



Management de la complexité organisationnelle des projets en ingénierie systèmes : Mise en place d'une approche socio-technique pour l'amélioration des aspects collaboratifs

Laura Roa Castro

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Par

Mme Laura Roa Castro

Managing Organisational Complexity in MBSE design projects:
Use of a Sociotechnical Perspective to improve Collaboration

Thèse présentée et soutenue à Chatenay-Malabry, le 24 mars 2017

Composition du Jury :

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Abstract

The organisational complexity implied by New Product Development (NPD) within the industry, is often induced by the complex nature of the products themselves. In this context, MBSE (Model Based Systems Engineering) and collaborative approaches address those complexities and have been recognised by their contribution to improve the NPD processes. A successful implementation of a collaborative MBSE design would allow to manage both complexities. This PhD thesis describes an investigation on collaborative MBSE design projects within French teams in automotive and aeronautics companies, with the purpose of enhancing them to improve product development. We understand collaborative MBSE design as a complex organisational system which implies different views or dimensions. The identification of those dimensions, their definition and the study of their interactions constitute the first objective of this research. Understanding each dimension in order to improve collaboration between the project members is the second objective. The third and last objective of this research is to propose Socio Technical Systems (STS) supporting this collaboration. The results of the thesis provide a methodology to manage organisational complexity in collaborative MBSE design projects. The methodology is a combination of four methods assisting the characterisation of the MBSE dimensions (people, process, information objects and tools), while defining their interactions. These methods support respectively: 1) The assessment and description of collaborative MBSE design projects from a systemic perspective 2) The establishment of a shared vision of the work 3) The analysis of the cooperation among the actors 4) The development of STS such as collaborative environment and a collaborative capitalisation support. The implementation of the proposed methods, process and guidelines in the industry has shown how the enhancement of collaboration in MBSE design projects can improve the overall product development.

Resumé

Du fait du développement de nouveaux produits (NPD) dans l'industrie, l'organisation devient de plus en plus complexe, ceci est dû notamment à la complexité même des produits. Dans ce contexte, le MBSE (Model Based Systems Engineering) et les approches collaboratives, qui adressent ces complexités, ont été reconnus pour leurs facultés à améliorer le NPD. Une implémentation réussie d'une conception collaborative du type MBSE, doit permettre de gérer ces deux complexités. Cette thèse de doctorat a pour objet l'étude de projets de conception collaborative MBSE au sein des équipes françaises chez des équipementiers automobiles et aéronautiques, afin de mettre en avant l'amélioration du développement des produits. La conception collaborative du type MBSE est assimilable à un système organisationnel complexe, impliquant des vues ou dimensions différentes. Ainsi, l'identification de ces dimensions, leur définition et l'étude de leurs interactions constituent le premier objectif de cette recherche. La compréhension de chacune d'entre elles pour améliorer la collaboration entre les différents membres du projet, est le deuxième objectif. Le troisième et dernier objectif de cette thèse est de proposer des systèmes socio-techniques (STS), assistant la collaboration. Les résultats de cette recherche, fournissent une méthodologie pour manager la complexité organisationnelle dans des projets collaboratifs du type MBSE. Elle est le produit d'une combinaison de quatre méthodes permettant la caractérisation de ses dimensions (processus, acteurs, objets et outils), tout en définissant leurs interactions. Ces méthodes assistent respectivement : 1) La description et l'évaluation de ces projets avec une perspective systémique 2) l'établissement d'une vision partagée du travail 3) l'analyse des coopérations entre les acteurs, et 4) le développement de STS tels quels des environnements collaboratifs et des supports collaboratif de capitalisation. L'implémentation en industrie des méthodes proposées, processus et recommandations, a montré comment la mise en avant de la collaboration dans les projets de design MBSE, permet d'améliorer l'ensemble du développement de produit.

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List of Abbreviations

AR	Action Research
CAD	Computer Assisted Design
CAE	Computer Assisted Engineering
CCW	Collaborative Collocated Work
CE	Concurrent Engineering
CED	Collaborative Engineering Design
CEDOSy	Collaborative Engineering Design Organisational System
CGT	Cooperative Game Theory
CSCW	Computer Supported Collaborative Work
DRM	Design Research Methodology
EWIS	Electrical Wiring Interconnection System
FAcT	Fears, Attractions, Temptations
GT	Game Theory
IAR	Insider Action research
MA	Model Architect
MBSE	Model Based System Engineering
MIC	Model Identity Card
MP	Model Provider
MPM	Model Provider Manager
NCGT	Non Cooperative Game Theory
NPD	New Product Development
PDP	Product Development Process
PCE/ CVE	Project Chief Engineer or Chief Vehicle Engineer
PLM	Product Lifecycle Management
SA	System Architect
SE	Systems Engineering
SLM	Simulation Lifecycle Management
STS	Socio Technical System
TDR	Technical Design Review
TRL	Technology Readiness Level

List of Definitions

Cooperative Relationships

Organisation of two or more people who work together without necessarily having a common goal to achieve. The organisational structure is not necessary the same and it can often be an imposed one. The people usually interact through informal communication channels. The interactions are mostly short and mid-term where neither the authority, nor the risks nor the rewards are shared. They are often the results of long-term relationships but they are not restricted to them.

In this PhD thesis we have focused our attention on the cooperative relationships among the MBSE projects members. We have studied cooperation instead of collaboration because the industrial reality (observations) corresponds to this kind of relationships (c.f. Table 7: Proposition of a comparison MBSE design project observations to cooperation and collaboration). However, as a matter of coherence with the literature we refer to collaborative MBSE design in most cases in this manuscript except in sub-section 4.3, where we have analysed in detail the relationships among the actors and we have used methods addressing cooperation and not collaboration. Thus, we have employed the term cooperation.

Collaborative Relationships

Organisation of two or more people who work together to achieve a common goal. They are organised through a common defined arrangement (but not imposed), supported by structured communication channels where the authority is shared along with the risk, resources and rewards. These interactions are often the results of long-term relationships but they are not restricted to them.

Collaborative MBSE

Activity involving simulation and design engineers, who share data, information and knowledge encapsulated in the simulation models. They use different resources or tools to perform the sharing and to accomplish the tasks related to the product development process at the simulation stages.

As the studied industrial reality correspond to cooperative relationships we consider collaborative MBSE as a theoretical concept, coming from the literature insights and the desired industrial situations.

CAE-CAE collaboration

Collaboration among engineers for the application of modelling to support analysis activities through the use of Computer Assisted Engineering (CAE) tools. It concerns the activities within simulation department teams or members. The term “collaborative simulation” is often used in the literature to refer to the technical needs related to this collaboration. Because of the engineers participating in it, this collaboration concerns multidisciplinary aspects (different technical background).

**CAD-CAE
collaboration**

Collaboration among engineers and designers for the application of modelling to support design and analysis activities through the use of Computer Assisted Design (CAD) and Computer Assisted Engineering (CAE) tools. It concerns the activities between performance and design departments assisted by the simulation teams. The term “CAD-CAE collaboration” is often used in the literature to refer to the collaborative problems between those departments from different points of view (technical but also organisational). This collaboration concerns the contradictory objectives to reach of design and performance departments.

PART 1: Thesis compilation

This thesis is a doctoral dissertation based on a *Thesis by publications* format. Instead of including our publications as chapters of the thesis, we have decided to split the manuscript into two main parts. The first one contains the global thesis dissertation and a summary of the contributions. The second one gathers the publications presenting in detail each contribution and its background.

Part 1 is constituted of six chapters presenting respectively: the context and the research questions, a global literature review positioning this research, the research framework and implemented methodology, a summary of the proposed methods, the results and contributions and the conclusions and perspectives.

The detailed state of the art related to each proposition, and the way they have been developed are presented in the related paper in Part 2.

PART 1 SHORT SUMMARY

Chapter I: Introduction	(P.3)
Chapter II: Research framework and methodology	(P.17)
Chapter III: Literature Review	(P.33)
Chapter IV: Proposition of methods and mechanisms to understand, analyse and improve collaboration	(P.51)
Chapter V: Conclusions, limitations and perspectives	(P.97)

I

Introduction

In this sub-section, we present the global research context and motivation as well as the objectives of our thesis. In sub-section 1.1 we introduce the academic and industrial context of the PhD research. In sub-section 1.2 we present the research background and motivation of this thesis. In sub-section 1.3 we explain the structure of the thesis and finally in sub-section 1.3 we present the objectives and the research questions of the PhD.

1.1. PhD context

The PhD thesis has taken place at the Research Institute of Technology (IRT) SystemX in partnership with Industrial Engineering Laboratory (LGI) from CentraleSupélec (ex- Ecole Centrale Paris). An IRT *is an interdisciplinary thematic institute that develops economic sectors related to its field through a balanced strategic public-private partnership* (SystemX n.d.). In this context, IRT SystemX gathers academic and industrial partners to launch diverse projects. The research done during the thesis is part of a project called SIM (French acronym for Engineering and Multi-Disciplinary Simulation). Four industrial partners have been part of the project: Airbus Defence & Space (ex-EADS Astrium), Airbus Group (ex-EADS), Esterel Technologies and Renault, as well as three academic partners: CentraleSupélec, ENSTA ParisTech and Supméca. The observations and use cases led during the thesis have taken place at the IRT SystemX, Airbus Group Innovations and Renault Technocentre.

This thesis is framed as a collection of four main papers proposed for publication in international. In consequence we separate the manuscript in PART 1 and PART 2.

1.2. Research background and motivation

The increasing customer demand for new and better products has raised market competition and has imposed new constraints to the companies. To meet the customer expectations, the companies must not only bring innovative products, but they should also deliver them as soon as possible with no room for error. This is the case of vehicle industry, where the **product complexity has increased exponentially** because of the customer demand (Aberdeen Group 2006), (Karlberg et al. 2013), (Cui et al. 2009)(Lindemann et al. n.d.), (Bonjour et al. 2013). This complexity is related to the integration of many components, systems and sub-systems and has been addressed with numerous approaches during the last decades (e.g. modularity approaches, system dynamics and domain matrix technics). Lindemann et al. (Lindemann et al. n.d.) offer an interesting approach and review different methods addressing the management of product design complexity.

More recently, System Engineering (SE) discipline has emerged as a new way to manage this complexity by creating and executing interdisciplinary processes to ensure the development of a system throughout its entire lifecycle and satisfying the stakeholder's needs. In this context, **MBSE (Model Based Systems Engineering)** approach appears as *the formalised application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases* (INCOSE 2015). The use of models is valuable in product design since they *simplify the description of the system under considerations, in order to simplify its complexity* (Zeigler et al. 2000). These technics are appreciated in the vehicle industry and have become a key element in the vehicle development process, because of their **efficiency to handle the high amount of knowledge and information required in the new product development process, improving in this way the management of product complexity and the preparation and anticipation of the test phases**. Indeed, if some of those tests were replaced by modelling and simulation technics (virtual tests) important savings would be done. Taking the example of the crash test¹ in the vehicle industry, the use of MBSE may significantly reduce the expenses related to redesign costs. Failing a test implies the cost of the crashed vehicle but also the cost of designing a new solution passing the test. The appropriated use of MBSE approaches could limit the risks of obtaining a bad results during the test because these

¹ Destructive test performed in order to ensure the safety of the vehicle. One of the most known example is the frontal test. In this test the vehicle must suffer a frontal impact upon a concrete wall

results could be anticipated by using simulation models. **Thus, the adequate and successful use of MBSE approach represent a major economical stake for the industry.**

Although MBSE approach assists the product complexity management, it leads the companies to lean on new technologies and to find more approaches to face the new technical needs, but also the organisational complexity (induced by the product complexity itself and by the use of the MBSE approach). On the one hand, technical needs are often related to the emergence of new and heterogeneous development environments, the new traceability needs and the new intellectual property constraints. These needs have been addressed in the literature by the introduction of different approaches such as product modularity, interfaces standardisation, Product and Simulation Lifecycles Management (PLM / SLM) and models encapsulation approaches (Roa-Castro & Stal-Le Cardinal 2014a). On the other hand, **the organisational complexity in this context is related to the increasing number of people involved in the product development process, the new relationships between them and the use of new knowledge through the models.** Some management disciplines such as project management, organisational design or even social network studies assist in general the study of the organisational complexity. However **in this context, collaborative approaches have emerged as a way to handle this complexity.**

We illustrate in Figure 1 and Figure 2 the differences between product complexity and organisational complexity.

<http://users.skynet.be/spotterfreak/airbus380.html> Las visit 03/12/2016

<http://www.flotauto.com/constructeurs-vers-un-vehicule-100-vert-20110919.html> Las visit 03/12/2016

In Figure 2, we use some of the examples studied by V. Krebs (Krebs & Michalski 1996) to illustrate organisational complexity.

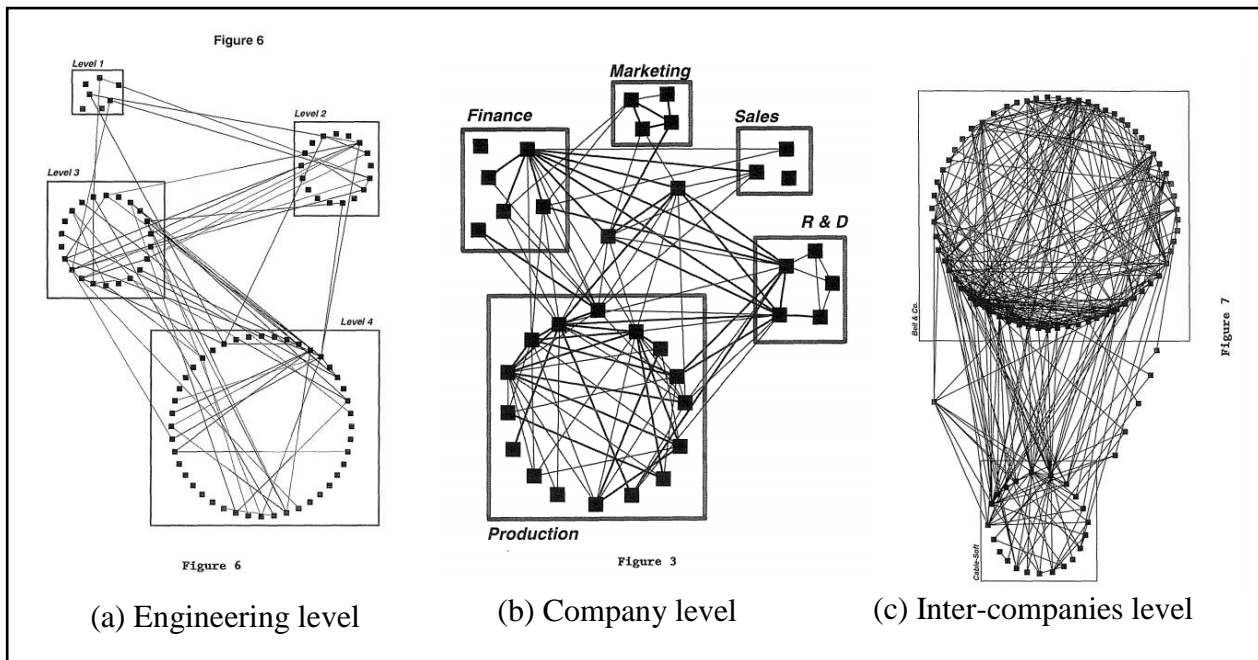


Figure 2: Organisational complexity illustration (Krebs & Michalski 1996)

These examples illustrate the spread communication network between the company members at different levels. Figure 2 (a) presents the expertise flows between the various engineer levels, which can be interpreted as a kind of organisational complexity at department level. Figure 2 (b) represents the emergent workflow within small firm, which can be interpreted as a kind of organisational complexity at company level. Finally, Figure 2 (c) represents emergent clusters showing alliances between two groups of companies, which can be interpreted as a kind of organisational complexity at inter-company level or market level.

To reach a successful product development process, a strong coupling between product complexity and organisational complexity is necessary. Some examples of that are Collaborative Engineering Design (CED) and Concurrent Engineering (CE) (Prasad 1997) approaches which have emerged as new design organisation forms to improve companies competitiveness (Bonjour 2008). These methods also assist the orchestration of both complexities and the improvement of the engineering processes. Nowadays, the number of studies in Collaborative Engineering Design (CED) have increased significantly (Deubzer et al. 2007). Even if several studies on organisational collaboration exist in the literature, few studies analyse the collaboration among the actors related to the use of emerging methods such as MBSE.

Taking the hypothesis that **an appropriate implementation of a collaborative MBSE design would allow to manage both complexities, the aim of this thesis is to study, understand and improve collaboration in MBSE design projects**. We summarise in Figure 3, the design research topics with the framework proposed by E. Bonjour (Bonjour 2008) to position our work.

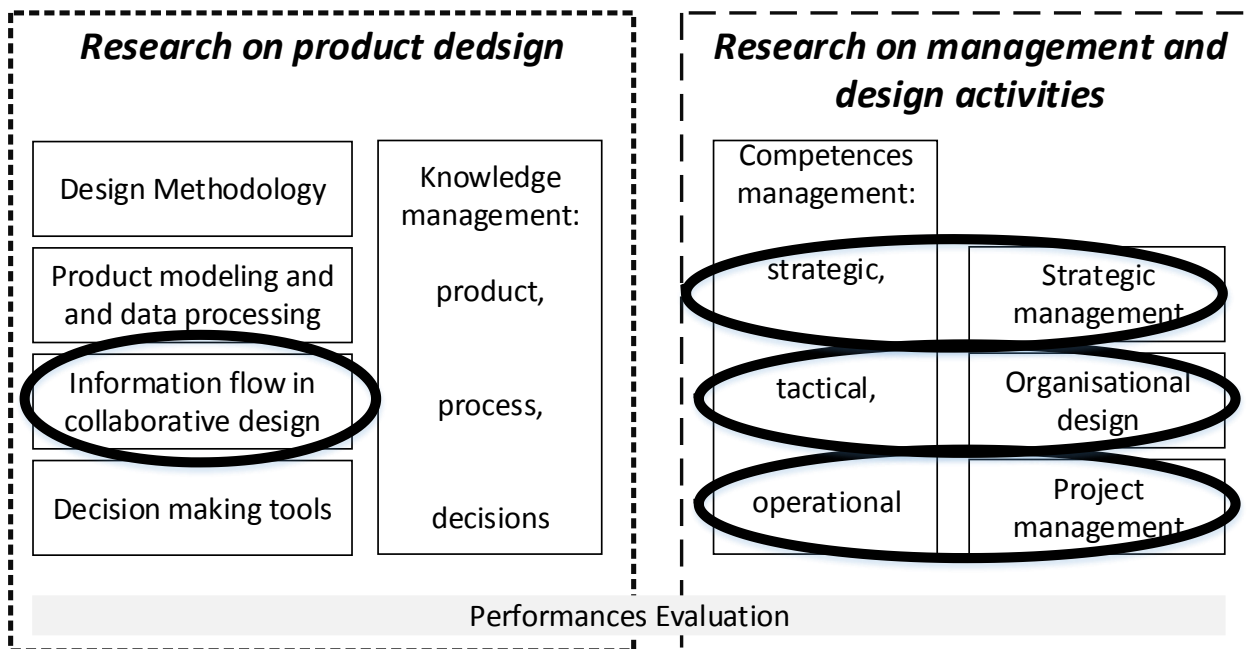


Figure 3: Research positioning regarding the research on design framework proposed by E. Bonjour. The original French version can be found in (Bonjour 2008)

In the research on product design field we aim at contributing to the proposition of collaborative process driven and capitalising design information among the members. In the research on management and design activities field we aim at contributing to the proposition of methods addressing management policies at the strategic level to improve collaborative design activities among the actors and having a positive effect on the other levels. Likewise we aim at contributing to the proposition of operational elements supporting those activities which in turn should have a positive effect on the tactical and strategic levels.

This thesis is focused on the collaborative interactions among the project members in MBSE design context. The MBSE scope is large. Nonetheless, we centre our attention in the use of behavioural and geometric models such as those built from CAE (Computer Assisted Engineer) and CAD (Computer Assisted Design) tools.

We illustrate in Figure 5 an example of collaborative MBSE scenario. This scenario is an example of one of the typical situations addressed in this research. The illustration represents six main representative stages of an MBSE design project that we have identified. We use orange or blue colours to distinguish the actor questioning position from the actor answering position. Likewise, we differentiate between what the actor says (speech bubble) and what the actor thinks (thinking bubble). Five different actors take part in the scenario: The Engineer in Chief (PCE), the System Architect (SA), the Model Architect (MA), the Model Provider (MP), and the Model Provider Manager (MPM). We present a brief description of their roles and their organisation in Figure 4.

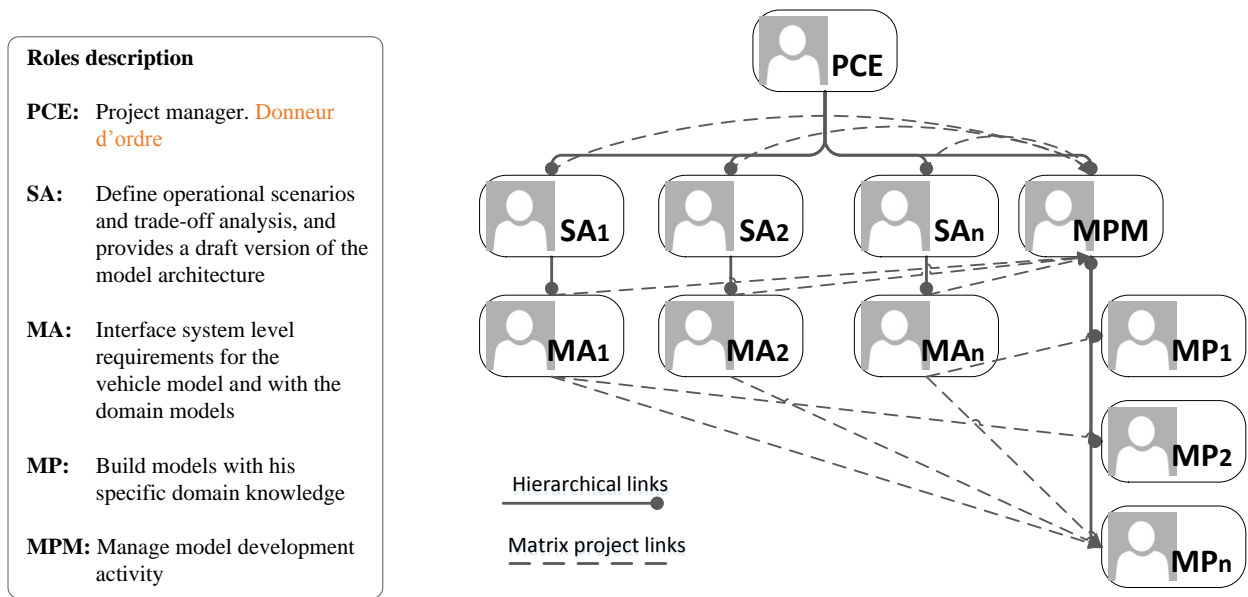


Figure 4: Actors involved in the typical collaborative MBSE design scenario

In Figure 4, we use the SA, MA and MP definitions proposed by (Sirin et al. 2015). The continuous lines represent the hierarchical relations while the dotted lines represent the relations regarding the project matrix organisation. In this thesis, we study this kind of organisation and the interactions among its members referred as: *CAE-CAE collaboration* and *CAD-CAE collaboration* (c.f.. List of Definitions).

We are conscious that the terms CAD and CAE define tools and not people. However, we have decided to use this terminology to facilitate the differentiation between the two kinds of collaboration that we study. We do not use the term “collaborative simulation” because our research does not only concern technical aspects, but it also addresses a holistic view of the elements and organisation needed so that collaborative MBSE projects could succeed.

In summary, the current demanding market has an important impact in the product complexity. The exponentially growth of that complexity confronts the companies to new PD challenges. In this context, MBSE approaches have emerged as a way to face these challenges. Although these approaches assist product complexity, they lead the companies to lean on new technologies and to find managerial models facing the new organisational complexity. Collaborative approaches have emerged as a way to handle this complexity. We think that an appropriate implementation of a collaborative MBSE design would allow to manage both complexities. This hypothesis brings us to study, understand and improve collaboration in MBSE design projects. Most precisely, CAE-CAE and CAD-CAE collaboration that take place in this context. To illustrate these kinds of collaboration we represent a typical collaborative MBSE design scenario in Figure 5.

In the scenario illustrated in Figure 5, we can see how people behaviour is driven by their own interests, for example:

- Reaching an objective such as in stage 2, where MPM expresses his need to sign a new contract, or in stage 5 where the SA₁ expresses his concern of making a decision,
- Respecting the constraints such as in stage 5 where SA₁ needs to consider the budget of his department,
- Preventing rework tasks such as in stage 3, where the MP expresses his concern of the insufficient requirements description.

Likewise, the scenario allows us to evidence the significant number of loops needed during the modelling process assisting the decision making. This situation is illustrated through the arrows in stage 4. In this stage MA and MP establish a relationship driven by the technical needs of the model development. These relations are informal (the official interlocutor is the MPM) and they come from the need to speed up the development process and to avoid administrative procedures that are time consuming. Sometimes, the direct dialog between MA and MP may bother the official interlocutor (MPM) who can consider him/herself bypassed. Nonetheless, most of the time MA and MP do not intend to neglect their managers but to facilitate their own work.

Contrary to the organisational complexity illustrated in Figure 2, the scenario illustrates the individual level more than the macro level of the organisational complexity. We have studied the individual level in this thesis, also called “microscopic level” in the literature (Micaëlli & Forest 2003), because its understanding is necessary so that we can suggest models describing

the macro level situation in future works. Thus, we are interested in the study of the interactions and cooperation within the project members.

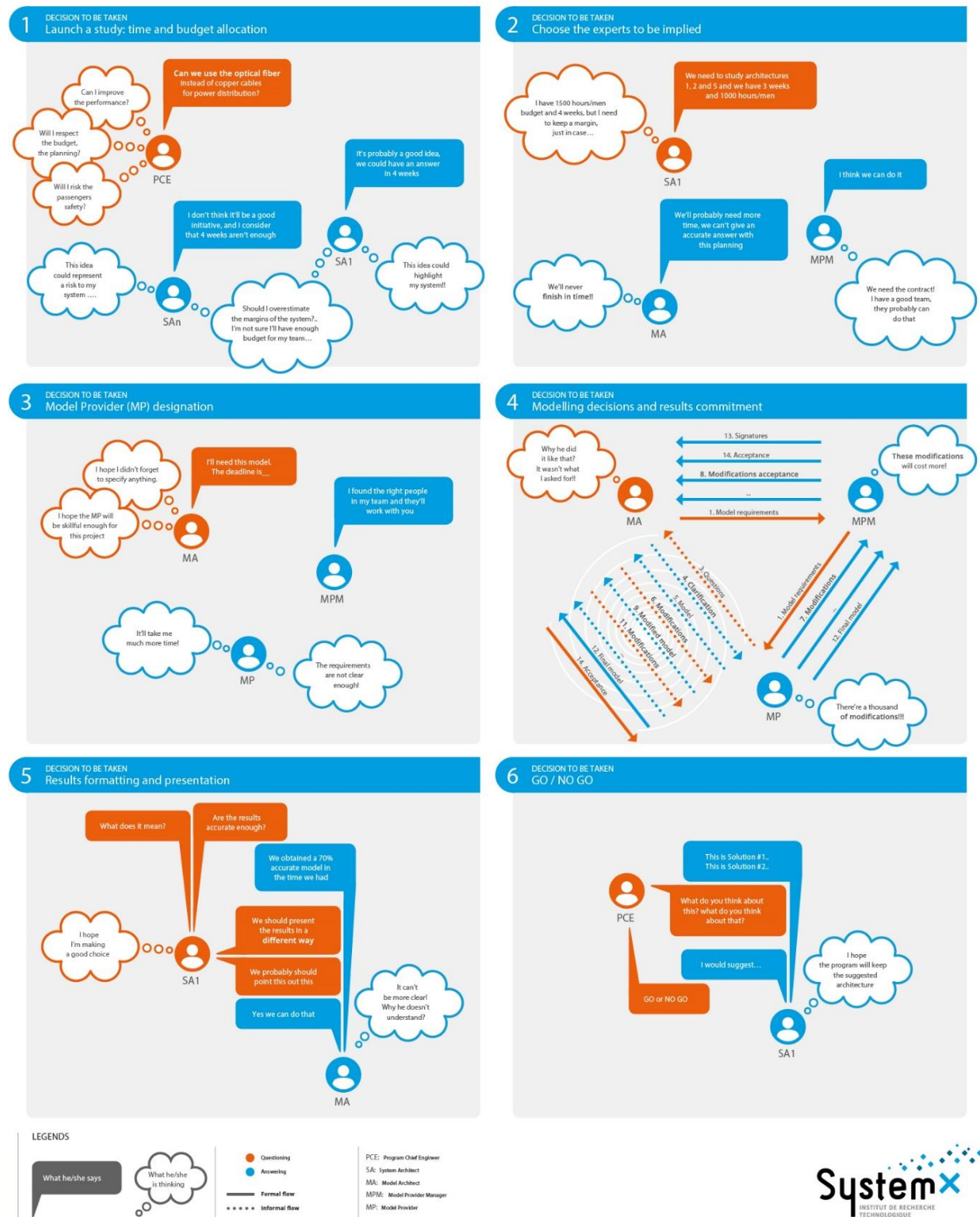


Figure 5: Illustration of a typical collaborative MBSE scenario

1.3. Research objectives and questions

This PhD thesis describes an investigation on collaborative MBSE design projects in French vehicle companies, with the purpose of enhancing these projects to improve product development. We understand collaborative MBSE design as a complex organisational system, which implies different views or dimensions. Thus, the identification of those dimensions, their definition and the study of their relationships constitute the first objective of this research. Then, understanding each dimension to improve collaboration among the project members, is the second objective. Finally, proposing Socio Technical Systems (STS) supporting this collaboration is the third and last objective of this research.

The main question driving the PhD thesis is:

How can we improve product development through the enhancement of collaborative aspects in MBSE design projects?

To make this question easier to consider, we split it into four research questions:

RQ1: How can we improve the global understanding of the organisational complexity in collaborative MBSE design projects?

RQ2: How can we improve the current MBSE design process to enhance collaboration?

RQ3: How can we understand, describe, characterise and improve cooperation among the project members?

RQ4: How can we include the social aspects of the organisation to support the development of collaborative environments and capitalisation supports assisting MBSE design projects?

1.4. Thesis structure

We have followed Design Research Methodology (DRM) (Blessing & Chakrabarti 2009) to structure the dissertation process. An overall view of the DRM framework used in this thesis is presented in chapter II. The framework presents the grouping logic of the studies into the papers and their respective research stages (research clarification, descriptive study I, prescriptive study I, descriptive study II).

PART 1 includes the present chapter and four more chapters organised as follows: In **Chapter II** we present the research framework and the followed methodology. A brief description of

each of the eleven studies is presented through the different research phases proposed in the DRM methodology. Likewise, the data collection protocols are described. In **Chapter III** we present a literature review on collaborative MBSE design and the position of our research. In **Chapters IV** we present the proposed global methodology to improve collaborative MBSE design and the proposed methods and mechanisms making part of the methodology. This chapter is only an introduction of our proposition. Indeed, the proposed methods and mechanisms are detailed in the related papers in PART 2. In **Chapter V** we present the conclusions regarding the research questions and the limitations and perspectives of this research. We present a visual overview of the PART 1 thesis structure in Figure 6.

PART 2 is constituted of five papers presenting the propositions introduced in chapter IV. In **Paper #1** we propose a systemic perspective of the collaborative MBSE design through the proposition of CEDOSy method (which stands for Collaborative Engineering Design Organisational System). CEDOSy assists the characterisation of the MBSE dimensions, while defining its interactions and ensuring the inclusion of the organisation social aspects during the development of the collaborative STS foundations.

In **Paper # 2** we present an added value process proposition for collaborative MBSE design. It includes the identification of the actors, their roles and the exchanged information objects. The implementation of the process points out the actors as the key element in collaborative design and raises a new research question: What are the factors motivating people to collaborate in this context and how can we measure them?

In **Paper # 3** we address this question proposing a coupling method between the Non-Cooperative Games Theory (NCGT) and the FAcT-Mirror method to understand and improve cooperation among the project members. The results show how cooperation is driven by information sharing. Finally, we demonstrate how it could be improved through the implementation of appropriate information sharing resources.

Finally, in **Paper # 4** and **Paper #5**, we propose two groups of guidelines to develop these resources. The guidelines assist the development of two kinds of STS. The first one is a collaborative environment, while the second one is a collaborative capitalisation support. The results show how an appropriate collaborative environment improves the global design process by decreasing collaborative issues and misunderstanding. Likewise, implementing suitable capitalisation means improves collaboration among the project members.

The thesis also contains a number of appendices, giving further information to the reader.

