a number of distinct areas created by the topology: a central triangle (with convex sides), O, referred to here as the *core* of the actor; three interacting *poles*, P_1, P_2 and P_3; and three (bilateral) *exchange spaces*, E_1, E_2 and E_3. The core of any actor can be linked to the core of another actor via one or the other of the actor's interacting poles, P_i, and the corresponding pole of the other actor, through the exchange space E_i with the same index i.



O: actor "core"

E_i: bilateral exchange space

P_i: interacting poles

- P_1: "what I request to be done"
- P_2: "what I actually do"
- P_3: "what I am asked to do"

Fig. 5 Interface model elementary tripolar cell

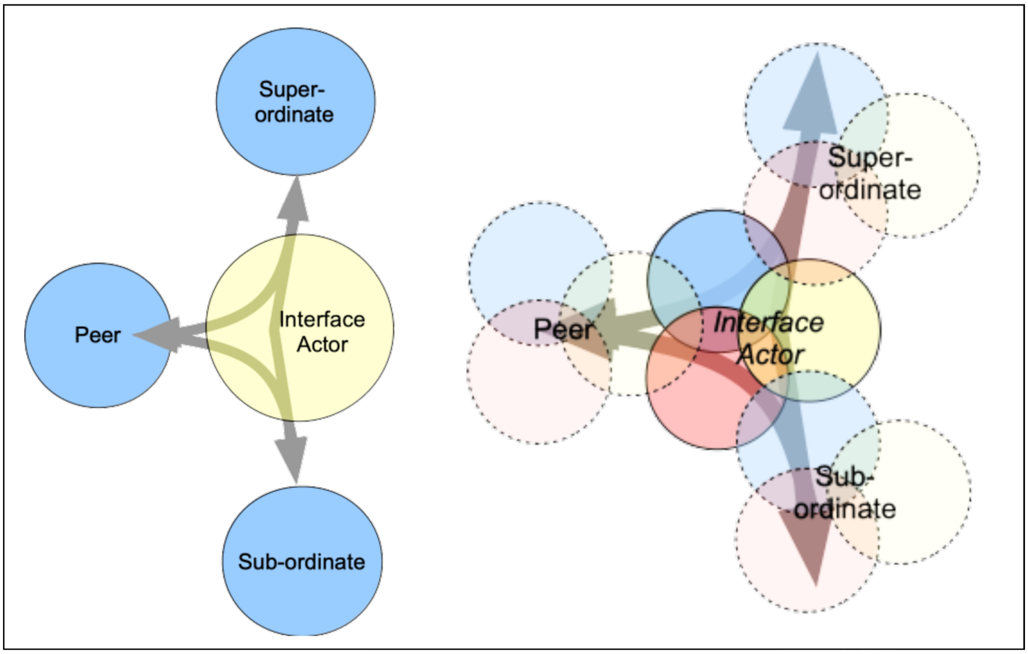


Fig. 6 Correspondence between the three ways of interfacing (left) and the tripolar interface model (right)

These exchange spaces, $E_{i,}$ are the channels through which the exchanges occur. Each channel entails a different type of operation, because the requirements are different in each case. For example, whether an engineer needs to forward a request from its hierarchy or line management to the team they lead, or whether the same engineer has to report to their superior on one of the ongoing projects carried out by their team, the communication requirements for each case are not the same and therefore, the translation operations differ. The common point is that, in both cases, the engineer holds the position of interface between their superior and their team.

The direct transmission of a message is rarely possible since the aim of the communication differs depending on the channel used. This is the reason why interfaces are required and also why all the actors in an engineering organization are potentially all in an interface position. To reflect this situation, a model can be adopted where the tripolar mesh represents the substrate upon which the messages will be transformed and exchanged. The communication framework therefore involves a sender, a receiver and an interface hence making up the afore-mentioned triad (Fig. 6).

In this triad, for instance, the interface actor is connecting its P_2 with the P_2 pole of its peer through the exchange channel E_2 of the interface actor, and so on.

This theoretical model has been jointly co-developed, refined and implemented with a constructivist approach. It will be described in more details in Sect. 5 after our research approach will have been clarified in Sect. 4.

4 Research approach and method

Our methodological approach is based on a longitudinal empirical study (Yin 2009) and applies constructivist theory (Avenier 2010). We used direct participant observation as part of our ethnographic exploration (Bucciarelli 1994) and adopted a reflexive attitude (Schön 1990) in the field. This means that the first author, who is part of the CERN technical staff, acted as an engineer while conducting the research. During this period, he has successively or simultaneously been the engineer in charge of the integration of the whole ATLAS detector (case n°1, not covered in the present paper) and the project leader of the Feet & Rails support structure (case n°2). The observations spanned over a period of approximately fifteen years. The first observations took place in the late 90 s and the theoretical models appeared in the middle of 2000. The model was tested on the MedAustron project (case n°3) in the beginning of 2010s. Along this period, interviews and document analysis (particularly e-mail exchanges, field notes and other written documents) served as a basis for backing up our research with evidence. This material has been collected. The framework used is the "dialogical model" proposed by Avenier and Cajaiba (2012). This model allows the research question, relevant for both academia and industry, to be built in five steps:

1- Identification of the research gap and the research question. This step was achieved following an analysis of the Feet & Rails project (ATLAS detector project at LHC at CERN) between 1997 and 2004. The field study was backed up by a literature analysis that brought to light a number of specific aspects pertaining to large collaborations and revealed a research (and practical) gap in modelling tools (e.g., BPMN, Business Process Modelling Notation).
2- Building of local knowledge. This step applied to the entire study since 1995 but is not entirely described in this paper for the sake of clarity and concision. The knowledge built allowed local results regarding several aspects of the project to be put into practice by the research team. Notably, the BPM (Business Process Modelling) tool was enriched and management of the Feet & Rails and MedAustron projects improved. This was part of the daily work of the first author along the research period.
3- Construction of conceptual knowledge. This was achieved by combining important findings in the fields of organizational or cognitive sciences as part of an interdisciplinary approach.
4- Communication of knowledge. This was ensured through a PhD thesis, conference papers, a chapter of a book (in Boisot et al. 2011, chap. 9), internal seminars and numerous lectures.
5- Activation of knowledge. This was done in various settings and is still ongoing. It is illustrated in this paper through the MedAustron project case study, where knowledge was transferred from particle physics accelerator technology to medical applications for tumor treatment (hadronic oncology).

To sum up, the case studies engaged the researcher–practitioner (Coghlan 2007) in a longitudinal study lasting several years during which one of the authors was immersed as a project manager in the organizations. These circumstances made it possible to define the research question and the theoretical gap leading up to it. They also offered the conditions for implementing the results of the research. The first case study (ATLAS) helped us to frame the problem, while the second (MedAustron) was used for validation purposes.

5 The ATLAS Feet & Rails case study

Here, we explore a case study that was at the origin of the model and that illustrates two important interfaces. We show how these models are related to the empirical situation. These two interfaces are two configurations of the general model presented in Sect. 4.

5.1 The LHC ATLAS detector: complexity at work

The Large Hadron Collider (LHC) at CERN on the French-Swiss border near Geneva is considered one of the most complex, science-serving engineering endeavors achieved in particle physics. The sophistication extent of this engineering system can be grasped with the help of some figures. In order for the energy of the accelerated proton beams to reach center-of-mass 14 TeV energy, a 27 km circular collider was designed. Among many other types of components, the accelerator is made of large superconductor magnets at a temperature of 4 K, providing the 9 Tesla magnetic field used to bend the trajectory of the particles (Bruning Collier 2007).

ATLAS and CMS are two of the four particle detectors installed at LHC. When these were designed, one of their aims was to detect the famous Higgs boson, whose discovery was announced in July 2012 (ATLAS Collaboration, Aad et al. 2012). In 2013, this led to the Nobel Prize in Physics being jointly awarded to François Englert and Peter Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."*[1] along a period of about 15 years of professional life. Table 1 shows the timeline of the research project.

The ATLAS detector is a huge piece of machinery (ATLAS Collaboration, Aad et al. 2008), which consists of an impressive cylindrical structure of more than 40 m long, 25 m in diameter and weighing approximately 7000 tons. It is housed in a cavern 100 m below ground (Fig. 7). The detector is made of several subsystems, including a complex of superconductive magnets for the muon spectrometer and the inner tracker. At most, each proton beam crossing provides up to tens of collisions every 25 ns, which produces a huge amount of data that requires sorting, storage and analysis.

The engineering complexity matches the scale of the equipment. The design phase had to take into account not only the objects themselves but also their interconnections, support equipment and electrical and fluid feeding systems, together with their handling, maintenance and all phases of their lifecycle including future disposal. The engineering fields involved in the project ranged from civil engineering to electronics and control, while other fields such as mechanics, cryogenics, magnetic engineering, specific handling, cooling and ventilation, electrical engineering and geometrical surveying also participated. The specifications of the information system needed to support the designed

[1] https://www.nobelprize.org/prizes/physics/2013/summary/

Table 1 Timeline of the field involvement

Dates	CERN, LHC, ATLAS	First author at CERN	Cases studied	
1992	October: Charpak Nobel Prize	October: arrival at CERN as fellow		
1993	US project SSC cancelled			
1994	Approval of LHC project ATLAS Technical proposal	December: first engineer of the ATLAS Technical Coordination	Case n°1 ATLAS Integration	Case n°2 ATLAS "Feet & Rails" Project
1995	(First anti-atoms)	Start as integrator	X	
1996		Head of design office	X	
1997		ATLAS "Feet & Rails" project leader	X	X
1998	ATLAS TDRs (Technical Design Reports)	Start of research project	X	X
1999			X	X
2000	LEP stops	End as ATLAS integrator	X	X
2001				X
2002	LHC installation starts	End as design office head		X
2003	ATLAS: start of cavern installation			X
2004	LHC: first cryodipole	January: hand-over of Feet & Rails		X
2005				
2006	LHC: last cryodipole	Other activities for CERN (LHC installation, CLIC studies, PDM)		
2007	10 September: 1st beam in LHC		Redaction of the cases	
2008	19 September: incident at LHC		Elaboration of the tripolar model	
2009	LHC repair	WP holder « integration» for MedAustron project		
2010	October: LHC restarts		Case study n°3: MedAustron Integration	
2011	March: physics starts			
2012	July: Higgs discovery	End of research project		
2013	Higgs and Englert Nobel Prize			

CoPS—Complex Products and Systems (Hobday et al. 2000)—were quite challenging.

From an organizational point of view, big science projects in particle physics are based on collaborations rather than hierarchically structured organizations as stressed in the introduction. Chompalov et al. (2002) studied 53 multi-institutional collaborations in physics and allied sciences. They found that the major type of organization in particle physics is participatory and non-bureaucratic. According to Genuth et al. (2000), when faced with the incredible complexity of the experiment they wanted to build, the ATLAS physicists had to reconsider their position with respect to engineering projects: "*Particle physicists, building the first-time projection chamber, reluctantly and resentfully conceded that they had to abandon their role as patriarchal masters of their engineers. Instead, they created a power-sharing arrangement in which engineers managed construction and were entitled to veto physicists' ideas when they threatened the budget or schedule.*"

The ATLAS Collaboration is a good example of the complexity of a scientific organization specializing in particle physics. It involves almost 3000 people, over 140 laboratories, universities and research organizations from nearly 40 countries and more than 40 funding agencies around the world contributing to the Collaboration. It is organized as a federation of projects. Each subsystem and each activity are represented within the Executive Board, which acts as a kind of government and meets at least monthly at the invitation of the Spokesperson, the Technical Coordinator and the Resources Coordinator to discuss and make decisions on operational issues. The Technical Coordinator also runs a Technical Management Board that consists of technical subsystem representatives (project managers or project engineers), while the Resources Coordinator prepares the quarterly meeting of representatives of "funding agencies" to deal with financial issues. The Collaboration Board acts as a kind of parliament and deals with relations between institutes, while the Plenary Meeting brings together all collaborators as a kind of direct democracy forum.

The ATLAS top manager is neither called a President nor a CEO or even a project manager. It is very revealing of the spirit of these collaborations that the official title of the person who is elected leader of the collaboration is a "spokesperson" without, in fact, any direct authority over the thousands of physicists and engineers working on the project. First of all, the spokesperson is not nominated but

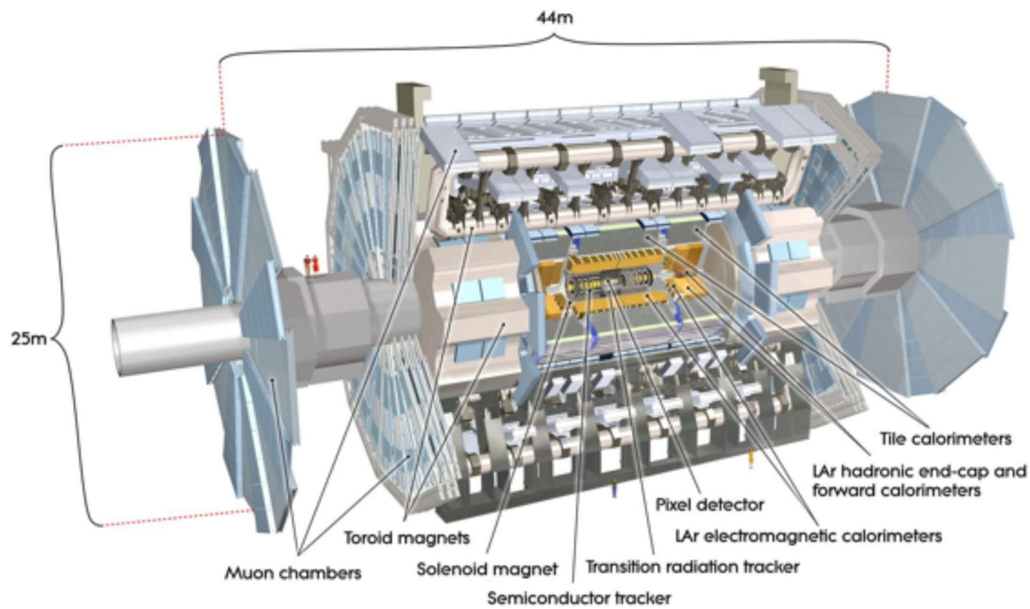


Fig. 7 A simplified 3D view of the ATLAS detector

elected by the Plenary Meeting, i.e., all the scientists gathered together. The role of the spokesperson is to delegate or "to guide smoothly" and upon request of the heads of subsystems or coordinators of activities and to exert arbitration in case of disagreements. The spokesperson leads the ATLAS Collaboration primarily by organizing discussions and rational justifications rather than controlling and directing. Important decisions are almost always taken by consensus and the organization's decision-making generally can be described as consensual and participatory (Chompalov et al. 2002). In accordance with the spirit of collaboration, the leaders and managers are called project coordinators. Scientists occupying these management positions promote horizontal coordination between the numerous institutions and the activities inside the collaboration, rather than establishing a kind of supervision leading to hierarchical relationships with their colleagues.