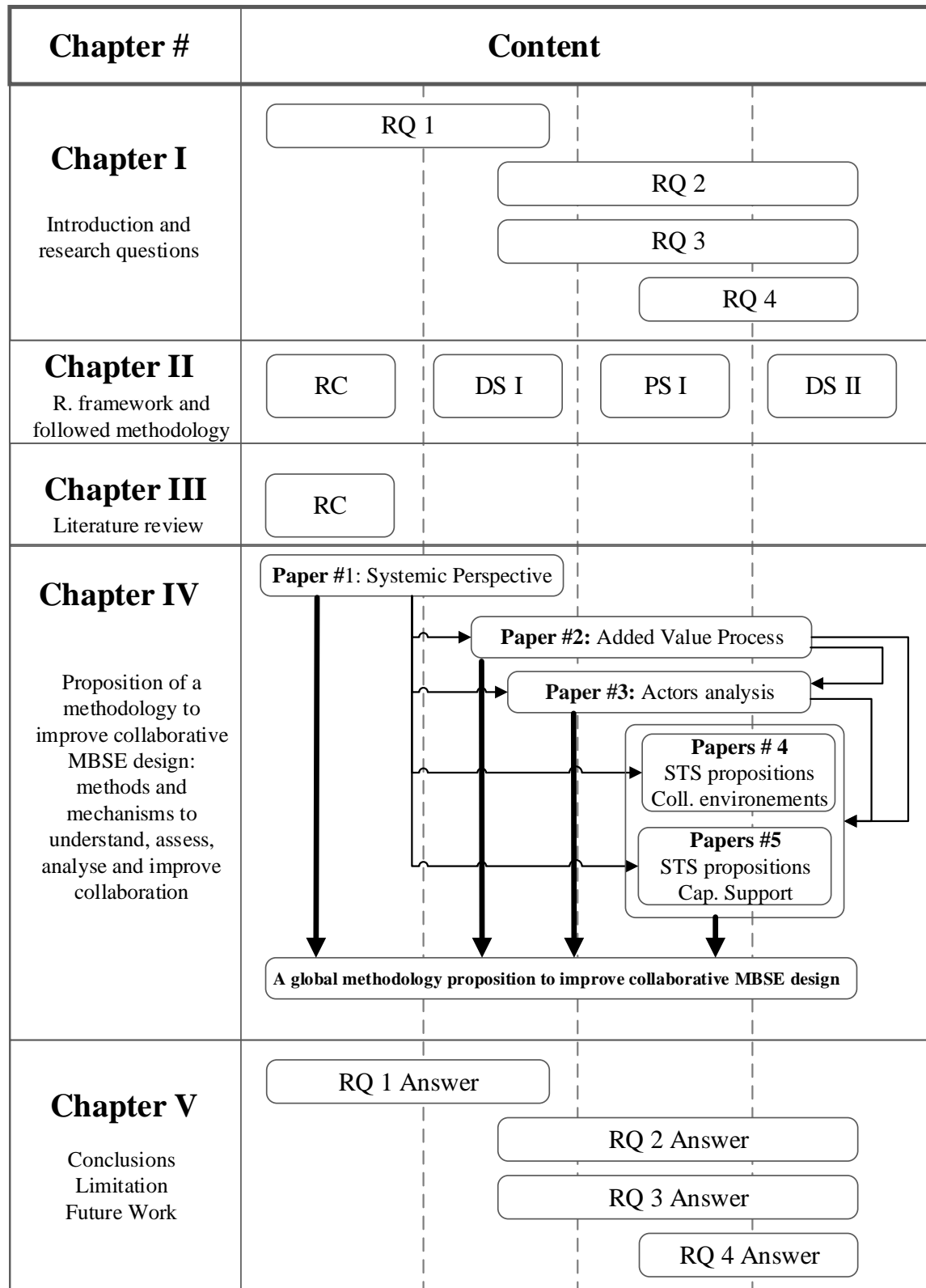


Figure 6: Visual overview of the thesis structure PART 1.

II

Research framework and followed methodology

The industrial context from which this thesis has been developed allow us to carry out an Action Research (AR) approach (Bjork 2003). The particularity of the AR approach resides in the fact that the researcher is inside the studied process. He or she can act as an observer or as an active member of the team performing the process or even as a team manager. We have played the role of the observer during the last three years of the collaborative design process studied in this thesis. AR carries out a great amount of information flows, which make its analysis difficult. However, it is ideal for the research on complex social systems, as it facilitates the interactions between practice and theory (Ottosson et al. 2006).

During the last three years, we have acted within three organisations: The research institute of technology IRT SystemX, the French car manufacturer Renault S.A. and the aircraft manufacturer Airbus Group Innovations (more precisely with a French team), where we have led different studies and observations that are detailed later in this chapter. Acting from inside the organisation means performing qualitative research, given the contextual character of the observations and the unplanned way that things happen in reality (Creswell 2013). Thus, we have used qualitative data collection methods such as observations, interviews, workshops and some document analysis. We present the data collection method used for the different studies in Table 1. We also describe the protocols used for the data collection in sub section 2.6 of this chapter.

Aiming at understanding the collaborative MBSE design phenomenon, but also aiming at using this understanding to improve the current situation we have used the Design Research Methodology

(DRM) proposed by Blessing and Chakrabarti (Blessing & Chakrabarti 2009). The goal of DRM is to improve design product and process. Therefore DRM helps us addressing collaborative issues in design. We have used DRM because it allows us to address our research in a scientific way in order to obtain valid results in a generic and practical sense. DRM facilitates the systematic knowledge validation through the four main stages: research clarification, descriptive study I, prescriptive study I and descriptive study II. The four stages, their basic means and their basic outputs are presented in the DRM framework proposed by Blessing and Chakrabarti in **Erreur ! Source du renvoi introuvable.** (Blessing & Chakrabarti 2009).

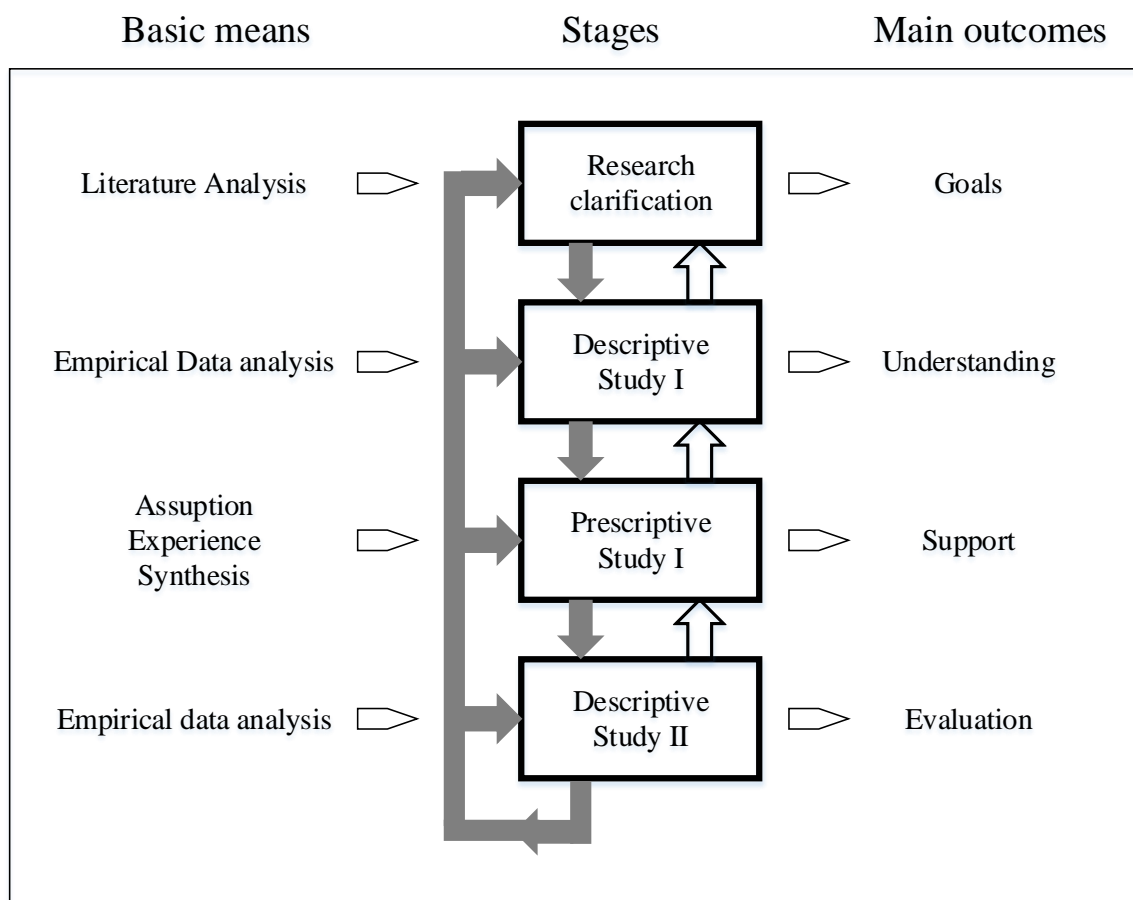


Figure 7: DRM research framework (Blessing & Chakrabarti 2009)

Blessing and Chakrabarti define the objective of the Research Clarification stage as the finding of evidence to formulate a realistic research goal. This step aims at the understanding of the situation. Its main output should be a first description of the *as is* situation and the desired situation. The second stage is the Descriptive Study I. During this study, the description of the situation should

be detailed enough to determine the factors to be addressed. Given that our thesis is based on an AR approach, most of the studies carried out during the descriptive stage are comprehensive, which means that the studies include a deeper literature review and empirical data analysis. Third, during the Prescriptive Study I stage, the researcher should use his/her increased understanding of the *as is* situation to elaborate a more detailed description of the desired situation. This description represents his or her vision on how addressing one or more factors in the existing situation would lead to the realisation of the desired, improved situation (Blessing & Chakrabarti 2009). Then, this understanding is used to develop the support assisting the improvement of the given situation. Finally, the descriptive study II stage aims at evaluating the support and investigating its impact on the outcome of the desired situation. The results and conclusions show how the new current situation can still be improved (as design is an iterative process). Thus, a new Description Study I is needed and the DRM loop starts again.

During this thesis, 11 different Work Package (WP) have been carried out through the different DRM stages. We summarise in Table 1 the 11 WP, their corresponding DRM stage and their aims. We define an ID number for each WP in order to refer to them in the text and in other figures of the chapter. Likewise, we describe the nature of the obtained deliverable at the end of each WP (industrial deliverable, workshop paper, conference paper, journal paper). We also present the qualitative data collection method that we have used (observations, interviews, workshops, document analysis). The detailed description of the protocols used for the data collection of the different WPs are presented in sub-section 2.6. Finally, in the research approach column of Table 1 we present the kind of AR approach used. Indeed, as an observer, two kinds of action research can be distinguished AR and IAR (Insider Action Research) (Ottosson et al. 2006). The difference between AR and IAR is that in AR the researcher has a sporadic presence, while IAR he or she is present at least 80% of the time. Among the WPs carried out during the thesis, two of them were review based only (1, 5), four come from AR perspective (2, 3, 4, 7), while the other five have been built as IAR practitioners.

Table 1: DRM and corresponding WP carried out during the PhD thesis

DRM stage	WP No.	Name of the WP	Aim (s)	Deliverable nature	Data collection	Research approach
Research clarification (RC)	1	State of the existence: industrial practices for “collaborative simulation”	- Understand general background on collaborative MBSE design	Industrial deliverable	Literature	Review based
	2	Problem-cause analysis from industrial observations: model architect working group at Renault and SIA (Société des Ingenieurs de l’Automobile) working group attendance	- Obtain and analyse empirical data on collaborative MBSE design projects	Industrial deliverable	Observations	AR
Descriptive Study I (DSI)	3	An overview of “collaborative simulation” on design process	- Formulate a realistic research goal: define collaborative MBSE design dimensions and literature gap	Workshop paper (IPD ‘14)	Observations	AR
	4	Towards an adaptive model for “collaborative simulation” from system design to lessons learned_ A use case from Aircraft industry	- Obtain and analyse empirical data and contrast research goals with industrial needs	Conference paper (CAS ‘15)	Interviews Document analysis	AR
	5	Definition of the collaborative modelling and simulation system (CM&SS) from a systemic perspective in vehicle industry context	- Deeper literature review - Problem reformulation - First problem modelling	Conference paper (ICED ‘15)	Literature	Review based
	MSc	Master of science launched during the thesis	- Deeper literature review: systemic modelling methods	Master report	Literature	Review based
	6	CEDOSy: The new Systemic Perspective of Collaborative Engineering Design. Application to simulation context in the vehicle industry	- Deeper literature review: MBSE projects kind of collaboration - Problem statement - Factors to address	Journal Paper (JED <i>under submission</i>)	Observations	IAR
	7	Collaborative analysis of EWIS project at Airbus Group Innovations	- Obtain and analyse empirical data	Industrial deliverable	Interviews	AR
	8	An added value process proposition for a collaborative design in early development phases using simulation models in the aeronautics and automotive industries	- Obtain and analyse empirical data - Deeper literature review: design process modelling - Proposition of the desired improved situation of the process	Conference paper (DESIGN ‘16)	Observations Interviews	IAR
	9	Crossing Games Theory and FAcT-Mirror methods to improve cooperative MBSE design projects	- Obtain and analyse empirical data - Deeper literature review: cooperative modelling methods - Proposition of the desired improved situation of the actors	Journal paper Co-Design (<i>under submission</i>)	Observations Interviews Workshops	IAR
Prescriptive study I (PSI)	10	Developing sociotechnical systems for collaborative design review. Part I: guidelines proposition and application for the development of collaborative environments	- Formal prescription and agreement of the desired situation - Deeper literature review: collaborative environments in technical design review - Proposition of the desired improved situation of the environment - Proposition of evaluation criteria	Journal paper & Industrial tool and guidelines (Design Studies <i>under submission</i>)	Observations Interviews Workshops	IAR
	11	Developing sociotechnical systems for collaborative design review. Part II: guidelines proposition and application for the development of capitalisation supports	- Formal prescription and agreement of the desired situation - Deeper literature review: collaborative capitalisation support for technical design reviews - Proposition of the desired improved situation of the cap. support - Proposed evaluation criteria	Journal paper & Industrial tool and guidelines (Design Studies <i>under submission</i>)	Observations Interviews Workshops Documents analysis	IAR

To offer the reader a better vision of the WPs carried through this research among the four DRM stages, we summarise in *Figure 9* (sub-section 2.5) the information presented in Table 1. We are now going to detail the four main DRM stages and the related WP we did.

2.1. Research Clarification

When starting the PhD thesis, the subject of our research study was called “collaborative simulation” and was consequently very large. Thus, we have started the Research Clarification stage by leading three studies (WP 1, 2 and 3 in Table 1). The results of these studies have enabled us to establish the first assessments of our thesis. WP 1 helps us to get familiar with the industrial context. We have found several industrial initiatives dealing with collaborative MBSE design and with collaboration (in a more general sense). In an internal IRT project deliverable, we describe nine main projects concerning collaborative MBSE design and seven concerning collaboration in other contexts. From the beginning, we have taken a look at collaboration in other context, because of its relation with people behaviour. Even if collaborative solutions coming from different fields cannot be directly applied, because of the specific context where they have been developed, they offer a wider scope of the collaborative features present in different fields. This analysis helps us to understand the inherent aspects of collaboration that are context independent. We decide then to focus especially on collaboration process.

WP 2 presents the first industrial observations. These observations have been done in order to compare the results obtained in WP 1 and 3 to the reality. They have taken place at Renault “Technocentre” (Paris Area). The collected results allow us to understand the collaborative MBSE design process and the problems that engineers could have during their activities.

WP 2 offers a larger overview on collaborative MBSE design. In addition to the 16 industrial projects described in WP 1, we have also looked in the literature for studies concerning collaborative MBSE design and research studies on collaboration in the general sense. A great quantity of studies for both works have been found. We have chosen the most pertinent studies regarding our context and needs: studies aiming somehow at the improvement of models exchange and sharing challenges for the first one, and works describing collaboration features for the second one. In total, we have studied 14 works in collaborative MBSE design field and 10 in general

collaboration. The analysis of those works allow us to identify the dimensions describing both, collaboration and collaborative MBSE design.

Comparing the elements obtained from WP 1, 2 and 3 we have been able to establish the dimensions of collaborative MBSE design and also to suggest an initial definition of collaborative MBSE design. The approach that we have used to get to the results is presented in WP 3 (Roa-Castro & Stal-Le Cardinal 2014a). We use an illustration coming from WP 3 and we have added bold frame borders to indicate the links between WPs 1, 2 and 3 in Figure 8.

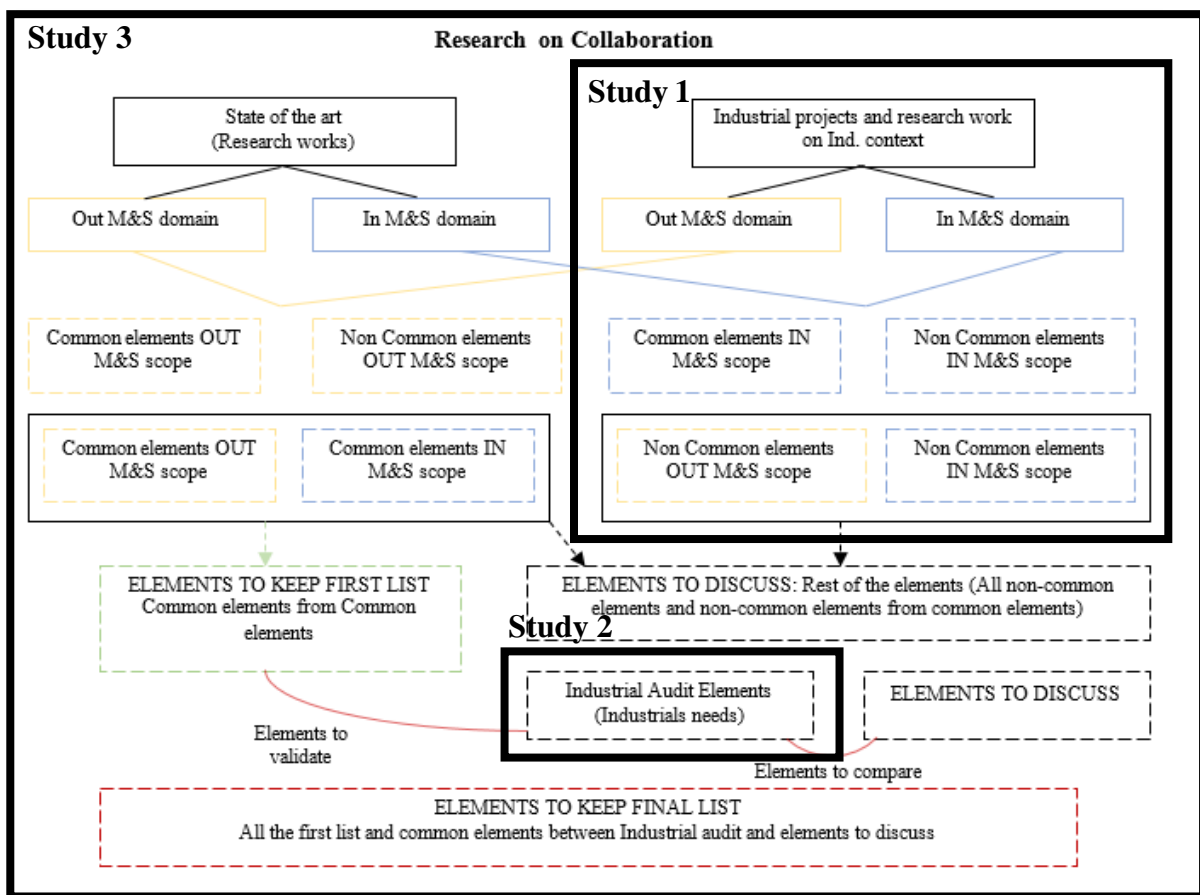


Figure 8: Approach used for the integrations of the elements coming from Studies 1, 2 and 3.

(Roa-Castro & Stal-Le Cardinal 2014a)

As showed in Figure 8 results obtained from WPs 1 and 2 have been gathered in the final deliverable of Study 3 (Roa-Castro & Stal-Le Cardinal 2014a) . Regarding DRM framework, we place WP 1 in the Research Clarification stage, whereas WPs 2 and 3 are placed between Research

Clarification stage and Descriptive Study, because even if WP 3 is strongly review based, it takes into account the outputs from WP 2 making the transition between the two stages.

2.2. Descriptive Study I

In order to provide a description of the situation as detailed and as accurate as possible, we have led most of the thesis studies in this stage. As suggested in DRM framework, the researchers could decide to focus on improving the quality of the problem definition and the most promising factors to address (Blessing & Chakrabarti 2009). This situation is actually very representative of our thesis. Because of the human nature of the collaboration, we have taken the time to deeply understand the situation, to propose a model describing it, and to choose the methods facilitating the analysis of the situation as well. Moreover, DRM authors also suggest that an incomplete problem definition in this stage leads to high percentage of time to be spent on modifications in later stages.

In addition to WPs 2 and 3, which make the transition from Research Clarification stage to Descriptive Study I stage, we have carried out six more WPs in this stage. WPs 4 to 7 belong only to this stage, whereas WPs 8 and 9 make the transition from this stage to Prescription Study stage. With the exception of WP 5 - which is a review based -, the rest of the WPs of this stage are comprehensive studies. The data analysis protocols used for each of them are presented in subsection 2.6.

WP 4 has taken place at Airbus Group Innovations. During this study, we have analysed the document driving simulation models sharing and exchange processes, called AP2633. We have analysed the process, the roles and the exchanged objects (simulation models but also other documentation) proposed in the document. Then, we have interviewed at the same time the person in charge of the AP2633 implementation and the person in charge of the methods and tools for the simulation department to discuss about the document analysis results. The results of both, document analysis and interviews have been summarised in the WP 4 deliverable (Roa-Castro et al. 2015).

In parallel to WP 4, we have launched WP 5 in order to analyse collaborative MBSE design using the systemic approach proposed by J.L Le Moigne (Le-Moigne 1990). The proposed systemic representation includes the four dimensions of collaborative MBSE design - identified in WP 3 -

from a systemic perspective. This study allows us to suggest the existing links between these dimensions, but also to observe the situation in a different way. Indeed, this study represents our first attempt to model collaborative MBSE design as a system, which has enabled us to understand it as a whole and not as separate dimensions. With this conclusion in mind, we have launched a Master of Science internship (Fatfouta et al. 2016) in order to review different systemic modelling methods. This research has allowed us first to define “collaborative MBSE design “ as a complex system and second to validate the systemic approach proposed by J.L Le Moigne as the most appropriate approach supporting the modelling of our system. Likewise at the end of WP 5, we have started WP 6, 7 and 8 in parallel.

Taking into account all this results, and in order to validate the collaborative dimensions and their links, we have carried out WP 6 where we have proposed CEDOSy method (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.), which stands for Collaborative Engineering Design Organisational System. We have built CEDOSy from a Systemic perspective. It supports the design of collaborative Socio Technical Systems (STS) in engineering design. We have applied this method to two industrial use cases in order to study different kinds of collaboration in MBSE projects. Likewise, during this study we have found that what the literature calls “collaborative simulation” refers to the technical aspects of collaborative MBSE design.

Then, on the one hand we have started the actors dimension analysis in WP 7 by considering role definitions, people organisation and stages during a project involving collaborative MBSE design at Airbus Group Innovations. During this study we have interviewed the project manager and analysed 6 meeting documents that he has provided us. On the other hand, we have analysed the process dimension in WP 8 where we have proposed an added value process for collaborative MBSE design(Roa Castro et al. 2016).

Finally, after validating the dimensions and the identification of the actors as the key one in WPs 6 and 8, we have lead WP 9, where we have carried out a deeper analysis regarding the relationships among the members. The outputs of WP 9, also drive the selection of the kind of support to be develop in the next DRM stage. We have dedicated more than a year to gather the information needed and to find the way to analyse it. This work has been summarised in the deliverable of this WP (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.).

We place WP 8 and 9 between Descriptive Study I and Prescriptive Study I. In fact, those studies have not only been useful to provide the final details to the situation description, but they also represent the proposition of the desired situation and the way to address people and process dimensions. Thus, it has been the first step towards the design of a collaborative STS support.

2.3. Prescriptive Study I

Due to the industrial opportunities, we have only developed IT supports for CAD-CAE collaboration. WPs 10 and 11 propose the guidelines for the development of collaborative environments and capitalisation supports respectively (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.); (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.). The application to an industrial use case has allowed us to develop and implement those supports at Renault “Technocentre” (Paris Area). Both supports have been developed using the proposed guidelines in a systemic way. As suggested in DRM framework, we have made a first evaluation showing that it has been correctly developed. These evaluations are the validation of the solution by the users.

WPs 8 to 11 are situated between Prescriptive Study I and Descriptive Study II, because they have either been subjected to an evaluation or we have proposed an evaluation method for them.

2.4. Descriptive study II

We have proposed different ways to evaluate the usefulness of each proposed support that we present below. In WP 8, we have carried out dynamic interviews at the end of the analysis in order to obtain user feedbacks. In WP 9, the evaluation is given by the mathematical results of the game. However, as these results drive the choice of the kind of supports developed during WPs 10 and 11, the evaluations of these WPs will indirectly evaluate the results of the WP 9. In WP 10, we propose a qualitative and a quantitative evaluation for the support. However, we have not been able to lead the qualitative evaluation because of the delay of the implementation. Finally, in WP 11, several implementations of the support have allowed us to include user’s feedback in it.

The results of the evaluations of the different WPs emphasize the improvements to be included, such as the linearity of the representation in WP 8, the subjective aspects of the inputs used for the game in WP 9, the missing implementation in WP 10 or the missing quantitative evaluation in WP 11. These improvements offer several perspectives and new current situations to be evaluated, opening the way to start new Descriptive Studies I.

2.5. DRM framework overall view

As DRM authors suggest, DRM framework should not be interpreted as a set of stages to be rigidly and linearly executed. Thus, we represent the non-linearity of the applied DRM framework for the thesis through the arrows representing the information flow in Figure 9. Likewise, we use three different conventions in the rectangle borders which mean:

- The rectangles using regular borders in the figure represent the AR WPs.
- The rectangles using bold borders in the figure represent the IAR WPs
- The rectangles using dotted borders in the figure represent the review based WPs

Finally, we use a triangle vignette in some rectangles to indicate the papers summarising the key contributions of our PhD thesis WP corresponding which we present in PART 2 of the manuscript.

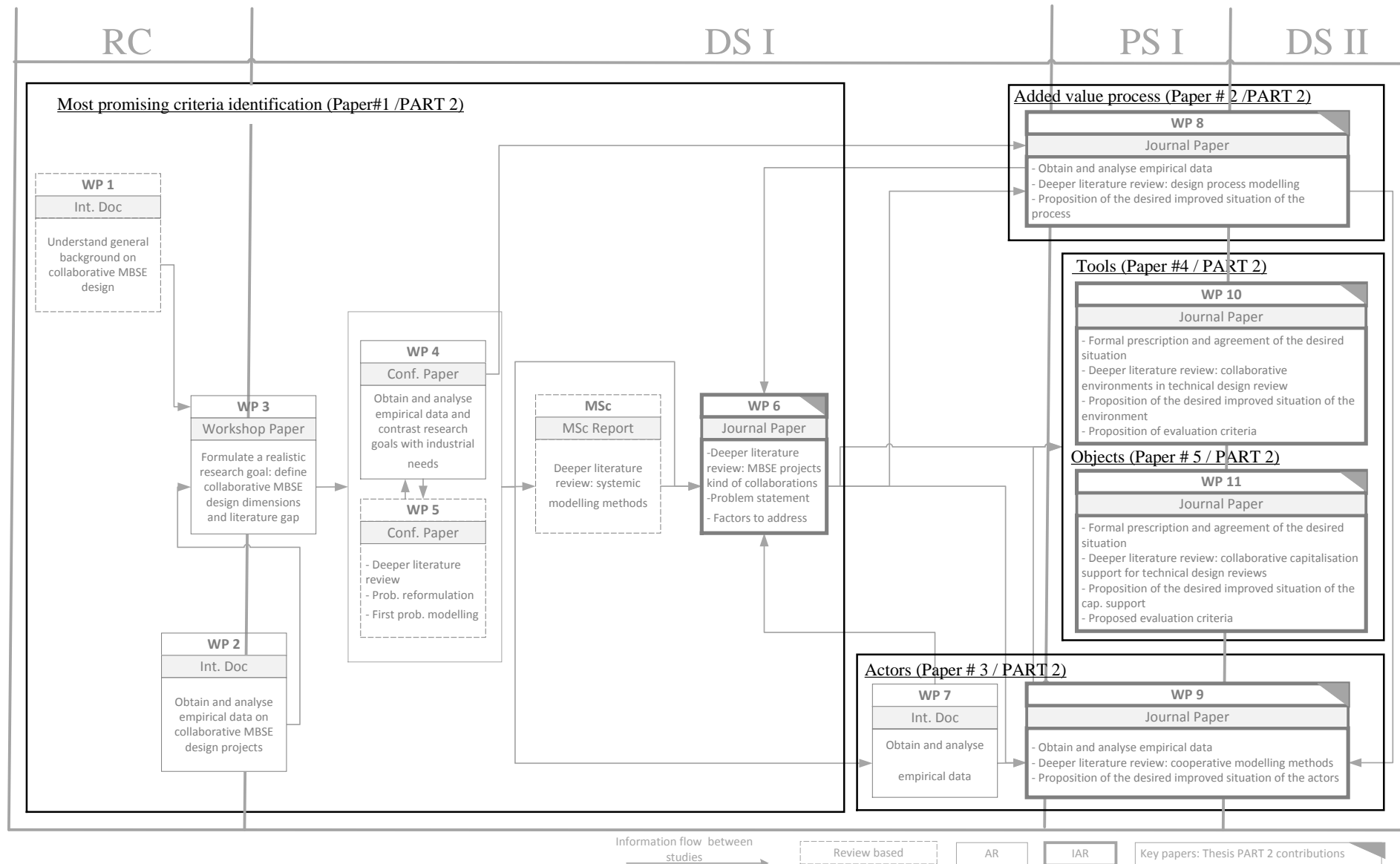


Figure 9: DRM global overview: Summary of WPs and Papers presented in PART 2.

In *Figure 9* we can distinguish two main phases. The first one concerns the RC and DS I stages. The second one concerns the PS I and DS II stages. During the first phase we have focused our effort in develop our understanding of the current situation and to study the works in the literature. These efforts have increased our knowledge and skills to analyse collaborative MBSE design projects. We can see through the arrows linking the different WPs how we have built step by step our main contributions (bold borders WPs). We can also see that the information flow among the different WPs is not linear. The most part of the efforts done during the first phase are recapitulated in WP6 (one of the key papers contributions) and have been the basis supporting the deeper analysis of each of MBSE dimensions. During the second phase, we were focused on the development of the methods addressing the gaps highlighted in the first phase and on the formalisation of those propositions through different journal papers (under submission). Contrary to the second phase where we have submitted several journal papers, during the first phase we have published mostly conference papers and industrial deliverables. Indeed, the exploratory nature of this phase has led to the proposition of a bigger number of studies summarising industrial initiative and literature works and establishing gaps and directions to explore. Finally, it seems pertinent to clarify that the length of the squares and rectangles representing the WPs in the figure are not representative of the time spent on them.

2.6. Data collection protocols

We present an overall view of the data collection protocols used through the WPs led during the thesis in Table 2. WPs 1 and 5 are not presented in this section since both are only review based. Four main data collection protocols have been used: project observations, interviews, workshops and working groups. For each kind of data collection protocol used we present in Table 2:

- The industry where the protocol has been carried out,
- The objective of the implementation,
- The studied collaboration (CAD-CAE or CAE-CAE. c.f.: List of Definitions),
- A short description of the implementation, the WP where the data has been used as we have usually used the data collected in more than one WP to lead different kinds of analysis.
- The quantitative data related to the protocol (number of sessions, session Length in hours (h), number of participants and date).

Table 2: Global data collection summary of collaboration study

Data collection protocols	Industry	objective	collaboration studied	Short Description	Used in WP	No of sessions	Session Length (h)	No. Participants	Date
Project observations (Meeting assistance)	IRT SysX	Observe and analyse how participants work on MBSE projects	CAE-CAE	The observed project correspond to a CAE-CAE collaboration	6, 8	10 – 20	1	4	Dec 2014 To Feb 2015
	Renault		CAD-CAE	The observed project correspond to a CAD-CAE collaboration	10, 11	25	1	5-12	June 2016 To Oct 2016
Interviews	Airbus Group Innov.	Understand the <i>As Is</i> situation regarding MBSE practices at AGI and AP2633 usage	CAE-CAE	First interview: exchange with the two key-leaders of MBSE practices at AGI. Second interview: Results sharing and incorporation of the participant's feedback in the results	4	2	1 – 2	2 interviewee 1 interviewer 2 attendee (backups in note taking)	Dec 2014 & May 2015
	Airbus Group Innov.	Understand and analyse the roles, interactions and stakes in MBSE design projects	CAE-CAE CAD-CAE	First interview: project manager of the EWIS Second and third interviews: Results sharing and incorporation of the participant's feedback in the results We have also analysed 6 project's documents in between the meetings	7	3	1	1 interviewee 1 interviewer 1 attendee (backup in note taking)	Oct 2015 & Nov 2015
	IRT SysX	Analyse roles, interactions and stakes in MBSE	CAE-CAE	We carry out dynamics interview where each participant has built his/her vision of the project exchange in terms of information	6, 8	4 dynamic interviews	1	4	Dec 2014 To Feb 2015
	Renault	Develop the foundations of the capitalisation support	CAD-CAE	The interviews aimed at involving the users in the development and evaluation of the capitalisation support assisting MBSE design projects	11	7	1	7	June 2016 To Oct 2016
Workshops	Renault	Understanding the <i>As Is</i> situation on MBSE design projects	CAD-CAE	Discussion and identification of the activities, the actors and the key meeting points of their current CAD-CAE collaborative activity	6, 10, 11	6	1	5 -12	Jan 2015 To Jan 2016
	Renault	Understanding the <i>As Is</i> situation on MBSE design projects	CAE-CAE	Use of brainstorming to identify the current problems in CAE-CAE collaboration.	2, 3, 8	5	1 - 2	5 -12	March To July 2014

				Use of five why's method to classify them					
	IRT SysX	Implementation of FAcT-Mirror to understand the interactions among the project members	CAE-CAE	Workshops organised in sub-groups	9	4	1	5	May 2015 To July 2015
	Renault		CAD-CAE	Workshops gathering all the participants	9	6	1	9	June 2016 To Oct 2016
	Renault	Analyse the needs related to a collaborative environment and capitalisation support	CAD-CAE	Workshops dedicated to analyse the current situation and to find out the real needs for a collaborative environment and capitalisation support among the MBSE project members	10	3	2	5-7	June 2016 To Oct 2016
Working group meetings	Renault	Develop the foundations of the collaborative environment	CAD-CAE	Working groups including the future users but also the IT department (which must ensure the operability and maintenance of the environment)	10	3	1	2	June 2016 To Oct 2016

2.7. Chapter Summary

In this chapter, we have presented the DRM methodology and its application to the thesis through the proposed DRM stages. Likewise, we have presented an overall view detailing: the WPs stage by stage and the main papers construction. Finally, we have described the data collection protocols used and we present a global view of all the industrial observations done and the WPs where these inputs have been used.

To position our thesis work we present the theoretical context of the research through a literature review on collaborative MBSE design in the next chapter.