Based on an interesting form of coordination, this management style raises new and challenging cooperation and decision-making issues (Boisot et al. 2011, chap. 1). The managers at every level of the organization need to develop interface skills for processing information in various ways to ensure that their team members gain a common understanding of it and so that the right decisions are made. A study by (Boisot et al. 2011, chap. 3) in the field of strategic management shows that this management style may prove to be very efficient, even for projects in more conventional hierarchical organizations. Such "participatory collaborations" (Chompalov et al. 2002) seem to be an alternative form to the model of "adhocracy" proposed by Mintzberg

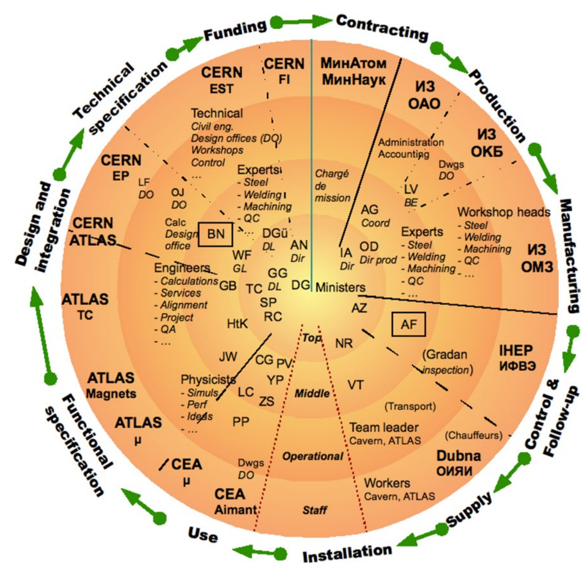


Fig. 8 Concentric model of the network of actors involved in the ATLAS "Feet & Rails" subproject (ad hoc representation)

(1978). This participatory model has certainly inspired the interface model proposed in this paper.

5.2 The "Feet & Rails" ATLAS subproject

One of the ATLAS subprojects is the main supporting structure called the "Feet & Rails" project. This is a large mechanical assembly consisting of 450 tonnes of non-magnetic stainless steel welded together with sub-millimeter accuracy over a distance of several meters. The purpose of this structure is to withstand and guide the movement of thousands of tons of ATLAS detectors and magnets.

This project was the subject of an in-depth case study (Boisot et al. 2011, chap. 9), which led to the drawing up of a map (Fig. 8) representing the relative position of the project's various stakeholders. The map sets out all the hierarchical levels of the organization and situates the various actors involved. All the actors are located around the center of a disc representing the project itself. Each radial sector corresponds to an organizational structure working on the project. The disk-shaped representation is composed of four concentric rings corresponding to the hierarchical levels considered in this model (as indicated in the bottom radial sector): top management (closest to the center), middle management, operational management and finally, in the outside ring, the executors represented collectively by the name of their employer. The intersection between a radial sector and a ring contains an actor or a group of actors, defined both by their approximate hierarchical level and by the organizational unit they belong to (outer ring in Fig. 8).

Around the disc, arrows indicate the schematic lifecycle of the project, starting from bottom left with the functional specification of the need, and ending with use of the structure by the ATLAS physicists. These scientists were partly at CERN and partly in other scientific organizations such as the French atomic energy agency CEA (*Commissariat à l'Énergie Atomique*), where the team in charge of the toroidal magnet supported by the Feet was located. Based on the scientific needs, the technical specification (requirements) served as a baseline for the design developed by the CERN Design Office (led by "BN" in Fig. 8), which was also managed by the ATLAS Feet & Rails project leader. The project was funded through an in-kind contribution of Russia to the ATLAS Collaboration. The funds actually came from Russian ministers, who selected a Russian company called Izhora (IZ) to carry out the manufacturing of the Feet & Rails. This phase was monitored mainly by a Russian scientific institute (IHEP, Institute of High Energy Physics), which was a member of the ATLAS Collaboration. The physicist in charge of the monitoring and successful completion of the structure (represented by "AF" in Fig. 8) also on the behalf of the Russian government was a staff member of IHEP (see a more in-depth description in ATLAS Collaboration, 2019). Installation was supervised by the ATLAS Technical Coordination team.

This figure shows that one of the middle managers (BN here) was in an interface position, which meant he had to deal with complex socio-economic and technical problems, as was equally his Russian counterpart AF. This interface position obliged both of them to process information in various ways before communicating it in different directions: not only up and down, but also laterally.

This concentric model illustrates the necessity for the middle manager to move and circulate across the web of different actors covering the whole surface of the disc. This especially concerned the CERN project leader and the Russian mediator. They both interfaced not only together on an almost daily basis, but also with their peers in the middle managers' ring and with actors in the top management ring, sometimes simultaneously to establish and regulate the organizational context within which the project unfolded. They also interfaced with the operational management ring since actions in the field had to be supervised and followed-up to ensure quality control, efficient data and document management, which meant they could be in contact with the design offices, the various workshops or the ATLAS cavern technical installation team.

The aim of the interface model proposed in this paper is to provide a tool to better characterize and represent how this organizational web works and to offer a way to coordinate the project based on an overall picture of the dynamic exchanges between all the actors during the lifetime of the project.

5.3 Situation example: interaction between a superordinate and a subordinate

We shall now consider the detailed mechanisms of the exchange taking place at the interfaces. To illustrate one of these types of interfaces, we shall take the typical case of a superordinate (A) and a subordinate (C) exchanging through an interface actor (O) (shown in Fig. 6). This situation is very common in projects, as illustrated in Sect. 5.1 by each relationship along the radial axis of Fig. 8. It is the kind of situation that occurs when a middle manager has to connect an actor from an outer circle with an actor from an inner circle, at any point in the circle.

5.3.1 Empirical situation

As an example of the situation introduced in Sect. 1.1, here is the message sent by the project leader BN (here acting as the interface actor *O*) to the designer in charge OJ (as subordinate *C*), reporting the compromise found in a meeting with the Technical Coordinator (as superordinate *A*) and giving instructions on how to proceed further with the design.

> BN to OJ, August 7th 2002– *We came to a compromise. In a nutshell: we adopt the principle of the bottom of our solution (by making it rectangular and no longer cylindrical); and we provide a horizontal surface at the level of the connection to the coil casing. I leave on your desk some sketches that I prepared in view of seeing what it looks like.*

This interface also operates in both directions, *i.e.* it shows the flow of the top-down instructions (orders, specifications, requests, etc.) sent by the superordinate (BN) to the subordinate (OJ) and the bottom-up information feedback (reports, indicators, results, questions, remarks, etc.) received by the superordinate from the subordinate. In this section, our tripolar model will help us explain what happens at the interface to ensure correct interaction.

To illustrate further on, let us take a second example from the ATLAS project where superordinate (*A*), i.e., the Technical Coordinator, asked the Feet & Rails project leader (*O*) to come up with a set of definition drawings to be approved by the final users. The project leader (*O*) asked a designer (*C*) to proceed with the execution of 3D models and 2D drawings according to certain rules and design principles and considering a set of design requirements. In turn, the designer (*C*) sent reports on the completion of his work or requested additional instructions along the process. When such requests fell outside of the project leader's (*O*) decision-making scope, for example when they concerned the introduction of a new material or an increase in space, they had to be escalated to the Technical Coordinator (*A*).

Sometimes during this project, the Technical Coordinator's (*A*) instructions were directly transmitted by the project leader (*O*) to the designer (*C*), because they could be directly understood by the designer, on a commissioning mode (see later Fig. 9, Sect. 5.3.2). In some other cases, the instructions needed some explanation or clarification, for example when the requirement was based on functional needs or when physics needs were not understandable from the designer. Transforming these needs into mechanical requirements demanded further guidance from the project leader. For instance, a question arose once concerning the reason why the material of a girder from the supporting equipment may have to be changed. OJ is the designer in charge (*C*), CG and LF are physicist from an external research center working on the design of the muon spectrometers (*A*). BN is the project leader (*O*). These emails are translated from French.

> OJ to BN (13th November 1998): *BN, I do not understand, we are already short of space, they want less material and they ask to change the [so-called] voussoirs' material from stainless steel to aluminum alloy. But with a 5083 alloy, I will lose almost a factor 3 on the mechanical properties, so the voussoir will be much higher to get the same inertia. My first calculation shows we have to make it about twice higher. Explain me, because they always fight for space, and now they ask us to make something bigger??*
> BN to OJ: *This is something to do with the hadron physics, I will investigate and come back to you.*
> BN to CG: *Dear C, I have just received the minutes of last magnetic field meeting held in October and I have a question. Let me quote:*
> *2) Impact of additional magnetic material, inside or outside the muon spectrometer: The effect of some structure elements (bedplates, forward chariot, neutron shielding...) has already been estimated in term of their impact on the field integral B dL [see below] (see Dubna note of 25th October 1997). It is quite alarming (not at all negligible) and some action has to be taken:*
> - Their impact on the muon track sagitta has to be calculated instead of the field integral which could be concentrated near the end of the trajectory.
> - […]
> CERN should provide them with the feet drawing, an estimate of the size of the weldings and the magnetic properties of the stainless steel.
> *Of course I will forward you the feet drawings (we hoped we had them already finalized, and I see that further investigation is required, "c'est la vie"...), and we are working on estimating the impact on changing the material of the voussoirs from stainless steel welded beams to 6082 casted or maybe another aluminum alloy that would be forged. But the impact on design is not negligible either, and actually OJ reported to me that the new design would lead to much more material (and taking more space against the BIL chambers), so where is the balance? On the weldings of the stainless steel, are you really ensitive to their magnetic properties, this is quite a local thing, no?*
> CG to BN, cc LF (15th November): *BN thanks for your question. This is linked to the integral of BdL. The radiation length of the aluminum is much smaller than for stainless steel. As I explained in the meeting, the radiation length characterizes the energy loss of the particles electromagnetically interacting with it, and it is related to the ratio between the atomic mass number and the atomic number (the formula is a bit more complex). The lower the radiation length, the further the particle goes through. And given that the stainless steel is highly alloyed with nickel and chromium, the X0 [radiation length] is way higher than for aluminum. I can give you the exact number but really, we prefer to have 5 times thicker aluminum parts! The position is also quite important: the struts of the warm structure of the barrel toroid can stay in stainless steel because their impact is much smaller: where they are, the muons already passed two of the three muon spectro stages.*
> LF to BN (16th November): *BN, to add up to CG's answer, the idea behind is the same for the welds, but more locally for the perturbance on the path of the*

particle, this can introduce errors on delta P over P which is really a problem. Can you work this out? Would be very important for the field quality! After all, this is for the physics that we are all working, pas vrai*?*

The explanation given by the LF and GC was to decrease the "integral of *BdL*" to avoid introducing disturbance too early along the particle's path as it moved away from the vertex (interaction point between the proton bunches). The famous radiation length quoted by CG was the key: not linked with the quantity of material but with its influence on the particles at the level of the nucleus! This is a good example of a mechanical design requirement stemming from particle physics. As per the welds' design, it led to many specific requirements on the ferrite level of the filling material and the discussions involved not only the welding engineers of the Russian subcontractor but also even the manufacturer of the welding wire, that ultimately developed a specific product for this application (a sub-case on its own, leading to cascades of translations all along the process).

The question is how the connection was established between CG and LF (*A*) and OJ (*C*) and what the role of BN (*O*) played at the interface. Let us come back to our tripolar model.

5.3.2 Mediating and commissioning interfaces

The interface formed is either a *commissioning* interface in the first (direct) mode (Fig. 9, left), or a *mediating* interface in the second (indirect) mode (Fig. 9, right).

In our tripolar model, in both cases, the interactions will follow a path through the various areas crossed from the core of actor (*A*) (emitting the message): the path starts at pole P_{3A} then moves into (bilateral) exchange space E_3 until it reaches the core of interface actor (*O*) (transmitting the message). The path then exits through exchange space E_1 before joining the core of actor (*C*) (receiving the message) through pole P_{1C}. The difference between the commissioning interface and the mediating interface emerges from the different inner paths between the various poles of interface actor (*O*). Let us describe these two different paths.

5.3.2.1 Commissioning interface Let us consider the case of a statement (*e.g.,* an instruction, order or request) travelling from (*A*) to (*C*) (Fig. 9, left) through (*O*). The global interface is composed of an inward transaction from (*A*) to (*O*) and an outward transaction from (*O*) to (*C*). These two transactions (inward and outward) are represented in Fig. 9 (left) by two arrows S_i: the arrow S_3 models the transaction between (*A*) and (*O*) from the pole 3 of (*A*) to the core of (*O*) (through the exchange space E_3), and the arrow S_1 models the transaction between (*O*) and (*C*), from the core of (*O*) to the pole 1 of (*C*) (through the exchange space E_1).

The interface thus formed is made up of two successive transactions without additional treatment occurring inside the core of actor (*O*). This first mode is *direct*, because it does not bring any additional value at the interface. With reference to Vinck and Jeantet's work (1995), we shall call it a "*commissioning*" interface mode. This has been illustrated by the first example, where BN (*O*) is simply reporting to OJ (*C*) a direct information from superordinate (*A*) in the message from August 2002 quoted above.

5.3.2.2 Mediating interface The second mode sees an additional internal operation at the level of interface actor (*O*),

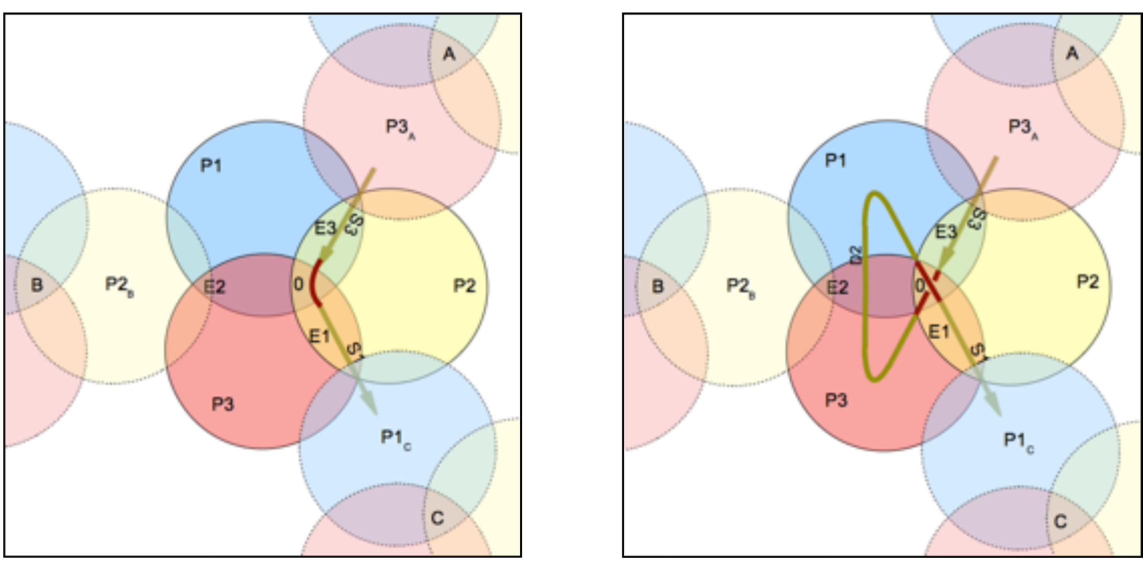


Fig. 9 Actor O playing the role of interface between actors A and C. Left: Commissioning interface where the interface actor forwards information without adding any value. Right: Mediating interface where the interface actor adds value to the connection

i.e., a *translation* operation. With reference to the terminology relating to intermediary objects (Vinck and Jeantet 1995; Vinck 2011), this interface mode will be called a "*mediating*" mode.

To represent topologically the translation operation from the P_3 type pole ("what I am asked to do") of the superordinate actor (A) to the P_1 type pole ("what I request to be done") of the subordinate actor (C), the inflow (specification or order, in our case) from this first protagonist (A) will not pass directly from the exchanges spaces E_3 to E_1 of the interface actor (O). Instead, this inflow travels through the corresponding *internal* poles of the interface actor (O) forming a loop, as shown in Fig. 9 (right), so that the information can be converted and translated before reaching the P_{3C} pole of the third protagonist in the interaction. The incoming statement of transaction S_3 benefits from the added-value internal treatment provided by interface actor (O). This is the reason why we see the path entering the P_{3O} internal pole of interface actor (O) before it reaches its P_{1O} pole after crossing exchange space E_2 *transversely*, and not longitudinally (as was the case for the arrows S_1 and S_3 modelling the transactions). This transverse crossing of the exchange space actually models a translation operation. This path is represented by the alpha-shaped arrow D_2 (translation of P_3 to P_1).