III

Literature Review

Several researches and industrial initiatives regarding MBSE have been developed. In order to position this research, we have studied the existing works in the literature and the industrial projects in collaborative MBSE domain. As the Collaborative MBSE scope is still very large, we have used the industrial context to delimit the literature review. As mentioned in sub-section 1.2, we concentrate our work on the use of behavioural and geometric models. Consequently, we have reviewed the existing works regarding CAE-CAE and CAE-CAD collaboration (c.f.: definitions table), and have included social studies on collaboration and insights from Concurrent Engineering (CE) works as well. We have added collaborative and CE studies to find the main characteristics of collaboration and to compare them to our specific context. We have consequently been able to propose a Collaborative MBSE definition. This definition plus the review results highlighting the gap in the literature constitute the basis of the propositions developed in this research.

We present in Figure 10 the literature review approach of this chapter which is organised as follows: In sub-section 3.1 we present the works on collaboration. Then, in sub-section 3.2 we introduce the review on CE and MBSE. In sub-sections 3.2.1 and 3.2.2, we present a literature review on collaborative MBSE (the application of CE in MBSE context) where we detail CAE-CAE and CAE-CAD collaboration works respectively. In sub-section 3.3, we summarise the literature review results and we present the collaborative MBSE definition. Finally, in sub-sections 3.4 and 3.5 we introduce the positioning of the thesis regarding the state of the art and we present a summary of the chapter.

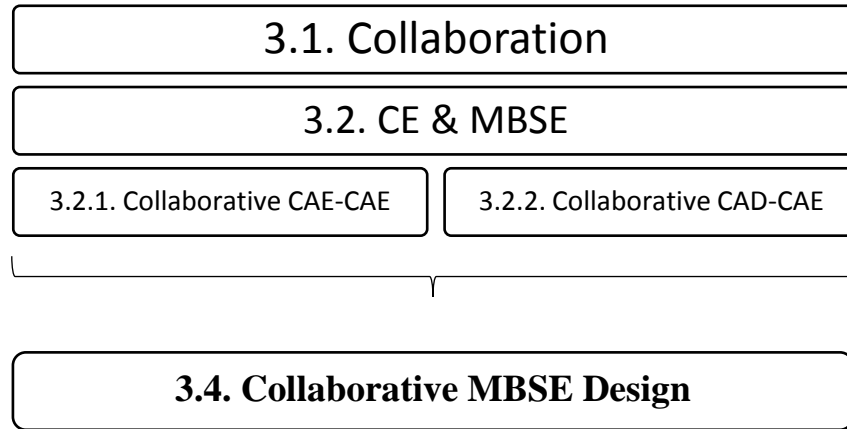


Figure 10: Literature review approach

3.1. The “Collaboration” concept

Collective human endeavours and cooperative behaviours have been emphasized as key aspects to be explored in collaborative engineering design (Lu et al. 2007), (Teichert 1993). Indeed, collaboration between different teams in the product development process has been highlighted as a strategic need along the industrial life cycle (Laborie 2006). In order to understand the meaning of collaboration, we present in the next paragraphs some definitions and concepts proposed in the literature.

Bedwell et al. (Bedwell et al., 2012) define collaboration as an “*evolving process whereby two or more social entities actively and reciprocally engage in joint activities aimed at achieving at least one shared goal*”. The authors also underline five assumptions of collaboration that they have mentioned as follows: “*collaboration is an evolving process, collaboration requires two or more entities, collaboration is reciprocal, collaboration requires participation in joint activities and collaboration is aimed at achieving a shared goal*”. Chiu & Cheng-kung (Chiu & Cheng-kung 2002) describe collaborative design as an activity where “*participants contribute to an interactive design team structure with a goal of achieving a common task by sharing expertise, ideas, resources, or responsibilities*”. Ostergaard et al. (Ostergaard & Summers 2009) define collaborative design as “*a collection of agents (human or artificial) that are working towards a common shared goal using shared resources or knowledge*”.

From a business process point of view, Mathew G. E (Mathew, 2002) describes collaboration as “*a process implying a technology component which enables to collaborate*”. In the same work,

Enterprise Collaboration is defined as “*the partnering of activities, knowledge and assets by multiple stakeholders in a dynamic environment, with the objective of gaining business advantage*”. Wood and Gray (Wood, 1991) take into account the stakeholders issue in their definition saying that collaboration takes place when a “*group of autonomous stakeholders of a problem domain engage in an interactive process, using shared rules, norms, and structures, to act or decide on issues related to that domain*”.

The terms communication, coordination and synchronisation have also been frequently found as concepts related to collaborative activities. Communication can be simply defined as a *message delivery*. Nevertheless, Burstein et al. (Burstein et al., 2010) distinguish communication from Effective Communication defining this one as a “*communication that produces the intended effect in the recipient*”. Salas et al. (Salas et al., 2000) define Coordination as a “*process by which team resources activities and responses are organised to ensure that tasks are integrated, synchronised and completed within established temporal constraints*”. Finally, M. Wooldrige (Wooldrige, 2009) characterises Synchronisation as “*the problem of designing the interaction between process, typically to ensure that they do not destructively interfere with one another*”.

Another term that we have found in the literature is cooperation. From a Game Theory point of view (GT), cooperation is established between two actors, when they obtain bigger profit when joining a coalition (acting together) than when acting by themselves (Von Neumann & Morgenstern 1953). In other words, “*the total profit of the team is more than any other non-cooperative optimal solution obtained*” (Semsar-Kazerooni and Khorasani, 2009). Thus, Cooperation corresponds to “*identifying and exploiting win-win situations*” (Cruijssen et al., 2007).

We have found that the terms cooperation and collaboration are sometimes used as synonyms whereas the literature indicates that their meaning are different. Ostergaard et al. (Ostergaard & Summers 2009) argue in their work that a distinguished characteristic of collaborative design versus concurrent or cooperative design is that participants share a common objective. T. Kvan (Kvan 2000a), also differentiates collaboration from cooperation: “*collaboration requires a higher sense of working together in order to achieve result*”. To define both collaborative and cooperative relationships Mattessich and Monsey (Mattessich & Monsey 1992) have gathered 8 elements in 4 points as follows: 1) vision and relationships, 2) structure and communication, 3) authority and

risks and 4) resources and rewards. On the one hand, they characterise cooperation as an “*informal relationship that exists without a commonly defined mission, structure or effort. Information is shared as needed and authority is retained by each organisation so there is virtually no risk. Resources are separated as are rewards*”. On the other hand, they characterise collaboration as a more durable relationship. They affirm that collaboration brings organisations into a new structure with a common mission where information channels must be defined. In this relationship, the authority is determined by the collaborative structure and the risk and resources are shared.

We summarise in Table 3 the characteristics of cooperative and collaborative relationships according to the literature insights. In general, these relationships are always presented as people interacting through different activities implying coordination, synchronisation and communication actions among them. However, even if cooperation and collaboration share these actions, they can be differentiated by other elements proposed in the literature. We use individually the 8 elements proposed by Mattessich and Monsey (Mattessich & Monsey 1992) - instead of their grouped proposition - to give details of cooperation and collaboration characteristics. In addition, we have added a new element (sharing of knowledge, expertise or ideas) and updated another one (common goal definition).

Table 3: A summary proposition of collaboration and cooperation characteristics coming from the literature

Characteristics		Cooperation	Collaboration	Literature sources
Common goal (Vision)	Defined		X	(Bedwell et al., 2012), (Chiu & Cheng-kung 2002), (Ostergaard & Summers 2009), (Kvan 2000a), (Wood, 1991), (Mathew, 2002), (Mattessich & Monsey 1992)
	Undefined	X		
Knowledge assets/expertise/ideas	Join		X	(Chiu & Cheng-kung 2002), (Wood, 1991), (Ostergaard & Summers 2009), (Mathew, 2002)
	Separate	X		
Relationship	Informal	X		(Mattessich & Monsey 1992), (Kvan 2000a), (Wood, 1991)
	Formal		X	
Common structure (roles, planning.)	Defined		X	(Mattessich & Monsey 1992), (Kvan 2000a), (Wood, 1991), (Bedwell et al., 2012)
	Undefined	X		
Communication channels *	Structured		X	(Mattessich & Monsey 1992)
	Unstructured	X		
Authority	Common		X	(Mattessich & Monsey 1992), (Kvan 2000a)
	Separated	X		
Shared Risk/Responsibilities	Yes		X	(Mattessich & Monsey 1992), (Kvan 2000a), (Chiu & Cheng-kung 2002), (Von Neumann & Morgenstern 1953), (Semsar-Kazerooni and Khorasani, 2009), (Cruijssen et al., 2007)
	No	X		
Resources	Common		X	(Mattessich & Monsey 1992), (Kvan 2000a), (Chiu & Cheng-kung 2002), (Ostergaard & Summers 2009),
	Separated	X		
Rewards	Common		X	(Mattessich & Monsey 1992), (Kvan 2000a), (Von Neumann & Morgenstern 1953), (Semsar-Kazerooni and Khorasani, 2009), (Cruijssen et al., 2007)
	Separated	X		
Time	Long term		X	(Mattessich & Monsey 1992), (Kvan 2000a)
	Mid-term			
	Short term	X		

We have noticed that all the definitions found in the literature call on a **common goal definition as the basis of any collaboration**. This characteristic differentiates collaboration from cooperation, where people aim at maximising their own objectives. However, this characteristic is not mentioned in this way in Mattessich and Monsey work. It is rather referred to as shared vision. We propose to refer to *common goal* as a result of this literature review. Likewise, we have found a new element related to knowledge sharing. As presented in the previous paragraphs, literature reveals that mobilising knowledge enables collaborative activities to be successful. Actually, the mentioned works note that people mobilise different kind of knowledge, such as ideas, expertise or know-how to achieve a defined common goal.

Regarding the rest of the elements, we observe that in collaborative relationships people have a common and defined structure coming from collaboration itself. Additionally to the structure, people collaborating also share the authority, the risk, the resources and the rewards. They

communicate through structured communication channels and their interactions often imply long term relationships. Contrary to collaborative relationships, people do not necessary share the same structure, authority, risks, nor rewards, in cooperative relationships. Their communication channels could be more informal and their interactions are the result of short, or mid-term relationships. Based on these characteristics, we can define collaborative and cooperative relationships as follows:

Collaborative relationships: Organisation of two or more people who work together to achieve a common goal. They are organised through a common defined arrangement (but not imposed), supported by structured communication channels where the authority is shared along with the risk, resources and rewards. These interactions are often the results of long-term relationships but they are not restricted to them.

Cooperative relationships: Organisation of two or more people who work together without necessarily having a common goal to achieve. The organisational structure is not necessary the same and it can often be an imposed one. The people usually interact through informal communication channels. The interactions are mostly short and mid-term where neither the authority, nor the risks nor the rewards are shared. They are often the results of long-term relationships but they are not restricted to them.

As mentioned at the beginning of the manuscript (c.f.: List of Definitions), **in this PhD thesis we have focused our attention on the cooperative relationships among the MBSE projects members.** We have studied cooperation instead of collaboration because the industrial reality (observations) corresponds to this kind of relationships (c.f. Table 7: Proposition of a comparison MBSE design project observations to cooperation and collaboration). However, as a matter of coherence with the literature we refer to collaborative MBSE design in most cases in this manuscript except in sub-section 4.3, where we have analysed in detail the relationships among the actors and we have used methods addressing cooperation and not collaboration. Thus, we have employed the term cooperation.

3.2. Concurrent Engineering and collaborative MBSE

The new market competitiveness, combined to the fast growth of computational power and engineering teams, has brought the companies to think of new approaches supporting their product development process. In this context - and as introduced in sub-section 1.2- collaborative

approaches have emerged to face these new needs. Collaborative or Concurrent engineering (CE) has appeared to support the new competitiveness requirements of the companies (Bonjour 2008). CE principles have been introduced for the first time in the 80's. They were presented as a systematic method using a simultaneous approach to develop products considering the concurrent nature of their related process as well as all the elements of the product lifecycle (Winner et al. 1988). The inclusion of CE practices in the industry has shown a positive impact on the design process reducing time to market (Prasad 1997). In addition, companies using concurrent engineering (CE) principles have found that people working in cross-functional teams are less likely to make mistakes during the Product Development Process (PDP) (Prasad 1993).

Several CE principles can be found in the literature. B. Prasad (Prasad 1997) refers to seven principles of CE as: *Parallel Work-group*, *Parallel Product Decomposition*; *Concurrent Resource Scheduling*; *Concurrent Processing*; *Minimise Interfaces*; *Transparent Communication*; and *Quick Processing*. He also proposes seven *forces* influencing CE (called 7Ts): *talents, tasks, teams, techniques, technology, time and tools*. To Lu et al. (Lu et al. 2007) collaborative engineering occurs in practice *when a team of stakeholders engages collaborative endeavour to attain a consensual agreement for complex tasks in organisation*. They have defined CE as a *discipline facilitating the communal establishment of technical agreements among a team of interdisciplinary stakeholders, who work jointly towards a common goal with limited resources or conflicting interests*. From his side, Anthony Mills (Mills 1998) defines CE as a collaborative exchange of resources among a group of stakeholders with some common creative purposes and a shared understanding, who are focused on a efforts technology-intensive. We summarise in Table 4 the most common characteristics used to describe CE that we have found in the literature.

Table 4: A summary proposition of the most common characteristics used to describe CE in the literature.

Reference Charact.	(Prasad 1997)		(Bonjour 2008), (Belkadi et al. 2013)	(Kamrani & Abouel Nasr 2008)	(Lu et al. 2007)	(Mills 1998)
People	Work-group Communication	Talents Teams	Team Communities Organisations	Designers interaction	Who	Stakeholders
Product	Product decomposition Interfaces information		Product information Information flow	Product information	What	
Process	Processing	Tasks	Process	Activities and process	How	Technology – intensive development efforts
Resources	Resources	Technologies Tools	Tools	Resources and tools		Resources
Time		Time	Project			
Knowledge		Technics	Skills Knowledge Know-how	Knowledge		
Shared vision			Awareness		Why	Common understanding and creative purposes

Comparing the characteristics describing CE proposed by the different authors, we suggest to group them into four main dimensions: people, process, information objects (containing product information) and tools. In addition to these aspects with which all the works agree, we have identified three more aspects that are not systematically mentioned in every work: The temporal dimension, the common understanding and the knowledge sharing. Taking into account the temporal dimension is important because collaboration occurs in a specific slot of time (e.g.: given situation or project) which implies a specific context. The context could change with time affecting these relationships. The common understanding has appeared in sub-section 3.1 as one of the elements characterising collaboration. Thus, it seems natural to include it as a feature characterising CE. However, we have surprisingly found that the studies do not necessarily illustrate this element. Finally, more recent studies have associated the shared knowledge as part of collaboration. In the table, we have classified the item “technics” as part of this group because it refers to know-how while the authors do not refer to it as knowledge. Likewise, we think that some works do not mention the shared knowledge because they could refer to it as shared information. Yet, it seems

pertinent to us to distinguish between both, knowledge and information, because first, they are clearly differentiated in the literature and second, people do not give the same importance to these two items. To better understand this difference, we can use the metaphor proposed by Russell Ackoff (Ackoff 1989): *An ounce of information is worth a pound of data. An ounce of knowledge is worth a pound of information.* Thus, in the suggested groups, the items related to the information correspond to processed data (product data for instance) whereas knowledge is much larger. It can be understood as a dynamic human process towards the truths (Nonaka & Toyama 2005).

Looking at a more precise scope of collaborative MBSE design (CE in MBSE context), Mas et al. (Mas et al., 2013) characterise CE as a shared timeframe with a unique team focused on the delivering of an “iDMU for all”(Industrial Digital Mock-up). In this context, the use of models (iDMU) provides a common virtual environment for all the aircraft development stakeholders. It is also known that the use of models is valuable in product design since they *simplify the description of the system under considerations, in order to simplify its complexity* (Zeigler et al. 2000). The collaborative issues coming from the use of models have been largely studied in both, industry and academy. Because of the industrial context of the thesis, we focus our attention on two main collaborative MBSE problems. These problems concern the particular application of modelling to support design and analysis activities through different tools, such as CAD (Computer Assisted Design) and CAE (Computer Assisted Engineering) software.

The first problem is often called in the literature “collaborative simulation”. This problem concerns the activities within simulation department teams. We have called this kind of interactions CAE-CAE collaboration (c.f. List of Definitions). As we have mentioned in sub-section 1.2, we are conscious that the terms CAD and CAE define tools and not people. However, we have decided to use this terminology to facilitate the differentiation between the two collaboration studied. CAE-CAE collaboration refers to collaborative problems often due to multidisciplinary context. The term “collaborative simulation” is often related to technical aspects, such as interoperability problems or monitoring difficulties (Jun et al. 2008; Freedman et al. 2015). The second problem refers to CAE-CAD collaboration. This problem concerns the interactions between embodiment design (CAD) and simulation department (CAE). Some holistic approaches regarding CAE-CAD collaboration have been found in the literature. Those approaches take into account, more dimensions of the problem: people, processes, information objects and tools (Deubzer et al. 2007;

Deubzer et al. 2005), (Matthias Kreimeyer et al. 2016), (M Kreimeyer et al. 2007; Maier et al. 2009). Nonetheless, only a few works suggest the existence and the link between those dimensions.

In the next two sub-sections, we detail the current literature regarding both, CAE-CAD and CAE-CAE collaboration.

3.2.1. Collaborative CAE-CAE

Looking for collaborative CAE-CAE works in the literature, we have found that several works address interoperability and standardisation problems. This fact can be explained by the multidisciplinary nature of this kind of collaboration. Indeed, in order to answer precise needs in different domains, very specific tools have been developed for years. Nowadays, the need for a system view has made interoperability a major factor conditioning the success of the system deployment process (Cornua et al., 2012). These issues have been addressed in the literature from different points of view such as model interfaces (Sirin 2015), data exchange, (Zhaia et al., 2010), mathematical model integration (Patzák et al., 2013) and modularity problems (Patzak et al. 2013), (Portegies Zwart et al., 2013). One of the most known initiatives addressing these issues is the FMU/FMI (Functional Mock-up Unit/ Functional Mock-up Interface) approach (Bertsch et al., 2014). This approach facilitates the models plug-in by standardising the interfaces. This concept is also related to *white box* and *black box* in model exchange context. (c.f. List of Definitions). Through the definition of the interfaces, FMI uses the black box model exchange approach dealing with know-how protection.

We have also found in collaborative CAE-CAE literature, several works addressing other subjects such as visualisation and monitoring capabilities (Yasuaki et al., 2008), (Badin et al. 2011), product lifecycle management (Jordan and Schmitz, 2014) and data reuse and capitalisation in this context (Badin et al. 2011). The initiatives mentioned before cover technical aspects in model exchange in particular, and they do not necessarily take into account the two basic elements of any cooperation/collaboration: people and activities. As literature on collaboration suggests the implications of people interacting through different activities, we focus our attention on the works also including people and activities in this context. We present in the next paragraphs, some of the most known initiatives addressing CAE-CAE collaboration that include these elements. Nonetheless, an extended review of the works treating the technical aspects mentioned before can be found in (Roa-Castro & Stal-Le Cardinal 2014b).

Collaborative problems within simulation teams have encouraged the development of several projects. Among them, three representative initiatives are FEDEP (Department of Defense 1999), ProSTEP (ProSTEP 2014) and AP2633 (Airbus 2005). These projects aim at improving CAE-CAE collaboration.

FEDEP is the acronym used for Federation Development and Execution Process. Its report describes a high-level process where the activities are related to high level architecture federations. Nevertheless, FEDEP documentation does not include any role for the process and it is mainly focused on tasks and documents identification. ProSTEP iViP Recommendations document aims at orchestrating different models of manufacturers and suppliers. This initiative offers an interesting structure regarding the product lifecycle in different scenarios. For some scenarios a significant description of the IT needs has been done. The ProSTEP reference process identifies three roles, three phases, thirteen activities and five elements of the behavioural model specification (model requirements). Nevertheless, the roles identified are still general and the outputs of each activity are not included in the process description but in other documents. Finally, the AP2633 or Airbus Procedure for Integration and Exchange of Simulation Models, also contributes in terms of process, tasks and role description. An analysis of this procedure and its limitations can be found in a previous work (Roa-Castro et al. 2015).

Another work proposing approaches much more related to information exchange and which also takes into account people and activities is proposed by Sirin et al. (Sirin et al. 2015). In this work, the authors suggest a standardisation of the model interfaces through a Model Identity Card (MIC). This work identifies three main roles in collaborative CAE-CAE: System architect, model architect and model provider. These roles represent different views and level in the modelling process. Take into account this multilevel integration on the design of complex systems has become one of the major bottlenecks in modern computer modelling (Portegies Zwart et al., 2013).

To conclude, we can say that several initiatives addressing technical issues in this context have been developed. However, the works including people and activities are less common. The process gathering these two elements and describing “collaborative simulation” (CAE-CAE) in the literature are still very general. However, they propose a description of the current model exchange context through some works such as the AP 2366, FEDEP and ProSTEP. Those process descriptions are a valuable initiative. Nevertheless a significant improvement could be done,

especially regarding the inclusion of new roles as well as the inclusion of model reuse and capitalisation steps. The fact that the last elements have already been highlighted in the collaborative CAE-CAE literature as *data reuse* problem is interesting. But, they have not been included as a part of a holistic view aiming at improving collaboration among the actors. Indeed, these elements offer contextual information of the model which has become a key factor for the performance of the task (Walker and Chapra, 2014), which is in this case the model reuse.

3.2.2. CAD-CAE collaboration

Efficient collaboration between design and simulation departments is a key factor for an effective product development. There are numerous efforts to systematically integrate product development activities using CAD and CAE systems (Kreimeyer et al. 2007). CAE-CAD integration is an important issue in vehicle industry. Whereas design engineers think in terms of their geometrical structure and focus on one component or assembly, simulation engineers think in terms of functions and focus on the whole product or larger parts. The coexistence of these two different paradigms: a topological one for the design teams and a functional one for the simulation teams, increases the demands on human communication between both departments. A close collaboration of design engineers and simulation engineers becomes a core element to foster product design (Maier et al. 2009).

Different approaches have been adopted in the literature to study collaboration. Deubzer et al. (Deubzer et al. 2005) (Deubzer et al. 2007) point out the importance of a goal oriented alignment. They distinguish four key dimensions for a successful collaboration: people, process, information objects and tools, and propose to identify their respective links through a matrix approach. Nevertheless, the system supposes two conditions: (1) a cooperation between design (CAD) and simulation (CAE) engineering teams; and (2) non-evolving requirements during the collaborative process. They identify people act at the centre of the collaboration whereas in another work, Kreimeyer et al. (Kreimeyer et al. 2007) address CAD-CAE integration problem from a communication point of view, describing the correlation between the elements product and people. They also use three main dependences matrix approaches: IDM (Information Driven Approach), DMA (Dependence Matrix Analysis) and DMM (Domain Mapping Matrix). Their research study

aims at designing a strategy to ensure a purposeful transfer of information from the right senders to the right recipients.

To conclude, the industrial need for closer integration of design engineer and simulation engineer departments is a business priority. A closer integration would allow both, to reduce the product development time (Mocko & Fenves n.d.) and to enhance the decision making process during the development phases (Broek & Dutta n.d.). Unlike “collaborative simulation” (CAE-CAE) literature, CAD-CAE integration works have explored holistic approaches. The research in this field identifies four key dimensions of the collaborative problem between both, design and simulation departments (people, process, information objects and tools). In addition, the authors explore a useful way to identify the relationships between the elements. Yet, the meaning of the relationships is still vague, and a clear proposition of elements and activities to improve collaboration between engineers in this context is missing.

3.3. Collaborative MBSE Design

As any other collaboration, designing with models implies specific features related to the context. To be accurate, this collaboration implies the transfer and exchange of a huge amount of data, information and knowledge contained in the models. We have not found a definition of collaborative MBSE design in the literature establishing these specific characteristics. Thus, we propose to define collaborative MBSE design, based on the elements that we have found.

The literature definitions describing CE disclose the narrow link between the technical efforts needed in the Product Development Process (PDP) and the people developing these products. These links evidence the existence of the suggested dimensions found in the literature describing CE: people, process, information objects and tools. Regarding collaborative MBSE design, we have mainly found works addressing tools and activities aspects in CAE-CAE, whereas holistic approaches are more recurrent in CAE-CAD. However, the meaning of the links among the characteristics is still vague.

Even if literature on CAE-CAE and CAE-CAD collaboration does not make explicit the concept of knowledge in their information objects, the use of models as information objects already implies encapsulation of a huge amount of data, information and knowledge. We use Figure 11 to illustrate these differences through the example of a project aiming at developing an Environmental Controller System (ECS) regulating the aircraft cabin temperature (Roa Castro et al. 2016).

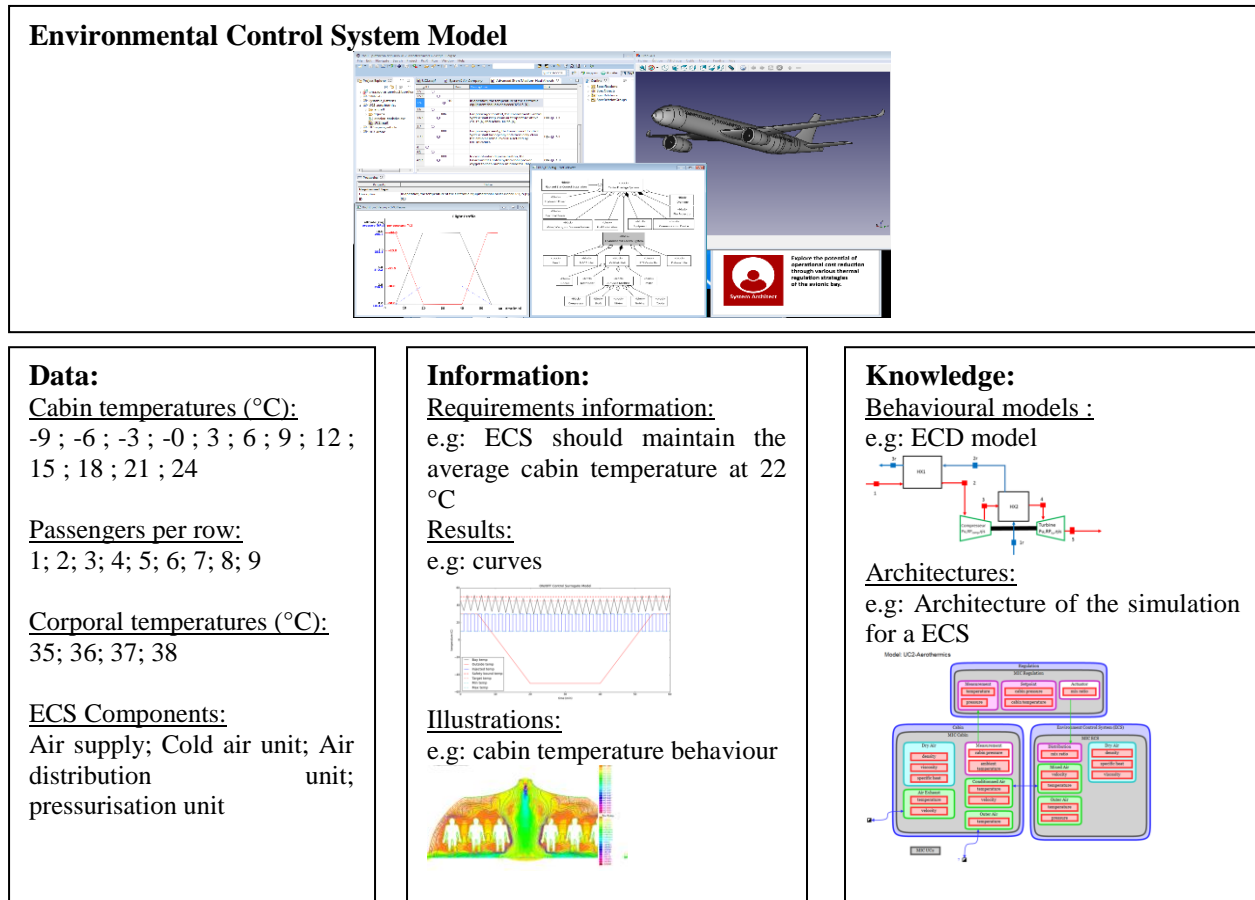


Figure 11: An Illustration of difference between data, information and knowledge in MBSE

The data contained in the model corresponds to all the raw data (cabin temperatures, number of passengers per row, possible corporal temperatures and ECS components). Presented as a list of numbers, it does not really make sense. But, organising and using it to describe the system (curves showing temperature over time, graphic illustrations of the cabin temperature around passengers), reveal valuable information of the model. Finally, people can fully understand the model, knowing about its architecture and performing behavioural simulations to see the real impact of the parameters on the system. This knowledge answers the questions of *how-to* (Ackoff 1989).

Finally, the last element found in the CE literature is directly related to the major feature characterising collaboration: having a shared common goal (c.f. sub-section 3.1). However, the literature often mentions a common understanding instead of a common goal. We propose to include this notion as it has been highlighted as the basis of any collaboration. Along with the other dimensions characterising collaboration, it should be included in the factors to be taken into account to incite engineering teams to collaborate.

As a conclusion, we define **Collaborative MBSE design** as *an activity involving simulation and design engineers, who share data, information and knowledge encapsulated in the simulation models. They use different resources or tools to perform the sharing and to accomplish the task related to the product development process at the simulation stages*. Nonetheless, as the studied industrial reality correspond to cooperative relationships we consider this proposition as a theoretical concept coming from the literature insights and the desired industrial situations.

We conclude that Collaborative MBSE design is characterised by:

- (1) The goals and profiles of people participating (simulation and design engineers).**
- (2) The encapsulation of the knowledge in the simulation models.**
- (3) The tools and resources supporting information and knowledge treatment (e.g.: CAD-CAE).**
- (4) The tasks related to design and simulation stages of the product development process.**

Collaborative MBSE Design covers several dimensions and factors. All of them are closely interconnected which hinder their separated consideration. Furthermore, the social aspects of the collaboration and the inclusion of new ways to share the knowledge (models) suggest that Collaborative MBSE Design should be analysed and studied as a complex system.

3.4. Positioning of the Thesis

In order to provide a global vision and a clear understanding of Collaborative MBSE Design, we propose to study it from a systemic perspective, where a global view containing the dimensions characterising this collaboration (people, process, information objects and tools) and their relationships can be represented. This representation should establish the basis for the development

of STS enhancing collaboration in this context. In addition, it should give some insights regarding the mechanisms that can be used for the deeper analysis of each of these dimensions. These mechanisms must allow the analysis of the behaviour of the people collaborating, of the knowledge that they share through the simulation models, of the tools that they use and of the way how they work. Contrary to the existing collaborative systems propositions addressing CAE-CAD and CAE-CAE collaboration, we analyse in detail the actors' relationships in this context and we use this analysis to develop suitable STS that respond to the real user's needs.

By addressing the description and understanding of Collaborative MBSE Design, and by analysing its different dimensions, we hope to be able to face some of the challenges suggested in the literature such as:

- The improvement of the awareness and common understanding of a given situation among the different stakeholders. (Bonjour 2008), (Ngwenyama & Lyytinen 1997)(Bedwell et al. 2012), (Belkadi et al. 2013)
- Getting the people to work together. (Kreimeyer et al. 2007), (Kvan 2000b),
- Introducing better theories, and more systematic methods resulting in long-lasting impacts and contributing to the progress of CE practices. (Lu et al. 2007).

3.5. Chapter Summary

In order to understand collaborative MBSE design, we have reviewed different kinds of work presented in the literature. The first one concerns the human factors of the collaborative relationships (sub-section 3.1) and the second one the works on CE in MBSE context (CAE-CAE collaboration in sub-section 3.2.1 and CAD-CAE collaboration in sub-section 3.2.2).

On the one hand, the works related to the social aspects of collaborative relationships evidence the difference between collaboration and cooperation. Likewise, they agree on the fact that sharing a common objective among the people involved is the basis of any collaboration. On the other hand, the review on CE has allowed us to list the dimensions of this collaboration. Furthermore, most of the works on CAE-CAE are focused on the tools and activities aspects, whereas holistic approaches are more recurrent for CAE-CAD. These approaches include four of the dimensions describing CE

(people, process, information objects and tools) but the meaning of their respective links is still vague.

We have not found any definition of collaborative MBSE design in the literature, neither an explicit characterisation of this kind of collaboration. Thus, we propose a definition based on the elements that we have found in both, CE and social works literature and we have listed its specific dimensions.

We conclude that, to our knowledge, the existing works do not provide a global vision and a clear understanding of Collaborative MBSE Design. Likewise, the current effort done in the development of collaborative systems in CAE-CAD and CAE-CAE collaboration do not take into account all the dimensions of the problem or do not analyse in detail the actors' relationships (which is essential to understand and improve their collaboration). Consequently, we propose to study Collaborative MBSE Design from a systemic perspective to establish the basis for the development of STS enhancing collaboration in this context based on the detailed analysis of the relationships among the involved actors.

IV

Proposition of a methodology to manage organisational complexity in MBSE design projects

In this chapter, we summarise in a global methodology the proposed methods to develop STS from a systemic perspective. The use of STS seems appropriate to develop systems that take into account the identified dimensions characterising collaborative MBSE design (people, process, information objects and tools). Socio-technical research claims that considerations of social and technical subsystems within an organisation must be jointly and simultaneously optimised for the greatest performances (Boujut & Tiger 2002). In fact, the advancements in technology assisting effective interactions between team members can serve to reduce the social complexity (Lu et al. 2007). Nevertheless, technological systems alone cannot provide an answer to the complexity related to the new organisation. This situation has motivated some authors (Carey & Kacmar 1997) to suggest that people should rethink the design of current collaborative technologies to ensure greater effectiveness.