The oriented interface thus formed is composed of an incoming transaction S_3 followed by a translation D_2, then an outgoing transaction S_1. The mediating interface is well illustrated by the second example quoted above, where BN, acting as interface actor (O), had to navigate between (A) and (C) to clarify and translate the requirements in such a way that (C) understands them.

6 Elaboration of the interface model

From the empirical observations exposed in the Feet & Rails case and the illustration of a first instantiation in Sect. 5 through the description of a mediating and a commissioning interface, which are the ones that are the most commonly found in our case, we have constructed a theoretical elaboration that considers systematically all the possible combinations of the model. This logical elaboration is a systematic investigation of the potentials of the model presenting all possible logical combinations and correspondence with previously known communication modes.

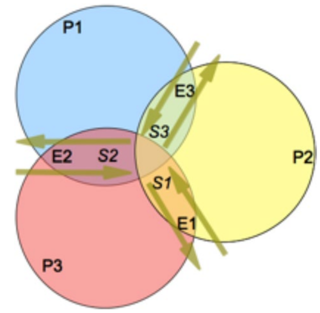


Fig. 10 The six possible oriented incoming and outgoing transactions between two actors in a given network

6.1 Logical composition of an interface

According to our model, each oriented interface is composed of three elements: one incoming transaction, one internal translation and one outgoing transaction:

$$\text{Oriented interface} = \text{incoming transaction} \oplus \text{internal translation} \oplus \text{outgoing transaction}$$

The incoming transaction corresponds to the interaction between an external actor and the middle manager (here in position of an interface actor), for example a superordinate prescribing something. The outcoming transaction is the same type of interaction but directed towards an external actor (for example a subordinate). The internal translation represents the transformation (the cognitive operation, or the action of the interface actor itself) that allows the message to be correctly conveyed.

6.2 Six transaction types

In the case of the vertical top-down interface presented above, two types of elementary transactions were described: the transaction between an interface actor and a subordinate and the transaction between a superordinate and this interface actor. The third type of possible transaction is the transaction between an interface actor and a peer (Fig. 10). In this case, the transaction is *lateral*. This transaction type has been somewhat neglected in literature in favor of vertical relationships. It is sometimes referred to as a "middle-out" transaction (Kinchla

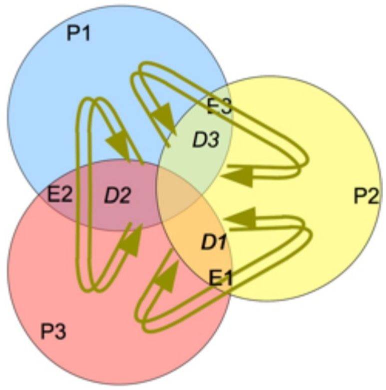


Fig. 11 The three types of translations inside the interface actor during interactions involving two other actors of different levels

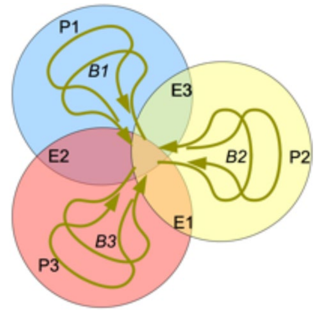


Fig. 12 The three types of "looping" translations used by the interface actor during interactions involving two other actors of same level

and Wolfe 1979), analog to our "outgoing" transaction. By extension, we propose to call an "incoming" transaction a "middle-in" transaction. Taking place between an interface actor and one of its peers, this typically consists of a task where the action of one actor (whatever the level: superordinate, subordinate or peer) is synchronized with the action of one peer of the interface actor (middle-in), or where information is sent to the interface actor's peer to enable them to be synchronized with the initial actor's action (middle-out).

When these two new transactions are added to the four introduced above, we reach a total of six possible oriented transactions. These are summarized in Fig. 10.

6.3 Six translation types

In Sect. 3.3, we described the D_2 type translation between P_1, "what I request to be done", and P_3, "what I am asked to do". The other two translations between the other two pairs of poles are, respectively, the D_3 *coordination* type translation between P_1 and P_2 and the D_1 *cooperation* type translation between P_2 and P_3.

Figure 11 provides a graphical summary of these six types of oriented translations. The figure shows that a translation involves two internal poles of the interface actor. This transverse crossing of the corresponding exchange space represents the necessary internal operation (inside the interface actor) required to transform the information from the incoming channel to the outgoing channel, *i.e*. from the sender to the receiver.

D_1 = cooperation

The term *cooperation* is used here in its common sense. It characterizes an action carried out by two parties sharing a common goal. Indeed, this translation involves a superordinate and a peer. The information transmitted and transformed by the interface actor involves an exchange with a peer and is based on a request from the hierarchy. From a strictly logical point of view, peer-to-peer exchanges are cooperative exchanges as no hierarchy is involved: the hierarchy triggers cooperation between peers at the inferior level.

D_2 = impedance matching

The term *impedance matching* comes from an analogy with acoustics. Acoustic impedance is the ratio between air pressure and velocity, it is representing a kind of resistance, or inertia, to the sound propagation. By analogy, impedance matching represents the adaptation of one language type to another, one type of sensitivity to another or one cognitive level to another (Galison, 1997; Wenger, 1999; Jung, 2006). In this mode, the interface actor translates part of the message "from the top" to be understood by the lower levels, as illustrated in the quote of Sect. 5.3.

D_3 = coordination

Coordination is a classical organization mode where a group of peers decide on the share of some activities with (a) subordinate(s). Here, a message from a peer is translated and transmitted to a subordinate in the form of a prescription. The interface actor then acts on behalf of the other peer and prescribes something to their subordinate. This is typically what happens when a manager coordinates the sharing of work within its team working for one of its peers.

6.4 Six "looping" translation types

These "looping" interfaces involve internal translations inside one and only one pole of the interface actor. This is shown in Fig. 12. There are three types of translation loop: a *conciliation* loop inside P_1 for "what I request to be done"; a *mediation* loop inside P_2 for "what I do"; and an *arbitration* loop inside P_3 for "what I am asked to do". The choice of these terms—conciliation, mediation and arbitration—aims at reflecting the subtle differences between the three loops.

Table 2 Summary of all possible oriented interface combinations

From/to	External pole	P_1 (what I request to be done)	P_2 (what I do)	P_3 (what I am asked to do)
External pole	Commissioning interface	S_1, bottom-up Verification	S_2, middle-in Synchronization	S_3, top-down Specification
P_1 (what I request to be done)	S_1, top-down Initiation	B_1 Arbitration	D_3 Coordination	D_2 Impedance matching
P_2 (what I do)	S_2, middle-out Exchange	D_3 Coordination	B_2 Mediation	D_1 Cooperation
P_3 (what I am asked to do)	S_3, bottom-up Orientation (global view)	D_2 Impedance matching	D_1 Cooperation	B_3 Conciliation

B_1: Arbitration
When two messages arrive from two different subordinates, their manager has to decide which one to consider first and which one to leave aside for the time being. If the two pieces of information are contradictory, arbitration is even more difficult. In this case, the interface actor is put in a position where he has to make a choice and inform the parties concerned of this choice.
B_2: Mediation
Mediation is required when two various peers give non-converging or even contradictory information to their peer interface actor. To align the points of view of these two peers, the interface actor has to act as a mediator in their relationship.
B_3: Conciliation
Conciliation is required when two superordinates give contradictory orders. For example, one suggests shortening the length of a task while the other suggests increasing the workload of this same task. In this case, the interface actor may have to make use of negotiating skills in order to appease both parties and reach an acceptable compromise.
Note that a real situation is a combination of these translation loops and entails more than one mode at a time. However, there is always a dominant mode that can be considered. For example, conciliation may be the dominant interface modality but may simultaneously require both mediation and arbitration to be achieved, depending on the number and level of total actors involved.