In order to propose a holistic approach for the development of STS, we suggest to establish its foundations using a systemic perspective. The adoption of this perspective will ensure the consideration of all the dimensions describing collaborative MBSE design. In addition, it will also be particularly helpful in the identification of the relations between these dimensions. Among the works proposed in the literature supporting the development of STS, Socio Technical Construction Procedure (STCP) (Lu et al. 2007) is a great example of a holistic approach. In this work, the authors propose 8 steps to ensure the development of coherent STS (*Baselines Process, Stakeholders, Concept Structure, Perspective Model, Perspective Model State Diagrams,*

Perspective Analysis, Conflict Management, and Shared Reality). These steps take into account the different features characterising collaborative relationships. Notwithstanding, as specified in its acronym, STCP corresponds much more to the establishment of guidelines setting the good conditions to collaborate among different departments in a company, than to guidelines to develop systems that support this collaboration. In addition, the proposed models for the analysis of the actors' interests (presented in steps: *Perspective Analysis* and *Conflict Management*) do not provide a clear vision of how to translate the reality (observations) into the inputs of the models.

The methodology proposed in this chapter is intended to rethink the way how collaborative systems can be developed and to clearly suggest how the real needs (observations) can be successfully assisted by this kind of systems.

In sub-section 4.1 we introduce CEDOSy (Collaborative Engineering Design Organisational Systems). CEDOSy method aims at establishing the basis for the development of STS assisting engineering design. We have applied CEDOSy to the specific context of MBSE design in order to enhance collaboration. This method suggests the use of different mechanisms facilitating the study of the current situations in collaborative MBSE design in terms of people, process, information objects and tools. The implementation of these mechanisms and the logic induced by CEDOSy lead to the development of suitable STS for the organisation. We introduce the suggested mechanisms as follows. In sub-section 4.2, we present an added value process description for collaborative MBSE design. In sub-section 4.3, we present a method allowing the analysis of the cooperation among the involved actors. In sub-section 4.4, we present a group of guidelines which goal is the development of collaborative environments and collaborative capitalisation supports assisting the models sharing, and enhancing collaboration in this context. Finally, in sub-section 4.5 we present a global methodology proposition to improve collaborative MBSE. This proposition gives to the group of methods presented from sub-section 4.1 to 4.4 a logical sense of their implementation.

Sub-sections 4.1 to 4.4 are a summary of all the methods and mechanisms proposed in this thesis. A more detailed description of them as well as their background can be found in the papers presented at the end of the manuscript. We present in Figure 12 the links between the collaborative MBSE dimensions and the methods presented in this chapter.

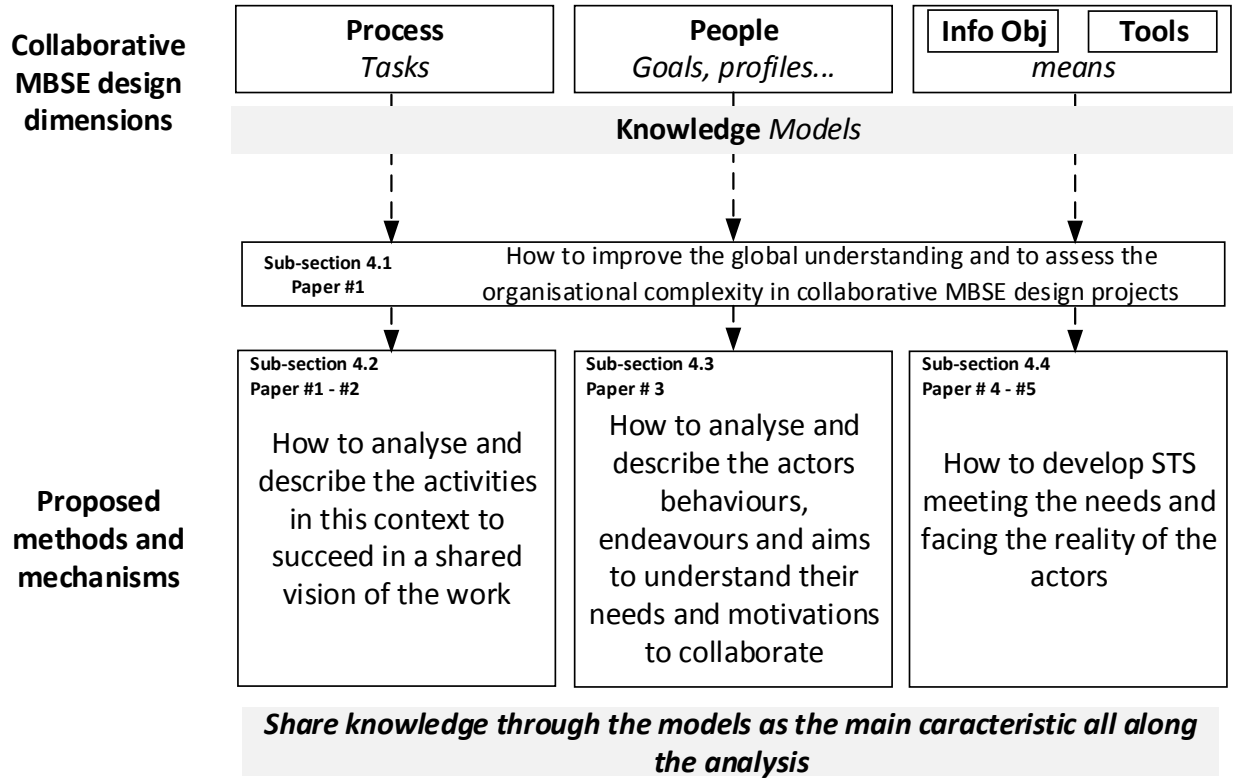


Figure 12: links between the collaborative MBSE dimensions and the proposed methods and mechanisms

The collaborative MBSE dimensions are presented at the top of the figure. At the bottom, we represent the proposed methods and mechanisms through the questions that have been addressed in their development. We illustrate through the dash-line arrows the links between the dimensions characterising collaborative MBSE design and the proposed methods and mechanisms presented in this chapter. The rectangle making the transition between the dimensions and the methods and mechanisms addressing them represents the departure point establishing a global view of the collaborative MBSE system. We also include in Figure 12 a grey rectangle representing the knowledge shared in this context. The knowledge is shared all along the process by the actors through different means.

4.1. Paper #1: CEDOSy method

As introduced in chapter 2, the findings in the literature suggest that collaborative MBSE design should be analysed and studied as a complex system. Such analysis has not been addressed yet. In this sub-section, we present CEDOSy method. CEDOSy aims at providing a global vision and a clear understanding of collaborative MBSE design. Likewise, it sets up the basis for the

development of STS enhancing collaboration in this context. The global description addresses the different dimensions characterising collaborative MBSE design that have been described in Chapter III (people, process information objects and tools). Additionally, CEDOSy method suggests the use of different mechanisms facilitating the study of each of those dimensions.

In order to choose the most promising approach to base CEDOSy on, we have found three main works addressing the modelling of organisational complex systems: the Operations, Information, Decisions and Knowledge method (OIDC) (Fatfollah 2011), the Soft Systems Methodology (SSM) (Wang et al. 2015), (Rodriguez-ulloa & Paucar-caceres 2005), and the Systemic approach (Le-Moigne 1990).

Among these modelling methods, the systemic approach is the most appropriate to build CEDOSy. Its axes match with the four dimensions allowing a detailed description of each of them. In a previous research study (Fatfouta et al. 2016), the methods have been compared using QFD method but the conclusion remains the same. The systemic approach covers all the dimensions related to collaborative MBSE design in a single representation facilitating the definition and illustration of the interaction among of them. We show in Figure 13 (b) the OCSM (Organisational Complex Systems Modelling) method (Jean 2013). OCSM is the closest application of the systemic approach to our research. Nevertheless, it is not completely adapted to describe collaborative organisational systems, neither to take into account the MBSE context.

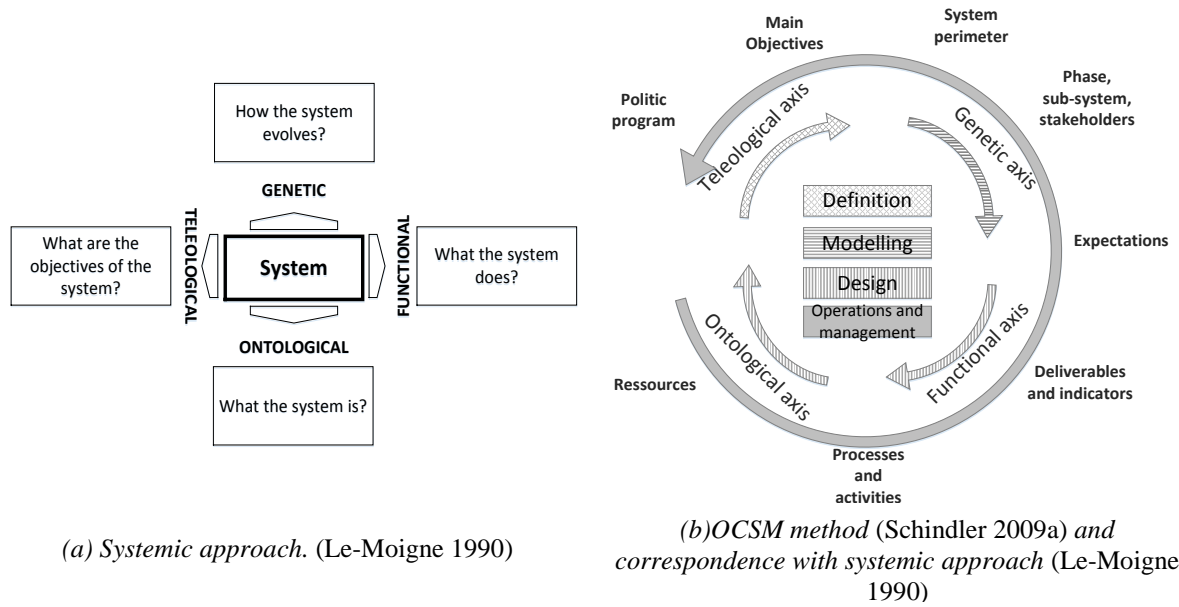


Figure 13: Systemic approach and OCSM method illustration

Figure 13 (b) represents OCSM in terms of the systemic approach axis as follows:

- The teleological axis is described in terms of the political program (or organisational strategy) and the main objectives of the system,
- The Genetic axis is described in terms of the system perimeter. Each phase of the system must be considered. Likewise, the stakeholders involved in each phase must be identified,
- The functional axis is described in terms of the stakeholders' expectations and the deliverables, activities, and added value processes resulting from those expectations,
- The ontological axis is described in terms of the means or resources needed to execute processes.

In addition, a verification of each item is proposed by going backward from the ontological axis to the teleological axis. The OCSM method proposes the organisation as a departure point for the system modelling, which ensures the socio-technical coherence of the propositions resulting from its application.

We present a global view of CEDOSy in Figure 14. Its implementation through two use cases can be found in Paper#1 at the end of the manuscript. In Figure 14, the full coloured rectangles denote

the new items regarding the OCSM method. CEDOSy proposes the necessary elements and tools facilitating the characterisation of each MBSE dimension and defines their interactions. As CEDOSy has been built using OCSM method, it guarantees the design of collaborative STS responding to the organisational aspects of this collaboration. Starting from the identification of the organisational objectives, strategies and context, and continuing by the stakeholders characterisation, CEDOSy method assists the definition of the collaborative points through the different MBSE design phases, where specific stakeholders expectations regarding the collaborative STS are identified, as well as the concerned activities and exchanged objects, in order to propose added value process with different scenarios variations, that must be supported by collaborative resources involving the future users. The characterisation of the elements proposed by CEDOSy defines the foundations needed for the development of collaborative STS in MBSE projects.

We illustrate in Paper #1 (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.) the use of CEDOSy through two use cases where we detail the elements enclosed in each axis.

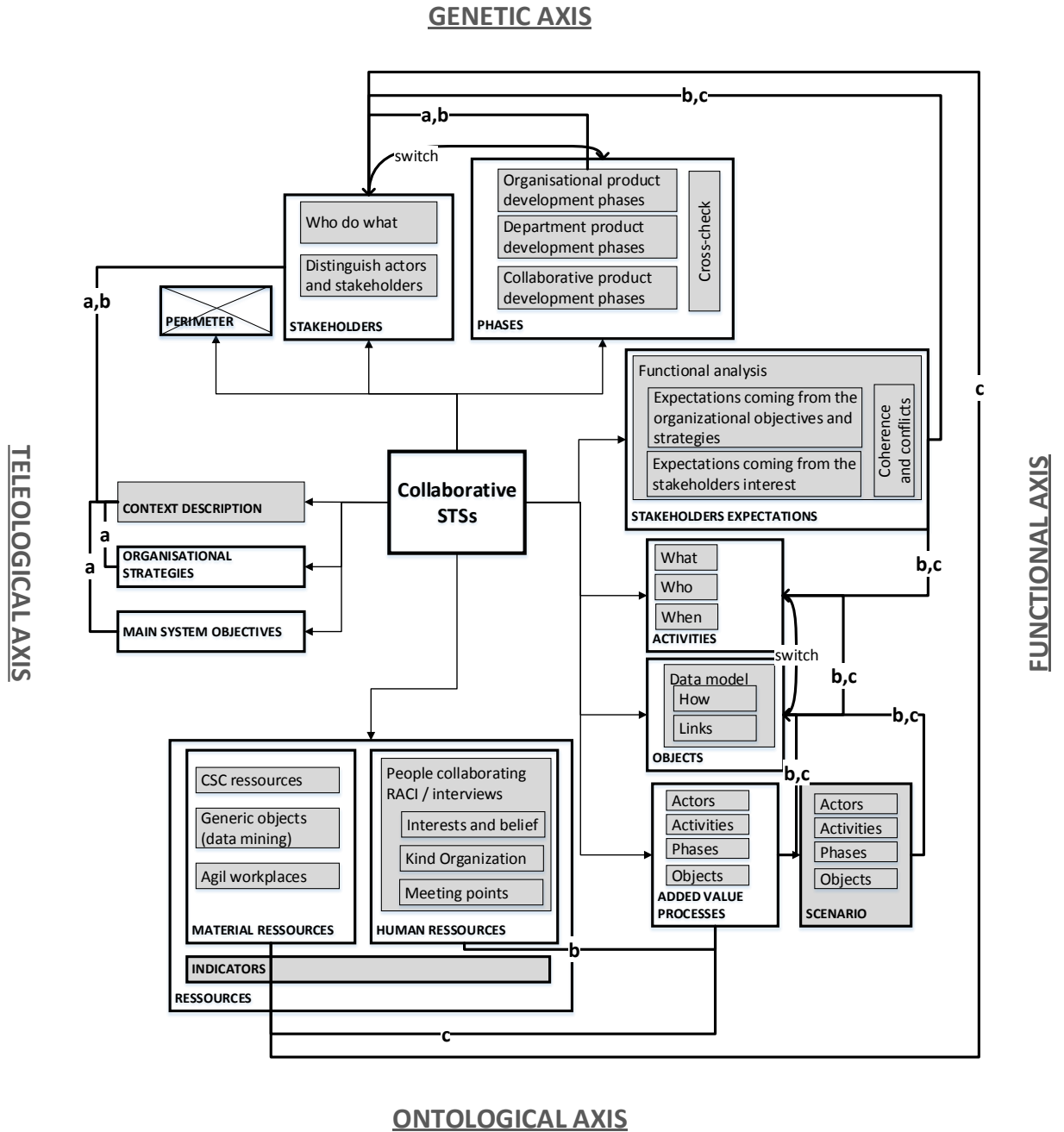


Figure 14: CEDOSy (Collaborative Engineering Design Organisational System): A method supporting the design of collaborative Socio Technical Systems (STS) in a MBSE projects

Regarding the teleological axis, we keep the same description proposed by the OCSM method and add the context description, since collaboration are often related to a specific situation (Le Cardinal et al. 2001). In the genetic axis we have removed the perimeter description to avoid repeating the

elements already described (built from the teleological axis information, plus the phases and identified stakeholders). We have also switched the stakeholders description and the phases definition. Indeed, the information coming from the teleological axis is sufficient to define the stakeholders of the system. Also, the phases definition in the projects depends on the matrix organisation. Thus, it is pertinent to identify first the actors and then the phases where they participate. In addition, we propose several elements (fulfilled rectangles assisting the description of each axis, and consequently the MBSE dimension).

Regarding the functional axis, we have switched the description order between activities and objects (deliverable in OCSM method) as it seems coherent to describe what the people do (activities) and then how they do it (objects). Like the genetic axis, we propose several elements for the description of the dimensions that we describe in detail in the use cases illustration. Finally, we have split the ontological axis into material and human resources. For each kind of resource we propose the elements corresponding to methods and tools supporting their development and/or study.

In the figure, the arrows coming out of the centre rectangle represent the breakdown of the system in different axis as proposed by J.L. Le Moigne. These axes are described by the elements proposed by OCSM (not fulfilled rectangles) or CEDOSy method (filled rectangles). The collaborative MBSE design dimensions - people, process, information objects and tools – suggested in the literature are represented through the elements describing the axis, as shown as follows:

- People: Organisation (teleological axis), the stakeholders definition (genetic axis), the stakeholders expectations (functional axis) and the human resources (ontological axis),
- Data: Objects (functional axis),
- Process: Phases (genetic axis) and activities, scenario and process (functional axis),
- Tools: Material resources (ontological axis).

The bold links connecting the elements (inter or intra) axis represent the interactions and logical connexion among those elements and consequently among the MBSE dimensions. We use lower case letters to refer to them in the text. The bold links *a* mean that the development of a collaborative STS starts by the description of a specific collaborative situation. The context description must be coherent with the organisational objectives and strategies must specify the

involved stakeholders and take into account the project context by defining the intervention of the involved stakeholders among the concerned phases. Context description should also include other environmental information helping in the understanding of the situation.

The bold links *b* show how the system development is driven by the social aspects. Starting from a given collaborative situation involving the identified stakeholders and aiming at achieving specific organisational objectives, this situation takes into account the constraints imposed by the matrix organisation (represented by the cross points among the phases for the different stakeholders) and is translated into stakeholders expectations regarding the collaborative STS. Then, the activities needed to be carried out by the stakeholders are described as well as the information objects (models) created as a consequence (e.g.: developing models) or as a support (e.g.: taking decision) of those activities. The stakeholders, activities and objects are used to create added value processes including all this information. These processes can be potentially declined into more specific collaborative scenarios. All those elements (added value processes, scenarios, single activities and information objects) are performed by the human resources (active stakeholders of the system). As people is the key element of any collaboration, the interaction among them merits to be studied in detail. Consequently, different methods found in the literature are mentioned in the human resources rectangles.

The bold links *c* show how the method also ensures the technical aspects of the system not only starting from the involvement of the stakeholders using the system, but also those developing the materials means (e.g.: IT services). Those means must support the creation of information objects, the activities related to their development, use and reuse, and the processes and scenarios using them. As for the human resources, we suggest the methods supporting the development of material resources (STS).

To verify that the proposed items satisfactory respond to the stakeholders' expectations, but also to the organisational needs, appropriate indicators as proposed by OCSM method can be used .

Finally, to ensure the global coherence of CEDOSy, we propose three questions linking the different axis. As a matter of readability, on Figure 25, we use Figure 26 to illustrate the summarised version of the links and to include the questions.

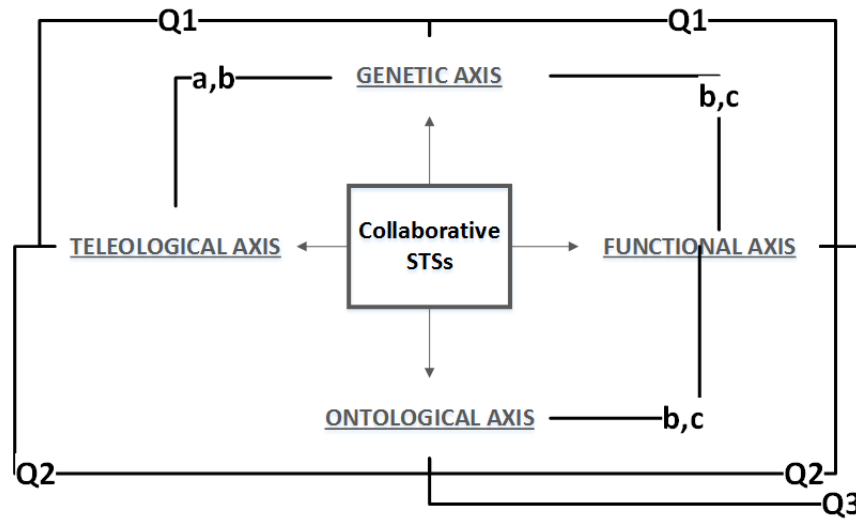


Figure 15: CEDOSy links

- Q1: Are the objectives and strategies of the company represented by the stakeholders through the expected values?
- Q2: Does the material resources and the proposed organisation support the collaborative processes and scenarios, and satisfy the organisational objectives?
- Q3: Does the collaborative process and scenarios represent the activities, deliverables, phases and stakeholders? Can we see how they all are linked?

The application of CEDOSy through two use cases has allowed us to establish a list of foundations for the development of STS in MBSE projects assisting each kind of collaboration: CAE-CAE and CAD-CAE. We present these lists in Table 5. The application of CEDOSy through the use cases is described in detail in Paper #1.

The collaborative STS supporting CAE-CAE collaborative projects must:	The collaborative STS supporting CAD-CAE collaborative projects must:
<ul style="list-style-type: none"> • Assist the development of simulation models in a multidisciplinary context. <ul style="list-style-type: none"> ○ This assistance must enhance the use of MBSE techniques to improve the management of the product complexity. It must also involve the right stakeholders as early as possible. ○ By assist the development of simulation models in a multidisciplinary context, we understand that the system must assist the SA (System Architect), MA (Model Architect), MP (Model Provider), the IRT (Research Institute of Technology) and the industrial partners to play their roles. 	<ul style="list-style-type: none"> • Assist the problem solving phase and facilitate the use of MBSE techniques and collaborative strategies in furtherance of bringing impartial results supporting the decision-making process. <ul style="list-style-type: none"> ○ Bring impartial results should help to reach vehicle performance as fast as possible. • Enhance and promote collaboration among the members of performance and design departments via simulation department services in order to support the organisation. • Be especially focused on the support of the meeting points concerning the identified stakeholders facilitating the activities carried out during the

<ul style="list-style-type: none"> ○ The assistance must be done by supporting the tasks that they need to carry out all along the project phases allowing a distinction between the system level, the development level and ensuring the main collaborative phases identified. ○ This assistance must support the access and the creation of the data models containing all the information needed to the model development, reuse and capitalisation providing a clearer visibility during the development process. ○ The system must be able to assist the entire added value proposed process by supporting the identified tasks and the access and creation of different information objects. ● The collaborative STS must support a given organisation among the actors facilitating interaction and communication when exchanging, sharing, developing, reusing and capitalising simulation models. 	<p>problem solving phase. Likewise, the management of the information objects exchanged, shared or created during the meeting points must be facilitated by the system as well as the assistance to the different scenarios.</p> <ul style="list-style-type: none"> ● Be robust enough to support different collaborative scenarios and be based on the necessary material resources enhancing collaboration that have been identified (such as the physical place and the current software solutions) but also on the deeper analysis of the stakeholders and their behaviours.
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Table 5: List of proposed foundations for the development of STS in MBSE projects

Basing CEDOSy method in the systemic approach enables the description of the dimensions describing collaborative MBSE design. The use of the different axis to describe the dimensions allows the representation of a comprehensive picture of the system, its elements and the relations among them. The implementation of CEDOSy has allowed us to validate the dimensions characterising collaborative MBSE design and their interactions. A reminder, these dimensions come from the literature analysis. In addition, they have facilitated the proposition of foundations for the development of collaborative STS in MBSE projects. The results of CEDOSy implementation highlight the stakeholders as the key element of collaboration. It is mainly because they are the ones who can establish the links among the different elements and who define the foundations through their expectations, needs and behaviours for the development of a collaborative STS in MBSE projects.

The use of CEDOSy has been recognised by the companies as a valuable initiative to create a common representation of collaborative STS for MBSE projects. This representation is important for them because no model describing the current situation exists, thus no common vision is shared. Likewise, establishing foundations enables to make a step forward in the development and implementation of collaborative STS contributing to the company objectives (no STS supporting MBSE collaboration exists today in the studied companies).

To conclude, the proposition of CEDOSy method and the results coming from its implementation encourage:

- The proposition of a shared vision of the work and information shared among the members, through the use of added value process and scenarios representations (c.f. 4.2),
- A deeper study of the actors behaviours and relationships (c.f. 4.3),
- The use of proposed foundations to help developing efficient collaborative STS in the company, such as collaborative rooms, activities and documents (c.f. 4.4).

These elements have been identified as crucial to understand the relations among the actors. The following sub-sections present the work done regarding each of them.

4.2. Paper #1 and Paper #2: proposition of a shared vision of the work

As suggested by CEDOSy model, the use of added value processes and collaborative scenario representations are helpful in the construction of a shared vision of the work among the actors. The identification of the activities carried out by the MBSE teams and the information objects that they share and exchange are the basis for their construction. In order to identify these activities and objects and to subsequently construct a shared vision of the work, we have analysed CAE-CAE and CAD-CAE collaboration in the use cases presented in Paper # 1. The observations suggest the use of a process view for collaborative CAE-CAE whereas a scenario view seems most suitable for collaborative CAD-CAE. The study related to CAE-CAE collaboration is presented in Paper # 2.

In both cases, we have analysed different processes and representations suggested in the literature as well as some industrial observations. Drawn from those analysis we highlight the following facts in the *As-Is* situation:

4.2.1. *As-Is Situation in CAD-CAE collaboration*

- The global phases of the process framing the activities in the company are well defined. They are also thoroughly known by the different stakeholders. Nonetheless, the description related to the different departments and their intersections are not well defined neither disclosed.
- A clear divergence of the vision of design and simulation departments is evidenced. Performance department expects to reach the vehicle performances in time for the master process respecting the technical constraints whereas, the design department is much more focused on the layout.

- There is no formal description of the activities to perform by each member at the department level. Nonetheless, participants are familiar with these tasks.
- There is no formal description of the information objects shared and exchanged during the process. Each participant proposes his own solutions.
- We have only found few formal intentions aiming at capitalising and reusing the data, information and knowledge in this context.

4.2.2. As-Is Situation in CAE-CAE collaboration

- Architecture changes are often requested during the simulation process. These changes are difficult to take into account with the current process.
- In the current descriptions:
 - Some stages have undefined outputs,
 - All the described roles are not used in the process description,
 - All the described documents are not used in the process description, one of them concerning interfaces agreement,
 - Additional undescribed supports are used but not documented,
 - No capitalisation stage is described during the process.
- The current process only considers the model development situation, missing the re-use cases when a model already exists,
- Simulation teams often need to request for additional information regarding the environment where their models are supposed to be used,
- When the assembly of the models takes place, the accuracy of the models is not appropriate. These inaccurate results often lead to rework tasks as well as other imprecise specifications during the model request stage. In general, a better upstream preparation of the model request is identified as an important need,
- A centralised vision of the entire model seems to be missing. As a result a lack of organisation aiming at the models convergence emerges.

In order to face these problems and to provide a common vision of the work as clear as possible, we have analysed different process modelling methods such as: flow charts, the IDEF, the Critical Path Method (CPM), the Design Structure Matrix (DSM), the Petri-net, the Data flow diagram (DFD), the Role activity diagram (RAD), the Business Process Modelling Notation (BPMN), the

Business Use Cases (BUC) and Business Object Interaction Diagram (BOID) (Huang et al. 2003), (Wang et al. 2006), (Yao et al. 2006), (Aldin & De Cesare 2009), (Perrot 2008a).

We have compared these methods to the dimensions characterising collaborative MBSE design in order to choose the most appropriate. The IDEF, RAD and BPMN seem to be the most appropriate approaches. The detailed description of the analysis can be found at the end of Paper #2. After several attempts using the three methods to represent information flow, activities and roles, a mix of the three seems to be the most adapted modelling process representation for collaborative CAE-CAE. Notwithstanding, when we have tried to use this representation for the global vision of the work in CAD-CAE collaboration the results have not been the same. In fact, the main constraint of this representation - its linearity - has brought us to propose a scenario approach in this case.

4.2.3. Establishing a shared vision of the activities in CAE-CAE collaboration

We present in Figure 16 the added value process proposition for a collaborative CAE-CAE. This proposition enables the representation of a process which includes in the same view:

- The roles (left side of Figure 16): they are represented with different colours to easily identify the activities related to each of them. In total we have identified 8 roles taking action in this process (System Architect, Model Architect, Librarian, Model Integrator, Model Adapter, Graphic Designer, Model Provider and Model executor). Three roles among the eight presented are the proposed roles by Sirin et al. (Sirin et al. 2015)(System Architect, System Model Architect, Model Provider),
- The activities (rectangles in Figure 16): we propose 14 different activities covering the current activities proposed in the state of the art, but also including the missed ones (such as the capitalisation stages),
- We identify 10 different objects that can be classified into 2 main categories: the solicitation package and the simulation configuration.

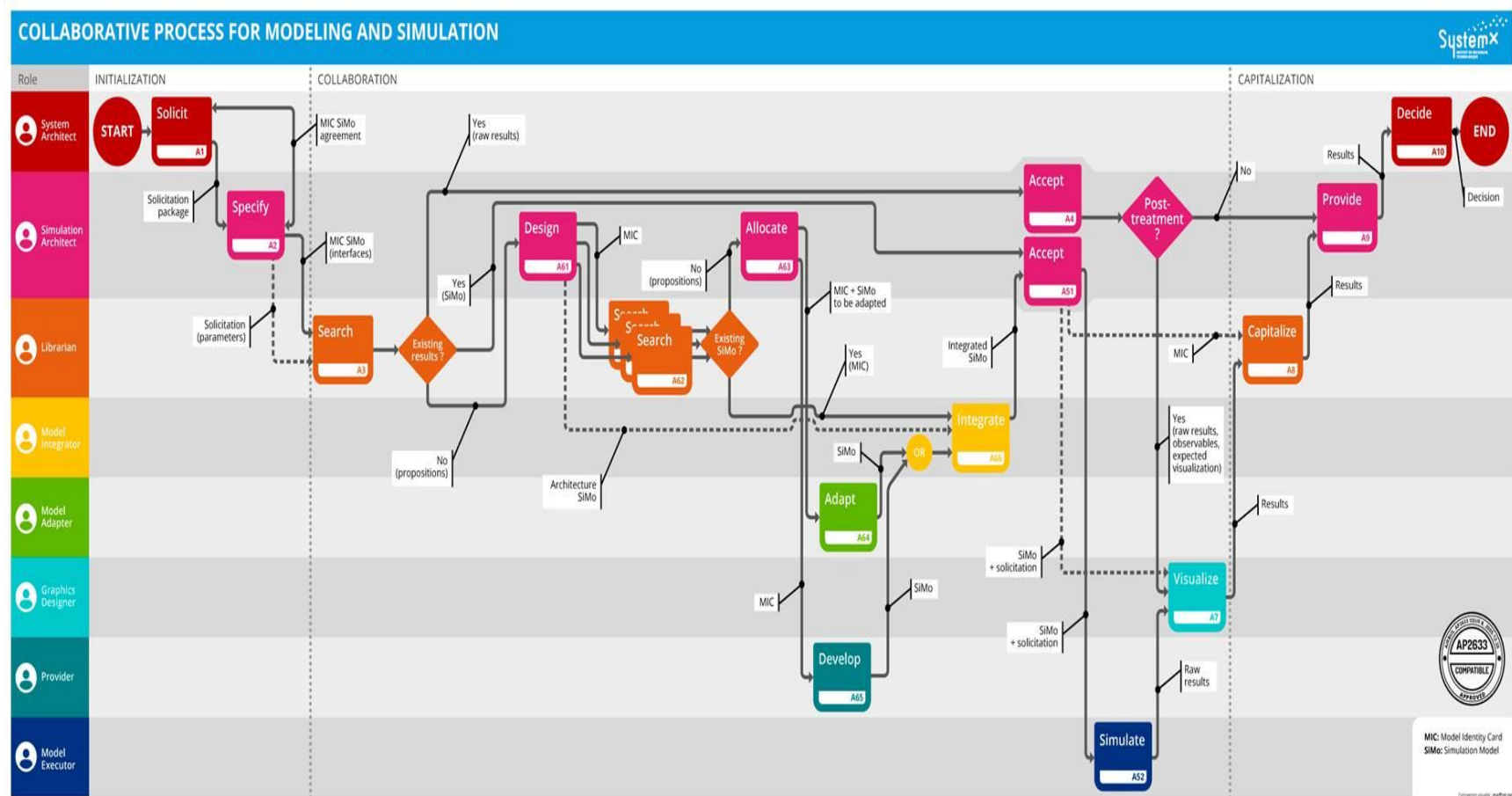


Figure 16: Added value process proposition for a collaborative CAE-CAE

4.2.4. Establishing a shared vision of the activities in CAD-CAE collaboration

To establish a shared vision of the activities in CAD-CAE collaboration we have used a TDR (Technical Design Review) context proposed by one of the industrial partners of the thesis. The analysis of the TDR seems pertinent to visualise this kind of collaboration since TDR are sessions where different stakeholders (in our case, design and simulation department) come to an agreement about some features of the product and/or solve some problems in order to reach the next TRL (Technical Readiness Level). Several TDR take place between two TRL. These TDR belong to the design review phase. We have identified five activities framing this phase: problem diagnosis (what/where the problem is), solution proposal (which are the possible solutions), solution selection (what is the feasibility of the proposed solutions, which one is the best one?), solution design (design the selected solution, CAE-CAE collaboration may be needed in this activity) and solution evaluation (evaluate the solution regarding the original problem).

It is important to identify the activities which need a TDR and the stakeholders participating in it. The process approach is appropriate to describe the design review phase. Nonetheless, to establish a shared vision of the collaboration taking place in the TDR itself, a process representation is not suitable because of the level of detail needed, the parallelisms of the tasks and the tasks iterations for some design aspects. In consequence, we suggest to establish different scenarios. To do so, we have looked at the global stages and activities taking place during the TDR. Then, for each stage we have identified one or several possible activities. The combination of the activities gives an overview of the potential collaborative scenarios. In Table 6, we present a simplified view of the scenario construction that we have carried out for collaborative CAD-CAE.

Table 6: Simplified view of proposed scenario construction for collaborative CAD-CAE

Stages	Actor	Activities	Scenario 1	Scenario 2
System start	All	Switch on and documents set up	X	X
Call set up	CAE team lead (TL)	Calls or video conference calls	X	X
Introduction, agenda	CAE TL	Introduce general information of the meeting	X	X
	All	Considerations		
Presentation, results, calculations	CAE team	Present simulation results	X	X
	All	Display necessary support	X	X
	All	Debate	X	
	All	Switch the information		X
Discussion and design	All	Build new design documents		
	All	Build support documents (e.g. : minutes)	X	X
	All	Discussions	X	X
	All	Switch the presentations		
	All	Highlight and point or design zones	X	
	All	Design (board, papers...)		X

In Table 6, we present the five main stages identified during the TDR meetings and their possible activities. For a given TDR, all the stages are systematically performed whereas the activities can take place or not. For instance, we use the two columns on the right of the table to illustrate this situation. In this example *Scenario 1* and *Scenario 2* share 7 activities (grey colour rows). These activities are always performed in all the TDR while the uncoloured rows might occur or not.

4.2.5. Establishing a shared vision of exchanged objects in CAE-CAE collaboration

As previously explained we have identified 10 different objects that can be classified into 2 main categories: the solicitation package and the simulation configuration. The first category is a single package containing the information needed to begin a simulation study (the initial problem, the constraints and the scenarios). Information such as the control parameters, the expected accuracy and visualisation, and the variables of interest can also be specified in this package. The second category is a combination of the nine additional objects: the model itself, the SiMo Architecture (architecture of the simulation), the Model Identity Card (MIC) (Sirin et al. 2015), the integration script, the development script, the user manual, the simulation results and the verification and validation mechanisms.

All these objects are represented in the added value process illustration in order to help stakeholders to be aware of their existence and of the people using them. We also suggest to build a data model where the relations among the objects can be clearly defined. A data model example is presented in Paper # 1 (c.f.: Use case 1/ Functional axis).

4.2.6. Establishing a shared vision of exchanged objects in CAD-CAE collaboration

We have identified five main information objects (used/shared/exchange) through the design review phase: Initial technical definition (DT₀), Final technical definition (DT_f), Expected performance (Pe), modifications (CM_{ij}) and Problem list (Ki). The relationships between these elements will drive the logic of the actions. Thus, if the initial technical definition (DT₀) does not reach the expected performance (Pe), it is because of technical problems (Ki). The main objective of the design review phase is to transform the initial technical definition (Dt₀) by adding some modifications (CM_{ij}) into a final technical definition (Dt_f) reaching the expected performance (Pe). For each problem (Ki), one or several modifications may be adopted (CM_{ij}). All the modifications proposed must be taken into account to solve the problems.

4.2.7. Impact of the establishment of a shared vision

The shared vision that we propose contribute to an added value solution at three different levels in the organisation: at operational level, at tactical level and at strategic level. At operational level the new process description avoids the rework tasks for CAE-CAE collaboration and fulfils the gap concerning the lack of capitalisation and problem diagnosis activities. At tactical level a clear vision of how and who does what is shared with all the actors. Likewise, the people involved have a larger vision of how their work is valuable for the organisation. At strategic level the process can be easily integrated in the organisation and match with the other existing processes. Furthermore, the capitalisation and problem diagnosis activities proposed could enhance the know-how of the organisation and could eventually reduce the time of development during the design.

Finally, even if the people involved, the activities and the information objects are completely different for each kind of collaboration, the establishment of a shared vision of collaborative MBSE design through the use of process and scenarios is an added value solution proposition to the current industrial needs and to the literature gap. These visions enable to gather the actors, activities and information objects in a single view, responding to questions such as how, who or when and improving the common understanding of a given situation.

4.3. Paper #3: A deeper study of the actors behaviours and relationships

As suggested by CEDOSy method a deeper study of the actors' behaviours and relationships is needed to better understand their real motivations to collaborate and consequently propose STS responding to the user expectations. Numerous researches on collaborative design can be found in the literature. However, only a few number of them address collaborative MBSE design. To our knowledge, no research addressing the analysis of the behaviours and motivations among the actors in MBSE design projects exists today.

In order to analyse these behaviours and motivations we have compared collaborative MBSE design observations to the collaboration and cooperation characteristics suggested in the literature first (c.f.: sub-section 3.1). The observations come from the different studies carried out during the thesis at Renault, Airbus Group innovation and IRT SystemX. We show the comparison results in Table 7.

Table 7: Proposition of a comparison MBSE design project observations to cooperation and collaboration characteristics

Characteristics		Coop.	Coll.	MBSE design projects	
				Charact.	Observations examples
Common goal (Vision)	Defined		X		We have observed that people only have a partial vision of the project, which encourages them to perform their tasks on their own and consequently impede the establishment of a common goal.
	Undefined	X		X	
Knowledge assets/expertise/ideas	Join		X		A centralised model repository does not exist today.
	Separate	X		X	Models are developed several times because their reuse is difficult
Relationship	Informal	X			The hierarchical relationships and the relationships between the project leader and the members are formal. Nonetheless, the relationships among the rest of the team members are still informal
	Formal		X	X	
Common structure (roles, planning.)	Defined		X		When the project is launched the planning, the WBS (Work Breakdown Structure), the roadmaps and all the information related to its organisation is well defined and structured. However, as time goes on, this information is not necessarily updated. The boundaries of the design tasks become less clear and overlaps occur more frequently
	Undefined	X		X	
Communication channels	Structured		X		Companies offer different communication channels to support the interactions among the project members. Still, most of the time the team members end by using their e-mail
	Unstructured	X		X	
Authority	Common		X		Because of the matrix organisation team members have two authorities. The first one is shared: the project leader, whereas the second one is not: department chief
	Separated	X		X	
Shared Risk/Responsibilities	Yes		X		As the members perform their tasks on their own, each person is responsible for the consequences of his/her own tasks
	No	X		X	
Resources	Common		X		The design and development resources still belong to the department and not to the project. Thus project members do not necessarily share it
	Separated	X		X	
Rewards	Common		X		The rewards that people participating in these projects obtain do not come from the project but from the department. These rewards (such as pay raise) are personal and they are not associated to the project achievement only but to their year performance in general.
	Separated	X		X	
Time	Long term		X		The observed projects concern the development of a product of the company. These developments are usually planned for the short and mid-term.
	Mid-term			X	
	Short term	X		X	

Comparing the cooperation and collaboration columns of Table 7 to the MBSE design project column, we notice that even if a general goal is set (the success of the project), the collective accomplishment of the project cannot be considered as a goal for the team members. Indeed, the isolated tasks they are assigned to, only give them a partial vision of the project and they do not necessarily feel involved in the collective effort to ensure its success. Likewise, they do not feel encouraged to share knowledge, ideas and expertise. Some of those elements may be shared through informal exchanges or formal meetings but they are not accessible to the whole team. This lack of accessibility complicates the reuse of the information and the knowledge transfer.

Regarding the relationships, the structure, the communication channels and the authority characteristics, MBSE design projects are situated in between cooperation and collaboration. The relationships among the project members are mostly informal mainly because of the project organisation, which is only detailed at the highest level. Thus, the common structure regarding the roles definition is not clear for the members. As mentioned in the example of the table, at the beginning of the project this information is well defined, but not updated with time. Although this situation occurs with elements such as the roles, other elements like the planning are still well updated. Regarding the communication channels, we can say that they share characteristics coming from both cooperation and collaboration. Even if some structured channels are provided by the company, we have observed that most of the time, people exchange using e-mail. Similarly, the authority in MBSE projects also shares characteristics coming from cooperation and collaboration descriptions. For instance, the team members share the authority of the project manager, but they do not share department manager.

Concerning the risks, resources and rewards, none of them is common in MBSE projects. If the project succeeds (or fails), design engineers will not get a reward (or penalty), contrary to the high level managers that may be confronted with this kind of system. Thus, we can consider that the risk is not shared among all the project members because the tasks responsibility is individual. If by any chance a bad product is developed, the entire team will not suffer the consequences. Likewise, the rewards are not common. It can be explained by the matrix organisation effect. In this organisation, people are often interested in obtaining personal rewards that only their department manager might offer them. We have also observed that the modelling and simulation resources are still assigned at the department level and not at the project level, thus the project

members do not share the same resources from this point of view. Finally, MBSE projects are mostly short or mid-term in the vehicle industry because of the length of the product development process determined by the companies, which is more and more reduced due to the market pressures.

These observations shows that MBSE design projects correspond more to cooperative characteristics than collaborative ones (c.f.: collaboration and cooperation definitions in List of Definitions). Thus, we suggest to study the cooperation among the actors.

4.3.1. Games Theory and FAcT-Mirror methods as a tool to analyse cooperative relationships

Cooperation is a large research topic including several disciplines in human sciences (sociology, linguistics, psychology, etc.). The aim of this thesis is not to propose a wide review of these studies but to explore the application of the Games Theory (GT) approach to analyse cooperative interactions among the members of MBSE projects. GT proposes a mathematical analysis of the cooperative issues between decision makers (Myerson 1991). The theory comes from the analysis of economics problems. However, it has been recognised as a valuable tool for the conceptual analysis of cooperation among the actors in different domains (Chatain 2014). In the MBSE design domain, we have found few works using this theory. Nonetheless, these works address the trade-offs between different design options (Press 2016), (Lewis & Mistree 1997), (Xiao et al. 2005) more than the analysis of the actors itself.

In this research, we focus our attention on the understanding of the interactions and behaviours at the actor level. Thus, we have based our study in the branch of the GT known as Non-Cooperative Game Theory (NCGT) which is interested on the agent actions modelling (Chatain 2014). To set the game, three elements are needed: the set of players $\{P\}$, the set of strategies $\{S\}$, and their respective pay-offs $\{x\}$ (or utility functions depending on the pay-off $\{U(x)\}$). Each player has a defined set of strategies to play (the actions describing the manifestation of his will). The pay-offs are the gains or losses that a player receives when choosing a certain strategy, given the strategies played by the other players (Von Neumann & Morgenstern 1953). NCGT states the problem by assuming that the players desire to obtain a maximum of utility or satisfaction.

We believe that the use of the NCGT for the analysis of MBSE design projects is useful to understand why and when a project member (player) will act in a certain way (chooses a strategy). This understanding is the basis of the *Nash equilibrium* concept in GT. A Nash equilibrium is reached when the players do not change their strategy as they do not have anything to gain by

changing it. The analysis of those equilibriums is helpful to find mechanism or incentives promoting cooperation among the players. Thus, by finding and analysing the incentives in MBSE projects, we can find mechanisms encouraging cooperation among the project members.

To define the set of strategies and pay-offs, it is necessary to know as much as possible the behaviour of the players in a given situation for which a careful analysis of everyday facts is needed to set a game. Consequently, we have based our research on the detailed analysis of the problem solving situations in MBSE design projects. However, it is extremely difficult to interpret the observations of everyday situations to constitute the set of strategies and pay-offs. To succeed in this interpretation, the FAcT-Mirror method (Le Cardinal et al. 2001) suggested in the literature seems appropriate since it proposes the elements facilitating the description of these situations.

FAcT-Mirror method describes relationships between people in terms of Fears (F), Attractions (Ac) and Temptations (T) - elements that are easier to identify than strategies and utility functions - and is based on the prisoner's dilemma (Games Theory example). The relation between the standard prisoner's dilemma and the FAcT-Mirror method is presented in Figure 17. Figure 40

Table of revenue for the prisoner's dilemma			FAcT-Mirror method relationship with prisoner's dilemma revenues $T > R > P > S$
Actor 1 \ Actor 2	Co-operative	Non-cooperative	
Co-operative	R' (=3) R (=3)	T' (=5) S = (0)	P-S = Fear of being betrayed Risk to lose more if they co-operate R-P = Attraction of achieving mutual co-operation Win R or do not lose P T-R = Temptation to betray the other Extra win thanks to betrayal
Non-cooperative	S' (=0) T (=5)	P' (=1) P (=1)	

Possible behaviours: co-operation; non co-operation (or defection)
 Revenues R, R' reward to mutual co-peration
 T, T' payoff due to unilateral betrayal
 S, S' corresponding payoff (sucker's payoff)
 P, P' loss du to mutual non co-operation

Figure 17: Table of revenue for the prisoner's dilemma and FAcT-Mirror method relationship (Le Cardinal et al. 2001)

G. Le Cardinal et al. (Le Cardinal et al. 2001) defines FAcT regarding the revenues of the prisoner's dilemma as follows. First, the *Fear* of being betrayed and suffering the consequences corresponds to the difference between loss and the *sucker's* pay-off ($P-S$). Second, the *Attraction* of achieving mutual cooperation corresponds to the difference between the rewards and the losses ($R-P$). Last, the *Temptation* to betray the other corresponds to the difference between the revenues from betrayal

and the rewards from cooperation ($T-R$). FAcT-Mirror method is based on five stages which are: the definition of the actors, the expression of FAcT, the individual notation of the expressed FAcT, the grouping of the FAcT into a few unavoidable themes, and the elaboration of recommendations. We offer a more detailed description of FAcT-Mirror method in Paper #3.

4.3.2. A coupling method proposition to analyse cooperative relationships

All the stages proposed by the method require the participation of all the actors involved. Thus, the implementation of the method requires a significant amount of time the participants should dedicate, which may hinder industrial implementations. This constraint suggests the need of finding an alternate way to gather all the information needed without asking too much time to the participants. One way to shorten this time, is to set a game back using the equivalences previously proposed in Figure 17. Nevertheless, the way to set a game back is not defined in the current method description and cannot be attained by the simple reversal of the equivalences presented in Figure 17 because Fears, Attractions and Temptations are qualitative descriptions. Therefore, we propose a coupling method establishing the relations between FAcT, and the strategies and pay-offs values needed to set a game.

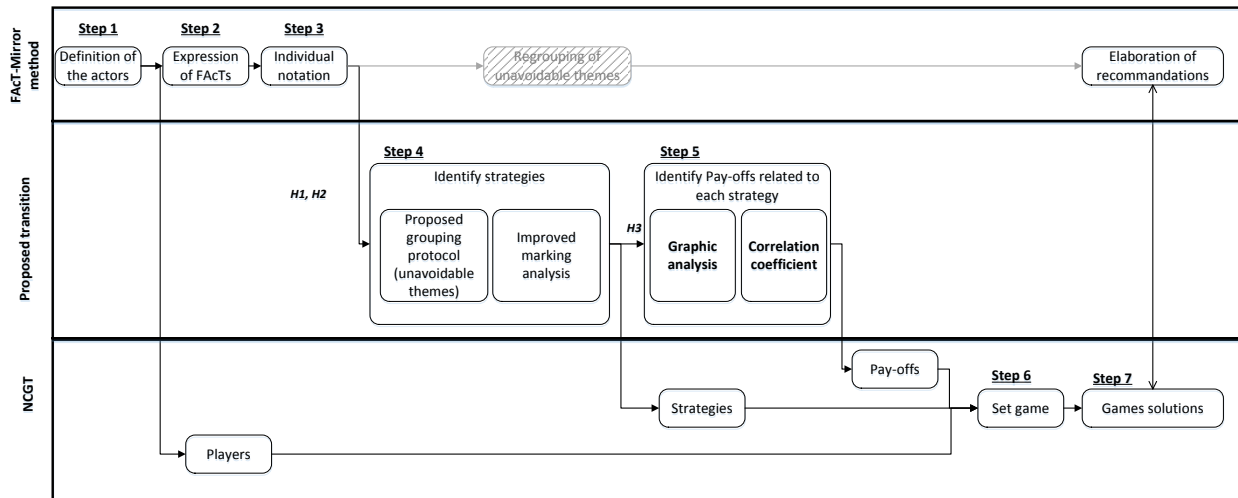


Figure 18: A summarised version of the coupling method proposed between FAcT-Mirror Method and Games Theory Inputs

We present in Figure 18, a summarised version of the coupling method proposed. The top row of the figure contains the five main stages of the FAcT-Mirror method. The bottom row contains the inputs needed to set a game in NCGT. The row of the middle contains our propositions to couple both methods and the three hypothesis under which these propositions have been done (H1, H2,

and H3). We use the first two steps of the FAcT-Mirror method to establish the inputs of the game. These inputs correspond to the observations of the reality through a list of Fears, Attractions and Temptations. All the arrows in the figure represents the information flow among the different elements to get to a solution.

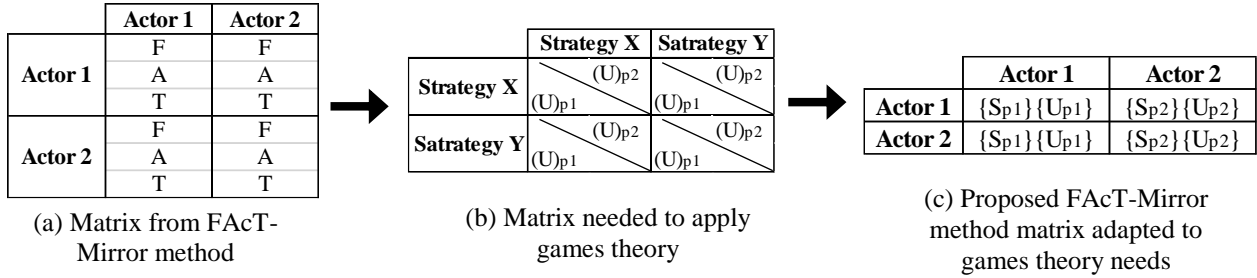


Figure 19: From FAcT-Mirror matrix to games theory matrix

We illustrate in Figure 19 the equivalence that must be done between the identified FAcT and the parameters needed to set a game. On the left side (matrix (a)) of the figure, we present the matrix coming from the data collected through the FAcT-Mirror method. On the middle (matrix (b)) of the figure, we present the matrix needed to solve a game, where $(U)_p^i$ is the utility function of the player I, when each player chooses a given strategy. As a reminder, the utility function is the sum of the *pay-offs*. By analysing matrix (a) and (b), and taking into account the link of FAcT-Mirror method regarding the prisoner's dilemma (c.f.: Figure 17), we can deduce the relation presented on the right side of the Figure 19 (matrix (c)). Matrix (c) presents a lecture of the matrix (a) in terms of strategies and pay-offs. This statement is our first hypothesis:

Hypothesis 1: *As FAcT-mirror is based on the Games Theory, we can assume that the set of fears, attractions and temptations describing each relationship are equivalent to the set of strategies and pay-offs for each couple of actors. c.f.: Figure 43 (c).*

Once we assume that the set of FAcT represent the set of strategies and pay-off, we need to know which of those fears, attractions and temptations are strategies and which ones are pay-offs. Thus, our second and third hypothesis are:

Hypothesis 2: *As fears and attractions are feelings, and temptations are probably actions, we define the group of temptations of an “unavoidable theme” as the group of strategies and the group of fears and attractions as pay-offs.*

Hypothesis 3: : We consider that each attraction and fear associated to a given strategy could increase or decrease from one unit the pay-off of the actors or have simply no effect on the pay-off.

Under these three hypothesis, we are able to calculate the game matrix through a graphical and statistical analysis of the list of FAcT following the next steps:

- 1) Identify the actors participating (players) - *FAcT-Mirror method Stage (1) / NCGT input (a)* in Figure 18-
- 2) Ask the participants to express the list of FAcT - *FAcT-Mirror method Stage (2)* in Figure 18 -
- 3) Ask the participants to mark those items (the marks represent probability of a given item occurs) - *FAcT-Mirror method Stage (3)* in Figure 18.
- 4) Identify the strategies
 - 4.1) Identify the group of *unavoidable themes* through a text analysis protocol: Identify the key word used to express the FAcT and group them by theme.
 - 4.2) Identify the dominant strategies (c.f.: Hypothesis 2): use the participants mark. We suggest to use three different measures to triangulate the results.
 - a) Calculate the average of each *unavoidable theme* using the marks of the *Temptations* related to it.
 - b) Calculate the number of *Temptations* of each unavoidable theme (frequency).
 - c) Calculate the standard deviation and the 4 or 5 quantiles (quartiles or quintiles), to be sure that at least 75% or 80% of the participants have marked the item above a certain value.

The *unavoidable theme(s)* getting the highest marks (frequency and average) and the lowest standard deviation, correspond to the *unavoidable themes* from where the strategies must be deduced.

- 5) Identify the *pay-offs* related to each strategy. To identify the *Fears* and the *Attractions* related to the selected *unavoidable theme(s)*, we suggest to analyse this relation using a graphical analysis and a correlation coefficient:

- a) Graphically analyse the results: Calculate and plot the frequency and the average of the *Fears*, the *Attractions* and the *Temptations*. Visualising these results gives a first idea of the relation among the items.
- b) Calculate the *Jaccard correlation coefficient* (*Jaccard index*³) between the selected *unavoidable theme(s)* and the *Fears* and *Attractions* of the other unavoidable themes. To calculate the index, the frequencies must be normalised (1-0). The *Fears* and *Attractions* with a *Jaccard index* superior to 0.5 can be considered as significantly correlated to the selected *unavoidable theme(s)*.

As *Fears* and *Attractions* are not quantitative, we are not able to define how much an attraction or a temptation will influence the pay-offs. Nonetheless, we can affirm that they either increase, decrease or have no impact on the pay-offs (**c.f.: Hypothesis 3**)

- 6) Build the game matrix: The identified strategies and the pay-offs constitute the set of data needed to set the game. We propose to summarise this information in a Table 8, to facilitate the construction of the game matrix (Table 9). We use two arrows between Table 8 and Table 9, to indicate how this information fills the game matrix. The information used as an example in Table 8 (*italic font*), comes from the use case presented in Paper # 3, where we have implemented the proposed coupling method to analyse MBSE design projects.
- 7) Analyse and solve the game: The game is solved when the *Nash Equilibrium* is reached. This equilibrium is represented by the point, indicating that the players will not change their respective strategy. The best response analysis, helps to find this equilibrium. This analysis consists in identifying the best response (strategy) that a player can choose (biggest pay-off) given the strategy chosen by the other player. Then, some modifications can be done in the matrix game, in order to understand how the *Nash Equilibrium* can be moved towards more cooperative strategies. The elements which move the equilibrium are called mechanisms.

³ *Pearson coefficient* cannot be used in our case because the relationship between the variables (T regarding F and A) is not given by a distance, but by the presence or absence of a fear or an attraction regarding a given temptation. Thus, we propose to use *Jaccard index* (correlation coefficient used for binary variables). To use it, we normalise the frequencies denoting the presence (1) or absence (0) of the F and A.

Unavoidable theme

e.g: Creation of an information sharing and exchange policy

As a player i will catch, hide or share the information in order to improve my career, increase my knowledge and improve my own vendor or client strategy. However, depending on the other player strategies, I'll be afraid to not obtain the right information and loss my credibility regarding the other stakeholders

	S'1 <i>e.g: Catch as much information as possible</i>			
S2 <i>e.g: Hide as much information as possible</i>	Player 1 uses S2 and player 2 uses S'1. <i>e.g: One of the project members (P1) tries to catch as much information as possible whereas the other (P2) aims at hiding his information</i>			
	Attractions and Fears labels <i>e.g: A3 = The Attractions related to the knowledge acquisition (unavoidable theme 3). When P1 uses S2 and P2 uses S'1 e.g: F1 = The Fears related to the career recognition and roles definition (unavoidable theme 1). When P1 uses S2 and P2 uses S'1</i>			
	Pay-off for Player 1		Pay-off for Player 2	
	Pay-offs coming from each attraction for player 1 <i>e.g. A3 = 0 means that If P2 wants to catch as much information as possible (S'1), then the Attractions related to the knowledge acquisition for P1 will not increase neither decrease. Indeed, P1 is only hiding and not learning anything new</i>	Pay-offs coming from each fear for player 1 <i>e.g. F1 = 1 means that, If P2 wants to catch as much information as possible (S'1), then the Fears related to the career recognition for P1 will increase. In this case, the objective of P1 is to hide and someone tries to get the information he has</i>	Pay-offs coming from each attraction for player 2 <i>e.g. A3 = -1 means that If P1 hides the information (S'1), then the Attractions related to the knowledge acquisition for P2 will decrease because he is getting nothing from P1</i>	Pay-offs coming from each fear for player 2 <i>e.g. F1 = 1 means that, If P1 hides the information (S'1), then the Fears related to the career recognition for P2 will increase. In this case, the objective of P2 is to catch but as he is not able to get information from P1, he is not achieving his goal and consequently not getting any recognition</i>
	Utility function for Player 1: Attraction - Fears <i>e.g: A1 (0) + A3 (0) + A5 (0) -F1(1) -F4(-1) -F5(1) = -1</i>		Utility function for Player 2: Attraction - Fears <i>e.g: A1 (-1) + A3 (-1) + A5 (-1) -F1(1) -F4(0) -F5(1) = -5</i>	

Table 8: example of summarised information for the construction of the game matrix

	Strategy 1'	Satrategy 2'	Satrategy n'
Strategy 1	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)
Satrategy 2	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)
Satrategy n	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)	\sum Pay-offs (Player 2) \sum Pay-offs (Player 1)

Table 9: Games matrix

The coupling method proposition is more time consuming for the person leading the workshops, but less time consuming for the company and the participants, which can make FAcT-Mirror method more attractive for industrial applications. In addition, the use of GT in this context facilitates the understanding of the interactions and relationships among the actors and lead to the

identification of mechanisms improving cooperation among them. We have implemented the proposed coupling method to find a mechanism improving cooperation among the members in MBSE design projects. This implementation is presented in detail in Paper #4, even if we present a summary of the implementation results below.

4.3.3. Results of the method implementation to the MBSE projects

We have implemented the coupling method at the French car manufacturer Renault and at the French Research Institute of technology IRT SystemX, in a project context. We have identified three kinds of relationships in this context: the hierarchical relationship (e.g. chief-employee), the transversal relationship (e.g. internal client-supplier departments in a project organisation) and the competitive relationship (e.g. two departments promoting different technologies for the same system).

We have used the coupling method to study the transversal relationships. The results allow us to characterise them in a MBSE project context, mainly driven by strategies related to information sharing. Three main strategies regarding information sharing are identified. The first strategy is related to the information procurement and we call it *S1: catch as much information as possible*. The second strategy describes the protection of the information and we call it *S2: Hide as much information as possible*. Finally, the third strategy is the opposite of the first one; it characterises the accessibility of the information and we call it *S3: Give/show clear and transparent information*.

Among those strategies, the strategy *S1 (catch as much information as possible)* emerges as the predominant strategy, which always leads the Nash equilibrium to itself. The analysis of the proposed game through the modification of the pay-offs of the fears and attractions, demonstrates how the Nash equilibrium could be moved from *S1* to *S3*. Two solutions decreasing the fears related to information sharing, and increasing its attractions are proposed. These solutions could also be interpreted as the recommendation of the FAcT-Mirror method. The first one is the involvement of new management policies focused on the pros of information sharing more than the cons. The proposed game illustrate how these kind of policies are pertinent to decrease the fears related to the manager's opinion and job accomplishment, and to transform them into attractions. The second recommendation increasing the attractions and reducing the fears is the implementation of information sharing resources - ensuring the safety of the shared and exchanged information - and enhancing the knowledge development. Assuming that those increments and

reductions are significant for the actors, the Nash equilibrium of the game is moved towards (S_3, S'_3) .

4.4. Paper #4 and Paper #5: The development of efficient collaborative STS

The third and last point highlighted by CEDOSy method is the use of foundations to support the development of efficient collaborative STS in the company. This suggestion is also supported by the results obtained through the implementation of the coupling method to study cooperation in MBSE projects. Indeed, the results of this study highlight the implementation of new management policies, but also the implementation of systems ensuring the safety of the shared and exchanged information, and enhancing the knowledge development. Based on these results and on the need expressed by our industrial partner to develop these kind of systems, we propose two groups of guidelines addressing the development of the collaborative environments, and the capitalisation supports from a sociotechnical systems (STS) perspective. Because of the industrial constraints, this part of our work is focused on a particular design phase: the technical design review (TDR). Nonetheless, the proposed guidelines are also applicable to other design situations.

The development of tools supporting the interaction among a spread group of co-workers is usually called in the literature Collaborative Computer Supported Design (CCSD) (Shen et al. 2008b), or more general CCSW (Collaborative Computer Supported Work). However, in order to go further than computer support, we use a STS approach found in the literature as Agile Work Places (Joroff et al. 2003a), to support Engineering Design through the TDR. The implementation of this approach along with our findings presented in the precedent sections, have allowed us to propose the first group of guidelines, which concerns the development of collaborative environments and facilitates the knowledge transfer among the participants during the TDR.

The development and further implementation of the first group of guidelines, have led to the identification of the need of a support assisting the knowledge transfer between TDR. Thus, we address this need through the proposition of the second group of guidelines (Paper #5), which aims at assisting the development of capitalisation supports by first facilitating the transition of tacit knowledge into explicit knowledge and second, by enabling the explicit knowledge transfer through the TDR. We have based this group of guidelines on both collaborative mechanisms, improving common understanding (Kleinsmann et al. 2007) and knowledge capitalisation principles (Grundstein 2000), (Oladejo et al. 2010), (Renaud et al. 2004).

In the next sub-sections, we present the principles of the two groups of guidelines. A more detailed description of them can be found in Paper #4 and Paper # 5 at the end of the manuscript. The main objective of the proposed guidelines is to ensure lasting collaboration while supporting the TDR.

4.4.1. Guidelines proposition for the development of collaborative environments

In order to assist the development of a suitable collaborative support, we have used the Agile Workplaces approach proposed by Joroff et al. (Joroff et al. 2003a), as a mean to develop material resources supporting TDR. We have chosen this approach because it takes into account the *work, the workers and the workplace*, which is equivalent to the dimensions people, process and tools that must be addressed in this part of the research. Joroff et al. propose a five-steps framework for workplace-making: situation awareness, process design, artefact design, design making and evaluation. Situation awareness is identified by observing and mapping the current work, working with the participants and diagnosing the current problems. Process design aims at creating alternatives and implementing strategies of change. Artefact design is the design of the actual workplace itself and the generation of new ideas. The design making aims at identifying the elements of the new workplace and its support elements. And finally, the evaluation step is used to assess the work place and work practices.

The collaborative environment guidelines presented in this section materialise the process design, artefact design, design making and evaluation activities. Six guidelines are defined to assist the appropriate dimensioning of a collaborative environment. By appropriate, we mean that the workplace should support the totality of the activities carried out during the TDR, and it should be based on the behaviour of the organisation. The six proposed guidelines are:

(1) Scenario description

We propose to represent the basic scenario through UML activity framework. We do not advice IDEF framework in this case because of the amount of information that is represented at the same time (Inputs, outputs, control and mechanisms).

(2) Activities stamping (according to a proposed list)

In Figure 20, we propose a list of collaborative generic activities that take place during the TDR. We suggest to use the proposed list to stamp the activities described in *Step 1*. The proposed classification of the activities presented in the figure (oral communication activities, visual communication activities and readiness activities) has been developed according to industrial observations, the *exchange roles* describing DR activities (Huet et al. 2007), the social action framework (Ngwenyama & Lyytinen 1997) and the aspects of knowledge (PAUL 2006). A more detailed description of the development of this classification can be found in Paper # 4.

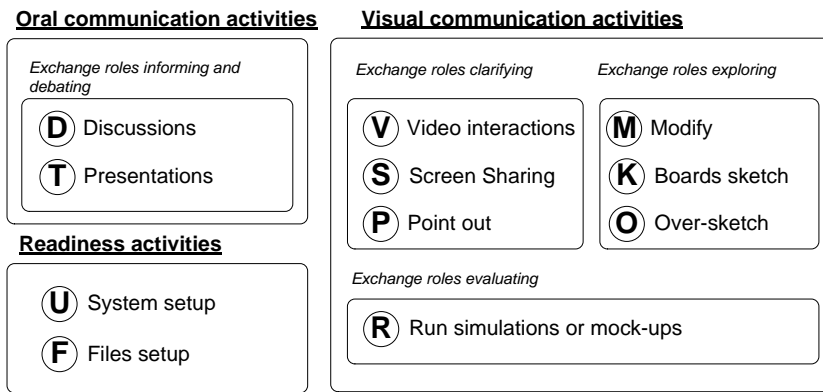


Figure 20: Generic activities proposition performed during the DR

Stamping the activities of the scenario according to the proposed list will group the activities and facilitate the user needs identification. This will also be helpful in the future quantification of the required ITCs (Information and Communication Technology) elements to support the activities.

(3) Listing of the user needs

We advise to use a functional analysis through the APTE formalism (de la Bretesche 2000). This formalism proposes to represent the system to be developed and the components having an important impact on the system. We have identified the collaborative workplace as the system to be developed. And four main categories of environments: the participants, the physical means, the IT means and the information and knowledge to be shared. The identification of the specific elements of each category should be conducted within a brainstorming process including the different stakeholders.

(4) Cross-checking the functions

Verifying that each activity is at least covered by one function (Checking between guidelines one and two concerning guidelines three).

(5) Dimensioning the environment elements

We propose a list of elements to quantify. The list can be easily filled in and transformed into the collaborative workplace specifications. The elements to be quantified for each communication activity are: the kind of access, storage, transfer and the manipulation required

(6) Feedback and evaluation

On the one hand, we propose to assess the developed environment with a template for a survey based on the qualitative dimensions proposed by B.E. Hayes (Hayes 1998) for the evaluation of customer satisfaction. On the other hand, we suggest to evaluate the number of loops saved during the design process to give a quantitative estimation of the gain.

In Paper #4, we detail the development of the guidelines and we also illustrate their use through a use case. The implementation of the guidelines through the use case highlights that even if an appropriate environment is set up, it is not necessarily enough to take the right decision at the end of the TDR process because of the insufficient transfer and capitalisation of the information discussed during the review. These observations have led us to propose the second group of guidelines presented in the next sub-section.

4.4.2. Guidelines proposition for the development of collaborative capitalisation supports

The proposition of the capitalisation guidelines is based on the juxtaposition of:

- The Industrial observations concerning knowledge transition (tacit to explicit knowledge),
- The capitalisation steps (Grundstein 2000), (Oladejo et al. 2010), (Renaud et al. 2004), the collaborative enablers (Kleinsmann et al. 2007) and the TDR success criteria (NASA 2007) suggested in the literature.