6.5 The complete set of elementary interfaces

The different types of transactions and translations comprising the interface between two actors through a third interfacing actor are summarized in Table 2. The poles considered are those of the two interfaced actors, these poles are connected on each side to the poles of the interface actor. Transactions S_i are shown in the first row and first column of the matrix, i.e., in the cells linking the pole of an external actor with the same pole of the interface actor. Looping translations B_i populate the diagonal of the matrix, while off-diagonal terms D_i (between the two internal poles of the interface actor) represent the remaining types of translations.

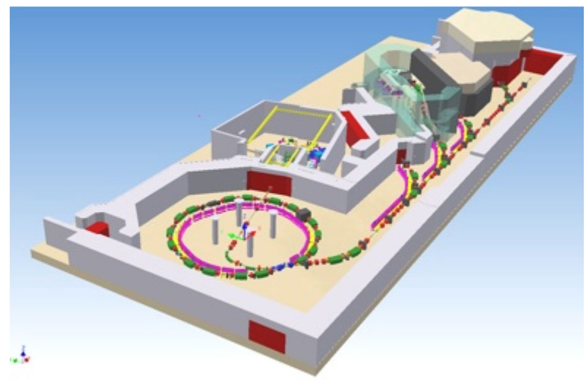


Fig. 13 Layout of MedAustron (including a circular synchrotron of diameter 25 m)

Thus, we obtain fifteen types of interfaces. For the non-looping translations D_1 to D_3, the direction along which these translations take place does not change the fundamental nature of the dynamic interface. Their number is thus reduced to12, making symmetrical the 3×3 sub-matrix of translations between internal poles of the interface actor.

In the case of a commissioning interface (first cell top right), the interface actor is not directly involved in the interaction between the two external poles.

The 3×3 sub-matrix of transactions between internal poles of the interface actor is symmetrical. This does not mean that the content of the exchanges is bound to be symmetrical too. The symmetry only indicates that the three actors involved in a given interaction act along the same path of communication, and that the type of interface is the same for everyone. If this were not the case, the interface actor would experience a conflict, have difficulty working properly and be unable to create a proper interface between the other two stakeholders (this of course can occur and would be the sign for a non-working or dysfunctional interface).

We consider that this set of elementary interfaces covers all interaction types we encountered and hence models all possible interactions between stakeholders.

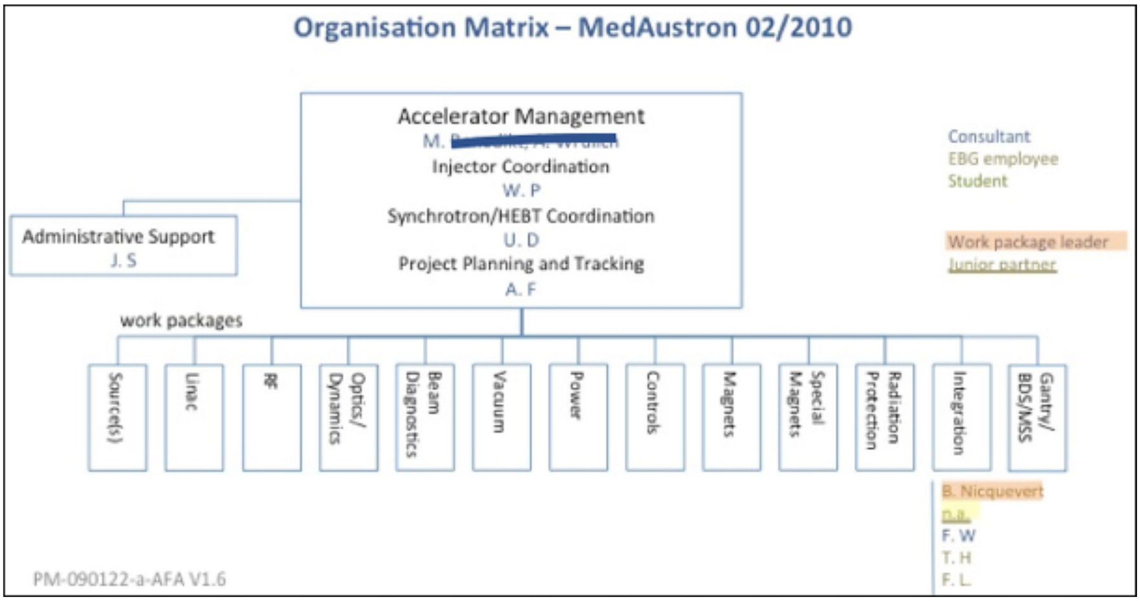


Fig. 14 The various work packages in the project organization (the original document has been slightly modified to render it anonymous)

7 The MedAustron case study

The theoretical elaboration presented above has been integrated and put into action by the engineer who was in charge of the technical coordination of the MedAustron project. This case study will be used to illustrate how the model has been used in this new project and how it served as a management tool for its technical coordinator (who is one of the authors of the paper). From an empirical point of view, this represents the action loop described by Chakrabarti and Blessing (Blessing and Chakrabarti 2009) in their DRM method as the second loop of the descriptive study in application of the research results (i.e., our tripolar model).

MedAustron (Medical Austrian Synchrotron) is an ion therapy center delivering ion beams for tumor treatment (Benedikt and Wrulich 2011). The overall layout shown in Fig. 13 includes an injector complex with ion sources and a short linear accelerator, a 25 m diameter synchrotron (bottom left), and a high-energy beam transfer line, split between research and treatment (top right). This accelerator complex was installed and is currently running[2] in a dedicated large building located in Wiener Neustadt, Niederösterreich (Lower Austria) (Garonna et al. 2016; Charitos 2019).

The accelerator project was run between 2008 and 2013. It was split into several work packages covering the main functional areas of the items to be procured: magnets, beam diagnostics, vacuum devices, power supplies, etc. (Fig. 14).

The goal attributed to the integration work package included tasks usually devoted to the technical coordination of such large-scale projects. The work package covered three closely connected aspects (Fig. 14): integration, design activities and installation coordination (Nicquevert, et al. 2011).

During the 2009–2012 design and integration phase, the aim of the integration work package was to deliver all the necessary design data to the suppliers of the accelerator's components, whilst ensuring that this data was consistent with geometrical constraints and requirements (infrastructure and neighborhood) and in line with the positions defined on the optical layout. The positions of the beam line components (including bending magnets, focusing quadrupoles, or beam positioning devices), had to be taken into account according to their function, as each could influence the behavior of the ion beams.

One of the authors of this paper was the leader of the integration work package (WP) during the initial phase of the MedAustron project. After being assigned this position, one of his first actions was to set up the resources to be able to fulfil the goal of the WP, considered as a subproject of the overall MedAustron project (Fig. 14).

The ISO 21500 standard on "Guidance on project management" proposes several processes in order to set up a project team:

- Process 4.3.15 Establish project team outlines how "*to acquire the human resources needed*". The advice given is that "the project manager, when possible, should take into consideration factors such as skills and expertise,

[2] https://www.medaustron.at/en

different personalities and group dynamics when establishing the project team";

- Process 4.3.16 Estimate resources outlines how "*to determine the resources needed for each activity*";
- Process 4.3.18 Develop project team outlines how "*to determine the resources needed for each activity*". It is recommended "to improve the performance and interaction of team members in a continuing manner".

A tripolar model was used to support these processes. At the start of the WP activities, a limited number of people were assigned to the WP: two designers, belonging to the company MedAustron, a designer seconded from the magnets working group and an alignment specialist from a collaborating institute. The first designer (TH) was Austrian, had a good academic level in spoken English, was at ease with computers but was not fully knowledgeable in design. He was allocated the task of designing the kicker magnets. The second designer (FL) was French, had substantial experience as a mechanical designer of small assemblies and a good knowledge of CAD tools but spoke hardly any English. He was put in charge of the overall integration. The designer on secondment was Austrian. He was accustomed to using a different CAD tool from the one chosen for the WP integration and wanted to be able to work autonomously. Finally, the survey specialist (FW) was a senior scientist of Chinese nationality who spoke no French and whose English was difficult to understand. The newly nominated WP holder, an academic engineer skilled in design and integration, spoke French, English and quite good German but not Chinese unfortunately.