We define the capitalisation guidelines *as a set of activities assisting the development of a capitalisation support through specific data elements*. The guidelines and the data elements are

helpful especially in the TDR context, but adaptable to other design situations. The eight proposed guidelines are:

- (1) Detail the problem context and specifications.
- (2) Describe the problem in detail and gather the historical information related to the problem.
- (3) Set the target to reach.
- (4) Deeply analyse the possible problem causes.
- (5) Identify possible solutions.
- (6) Detail the specific features of the selected solutions to be developed.
- (7) Present the results (for each solution).
- (8) Standardise (if new standards are emerging).

We also detail the data needed for each guideline. In total, we identify 37 data elements satisfying capitalisation steps and success criteria and supporting the collaborative enablers and mechanisms. These data elements are distributed over the eight guidelines, helping engineers to make the tacit to explicit knowledge transition in a standardised way, and providing at the same time, a mean supporting TDR capitalisation. We present in Figure 21 the 8 proposed guidelines and their related data elements. It results important to clarify that we do not present any element in the guidelines related to the user's need because this element is studied in the first group of guidelines presented in sub-section 4.4.1. Indeed, the establishment of a collaborative environment is necessary to develop collaborative supports.

PROBLEM DESCRIPTION																							
1. Detail the problem context and specifications <table border="1"> <tr> <td>ID</td> <td>Project Name</td> <td>Milestone</td> </tr> <tr> <td>Department</td> <td>Team</td> <td>Person in charge</td> </tr> <tr> <td>ID Model</td> <td>Zone</td> <td>Additional Information</td> </tr> <tr> <td>Start date</td> <td>Planned end date</td> <td></td> </tr> </table>		ID	Project Name	Milestone	Department	Team	Person in charge	ID Model	Zone	Additional Information	Start date	Planned end date		2. Describe the problem in detail and gather the historical information related to the problem <table border="1"> <tr> <td>Importance</td> <td>Abstract</td> <td>Symptoms</td> </tr> <tr> <td>Stakes</td> <td>No respected requirements</td> <td>Linked problems and requirements</td> </tr> <tr> <td>Released design rules</td> <td>Imposed design rules</td> <td>Last standardisation</td> </tr> </table>	Importance	Abstract	Symptoms	Stakes	No respected requirements	Linked problems and requirements	Released design rules	Imposed design rules	Last standardisation
ID	Project Name	Milestone																					
Department	Team	Person in charge																					
ID Model	Zone	Additional Information																					
Start date	Planned end date																						
Importance	Abstract	Symptoms																					
Stakes	No respected requirements	Linked problems and requirements																					
Released design rules	Imposed design rules	Last standardisation																					
3. Set the target to reach: <div style="border: 1px solid black; padding: 5px; min-height: 20px;"> Target(s) or objective(s) to attempt </div>																							

PROBLEM ANALYSIS						
4. Analyse deeply the possible problem causes <table border="1"> <tr> <td>Observable (s) : Detailed symptoms description</td> <td>Analysis</td> <td>Influencing factors</td> <td>Probable causes</td> <td>Major Cause(s): Hypothesis + test(s)</td> </tr> </table>		Observable (s) : Detailed symptoms description	Analysis	Influencing factors	Probable causes	Major Cause(s): Hypothesis + test(s)
Observable (s) : Detailed symptoms description	Analysis	Influencing factors	Probable causes	Major Cause(s): Hypothesis + test(s)		

PROBLEM SOLUTIONS											
5. Identify possible solutions <table border="1"> <tr> <td>Proposition 1 to n (possible solutions)</td> </tr> <tr> <td>Target impact</td> </tr> <tr> <td>Feasibility</td> </tr> <tr> <td>Impact on other performances</td> </tr> </table>	Proposition 1 to n (possible solutions)	Target impact	Feasibility	Impact on other performances	6. Detail the specific features of the selected solutions to be developed <table border="1"> <tr> <td>Proposition 1 to n (possible solutions)</td> </tr> <tr> <td>Test(s)</td> </tr> <tr> <td>Validation</td> </tr> </table>	Proposition 1 to n (possible solutions)	Test(s)	Validation	7. Present the results (for each solution) <table border="1"> <tr> <td>Current results</td> </tr> <tr> <td>Past projects results</td> </tr> </table>	Current results	Past projects results
Proposition 1 to n (possible solutions)											
Target impact											
Feasibility											
Impact on other performances											
Proposition 1 to n (possible solutions)											
Test(s)											
Validation											
Current results											
Past projects results											

STANDARDISATION
8. Standardise (if new standard is emerging) <div style="border: 1px solid black; padding: 5px; min-height: 20px;"> New standard or rules for problem solution </div>

Figure 21: Proposed guidelines for the development of capitalisation supports in DR context

In Paper #5, we explain the development of the guidelines and illustrate their use through a use case.

We conclude that each TDR is unique, and several factors, such as design complexity or people involved may turn a strict guidelines into an inappropriate support. Being able to create a support as specific and as general as possible, has been one of the most important challenges during its

development. Nonetheless, the implementation of both group of guidelines through the use cases allows us to conclude that their use facilitate the development of collaborative environments and capitalisation supports. It also improves the overall design process by reducing the number of iteration needed to solve the problems discussed during the TDR.

4.5. A global methodology to improve collaborative MBSE design

Each of the propositions presented from sub-section 4.1 to sub-section 4.4, aims at improving product development through the enhancement of collaborative aspects in MBSE design projects. The methods and mechanisms proposed support the understanding, analysis and improvement of collaboration among the members through:

- The assessment of the current situation from a systemic perspective,
- The establishment of a shared vision of the work among the members,
- The study and understanding of the actor's behaviours and relationships,
- The development of efficient collaborative STS in the company.

We present in Figure 22, the global methodology proposition containing all the methods and mechanisms proposed all along this section.

The proposed global methodology supports:

- 1) The analysis of the collaboration induced by the new product and organisational complexities in MBSE design context.
- 2) The implementation of solutions enhancing collaboration among the actors in this context.

Thus, we distinguish two main cyclical phases in the global methodology: the *collaboration analysis* and the *solution implementation*. The methodology assists those phases through the methods presented in this chapter (CEDOSy, global view representations, FAcT-Mirror and GT coupling method and STS guidelines).

The collaboration analysis is helpful at strategic level, especially for managers and team leaders, to better understand their team's needs and behaviours. Typically, the CVE, SA or MPM could benefit from this analysis (c.f.: Figure 4). The solution implementation is helpful at the tactical and operational level, especially for the team members themselves as these solutions facilitate their daily work. Moreover, using them also bring improvements at strategic level. As an example, the

use of those systems improves some collaborative aspects which should have a positive impact on the global PDP.

In Figure 22, we represent the *collaboration analysis* phases with a white background colour on the one hand and the *solution implementation* phases on the other hand. We position CEDOSy method and the coupling method proposition (FAcT-Mirror - GT) in collaboration *analysis* phase, whereas the global view representation and the STS guidelines are positioned in *solution implementation* phase.

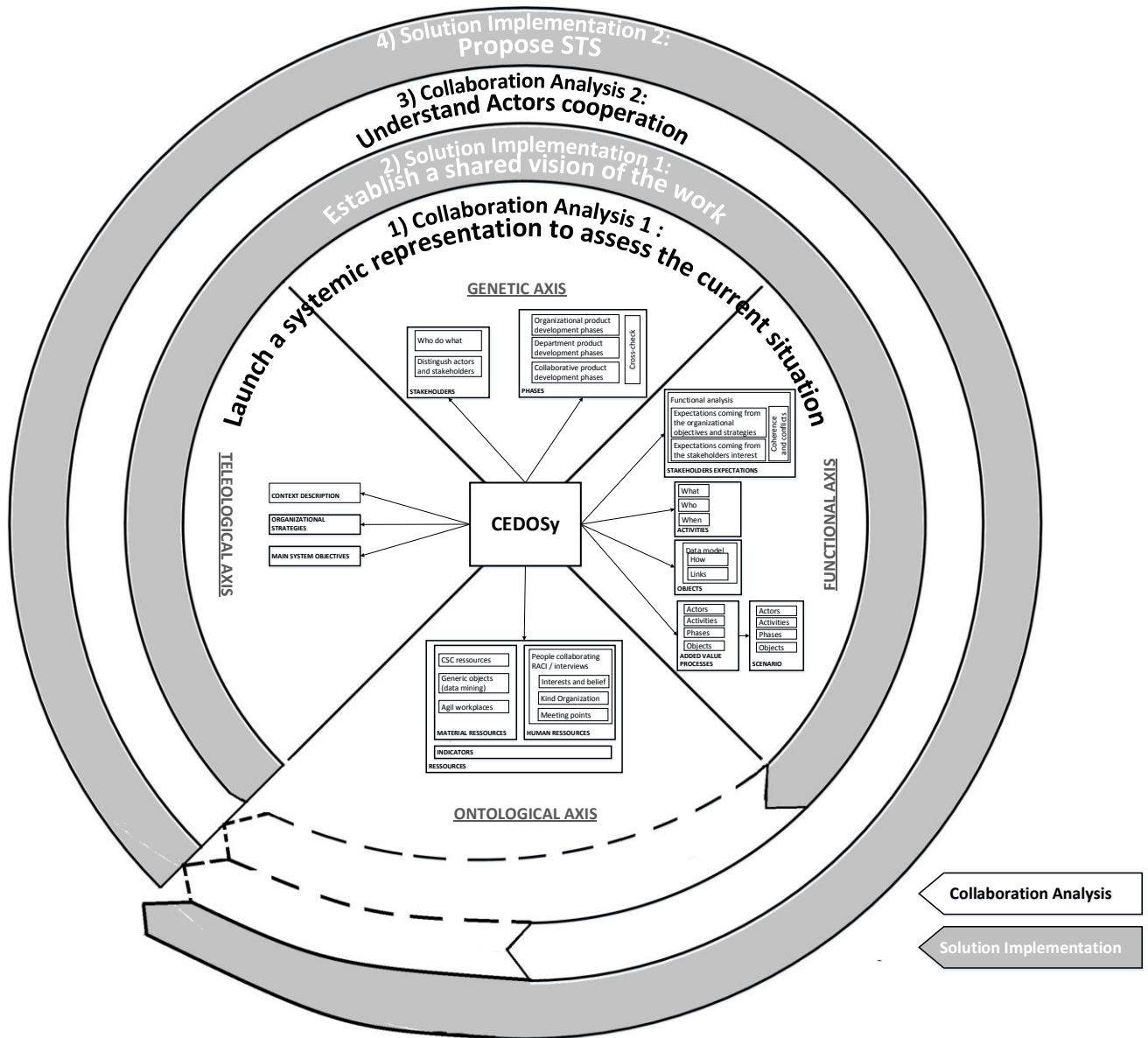


Figure 22: Global methodology proposition to improve collaborative MBSE design

Each arrow in Figure 22 ends at different points regarding CEDOSy. Those points represent the dimensions addressed by each method. For example, the *solution implementation 1* refers to the creation of a shared vision through the proposition of process and scenarios. This proposition addresses the process dimension, which is represented through the functional axis of CEDOSy. The overlapping within the arrows means that the implementation of each method requires the understanding of the elements studied during the precedent phase. In consequence, we are able to progressively establish a deeper comprehension of the collaboration among the actors by applying the different methods. We represent this progression through the dotted arrows in Figure 22.

4.5.1. Collaboration Analysis 1: Launch a systemic representation to assess the current situation

The first collaboration analysis concerns all the dimensions (people, process, actors, information objects and tools). During this phase, a global assessment of the current situation should be done through the implementation of CEDOSy method. This proposition implies a systemic representation of collaborative MBSE organisational system, which starts from the objectives of the company and the description of their specific context (teleological axis). Likewise, it is important at this point as a manager to consider and define the objectives of improving collaboration among his/her team members and the objectives of developing systems to support this collaboration.

The next steps of this consideration correspond to the identification and description of the current collaborative dimensions existing in the company and their links. These dimensions (or most promising factors in DRM) are described through the genetic, functional and ontological axis of CEDOSy. We outline in sub-section 4.1 the proposed mechanisms to get to this description. A more detailed description and its applications to two uses cases can be found in Paper # 1. The implementation of CEDOSy must also result on the proposition of foundations for the development of collaborative STS in MBSE projects.

We present below the main results obtained from the implementation of CEDOSY through the uses cases (c.f.: Paper #1)

- Regarding the assessment of the current situation, the breaking down of the processes, information objects and means assisting collaboration have been pointed out by the companies as crucial to understand the relations among the actors. Thus, these elements,

their interactions and their impact on collaboration also need to be analysed further. We present in Table 10 the principle pros and cons of the assessment in terms of process, actors and exchanged objects among our industrial partners.

	Pros (+)	Cons (-)
Process	The model exchange process is very general and could be adapted to different situations through other procedures in association with the current process	The links between the different Airbus procedures (AP) process are not clear. Thus, it results very difficult to monitor the collaborative interactions
		The process for the presented model exchange does not make any difference between the extended company situation and the proper company context
Actors	A generic definition of the roles and responsibilities is proposed	Even if the roles are well defined, their implementation is still difficult
		Since every level of the organisation responds to specific constraints, the global coherence between the constraints and the actors is still laborious to reach
		Understanding the simulation objectives remains difficult, because there is no shared vision of the main simulation goals
		Some situations needing an arbitration, are still not clearly defined
		At functional level, the synchronisation of the models is complicated although some means thought to bring some help have been developed
		For complex simulation in a larger scale, the models coupling situation and the traceability problems become difficult to handle
Object	The description of the models to exchange is very detailed	Other objects to exchange, such as scenarios or hypothesis, are not formally described
		In practice, a strong iterative mode is required to complete the description
		The change propagation procedure is not well defined. Today, the links identification between the actors and the objects is not done.

Table 10: Pros and cons in the current situation at Airbus Group Innovations

- The proposed foundations correspond to the complete systemic view of the collaborative organisations in each use case (characterised elements and their interactions). The lists of foundations include the social aspects of the organisation while assisting engineering design and may help in the development of efficient collaborative STS in the company, such as collaborative rooms, activities and documents.

In conclusion, the use of CEDOSy during the first analysis phase creates a common representation of collaborative STS for MBSE projects in the company and takes a step forward in the development and implementation of collaborative STS contributing to the company objectives.

Likewise, it provides the appropriate insights to study the actors, the process, the objects and the tools taking part of the collaborative MBSE design projects.

4.5.2. Solution Implementation 1: Establish a common view representation

The first solution implementation phase concerns the dimension related to the process and scenarios (a common view representation). The development of those processes and scenarios must take into account the elements provided by CEDOSy through the teleological, genetic and functional axis.

To establish a process representation we propose to use a description gathering some aspects of the IDEF, RAD and BPMN process representations proposed in the literature (Huang et al. 2003), (Wang et al. 2006), (Yao et al. 2006), (Aldin & De Cesare 2009),. The process representation must contain the illustration of the roles, activities, exchanged information objects and collaborative phases in a single view. The process representation is suitable to illustrate high level interactions among the members. Nonetheless, we rather suggest the use of scenarios to represent more detailed interactions.

The establishment of those process should be based on the analysis of the assessment done through the implementation of CEDOSY. All the proposed activities should transform their information objects inputs. We consider the activities without transformation as non-added value activities. Likewise, all the information objects identified during the assessment should appear in the representation. At any time people must be able to identify the links between the information objects, the roles and the activities (e.g.: If we are looking for a data-object in the representation we must be able to see the roles and the activities using the data-object as well). In the representation it is also important to distinguish between roles and actors (An actor can play different roles). Any of both descriptions can be used but this information must be clarified to the reader. Sometimes companies do not necessarily differentiate roles from actors, in these cases it could be helpful to describe the functions of each actor (who does what) and the limits of their functions. Finally, the proposition must be compatible with the current – internal and/or external- standards used in the company.

In sub-section 4.2 and in Paper # 2 we expose in detail two examples of the proposed representations. .These propositions address the current industrial needs and the literature gaps regarding the representation of collaborative MBSE design projects. In addition, they provide an

added value solution at three different levels in the organisation: operational, tactical and strategic levels.

- At operational level, the propositions limited the rework tasks during the development process. They also fulfil the gap concerning capitalisation activity. In addition, some recommendations to the current industrial process guidelines are suggested,
- At tactical level, a clear vision of the *how and who does what*. Likewise, people involved in the process have a larger vision of how their work is useful to the organisation,
- At strategic level, these process and scenarios can be easily integrated to the organisation and match with the other processes. Furthermore, the hypothesis of model reuse proposed in the process could enhance the know-how of the organisation and could eventually reduce the time of development during the design.

The process implementation through an industrial use case is presented in Paper #2. Through this implementation we have confirmed that collaboration in MBSE projects is not a linear problem at all, but the proposed representation is highly appropriate to improve the global comprehension and to understand the context. The implementation has brought to light an important part of the human behaviour in collaborative problems as well, pointing out the actors as the key element on the collaborative design and suggesting a deeper study of the factors motivating people to collaborate in this context.

4.5.3. Collaboration Analysis 2: Understand actors cooperation

During the second analysis phase a deeper analysis of the actor's cooperation must be carried out. To succeed on this analysis, a clear understanding of the elements related to the precedent dimensions is necessary. The arch corresponding to this analysis phase ends at the middle of the ontological axis, this is because ontological axis addresses human and material resources, and at this stage we are interested in the analysis of human resources. The material resources (tools) are addressed during the second applicative phase.

To better understand the actor's cooperation in MBSE design projects we propose a coupling method between FAcT-Mirror method and NCGT (Non-Cooperative Games Theory). A detailed vision of the method's stages is presented in sub-section 4.3 (c.f.: Figure 18) as well as in Paper #3.

To implement the *coupling method*, the managers should identify the conflictual relationships or the relationships that deserve to be improved in the assessment results. Then, they should gather the concerned actors to agree on the needs to work on them and to propose the coupling method for their analysis. The first steps of the coupling method (those that are related to the FAcT-Mirror method) must be carried out with the actors. It is extremely important to involve the actors during these stages because the expression of their FAcT are the representation of the current situation in terms that we are able to analyse from a Game Theory (GT) perspective. After having collecting these terms or data, the analysis of the actor's cooperation using the GT approach can be launched. To interpret the collected data as a game, the managers carrying the analysis should lean on the proposed transition steps of the method. Those steps help to establish the equivalence between the FAcT, and the strategies and pay-offs needed to set the game and solve it. The solution of the game (Nash equilibrium) must be subject to a *best response analysis* aiming at determining which incentives could improve the cooperation among the actors. The next sub-section deals with the implementation and/or development of those incentives. .

The proposed method reduces the time needed with the participants which facilitates the use of FAcT-Mirror method in the companies when imposed constraints may complicate its practice (e.g. the participants are not available altogether at the same time, the delay to implement the method is too short, etc.). Likewise, the method facilitates the use of NCGT by simplifying the abstraction of everyday situations representing the strategies and the pay-off needed to set the game. Finally, the use of NCGT facilitates the understanding of the actors' behaviours and preferences in collaborative MBSE projects and simplifies the analysis of the situations.

We have implemented the analysis method to two industrial use cases. The details of the implementations are presented in Paper #4. As a result of these implementations we have been able to characterise cooperation in MBSE design projects and to suggest some mechanism improving it. The most important result shows that the transversal relationships in MBSE projects are mainly driven by three main strategies related to the information sharing:

- *S1: catch as much information as possible*. This strategy is related to the information procurement,

- *S2: Hide as much information as possible.* This strategy describes the protection of the information,
- *S3: Give/show clear and transparent information.* This strategy is the opposite of the first one (it characterises the accessibility of the information).

The analysis of the proposed game through the modification of the pay-offs (fears and attractions) demonstrates how the Nash equilibrium could be moved from S1 to S3. Two solutions decreasing the fears related to the information sharing and increasing its attractions are proposed:

- The involvement of new management policies which focus on the information sharing benefits more than the inconvenient,
- The implementation of information sharing resources ensuring the safety of the shared and exchanged information and enhancing the knowledge development.

The future implementation of the proposed solutions should assist the improvement of cooperative MBSE design projects.

In conclusion, the second analysis phase increases the understanding of the relationships among the actors and gives some insights to drive the development of solutions assisting this cooperation. Thus, those insights constitute the departure point of the next solution implementation.

4.5.4. Solution Implementation 2: Propose efficient STS

During this phase, an accurate comprehension of all the elements coming from the precedent phases is necessary to propose STS responding to the organisational objectives and to the *incentive mechanisms* of the actor (mechanisms motivating cooperation). To do so, they must be compatible with the established processes and scenarios, and must support the insights of the actors analysis (the information sharing in our use case). Taking these elements into account, we propose to develop two kinds of STS supporting collaborative MBSE design. The first one aiming at the development of a collaborative environment (workspace)) and the second one aiming at the development of a capitalisation support.

To develop these kinds of STS we suggest the use of two groups of guidelines. Even if the collaborating actors have already been identified in the precedent phases of the methodology, new stakeholders may appear and must be taken into account during the implementation phase. The IT department of the company, the eventual providers of the system and the maintenance services are

some examples of new participants in the working group. The integration of all the stakeholders taking part in the development of the new STS is necessary to efficiently implement the system and assure its longevity. In sub-section 4.4 as well as in Paper # 4 and Paper #5 we detail the two groups of guidelines assisting the development of both, collaborative environments and capitalisation supports for the TDR.

The development of collaborative environments on the one hand, and the knowledge capitalisation field on the other hand, have been largely treated in the literature. Nonetheless, their application to DR has not been sufficiently explored. We advise to first develop the collaborative environment, and then the capitalisation support following the proposed guidelines. Indeed, the creation of capitalisation support demands the existence of collaborative environments facilitating knowledge creation and exchange. The development of both kinds of STS can be independent as soon as the user needs have been defined. Nonetheless their use must not be dissociated to significantly improve collaboration among the actors.

We have been able to implement the guidelines to develop STS in an industrial use case to support TDR. The results related to their implementation show that:

- The use of the guidelines facilitates the development of the collaborative environments and improves the overall design process by reducing the number of iteration needed to solve the problems discussed during the TDR,
- We estimate the savings generated using the environment to 2000 men/hours per year,
- The collaborative environment developed through the use case has demonstrated that an appropriate set up environment is not necessarily enough to make the right decision at the end of the TDR,
- Participants using and evaluating the capitalisation support guidelines estimate that they can avoid development loops if the past project information is exploitable. They also consider that the guidelines will favour this exploitation,
- The reduction of misunderstanding problems is possible through an appropriate knowledge transfer. Reducing those problems improves collaboration in the TDR whereby we conclude that the implementation of an appropriate capitalisation support improves collaboration through TDR participants.

The implementation and further development of STS based on the progressive comprehension of the collaboration in MBSE projects respect the nature of the organisation by driving the STS development on its behaviour and the interest of its members. The guidelines are especially helpful in the TDR context, but also applicable to other design situations.

To conclude, this solution implementation phase opens new perspectives, especially those related to the enhancement of the knowledge capitalisation. We represent the opening to new perspectives through the end of the arrow of the last solution implementation phase in Figure 22 where we have decided to not to close the cycle but to let it open for the future analysis.

4.6. Chapter Summary

In this chapter, we present a global methodology to improve collaborative MBSE design (c.f.: sub-section 4.5). The global methodology is based on analysis-implementation cyclical phases, and can be summarised as follows:

- The assessment of the current situation from a systemic perspective,
- The establishment of a shared vision of the work among the members,
- The study and understanding of the actor's behaviours and relationships,
- The development of efficient collaborative STS in the company.

To introduce the global methodology we have first introduced the methods and mechanisms intended to rethink the way how collaborative systems can be developed. The use of the proposed methods in the global methodology framework suggest how the real collaborative needs (observations) of MBSE projects can be successfully assisted by implementing appropriate STS. First, we introduce CEDOSy method in sub-section 4.1. The objective of CEDOSy is to assist the development of STS from a systemic perspective. It offers a holistic view of the dimensions constituting collaborative MBSE design projects suggested in the literature: people, process, information objects and tools and the links between them. The implementation of CEDOSy encourages a deeper study of those dimensions through:

- The proposition of a shared vision of the work and information shared among the members, through the use of added value process and scenarios representations.
- A deeper study of the actors' behaviours and relationships.

- The use of foundations to help developing efficient collaborative STS in the company, such as collaborative rooms, activities and documents.

Then, we have made propositions addressing these dimensions. In sub-section 4.2, we propose an added value process and different scenario representations assisting the establishment of a shared vision among the project members. The results of these propositions show their pertinence to provide a global view and support the need of a different way to study the relationships among the members already identified through the implementation of CEDOSy. Then in sub-section 4.3 we present a coupling method proposition to study cooperation among the members using games theory. The implementation of the method to study MBSE design projects demonstrate the need to implement information sharing resources enhancing the knowledge development (insight suggested with less detail in the CEDOSy implementation results) and the creation of new management policies focused on the pros of information sharing more than the cons. Along with the insights suggested by CEDOSy implementation, these results have led us to propose two groups of guidelines that we present in sub-section 4.4. The aim of these guidelines is assist the development of collaborative environments and capitalisations supports.

After the presentation of the global methodology and the methods and mechanisms associated to it, we present in the next chapter the conclusions, limitations and perspectives of our work.



Conclusions, limitations and perspectives

The work carried out during this PhD thesis has brought several academic and industrial contributions. From an academic point of view, we have highlighted the research gaps concerning the representation, understanding and improvement of collaborative MBSE design projects and we have proposed a global methodology resulting from a combination of methods and mechanisms addressing these gaps. From an industrial point of view we have proposed collaborative solutions regarding the process, the collaborative environments and the capitalisation supports.

During the first part of our research we have explored the current situation of collaborative MBSE design through the analysis of both, industrial practices and academic works. From this analysis we can conclude that:

1) The current initiatives and works do not tackle collaborative issues from an actor perspective to our knowledge.

The state of the existence of the industrial practices for collaborative MBSE design offers a large overview of the current situation. We have summarised this information in one deliverable containing a brief description of nine industrial initiatives to share and exchange simulation models. Among these initiatives, we consider FEDEP, ProSTEP and AP2633 as the initiatives offering the most complete frameworks, which include a process and scenarios description, some templates for workshare definition, some elements for models specifications and some roles definition

Those initiatives contribute to establish a technical basis for model exchange process. However, collaborative issues from an actor perspective (interactions among the actors,

possible issues and way to handle it) are not mentioned. Likewise, we have found several drawbacks on these propositions that we have exposed in (Roa-Castro et al. 2015)

2) Collaborative MBSE dimensions presented in the literature can be grouped in four dimensions: people, process, information objects and tools

After comparing the collaboration characteristics to collaborative MBSE researches, industrial initiatives and industrial audit results, we have identified ten recurrent topics that we have grouped into four key dimensions describing collaborative MBSE design. We use Figure 23 to present the topics through the dotted line rectangles and the four key dimensions through four quadrants: people, process, information objects and tools. The original representation can be found in (Roa-Castro & Stal-Le Cardinal 2014a).

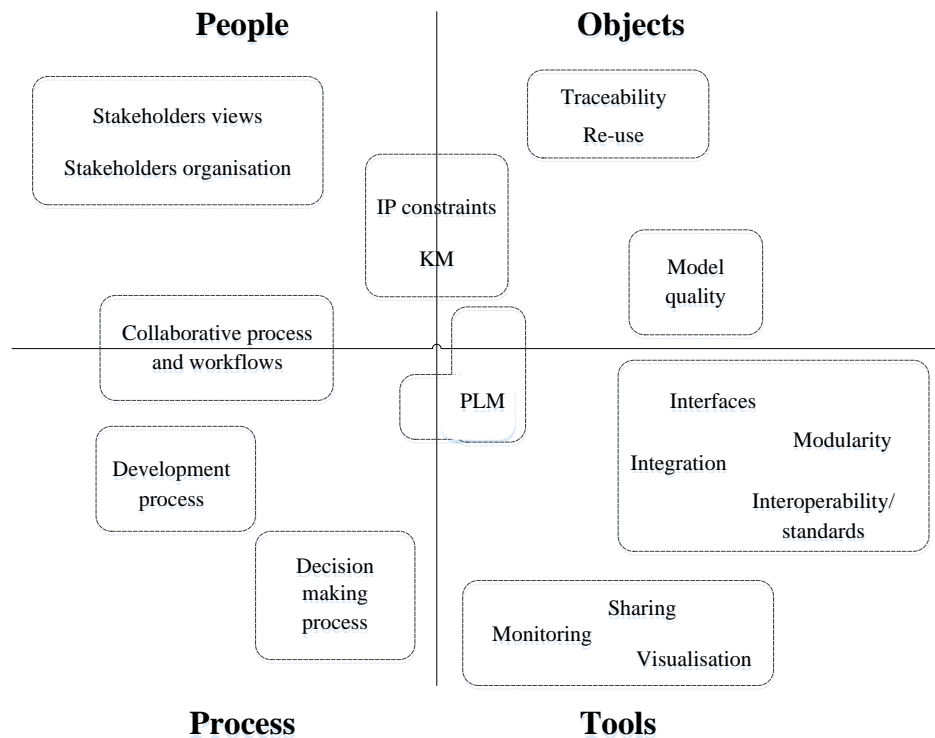


Figure 23: Recurrent topics and four key dimensions describing collaborative MBSE design

The information objects *dimension* is related to the object to be shared during the simulation process. We have named this object *Simulation Artefact*. The simulation artefact integrates the simulation models to be exchanged and other information objects needed to perform a simulation study (the requirements, the MIC or the simulation architecture are examples of

these objects). The *people dimension* is linked to the stakeholder points of view and to the interests and behaviours of the actors performing the simulation study. The *Process dimension* is focused on the activities needed to perform a simulation study and the information flow in between. Finally, the *tools dimension* refers to the IT tools supporting the development and execution of simulation models and information exchange around them.

3) Two main kinds of collaboration in MBSE design projects are suggested in the literature. They are addressed under different names such as collaborative simulation or CAD-CAE integration. In this thesis we have called them: CAE-CAE and CAD-CAE collaboration

We have found that what the literature calls “collaborative simulation” mostly refers to the technical aspects of collaborative MBSE design. The results of the literature review suggest two different kinds of collaboration in MBSE design projects that we have identified as: CAE-CAE collaboration and CAD-CAE collaboration (c.f. List of Definitions). The works on CAE-CAE collaboration address most of the time the tools dimension, whereas the works on CAD-CAE collaboration offer more holistic approaches.

4) The most suitable approach to analyse and assess collaborative MBSE organisational systems and its dimensions in our context is the systemic approach

We have compared different process modelling methods and different approaches to model collaborative MBSE design dimensions (Fatfouta et al. 2016). To our knowledge, no method existing today is exclusively dedicated to collaborative MBSE design description in a single view. These researches allow us to identify the systemic approach as the most appropriate method to model and assess this kind of collaborative system.

5) Regarding the deeper analysis of the collaborative MBSE dimensions we conclude that:

The process: Reviewing several process modelling approaches to represent the process related to this collaboration bring us to conclude that the most appropriate representations for this purpose are IDEF, RAD and BPMN. After several attempts using the three methods to represent information flow, activities and roles, a mix of them seems to be the most suitable modelling process representation in this context.

The actors: The use of methods focused on the study cooperative behaviours of the people, such as Games Theory and FAcT-Mirror method, is suitable to analyse the actors' relationships, endeavours and behaviours. However, these two methods need to be coupled to face real life constraints.

Due to the industrial constraints, we have studied the next two dimensions regarding the Technical Design Review context (which is only a part of collaborative MBSE design process).

The information objects: Only few researches in engineering design field address TDR issues. No capitalisation support assisting TDR exists today even so the literature confirms the importance of historical information in this context. We have confirmed that the current knowledge creation activities observed in the industry do not completely fulfil the principles proposed in the literature (capitalisation steps, TDR success criteria and collaborative mechanisms and enablers).

The tools: As for the information objects, we have not found any protocol to develop collaborative environments that takes into account the specific features of the TDR neither a protocol driven by the analysis of the actors relationships (cooperative needs).

- 6) We consider collaborative MBSE design as a complex system. Although the methods used in the literature to model complex systems facilitate the description of some of the MBSE dimensions, they do not allow a further analysis of the actors' relationships nor the development of STS**

In order to address these gaps, we propose a methodology with the goal of improving product development through the enhancement of collaborative aspects in MBSE design projects. The proposed methodology supports the assessment, analysis and enhancement of collaboration among the actors through different methods and mechanisms.

The proposed methodology answers the main question driving this thesis. Then, the proposed methods and mechanisms respond to the four sub-research questions. Subsequently, we present the

four research questions and their respective answers. Then, we present the global methodology addressing the main research question.

RQ1: How can we improve the global understanding of the organisational complexity in collaborative MBSE design projects?

We have only found a few works addressing collaborative MBSE issues. However, as no work in the literature refers specifically to organisational issues of collaborative MBSE design, we have decided to explore both, collaborative MBSE and organisational complex systems modelling methods. Among the different methods proposed, OCSM method (Organisational Complex system Modelling) (Schindler 2009b)–derived from the systemic approach (Le-Moigne 1990) have been identified as the most appropriate method to model the organisational complexity of the collaborative MBSE.

This approach allows us to propose CEDOSy method, which stands for Collaborative Engineering Design Organisational System. CEDOSy uses a systemic perspective to support the design of collaborative Socio Technical Systems (STS) in engineering design. It assists the characterisation of the MBSE dimensions, while defining its interactions and ensuring the inclusion of the social aspects of the organisation in the development of foundations to develop collaborative STS for MBSE projects.

We have implemented CEDOSy through two industrial use cases describing the representative aspects of collaborative MBSE. The first use case illustrates the CAE-CAE collaboration, while the second illustrates CAD-CAE collaboration. The implementation of the method has validated the proposed elements characterising the dimensions of collaborative MBSE design and their interactions. Likewise, it has facilitated the proposition of the foundations for the development of collaborative STS in MBSE projects in both use cases. The foundations correspond to the complete systemic view of the collaborative organisation in each use case (characterised elements and their interactions).

Finally, the results obtained from the implementation of CEDOSy and the analysis of the literature allow us to propose a definition of collaborative MBSE design. We define Collaborative MBSE design as *an activity involving simulation and design engineers, who share data, information and knowledge encapsulated in the simulation models. They use different resources or tools to perform*

the sharing and to accomplish the task related to the product development process at the simulation stages. Nonetheless, as the studied industrial reality correspond to cooperative relationships we consider this proposition as a theoretical concept. We conclude that collaborative MBSE design is characterised by:

- (1) The goals and profiles of people participating (simulation and design engineers),
- (2) The encapsulation of the knowledge in the simulation models,
- (3) The tools and resources supporting information and knowledge treatment (e.g.: CAD-CAE),
- (4) The tasks related to design and simulation stages of the product development process.