The initial tripolar mesh established thanks to the tripolar model (that unfortunately cannot be made public due to the nature of data contained) clearly showed many gaps and mispositioning in the WP integration project team setup. As mentioned above, one issue stemmed from the language skills of the stakeholders. In spite of the team's small size, there was no common language for them to communicate in. This meant that interaction required intermediation along the mode "impedance matching" and "coordination". Since the project's official language was English and the Austrians were able to communicate in German, any stakeholder who was not at ease with at least one of these two languages could hardly hold a position of interface. A mismatch between skills and position was then identified. This led TH and FL to being interchanged: FL was put in charge of the kicker magnet design while TH took over machine layout and integration. It was found that other positions had to be provided for, not only due to missing resources, but also because the interface positions had to be filled in the mesh: a designer in charge of the integration of general services and civil engineering; a designer responsible for beam diagnostics devices; a junior engineer to look after the support

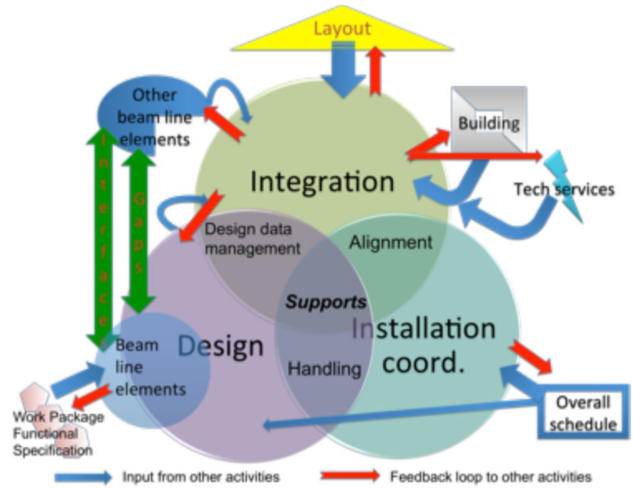


Fig. 15 Instanciated version of the tripolar model—Integration tasks, and links with other project activities (from Nicquevert, Hauviller and Benedikt 2011)

subproject; a junior computer scientist to set up and maintain a PDM (Product Data Management) system and support the verification and validation processes for the design and integration envelopes; and last but not least, a deputy WP holder to specifically plan and coordinate on-site installation.

For each of these recruitments, the tripolar mesh was used to identify the required skills (both technical and interpersonal) of each stakeholder according to their position on the mesh. Special attention was given to the interfaces shown in Fig. 15. The blue and red lines of this figure are actually the "visible parts" of the tripolar mesh, that was actually used only by the integration work package leader as a personal design tool to cover his managerial needs.

This analysis showed that some stakeholders could not be positioned on the mesh. First, as the senior surveyor (FW) partially lacked the ability to communicate (due to his difficulty to speak English) and collaborate, he was withdrawn from the project and his responsibilities transferred mainly to TH. Unlike FW, TH was able to communicate directly with the Austrian members of the project, in particular with the architect-engineer and "general planner" in Vienna. S_3 "Specification" mode was their communication mode (Table 2). Second, interactions with the designer on secondment from the Magnets WP, who used a different CAD system than the requested one, created many interfaces at many levels: transfer of CAD data to the central PDM system, a specific process for verification and validation, and communication between him and the French designers. To fill this gap, TH acted as a mediating interface "between peers" according to the B_2 "Mediation" mode (Table 2).

These examples show how the tripolar mesh was used by the WP leader as an operational management tool to frame and facilitate interactions between the members of his

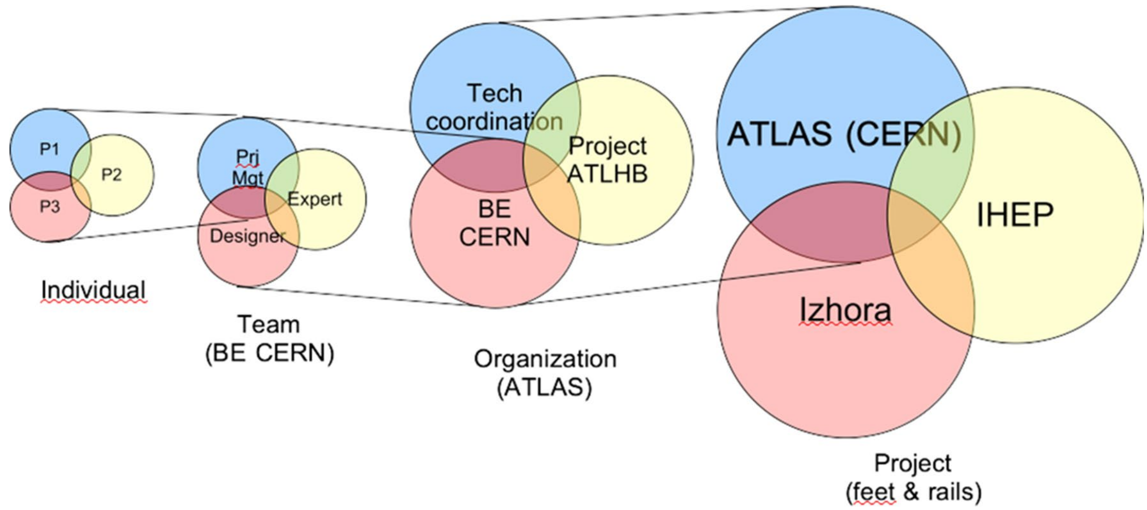


Fig. 16 Simplified view of the recursiveness of the tripolar model within the ATLAS Feet & Rails project

project team, and between this team and the external stakeholder, hence improving collaboration efficiency. His regular modus operandi was based on the D_3 "Coordination" mode. Without this tool, management would have been essentially based either on feeling or experience, probably adding many more trial and error loops. Such loops can be highly costly in terms of time and energy and would have probably led to time overruns, not to mention their potentially negative impact on the quality of the outcome itself.

8 Discussion on the tripolar model

We introduce in this section a discussion on potential developments of the model that extend the approach on two directions. One relates to the collective and collaborative dimension of the model and the other its multi-layer dimension.

8.1 Recursiveness at work

The map of the stakeholders involved in the overall Feet & Rails project can be represented by the concentric model shown in Fig. 8. The elementary cell of the tripolar model can be used to represent various levels of granularity in a multi-layer decomposition or aggregation (Fig. 16). At the level of the human actors, the tripole at the furthest left represents a given actor (in this case, the project leader); the three poles shown immediately at the right are three internal actors in relationship with other concentric upper, lower and equivalent (peers) levels of the model. This reflects the way the middle manager moves inside the different levels of the organization (Reich and Subrahmanian 2020).

The teams are made up of various actors forming tripoles within a given team, like the BE"—(i.e., design office, in French Bureau d'Études), within which various relationships can be observed: the head of the office ("Prj Mgt" in the "Team" tripole), the Designer, and the Expert for instance the mechanical simulation expert (for finite elements analysis). Actually, there are many more actors (more experts depending on the fields and more than one designer), but each of them can be characterized by one of these three poles in the team.

The same way, the various organizational units involved within ATLAS are represented at a higher level ("Organization" tripole), including the design office previously modeled that provides design resources for the project ATLHB (Feet & Rails) for which the Technical Coordination acts as a project sponsor. The ATLAS Technical Coordination entity, whose mission was inter alia to monitor the successful completion of the project paid from the Common Fund (Nicquevert et al. 2011a, b) on behalf of the whole Collaboration, was acting as the product owner (modelled as "ATLAS (CERN)" in Fig. 13). The ATLHB project management itself, with a board also including a representative from the CERN Experimental Physics division, was acting as the project owner, and, amongst other "executive" poles, the "BE CERN" design office previously modeled, within this division, was providing design resources for the project ATLHB (Feet & Rails).

At the inter-organizational level, the model is also used to represent the overall project during the manufacturing phase, as seen in the "Project" tripole. At this level, the three stakeholders are three organizations: the ATLAS Collaboration entity, in charge of the technical specification and of the requirements setting; the Russian firm Izhora executing the

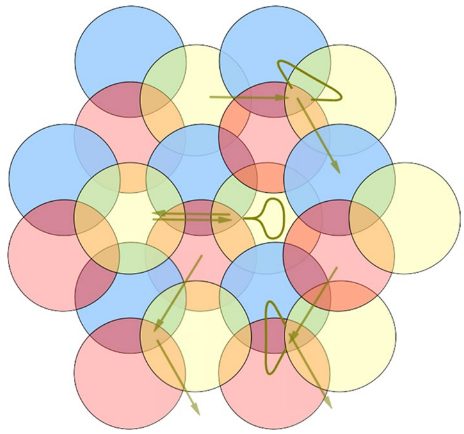


Fig. 17 A 2D representation of the tripolar mesh at a given time

work; and the collaborating institute IHEP responsible for monitoring the production.

This model can be used to trace the transactions as they unfold. This is described by Boisot et al. (2011, see in particular chap. 2 and 9) when the authors refer to the i-space of the company Izhora (which was renamed "Ingenio"). It is especially useful for representing the way in which so-called "codified knowledge" in the form of specifications is shared by the three actors of the project: Izhora, ATLAS CERN group, and IHEP.

This recursiveness can be extended further to identify which human stakeholder, within these organizations, is holding which pole at each stage. For ATLAS, it might be suggested that the Technical Coordinator is holding pole 3, the head of the CERN research department pole 1 and the project manager ("BN" in Fig. 8) pole 2. Inside Izhora, the project manager is in pole 3, the manufacturing foreman in pole 1 and the design office in 2. In the case of IHEP, the chief physicist may be placed in pole 3, the verification/quality office in pole 1 and the engineer-physicist ("AF" in Fig. 8) in pole 2. This process can be continued until we reach back the bottom of the organization in a recursive way.

From a theoretical point of view, this approach provides a framework to model engineering interfaces at different levels of the organization and allows to connect these different levels thanks to the recursive principle. As a perspective, this recursive dimension could be introduced in process models through the use of our tripolar model. The PSI (Problem, Social and Institutional Spaces) network model introduced by Reich and Subrahamanian (Reich and Subrahmanian 2019) (Reich and Subrahmanian 2020) is an interesting conceptual framework to model the interconnection between different layers (strategic and operational) and the social and institutional dimensions. Potential misalignments in the PSI network could be identified and solution derived for a tripolar model analysis. Our model may also be considered as the model of an actor in a larger model such as BMPN or other more elaborated modelling tools.

8.2 From the tripolar cell to the tripolar mesh

If it were possible to take a picture of the communication processes between a given set of actors at a given time, it would display a network of actors interacting through a continuous web of interconnected circles (Fig. 17). As their respective positions constantly evolve, the network is in reality highly dynamic. Each actor is potentially an interface at any given point in time. We call this complete model a *tripolar mesh model*. It is impossible to represent this mesh in a simple graphical manner, as it is a multi-dimensional dynamic web. This would require animated images.

For the sake of example, Fig. 14 displays a number of possible oriented interfaces in a web. It shows one looping translation, two non-looping translations and one commissioning interaction (direct transmission without any added value provided by the interface). The complexity is partly due to the fact that each actor holding a given interface position has got a high number of other potential interactions with other stakeholders at the same time. However, seeing the interfaces in this way may help the interface actor to deal with some conflicts. The representation gives a view of the different positions held by the interface actor and may therefore help the actor to adopt the relevant managerial behavior for each one.

Figure 17 shows a two-dimensional section of the web with each tripole cell representing an actor. At the lowest level, actors are individuals. However, this representation can also work at other levels such as company level, as we shall see in Sect. 6. It may also be used to model relationships between suppliers.

The model is a first step towards an operational setup of the concept of trading zones (Galison 1997), as it pools a series of bilateral exchange spaces between several collaborating actors belonging to different communities of practice. As both a historian of science and a physicist, Peter Galison had the intuition that in large scientific collaborations the various actors involved had to create cognitive trade-off spaces where negotiation can occur. These zones have specific functions that are well known to engineers. In the case of the complex projects described in this paper, they also include both physicists and non-technical personnel. Our tripolar model strives to grasp and model these zones from an operational point of view.

As a perspective, this aspect could be the prefiguration of a multi-agent approach where the dynamics of the network could be modelled and simulated. We could imagine a network model of the project where we visualize in real time the interactions of the agents (the tripoles). This could serve as a visualization and simulation tool where we could simulate for example the excessive prescription of the superordinate, the lack of interaction with peers, etc. This could provide an interesting project dynamics (or behavior) simulation.

9 Conclusion and future work

This paper presents a model for managing interactions in the context of large engineering projects. The interface concept is used to describe the position of middle managers in the dynamic environment in which interactions take place. This model is generic and captures all types of possible interactions between actors. It offers a human-centric view that starts with the interface and considers that, potentially, each actor can find itself at the center of this interface. Based on a longstanding immersion in engineering processes in the context of large collaborations at CERN, the proposed model provides an original approach to the concept of engineering design interface.

From a theoretical point of view, the very important work made by Engestrom, Kuuti and their predecessors on activity theory is complemented by our approach which models the design interactions themselves that are not captured by the theory. In activity theory, only the relations between objects, subjects, artefacts and other high-level entities are modeled. Here we provide another dimension which consists of modelling subject–subject interactions. This model is compatible with classical activity theory models as our interface can imply the use of artefacts or tools and one of the poles can be the subject of the interaction. The object of the interaction is not captured by our model though. This can be considered as a drawback or a limitation.

In the same way, there has been a huge amount of work on boundaries and interfaces, however, this paper proposes an original approach to the question of boundaries in engineering organizations. Beyond the initial application domain, this model can be used to characterize the types of interfaces that are required to allow boundary crossing in organizations. For example, between a supplier and a buyer, the interface actor is in position of mediating between a superordinate (the company) and a subordinate (the supplier). Or, in inter-departmental collaboration, it might be in position of peer-to-peer collaboration, which is also captured by our model. Furthermore, we did not investigate the multi-level aspect of the model which is discussed in the previous section. We did not investigate the situations where the poles of the tripole are of different nature (departments, companies, etc.). This is also an interesting potential follow-up to this study.

We believe this work can also provide a conceptual framework for researchers to analyze other cases and discuss concepts according to their findings, including potential integration within other multi-layer frameworks such as the aforementioned PSI model. We also would like to promote the application of this approach in other domains than particle physics, in big engineering design projects such as power plant design or infrastructures for example.

From a practice point of view, the model itself can also be used by practitioners to manage their teams from an interface-based perspective. This allows to define the interface roles at each step of the design process and for each situations the manager is facing. This framework recognizes the specific roles (mediating, commissioning, impedance-matching) and allows the identification, at each step, of the required interface skills (i.e., language, communication, technical…).

Additionally, as we have presented it in the case studies and in the introductory sections, the complexity of a large engineering project in particle physics creates situations where the actors are experiencing entanglement of their roles and face real difficulties in navigating in the complexity of the organization. The important number of decision layers and the heterogeneity of the actors (research institutes, small and big companies, governments, global dimension, etc.) often put the middle manager in very tricky situations where he/she needs to constantly adapt its behavior. On the individual level, this model may act as a compass for the design practitioner. This is one of its main virtues from our point of view, as our engineer experienced it in the MedAustron project for example. The tripolar model captures the potential configuration and allows the middle manager to recognize it and adapt its behavior accordingly. From this model, it might be possible to develop practical guidelines documenting the potential action/behavior (or tool) suggested in each situation.

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