Collaborative MBSE design covers several dimensions and factors. All of them are closely interconnected, and their sum does not represent the whole. The interconnections between the dimensions and factors influencing the behaviour of the system make us considered Collaborative MBSE design as a complex system in the organisation.

RQ2: How can we improve the current MBSE design process to enhance collaboration?

To improve the current MBSE design process we have compared several modelling methods regarding the characteristics of collaborative MBSE design to be represented. After several attempts using these methods, a mix of the representations IDEF, RAD and BPMN seems to be the most appropriate in our case.

Based on these methods, we suggest an added value process proposition for CAE-CAE collaboration and a scenario analysis for CAD-CAE collaboration. These propositions include in their representation three of the four collaborative MBSE design dimensions (actors, activities and information objects). The results show that the use of process and scenarios is useful in both cases to establish a shared vision of the work even if the activities and the information objects are completely different for each kind of collaboration. This vision contributes to an added value solution at three different levels in the organisation: the operational level, the tactic level and the strategic level.

After implementing and evaluating the propositions, we conclude that collaboration in MBSE design is not a linear problem at all. The proposed representation is highly appropriate to improve the global comprehension but the results have pointed out the actors as the key element on collaborative design activity, and the need in this context to further study the actor's relationships.

RQ3: How can we understand, describe, characterise and improve cooperation among the project members?

To analyse actors cooperation we have explored the application of the Games Theory (GT) approach to collaborative MBSE projects. Only few works using Games Theory (GT) in this context exist in the literature. Nonetheless, those works are mostly related to the trade-offs between different design options (Press 2016), (Lewis & Mistree 1997), (Xiao et al. 2005) more than the analysis of the actors itself. These findings prove the originality of our proposition: apply GT to improve collaborative MBSE design.

As the success of the GT application is based on the inputs used to describe the game, we have looked for a method allowing the abstraction of this information from real collaborative MBSE projects. As a result of this research we propose a coupling method between the FAcT-Mirror method and the Non-Cooperative Games Theory (NCGT). The use of FAcT-Mirror method and the proposed method is useful to translate the reality (observations) into a non-cooperative game.

The application of this method enables the proposition of a game, which assists the understanding, description, characterisation and improvement of the transversal relationships in collaborative MBSE projects through the analysis of its Nash equilibrium. Involving new management policies focused on the benefits of the information sharing more than the inconvenient or implementing information sharing resources guaranteeing knowledge protection, are some examples of the mechanisms found to improve cooperation.

Furthermore, we propose the use of *cooperative* MBSE design projects terminology instead of *collaborative* MBSE design terminology. We consider that people are organised in a cooperative mode more than in a collaborative mode mostly because of the specific features characterising the project organisation.

RQ4: How can we include the social aspects of the organisation (the new comprehension of the member's cooperation) to support the development of collaborative environments and capitalisation supports assisting MBSE design projects?

To include the social aspects of the organisation, we have looked for ways to implement information sharing resources in collaborative MBSE projects. Due to the industrial constraints, we have focused our attention on the TDR phase for this implementation. The literature review has shown that only a few works address TDR issues. Among these researches, we have not found any protocol to develop collaborative workplaces or capitalisation support assisting TDR. These results have encouraged the development of two groups of guidelines, which are driven by organisation expectations and the analysis of the actors cooperation.

To propose the first group of guidelines we have explored the literature in CCW (Collaborative Collocated Work) and CCSW (Computer Supported Collaborative Work). To propose the second group of guidelines we have explored the literature in KM, more exactly the capitalisation steps. Likewise, we have reviewed the TDR success criteria and collaborative mechanisms and enablers.

The implementation of the guidelines confirms the four hypotheses driving these researches.

H1: Minimising collaborative problems, has a positive impact on the TDR process and consequently on the global design process.

H2: No appropriate environment leads to collaborative problems, having a negative impact on the TDR process and consequently on the global design process.

H3: Minimising misunderstanding problems improves the collaboration in the TDR context.

H4: We can reduce the misunderstanding problems through an appropriate capitalisation and knowledge transfer support.

Thus, we affirm that the use of an appropriate work environment and capitalisation support improves the global design process by decreasing collaborative issues and misunderstanding. The proposed guidelines are helpful especially in the TDR context but also adaptable to other design situations.

The answers obtained from the four research questions presented before endorse the answer to the global research question driving this thesis:

How can we improve product development through the enhancement of collaborative aspects in MBSE design projects?

To give an adequate response to this question, we propose a global methodology to improve collaborative MBSE design. The proposed methodology is helpful at strategic level for managers and team leads, to better understand their team's needs and behaviours. At the tactical and operational level, the methodology is especially helpful for the team members themselves as these solutions facilitate their daily work.

The proposed methodology is driven by two main cyclical phases: the *collaboration analysis* and the *solution implementation*. The objective of the *collaboration analysis* phases is to focus on the study and understanding of the global system and the people dimension. The *solution implementations* phases aims at applying operational solutions. Each of the proposed methods has been developed to fulfil literature gaps and has been applied to industrial use cases.

Each method and mechanism used during each phase improves the understanding of collaboration. Thus we propose to progressively establish a deeper comprehension of collaboration among the actors by applying the different methods to reach at the end its improvement. We summarise the methodology as follows:

- (1) ***Collaboration Analysis 1. Launch a systemic representation to assess the current situation:*** The objective of this phase is to understand, represent and assess the collaborative MBSE projects as a complex organisational system. We propose the use of CEDOSy method to reach this objective. The result of this analysis must also facilitate the expression and formalisation of the foundations to develop suitable STS for the organisation.
- (2) ***Solution Implementation 1. Establish a shared vision of the work:*** The aim of this phase is to propose added value processes and scenarios supporting the improvement of the current situation in the organisation and fulfilling the gaps of other process propositions. The representations must facilitate the global comprehension of the stakeholders regarding the tasks that they should accomplish, the objects that they should provide and the interfaces with other actors.
- (3) ***Collaboration Analysis 2: Understand Actors cooperation:*** Understanding the actor's endeavours and behaviours is the only way to improve this collaboration from its roots. The

use of an appropriated method is necessary to ensure a successful analysis. We provide a coupling method proposition between FAcT-Mirror method and Games Theory.

- (4) ***Solution Implementation 2: Propose STS:*** The purpose of the last phase is to recommend means that recognise the interaction between the resources supporting this collaboration and the organisation, and that consider actors cooperation in their development. To succeed in this recommendation we propose two groups of guidelines supporting the development of STS in this context. This proposition is based on the progressive comprehension of the collaboration built through the precedent phases.

The implementation of the proposed methodology, methods and mechanisms in the industry, has shown how the enhancement of collaboration in MBSE design projects can improve the overall product development, fulfilling in this way the objective of this thesis: enhancing collaborative MBSE design projects to improve the product development.

5.1. Limitations

Although the proposed methods, process and guidelines contribute to the enhancement of cooperation in MBSE context, this research presents some limitations.

The main limitation of CEDOSy method and the added value process proposition corresponds to the difficulty to represent the richness of the actors' cooperation. Likewise, as any complex system, the MBSE collaborative organisational system is dynamic, and the current systemic representation must evolve to include new pertinent elements emerging in future researches. The activities and the roles in the organisation could change. Thus, a way to facilitate the process adaptation and monitoring must be explored.

Regarding the coupling method, the first limitation to mention is the statement of the three-proposed hypothesis. Indeed, the coupling method is only possible if all the three are fulfilled. As a reminder, the three hypotheses assume that:

- The set of fears, attractions and temptations describing each relationship are equivalent to the set of strategies and pay-offs for each couple of actors,
- The group of temptations of an “unavoidable theme” correspond to the group of strategies and the group of fears and attractions correspond to the pay-offs,

- Each attraction and fear associated to a given strategy may increase or decrease from one unit the pay-off of the actors.

Another limitation is the time required to obtain the results. Although the coupling method reduces the time spent with the group of actors, the analysis proposed is still time consuming for the researcher.

The subjectivity of the inputs (fears, attractions and temptations) may also be considered as a limitation of the research to propose a generalisation. Nonetheless, we think that the subjectivity of the inputs represents the appropriateness of the proposed solutions. Indeed, even if the inputs are subjective and not absolute, they represent the reality of a given situation.

Similarly, it is important to say that the use of the method will not give a complete representation of the human being behaviour. In fact, that has never been our intention, but instead, it will assist the analysis and understanding of specific cooperative aspects.

Regarding the proposed guidelines, the main limitation concerns the missing qualitative evaluation of the collaborative environments and the number of implementations of the capitalisation support. A greater use of the proposed support and more implementation of the guidelines may improve the evaluation of those propositions

5.2. Perspectives

In general, more implementations of the propositions in the same or other contexts are suitable to improve them. Further research must explore the adaptability and the flexibility of the proposed process, methods and tools.

Concerning the actors, we notice that the Model Architect (in CAE-CAE collaboration) and the simulation department (in CAD-CAE collaboration) are key to improve the management of the organisational complexity. Indeed, they facilitate the interactions among the project members by offering objective elements (simulation results) to the decision maker.

Regarding the proposed coupling method, some automations to reduce the time needed for the analysis must be considered. For example, the use of some simple algorithms assisting the mark and re-grouping protocol, or the automatic creation of correlation tables and games matrices. All

these elements are necessary to implement this kind of analysis in an industrial context. They are also needed to move the analysis to the next level in terms of actors and strategies (analyse more actors and strategies). Another interesting path to explore is the use of repeated games, where the player takes into account the impact of his/her decisions in the future. By repeating a game, the players learn about the behaviours of each another and can change their strategies. For instance we can imagine that, if a player steals another player's information the affected player may not share his/her information at all during the next game.

Another perspective is the use of the gathered information through the implementation to lead other analysis (e.g. the characterisation of other relationships identified: individual and hierarchical). Regarding the individual relationships, their generalisation is probably not the most interesting analysis since they remain personal and applicable at the individual level.. But if recurrent features are identified, we can include them in the analysis of the other relationships. Although the hierarchical relationships do not involve an important number of cooperative stakes, their study could be interesting for the proposition of new management policies or the improvement of the relationships between managers and employees.

Regarding the transversal relationships, which we have studied in detail in this research, including the attractions and fears that are not common to both use cases (A7, F6 and F8) and comparing the results could be interesting. Likewise, instead of gathering all the information to triangulate, each use case could be separately analysed.

Another path to explore comes from the limited samples extracted from the competitive relationships, which do not allow us to propose a characterisation as we did for the transversal relationships. Thus, obtaining more information to fulfil this gap should allow this characterisation. Similarly, repeating the FAcT-Mirror method mirror to collect information from other projects within the company could be convenient to verify if the strategy stays the same or not. Likewise, the application of the method in other contexts or industries could also be appropriate to analyse the differences. Those analyses may assist the definition of a more general tendency for each kind of relationship.

Regarding the proposed games, other forms of games such as cooperative games and biform games can be explored. Cooperative games exploration will assist the exploration of the possible coalitions between the actors, while biform games could gather both analysis (cooperative and non-

cooperative). In addition, the information gathered from the implementation could be useful to explore other analysis and methods based on the actors such as agent based modelling approach.

Concerning the collaborative environment, the short-term perspectives are focused on the qualitative evaluation of the implemented environment at Renault and the future implementation in other contexts. Nevertheless, several long-term perspectives have been identified, like the examination of the recording methods allowing the participants to be more focused on the discussion than notes writing. Likewise, we are still working on some metrics allowing to measure the impact of the collaborative solutions at different levels in the company. Finally, another interesting point to explore will be the adaptation of the guidelines to other design situations and its generalisation.

Regarding the capitalisation support, more implementations of the support will be helpful for the evaluation, as well as its implementation in other design phases. Likewise, the measurement in terms of collaboration (improved or not) when participants capitalise and when they do not may give interesting results. Finally, the study of the ontologies and data mining approaches to define fixed values for each data element could also be an interesting hint to explore.

Finally, the development of collaborative tools to enhance information sharing and capitalisation in MBSE context is still a large and interesting field to explore. Even if some solutions addressing the models lifecycle (e.g.: simulation lifecycle products) exist today, their usage has not been completely adopted in the enterprises. The exploration of new means such as those used in the agile software development can be considered as a clue. Likewise, new forms of communication such as social networks and mobiles application may offer an interesting support in this context.

List of Publications

JOURNAL PAPERS

1. Laura Roa-Castro, Julie Stal-Le Cardinal, Martine Callot, Eric Landel. **CEDOSy: The new systemic perspective of collaborative engineering design. Application to simulation context in the vehicle industry.** *Journal of Engineering Design (under submission)*
2. Laura Roa-Castro, Julie Stal-Le Cardinal, Martine Callot, Eric Landel. **Collaborative Engineering Design: a games theory perspective.** *Technovation Journal (under submission)*
3. Laura Roa-Castro, Julie Stal-Le Cardinal, Eric Landel, Naouress Fatfouta. **Developing collaborative design review supports. Part I: guidelines proposition and application to the vehicle industry for the development of collaborative environments.** *Concurrent Engineer Research Applications Journal (under submission)*
4. Laura Roa-Castro, Julie Stal-Le Cardinal, Eric Landel, Naouress Fatfouta. **Developing collaborative design review supports. Part II: guidelines proposition and application to the vehicle industry for the development of capitalisation supports.** *Concurrent Engineer Research Applications Journal (under submission)*

INTERNATIONAL CONFERENCES (PROCEEDINGS AND PEER REVIEW)

5. Laura Roa Castro, Julie Stal-Le Cardinal, Laurent Gasser. **Added value process proposition for collaborative design in early development phases using simulation models in aeronautics and automotive industries.** *DESIGN 2016 14th International Design Conference*, May 2016, CAVTAT, DUBROVNIK, Croatia. DS 84: Proceedings of the DESIGN 2016 14th International Design Conference
6. Laura Roa Castro, Julie Stal-Le Cardinal. **Definition of the collaborative simulation system (CM&SS) from a systemic perspective in vehicle industry context.** *International Conference on Engineering Design (ICED 15)*, Jul 2015, Milan, Italy. DS 80-6 Proceedings

of the 20th International Conference on Engineering Design (ICED 15) Vol 6: Design Methods and Tools - Part 2, 2015

7. Laura Roa Castro, Julie Stal-Le Cardinal, Martine Callot. **Towards an adaptive model for collaborative simulation: from system design to lessons learned. A use case from aircraft industry.** *Complex Adaptive Systems Conference*, Nov 2015, San Jose, CA, United States. *Procedia Computer Science* Volume 61, 2015, Pages 267-273, 61, pp.267-273,

INTERNATIONAL WORKSHOPS PUBLICATIONS

8. Laura Roa Castro, Julie Stal-Le Cardinal. **An overview of collaborative simulation on design process.** *Proceedings of the 10th International Workshop on Integrated Design Engineering*, Sep 2014, Gommen, Germany. *Proceedings of the 10th International Workshop on Integrated Design Engineering*, pp.117-132, 2014,
9. Laura Roa Castro, Farrugia Lawrence, Ben Nesrine, Wünsch Andreas, Hagman Jens, et al. **Cleaning genie: an international case study in integrated product development.** *Proceedings of the 10th International Workshop on Integrated Design Engineering*, Sep 2014, Gommen, Germany

PARTICIPATION (WITHOUT PUBLICATION)

10. Laura Roa Castro, Julie Stal-Le Cardinal, Martine Callot. **Towards the actor based design for a collaborative modelling and simulation system.** PURESAFE final conference, Jan 2015, Genève, Switzerland
11. Laura Roa Castro, Julie Stal-Le Cardinal. **Poster: an overview of collaborative simulation on design process.** ForumSTIC Paris-Saclay. 2014 Palaiseau, France.
12. Laura Roa Castro, Julie Stal-Le Cardinal. **A business process modelling approach for collaborative modelling & simulation problems.** GUC innovation workshop. Oct 2014, Gjøvik, Norway.

OTHER PARTICIPATIONS

13. Publish-ed workshop 2016

14. IPDS summer school 2014

TEACHING ACTIVITIES

« TD »: Industrial engineer introduction 2014

Innovation project academic supervisor 2015 and 2016

1 Master of Science student

1 Internship

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PART 2: Publications

Part 2 of this thesis is constituted of five papers presenting the propositions introduced in chapter IV. Paper # 1 presents CEDOSy method, gives a description of the *as is* situation and identifies the factors to be addressed (people, process, information objects and tools). The rest of the papers, address each of those factors as follows. Paper #2 addresses the first factor by suggesting added value process and scenarios. Paper # 3 deals with the analysis and improvement of the cooperation between the actors. Finally, Papers # 4 and #5 address the last two factors through the development of guidelines supporting the implementation of collaborative environments and capitalisation supports.

PART 2 SHORT SUMMARY

Paper # 1: CEDOSy: The new Systemic Perspective of Collaborative Engineering Design. Application to simulation context in the vehicle industry. (P. 131)

Paper # 2: Added value process for collaborative early design using simulation models in aeronautics and automotive industries. (P. 169)

Paper # 3: Crossing Games Theory and FAcT-Mirror methods to improve cooperative MBSE design projects. (P. 187)

Paper # 4: Developing sociotechnical systems for collaborative design review Part I: Guidelines proposition and application to the vehicle industry for the development of collaborative environments. (P. 223)

Paper # 5: Developing sociotechnical systems for collaborative design review Part II: Guidelines proposition and application to the vehicle industry for the development of capitalisation supports. (P. 253)

Paper # 1

CEDOSy: The new Systemic Perspective of Collaborative Engineering Design. Application to simulation context in the vehicle industry

Submitted to:

Journal of Engineering Design

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Abstract: *The organisational complexity implied by New Product Development (NPD) within the industry, is often induced by the complex nature of the products themselves. Finding alternatives to manage the NPD complexity has become one of the main stakes in engineering design research field. Among the approaches stated by the literature to address both, organisational and product complexities, Model Based Systems Engineering (MBSE) and collaborative approaches address respectively those complexities and have been recognised by their contribution to improve the NPD processes. The goal of this research is to propose a method supporting the development of collaborative systems while assisting engineering design. Our method is called CEDOSy and stands for Collaborative Engineering Design Organisational System. CEDOSy uses a systemic perspective to support the design of collaborative Socio Technical Systems (STS) in engineering design. We illustrate CEDOSy implementation through two industrial use cases in MBSE projects in the automotive and aeronautics industries. The results, shows how CEDOSy assists the characterisation of the MBSE dimensions, while defining its interactions and ensuring the inclusion of the social aspects of the organisation in the development of foundations to develop collaborative STS for MBSE projects*

Key words: *collaborative engineering design; collaborative MBSE; CAD -CAE collaboration; CAE-CAE collaboration; systemic modelling; Socio Technical Systems*

1. Introduction

During decades, very common practices in the industry were those related to Taylor and Toyota principles. These practices, initially thought for production systems, were rapidly expanded and adapted to design and engineering phases. Consequently, sequential engineer approaches were implemented through engineering teams, giving good results. Nevertheless, as the products became more and more complex the roles in the organisation became more specialised. Therefore, the sequential approaches were less adapted to manage the new complexities and the interactions among the specialists. On the one hand, the complexity related to the organisation, has been handled by adopting new approaches, such as concurrent and collaborative engineering (Deubzer et al. 2007). On the other hand, the complexity related to the new products design itself, has been handled by the inclusion of Model-Based Systems Engineering (MBSE). MBSE is the formalised application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases (INCOSE 2015). The particular application of modelling to support design and analysis activities is assisted by different tools, such as CAD (Computer Assisted Design) and CAE (Computer Assisted Engineering) software.

Nowadays, the product development process is still a very top-down approach. Even if the collaborative engineering concept has been introduced, the processes, methods and tools are still not mature enough, but at least, they started to become available. J.C. Brewer (Brewer 2005b), suggests that tools and processes for collaboration will become available as they are now for lean manufacturing. His work suggests that people studying collaboration will make the knowledge available allowing collaboration to spread, such as the students of the Toyota Production System did.

Today, the number of studies in Collaborative Engineer Design (CED) have become more and more significant (Deubzer et al. 2007). They cover different dimensions, such as new processes, tools, products and naturally people aspects. Nevertheless, the studies in collaborative MBSE design have not been explored enough. Some works in the literature suggest the existence and the link between those dimensions, when engineers use CAD and CAE tools. For instance, Kreimeyer et al. (Kreimeyer et al. 2007) address particularly the correlation between the dimensions: product

and people. Deubzer et al (Deubzer et al. 2007)(Deubzer et al. 2005), discuss the link between the dimensions: product, people, data, tools and processes using domain structure matrix (DSM), domain mapping matrix (DMM) and influence matrix approaches. However, the meaning of the links between the different dimensions is still vague, and a clear proposition of elements and activities to improve collaboration between engineers in this context is missing. Thus, this work is driven by three main research questions:

- How can we characterise the MBSE dimensions proposed in the literature??
- How can we define the interaction among them?
- How can we include the social aspects of the organisation to support the development of collaborative systems while assisting engineering design?

To answer these questions, we propose CEDOSy method which stands for Collaborative Engineering Design Organisational System. CEDOSy represents collaborative MBSE dimensions proposed in the literature (people, process, information objects and tools) (Ostergaard & Summers 2009)(Deubzer et al. 2005)(Kreimeyer et al. 2007)(Deubzer et al. 2007) in a single representation. In addition, it proposes different methods and tools assisting the characterisation of the each dimension. CEDOSy has been built through the application of the systemic approach (Le-Moigne 1990), (Schindler 2009b) CEDOSy supports the design of collaborative Socio Technical Systems (STS) in a MBSE projects by defining the foundations needed for the development of those systems. We illustrate the implementation of CEDOSy through two use cases from the vehicle industry. The use cases represent respectively two types of MBSE collaboration that we call from this point forward: CAE-CAE and CAD-CAE. CAE-CAE concerns the activities within simulation department teams, while CAD-CAE concerns the interactions between embodiment design (CAD) and performance department (CAE) through the use of simulation models.

This paper is organised as follows: Section 2 presents a background of collaborative engineering design and systems modelling. We present CEDOSy method in section 3 and its implementation through the two use cases in section 4. The results and discussion are presented in section 5 and a short description of the further work done is presented in section 7. Finally, section 8 summarises the conclusions and the future work.

2. Literature Review on collaborative engineering design and systems modelling

The importance of MBSE technics for the industry has grown during the last decades. It is commonly known that replacing physical prototypes by virtual prototypes using simulation models through CAD and CAE tools, is both cost- and time-efficient (Brewer 2005a), (Schelkle et al. n.d.). MBSE brought an important value to the vehicle industry by assisting the progress of complex systems design. The understanding of organisational complexity of the collaborative MBSE design, and the improvement of this particular collaboration from a systemic perspective, constitute the scope of this research. Joining MBSE dimensions proposed in the literature (people, process, information objects and tools) to CED definition (Fatfouta et al. 2016), we can describe collaborative MBSE design as an activity involving simulation and design engineers, who share information and knowledge encapsulated in the simulation models. They use different resources or tools to perform the sharing and to accomplish the task related to the product development process at the simulation stages. Only few works addressing collaborative MBSE have been found in the literature (Bajaj et al. 2011; Tschirner et al. 2014). However, as no work in the literature refers specifically to organisational issues of collaborative MBSE design, we decided to explore both, CED modelling and organisational complex systems modelling methods.

Looking in the wider scope of CED in the literature, no common modelling method has been found. However, both traditional and relatively new modelling approaches are used. Among the traditional approaches, the most commonly used modelling methods are: the flow charts, the IDEF, the Critical Path Method (CPM), the Design Structure Matrix (DSM), the Petri-net, the Data flow diagram (DFD), the Role activity diagram (RAD), the Business Process Modelling Notation (BPMN), the Business Use Cases (BUC) and Business Object Interaction Diagram (BOID) (Wang et al. 2006), (Aldin & De Cesare 2009), (Perrot 2008b). As part of the new modelling approaches, two concepts are interesting, they are the Cooperating Correlative Map Base on Activity (CCM_A) (Cui et al. 2009) and the Collaborative Architectural Design Processes (Frost & Warren 2000). The CCM_A process modelling method takes into account some of the important aspects of the collaborative design, such as people and activities. However, the roles and the interaction within the stakeholders are still difficult to interpret. The Collaborative Architectural Design Processes is characterised by a collaborative commitment of all stakeholders. This approach structures different

design tools and design events, as walkthroughs and design games, aiming at promoting creativity and facilitating common understanding of the design tasks.

Within all these approaches, only IDEF allows the representation of the four collaborative MBSE dimensions at the same time (representing the process dimension as a decomposition of activities, the people and the tools as mechanisms and the information objects as constraints). However, this method is still a very linear representation. Thus, it is not adapted to CED representation, since CED is classified as an iterative activity (Wynn et al. 2007). The rest of the approaches allows the representation of at least, three dimensions at the same time. Several diagrams will be needed to have a complete description. Then, the meaning of the links between all dimensions will be difficult to represent in a single view.

Regarding organisational complex systems modelling methods, three main approaches were found in the literature: the Operations, Information, Decisions and Knowledge method (OIDC) (Fatfhallah 2011), the Soft Systems Methodology (SSM) (Wang et al. 2015), (Rodriguez-ulloa & Paucar-caceres 2005), and the Systemic approach (Le-Moigne 1990).

On the one hand, the OIDC method defines four layers (Operations, Information, Decisions and Knowledge). Each layer is denoted as a subsystem. OIDC method confirms the existence of the links between each subsystem. On the other hand, the SSM is interesting as it checks the coherence between two worlds: the “real world” and the “conceptual word”. The methodology proposes seven cyclic steps starting and ending in the real world. Only the first four steps are related to the conceptual modelling. However, none of the two methods allow neither a detailed description of the four dimensions (people, process, information objects, and tools), nor a precise matching between the subsystems (or steps) and the dimensions.

The last method, the systemic approach, proposes a representation of the system based on four axes: ontological, functional, genetic and teleological axis. Each axis describes respectively: what the system is, what the system does, how the system evolves and what are the system objectives. To facilitate the description of each axis, J-L. Le Moigne suggests to turn the axis description into questions. Figure 24 (a) shows the representation proposed by the author of the four axis and their related questions.

Among the different modelling methods mentioned before, the systemic approach is the most appropriate method to build CEDOSy. Its axes match with the four dimensions allowing a detailed description of those. In a previous research (Fatfouta et al. 2016) the methods were deeply compared using QFD method, but the conclusion remains the same: the systemic approach covers all the dimensions related to MBSE design in a single representation and facilitate the definition and illustration of the interaction among the dimensions.

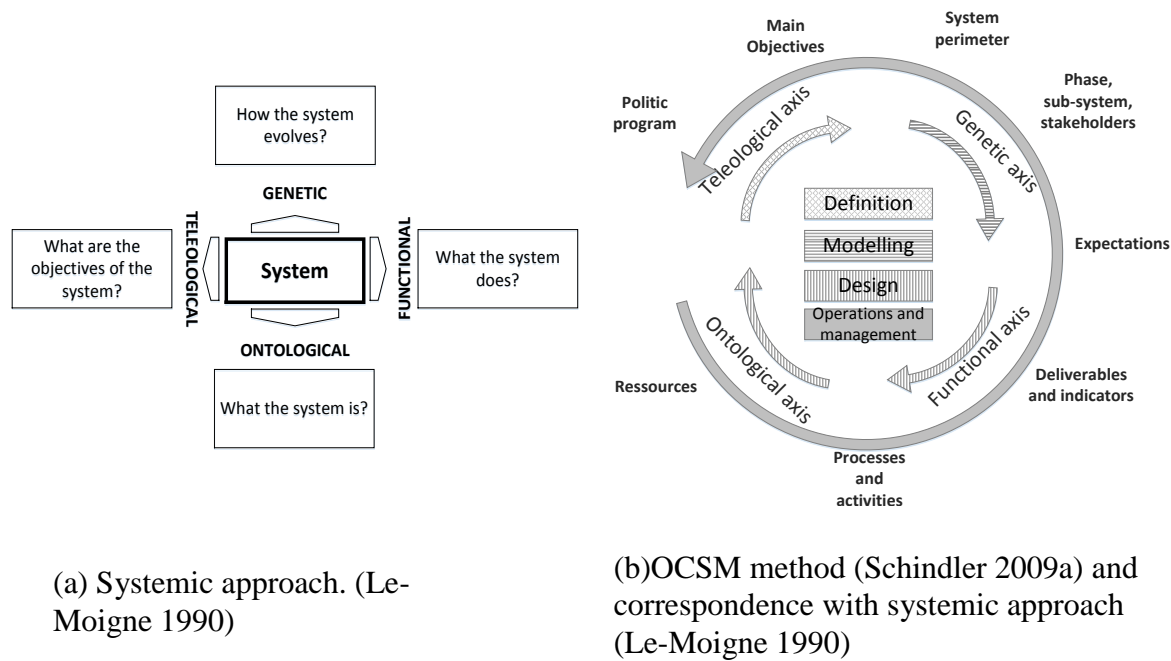


Figure 24: Systemic approach and OCSM method. (b)OCSM method (Schindler 2009a) and correspondence with systemic approach (Le-Moigne 1990)

The OCSM (*Organisational Complex System Modelling*) (Jean 2013) method shown in Figure 24 (b) is based on the systemic approach and represents each axis of the systemic approach in terms of:

- The teleological axis is described in terms of the politic program (or organisational strategy) and the main objectives of the system.
- The Genetic axis is described in terms of the system perimeter. Each phase of the system must be considered. Likewise, the stakeholders involved in each phase must be identified.

- The functional axis is described in terms of the stakeholders expectations and the deliverables, activities, and added value processes resulting from those expectations.
- The ontological axis is described in terms of the means or resources needed to execute processes.

In addition, a verification of each item is proposed by going backward from the ontological axis to the teleological axis. As the OCSM method proposes the organisation as a departure point for the system modelling, we use this systemic modelling method to study MBSE design projects in the use cases presented in next section. Indeed, starting from the organisation ensures the socio-technical coherence of the propositions resulting from its application

In summary, the systemic approach enables the description of the system by representing each axis in terms of the items described in Figure 24 (b). The description of each item could be as detailed as desired, allowing the representation of a comprehensive picture of the system, its elements and the relationship between them.

3. CEDOSy method

As mentioned in previous paragraph CEDOSy stands for Collaborative Engineering Design Organisational System. It has been built from a systemic perspective using the OCSM method – mentioned in section 2 and it is an improvement of the CM&SS representation (Collaborative Modelling and Simulation System) suggested in a previous work (Roa-Castro & Stal-Le Cardinal 2015). We present a global view of CEDOSy in Figure 25.

In the figure, the full coloured rectangles denote the new items regarding the OCSM method. CEDOSy supports the design of collaborative Socio Technical Systems (STS) in a MBSE projects by first, proposing the necessary methods and tools facilitating the characterisation of each MBSE dimension and second, by defining their interactions. As CEDOSy has been built using OCSM method, it guarantees the design of collaborative STS responding to the organisational aspects of this collaboration. Starting from the identification of the organisational objectives, strategies and context, and continuing by the stakeholders characterisation, CEDOSy method assists the definition of the collaborative points through the different MBSE design phases, where specific stakeholders expectations regarding the collaborative STS are identified, as well as the concerned activities and exchanged objects, in order to propose added value process with different scenarios

variations, that must be supported by collaborative resources involving the future users. The characterisation of the elements proposed by CEDOSy defines the foundations needed for the development of collaborative STS in MBSE projects.

We illustrate in section 4 the use of CEDOSy through two use cases where we detail the elements enclosed in each axis.

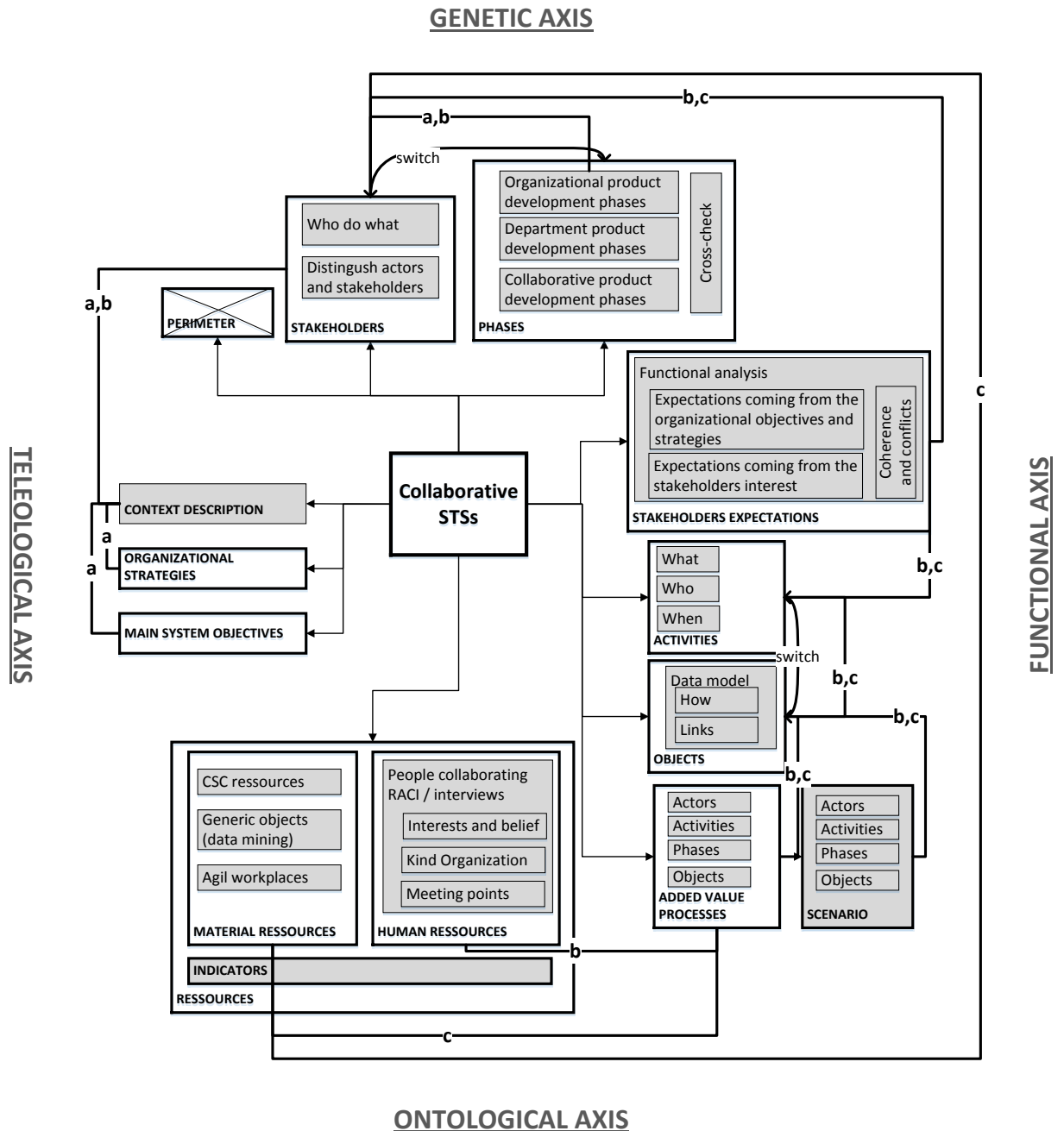


Figure 25: CEDOSy (Collaborative Engineering Design Organisational System): A method supporting the design of collaborative Socio Technical Systems (STS) in a MBSE projects

Regarding the teleological axis, we keep almost the same description proposed by the OCSM method, but we add the context description, since collaboration are often related to a specific situation (Le Cardinal et al. 2001). In the genetic axis we have removed the perimeter description to avoid repeating the elements already described (built from the teleological axis information, plus the phases and identified stakeholders). We have also switched the stakeholders description and the phases definition. Indeed, the information coming from the teleological axis is sufficient to define the stakeholders of the system. Also, the phases definition in the projects depends on the matrix organisation. Thus, it is pertinent to identify first the actors and then the phases where they participate. In addition, we propose several elements (fulfilled rectangles) assisting the description of each axis, and consequently the MBSE dimension.

Regarding the functional axis, we have switched the description order between activities and objects (deliverable in OCSM method). Indeed, it seems coherent to describe what the people do (activities) and then how they do it (objects). As for the genetic axis, we propose several elements for the description of the dimensions that we describe in detail in the use cases illustration. Finally, we have split the ontological axis into material and human resources. For each kind of resource we propose the elements corresponding to methods and tools supporting their development and/or study.

In the figure, the arrows coming out of the centre rectangle represent the decomposition of the system in different axis as proposed by J.L. Le Moigne. These axes are described by the elements proposed by OCSM (not fulfilled rectangles) or CEDOSy method (filled rectangles). The MBSE dimensions - people, process, information objects and tools – suggested in the literature are represented through the elements describing the axis, as shown as follows:

- People: Organisation (teleological axis), the stakeholders definition (genetic axis), the stakeholders expectations (functional axis) and the human resources (ontological axis)
- Process: Phases (genetic axis) and activities, scenario and process (functional axis)
- Data: Objects (functional axis)
- Tools: Material resources (ontological axis)

The bold links connecting the elements (inter or intra) axis represent the interactions and logical connexion among those elements, and consequently among the MBSE dimensions. We use lower case letters to refer to them in the text. The bold links *a* mean that the development of a collaborative STS starts by the description of a specific collaborative situation. The context description must be coherent with the organisational objectives and strategies, must specify the involved stakeholders and must take into account the project context by defining the intervention of the involved stakeholders among the concerned phases. Context description should also include other environmental information helping in the understanding of the situation.

The bold links *b* show how the system development is driven by the social aspects. Starting from a given collaborative situation involving the identified stakeholders and aiming at achieving specific organisational objectives, this situation takes into account the constraints imposed by the matrix organisation (represented by the cross points among the phases for the different stakeholders) and is translated into stakeholders expectations about the collaborative STS. Then, the activities needed to be carried out by the stakeholders are described as well as the information objects (models) created as a consequence (e.g.: developing models) or as a support (e.g.: taking decision) of those activities. The stakeholders, activities and objects are used to create added value processes including all this information and that can be declined into more specific collaborative scenarios. All those elements (added value processes, scenarios, single activities and information objects) are performed by the human resources (active stakeholders of the system). As people is the key element of any collaboration, the interaction among them merits to be studied in detail. Consequently, different methods found in the literature are mentioned in the human resources rectangles.

The bold links *c*, show how the method ensures also the technical aspects of the system. Starting not only from the involving of the stakeholders using the system, but also those developing the materials means (e.g.: IT services). Those means must support the creation of information objects, the activities related to their creation, use and reuse, and clearly the added value processes and scenarios using them. As for the human resources, the methods supporting the development of material resources coherent with our collaborative STS method are mentioned.

To verify that the proposed items respond satisfactory to the stakeholders expectations, but also to the organisational needs, the use of appropriate indicators (as proposed by OCSM method) can assist this check coherence

Finally, to ensure the global coherence of CEDOSy, we propose three questions linking the different axis. As a matter of readability, on Figure 25, we use Figure 26 to illustrate the summarised version of the links and to include the questions

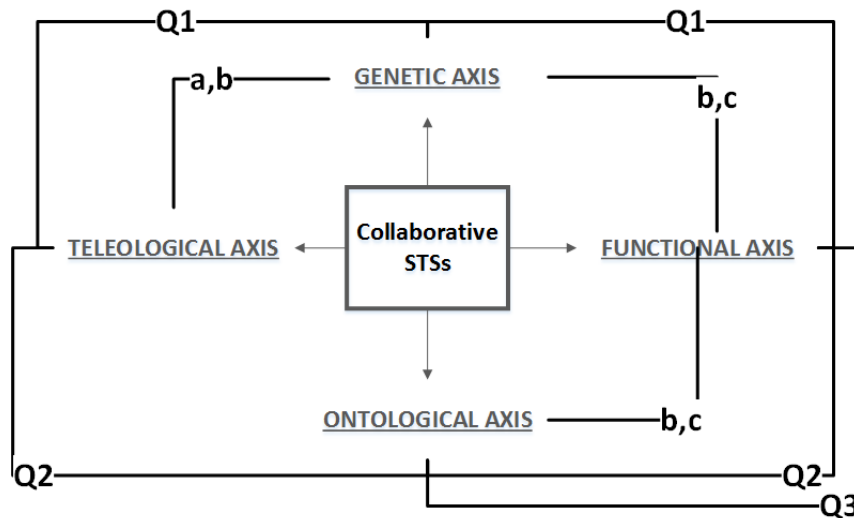


Figure 26: CEDOSy links

- Q1: Are the objectives and strategies of the company represented by the stakeholders through the expected values?
- Q2: Does the material resources and the proposed organisation support the collaborative processes and scenarios, and satisfy the organisational objectives?
- Q3: Does the collaborative process and scenarios represent the activities, deliverables, phases and stakeholders? Can we see how they are all linked?

4. Use cases: CEDOSy implementation in MBSE design projects

The first use case illustrates a collaborative simulation project (CAE-CAE). The activities within simulation department teams (CAE-CAE), often have collaborative problems because of multidisciplinary context. This use case presents a project using MBSE technics during the design process from December 2014 to February 2015 . A team of four engineers was confronted to a given problem related to the choice of an Environment Controller System (ECS) to regulate the

cabin temperature. More precisely, they had to choose between two control models (On/Off controller or PID controller). At the end of the project, four dynamic interviews were organised to understand the collaborative interactions that could not be observed.

The second use case has been carried out with our partner, the French car manufacturer Renault, in a re-organisation context concerning the projects of embodiment design (CAD) and performance department (CAE) through the use of simulation models. A new organisation was proposed in the company in 2015, to centralise simulation teams at the vehicle level in order to: organise the activity, centralise the models, speed up the development process and help in the decision-making process by giving an objective point of view. The organisational change is illustrated in Figure 27. In the previous organisation, the vehicle services were split into performance department (such as acoustics, aerodynamics, safety...) and design departments (such as chassis, seat, body...) at three different levels: Vehicle level, System level and Component level. Both, performance and design departments are supported by simulation teams. The new organisation should avoid the conflicts between performance department and design department, given that those department used to have contentious interests (e.g.; the performance department aiming at developing a fast vehicle whereas the design department could include heavy , but nice, pieces slowing down the vehicle). This situation has motivated in the past the use of simulation technics to favour the own department interest more than the interest of the project. By centralising simulation department teams, the request of a simulation needed by design and/or performance departments is centralised before being developed, which will ensure the coherence between the requests and consequently the coherence in the model development process. Thus, simulation models could finally be used as an objective mean in the decision making process as well as the number of development loops.

We apply CEDOSy method to the current MBSE design, during the problem-solving phase. We led 6 workshops with the employees, each having between 5 and 12 participants. The participants were experts and employees of the simulation teams performing collaborative tasks.

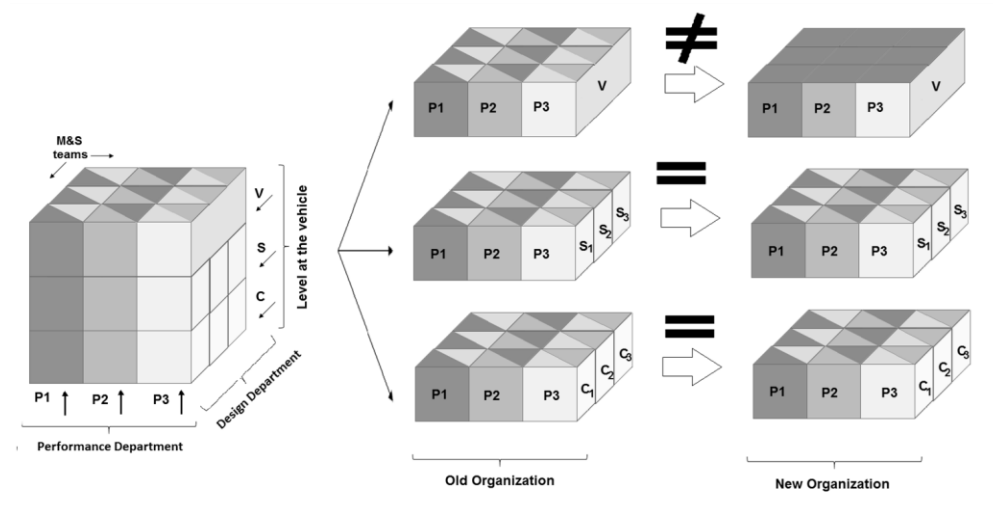


Figure 27: Use case 2: Organisational change at Renault

The application of CEDOSy method to the use cases enables to establish the foundations for the development of a collaborative STS describing and linking the MBSE dimensions, through the elements proposed for the description of each axis, in an industrial context. In addition, the results of the implementations highlight the industrial need for closer integration between design engineers and simulation engineers, as well as a better cohesion among simulation engineers, is a business priority. The development and implementation of a collaborative STS enhancing cooperation among the actors would allow to reduce the product development time (Mocko and Fenves, n.d.) and also enhance the decision making process during the development phases (Broek and Dutta, n.d.).

We describe in detail and illustrate the use of each of the four axes of CEDOSy (teleological, genetic, functional and ontological) and their respective elements (Figure 25) through the use cases from sub-section 4.1 to 4.4. Finally, the use cases results are presented as foundations propositions to develop a collaborative STS in sub-section 6

4.1. Teleological axis

The first axis of the method is the teleological axis. We present in Figure 28 the teleological axis elements proposed in CEDOSy and their illustration through the two use cases.

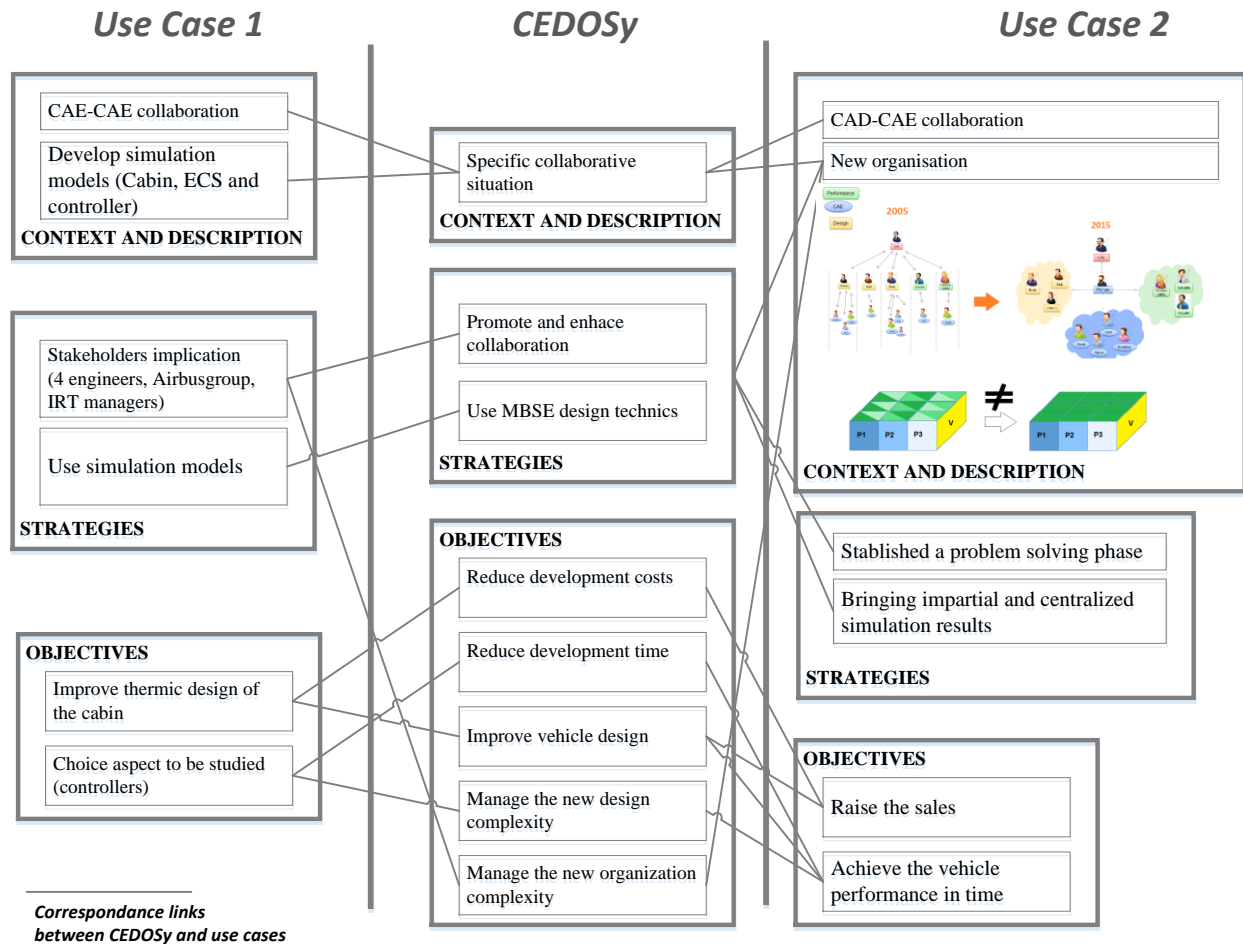


Figure 28: Teleological axis illustration of CEDOSy implementation

This axis describes the environment of the CED system in terms of two main components: the main objectives of the system and the politic program (or organisational strategy). First, the elements suggested in the literature regarding the main objectives of the system are related to cost savings and design improvement (Brewer 2005a) (Schelkle et al. n.d.). One way to reach cost reduction is by decreasing the product development time. We consequently identified the reduction of the product development time as an objective. Likewise, we have identified the management of the new complexities (product and organisation) as another objective in order to enhance product design.

Second, the strategies adopted by the organisation to reach their objectives are large. However, we focused our attention on the strategies related to collaborative product design and to MBSE technics. On the one hand, the strategies associated to collaboration meet the objectives of time reduction and complexity management. In fact, collaboration between engineering teams has been studied as a way to reduce product development time (Deubzer et al. 2007), (Brewer 2005b). Likewise, the research of Chiu and Cheng-kung (Chiu & Cheng-kung 2002) proposes a link between collaboration practices and the management of the new complexities. On the other hand, the strategies associated to the usage of MBSE technics, facilitate the test phases preparation. Thus, the usage of MBSE technics meets the objectives of costs reduction and vehicle design improvement (Group n.d.).

In this axis we propose an additional item, which is the context (or problem) description. Indeed, collaborative problems are closely related to a specific situation. A collaborative solution is not generic to all the problems, it often needs to be adjusted and so forth, the way to approach the problem can be adapted.

a) Use case 1 (CAE-CAE)

First, the context of the use case is given by the purpose of the project itself and by the kind of collaboration (CAE-CAE). The purpose is to improve the thermic design of the aircraft cabin. It was done by analysing two different control models playing the role of an ECS (On/Off controller or PID controller). Implicating the right stakeholders was part of the key discussions before launching the project.

In order to choose a solution, different alternatives need to be considered. We studied six alternatives during the project. Each one is a combination of a cabin model and a control model. The choice of the alternatives to be studied will decrease - or increase - the complexity of the design but also the organisation to set up. For instance, the number of {cabin/control} model pairs will increase or decrease the number of alternatives. Likewise, the level of desired details for each model will influence the number of components to be modelled, the links between them, the possible system behaviours and the number of people involved.

b) Use case 2 (CAD-CAE)

In the second use case, the context is given by the re-organisation situation in the company. In addition, this context is also framed by the kind of collaboration (CAD-CAE). The objectives at the highest level regarding the situation studied in use case 2, are the same ones than in any other company: the company needs to increase sales. In order to do so, achieving vehicle performance in time has become a significant concern. In this way, the company has set up at the end of each design phase, a design review phase (where design problems are addressed). The solutions derived from this phase should be based on the results of the simulation models. But as the simulation results are often delayed – due to the current organisation – the CED system should primarily meet the deadlines. The design review phase only makes sense if the models are centralised and provide a unified view of the vehicle. Thus, the second strategy of the system is to improve the decision making process by bringing impartial and centralised simulation results.

c) Teleological axis conclusions

By confronting CEDOSy to use case 1 (left side of Figure 28), we confirm the usefulness of MBSE technics during the design process. In fact, these technics have been used in the use case to improve some technical aspects of the product. In addition, the importance given to the selection of the right stakeholders was fundamental in the later success of collaborative interactions of the project. Likewise, by confronting CEDOSy to use case 2 (right side of Figure 28), we observe consistency between the highest level objectives of the company and the elements proposed in CEDOSy. In the same way, we identified the organisational change and the setting up of a design review phase as strategies to encourage MBSE technics. Even so, no explicit strategy meant to directly improve collaboration has been identified.

Even if the use cases have a very different organisational context, both projects based their strategy on the use of MBSE technics. Likewise, even if their objectives seem very different at first sight, the global strategy is the same in both use cases: save costs and/or increase sales by introducing MBSE technics. The use of these technics implies collaborative activities and needs suitable means supporting them. To do this, in use case 1 the stakeholders got involved earlier (their identification is part of the strategy, thus they have been designated in this frame while CEDOSy advise their identification in the genetic axis) and in use case 2, a new organisation to avoid past conflicts is proposed.

As a conclusion of both implementations, we notice that the description of the context, objectives and strategies seems to be an appropriate starting point. The objectives and strategies identified in CEDOSy matched with the elements of the use case except for the promotion of an explicit collaborative strategy.

4.2. Genetic Axis

We present the genetic axis elements proposed and their illustration through the two use cases. In Figure 29. The middle panel of Figure 29, presents the genetic axis items of CEDOSy. The top of the figure shows use case 1 illustration and the bottom side the use case 2.

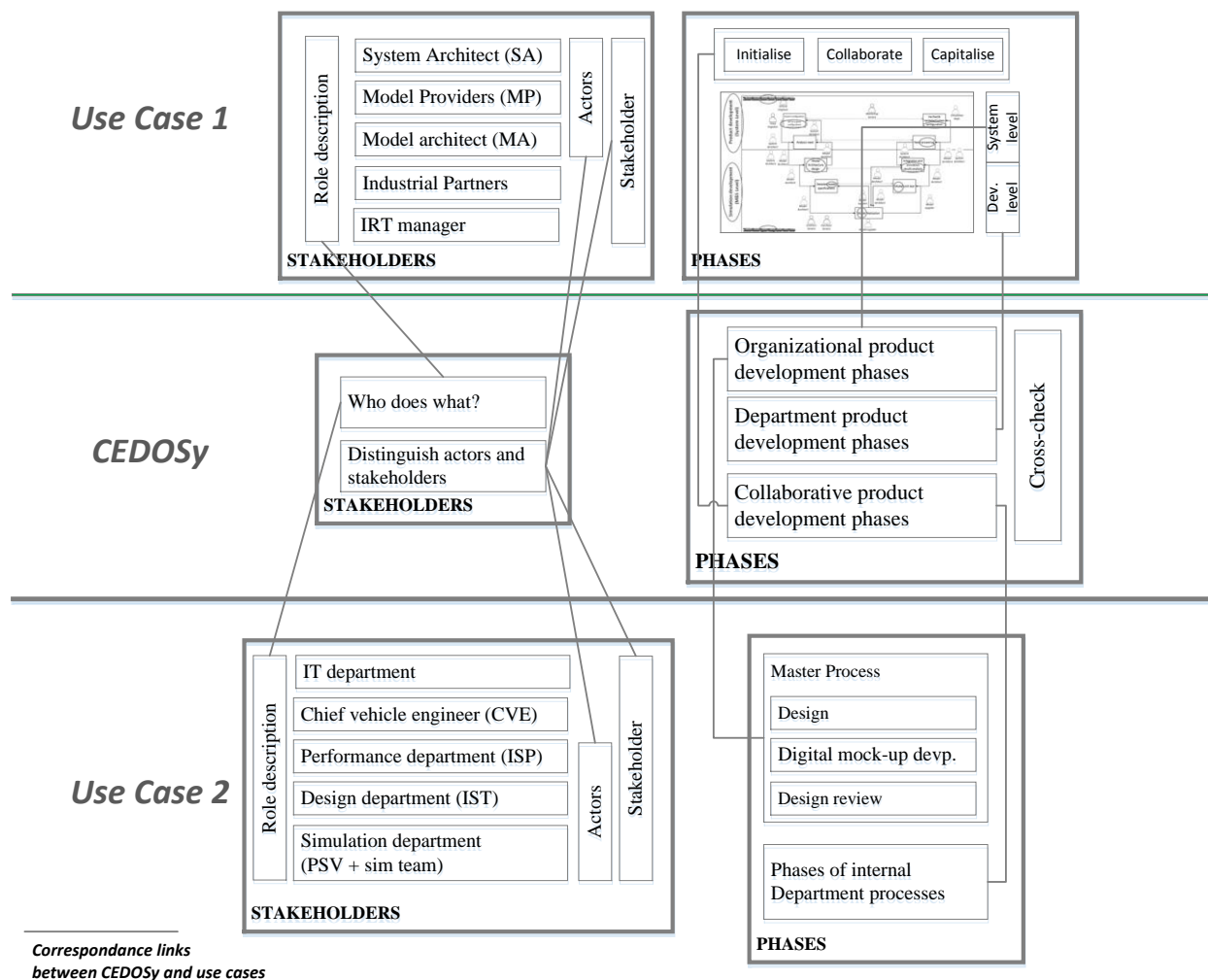


Figure 29: Genetic axis illustration of CEDOSy implementation

The traditional description of the axis starts by the perimeter description. However, we decided not to include this item here given that we already defined a context. The stakeholders identification then becomes the priority, because of two reasons. They are needed for the definition of the following axis elements, and the evolution of the collaborative system depends directly on the people. Thus, people are the key element of the system. We propose in the first place to identify the stakeholders and the actors of the system, but also to integrate a short description of their respective roles. As we are in a collaborative MBSE context, the stakeholders of the systems are mainly simulation engineers. However, other stakeholders such as system architects, design engineers, performance engineers, IT engineers and program chiefs are also involved. The identification of the stakeholders is still specific to each context and is clarified for each use case.

The phases definition is a good starting point for the later activities definition. Nonetheless, the system contains phases at different levels. These phases should be identified at the department level and at the organisational level. The definition at different levels is helpful for the orchestration and the synchronisation between the departments. Finally, the definition of collaboration phases is needed as well. It is important to define the main phases to establish a collaboration, and establish a cross-check between all these phases (e.g.: When do people start to collaborate? when do the department phases converge?)

a) Use case 1

The phases of the system, regarding use case 1, are those related to the model development process. These phases are often represented using the standard V cycle (INCOSE 2012). The project was driven by the adaptation of the V cycle to the simulation process (Sirin et al. 2015). This adaptation includes the main stakeholders of the simulation in the V cycle representation, as well as distinction between system level and development level. In addition, three main collaborative phases were identified: the initialisation, the collaboration itself and the capitalisation.

Five stakeholders were identified. We use the definition proposed by Sirin et al. (Sirin et al. 2015) for the first three of them. First, the System Architect (SA), who defines operational scenarios and trade-off analysis, and provides a draft version of the model architecture. Second, the Model Provider (MP), who is a domain expert who builds models with his specific domain knowledge. Third, the Model architect (MA), who has also a deep understanding of the system level requirements for the vehicle model and how the models must be interfaced with other domain

models. Fourth, the industrial partner for the case study (Airbus Group Innovations). Fifth, the IRT manager involved in the organisation of Futur@SystemX event, who was also identified as stakeholders of the system, mainly because of the constraints that they could impose. Among the five stakeholders, three of them (SA, MA and MP) were identified as actors as well. It means that they play an active role during the collaborative MBSE design activity.

b) Use case 2

The stakeholders of the system, are those directly involved in the new organisation (the performance department, the design department and the simulation department), plus, the chief vehicle engineer, who represents the interest of the company and look for the best cost/performance trade-offs. And an IT department, who assists MBSE technologies in the company. We identified the stakeholders directly involved in the new organisation as the active actors, and the roles were defined with respect to their job position. The phases of the system were determined by the phases of two kind of company process. The first one is the *master process*. It represents the most general product development phases set by the company: design, digital mock-up development and design review. The second one, is the *internal department process*.

During the design phase of the *master process* different propositions are proposed to reach the requirements. Then, during the digital mock-up development phase, the propositions are included in the general mock-up of the project and the simulations are executed. The simulation results point out the problem (requirements unattended) that should be addressed during the design review phase. At the end of the review, new design modifications will be requested and the cycle will start again refining the design until all requirements will be fulfilled. The *master process* must keep a good timing to synchronise all the company activities.

The activities constituting the *internal department processes* of each service must be finished in time in order to reach the master process milestones.

This use case is focused on the junction of the performance, design and simulation *internal department process* and the design review *master phase*. During this phase, people from different services need to work close together, much more than in the other phases. Collaboration becomes a fundamental factor all along this phase.

c) Genetic axis conclusions

In use case 1, the phases frame contains the adaptation of the V cycle to the simulation process and the collaborative phases, representing both, organisational Product Development (PD) phases at the system level and department PD phase at the model development level. Likewise, in use case 2 the described phases are the company high level phases (*master process*) and the department level process. However, the phases of the collaboration are not explicitly identified as such for use case 1, but they can be deduced by identifying the meeting points of the actors at the intersection of master process phases and department phases. The stakeholders frame presents in both cases the differentiation between actors and stakeholders. The identification of those elements are mandatory for the orchestration and synchronisation of activities among the actors.

To conclude, the phases definition seems appropriate to understand collaboration since it takes into account the phases at different levels in the company and their orchestration. Similarly, the stakeholders identification and role definition, are necessary to avoid an incomplete portrait.

4.3. *Functional axis*

The third axis of CEDOSy is the functional axis which describes the system in terms of stakeholders expectations, deliverables, activities, and added value processes. We present in Figure 30, the functional axis element proposed in CEDOSy and their illustration through the two use cases.

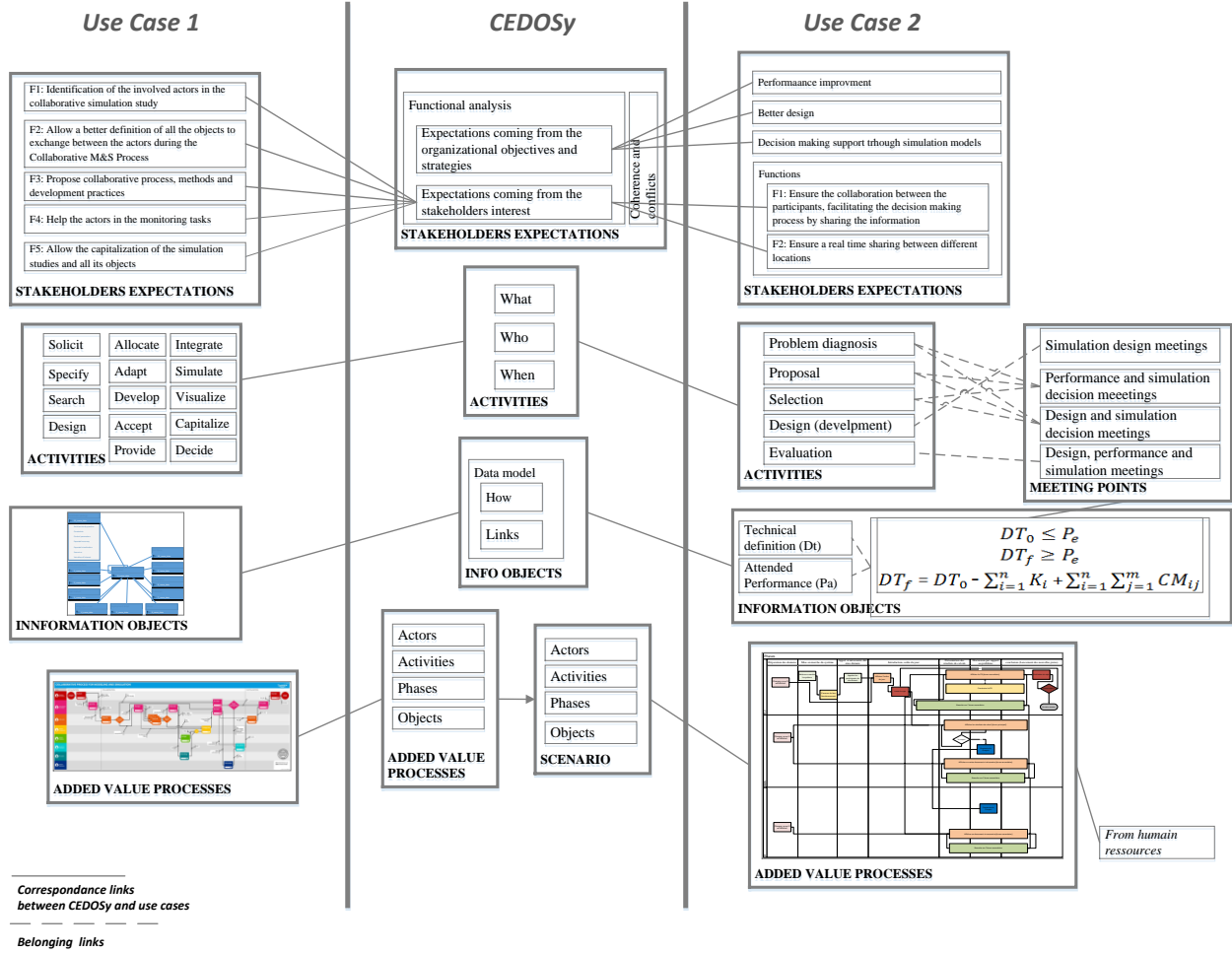


Figure 30: Functional axis illustration of CEDOSy implementation

Regarding the stakeholders expectations, it is important to differentiate the expectations resulting from the objectives, the strategies and the context, and those coming from their individual interests. It ensures the coherence between objectives and expectations, but also highlights possible conflicts. To define the expected values, we propose to use a simplified functional analysis of the system within the stakeholders.

The identified deliverables should provide an objective mean for the decision making process, such as, simulation results. Intermediate deliverables or objects to exchange, can also be identified. Nonetheless, the label *deliverable* could be too specific. We propose a label *information objects*, allowing the inclusion of all the objects to share, exchange or deliver during the process. We also propose to determine the objects after the activities, which allows us to focus first on the what, who and when (activities) and then, on the how they do (objects). The last improvement concerning the

objects, refers to the way of representing them. We propose to represent them through a data model, which highlights the link or dataflow from an object to another.

The elementary activities support design process and collaboration between people as well. The level of details in the activities description will depend on the problem, and it should be decided with the actors of the system

Finally, the added value process proposition should include as much information as possible, keeping it readable. It is important to identify when (moment), and how (actions) the actors will collaborate and what (deliverables) objects they will exchange for the two processes of special interest to this research: a) modelling and simulation processes (e.g. first use case) and b) collaborative engineering design processes (e.g. second use case). So forth, we propose to include the actors, the activities, the phases and the objects. However, the process representation is still linear and the some collaborative issues do not appear. Then, we propose the use of scenarios derived from the process.

a) Use Case 1

In use case 1, we observed that the stakeholders expectations were mainly driven by their role in the company, their responsibilities and also by their interest on the project success. Then, we asked them what should be the specifications of a collaborative STS for MBSE projects. To answer this question, they identified five main functions that the specifications should contain: 1) the identification of the involved actors in the study (or project); 2) the definition of all the deliverables during the simulation process; 3) the identification of collaborative process, methods and development practices; 4) the tasks monitoring; and 5) the capitalisation of the simulation studies and all its deliverables. The left column of Figure 30 presents the illustration of each item regarding this use case. The stakeholders box contains the functions of a collaborative STS for MBSE projects identified by the actors. The activities presented are those coming from the process view. The deliverables box contains the data model presented in Figure 32. Finally, the added value process gathers activities, objects and roles representations in a single view.

We represented in Figure 31, the identified activities (14) and roles (8) describing collaborative MBSE design in CAE-CAE context. The upper side titles are the collaborative phases (Moly et al. n.d.). Each activity (rectangle) is represented as a process (Roa Castro et al. 2016). The callouts symbolize the objects exchanged between two activities and the diamonds represent the decision

nodes. This illustration does not imply that collaborative MBSE design is a linear activity. It rather aims at giving a general guideline.

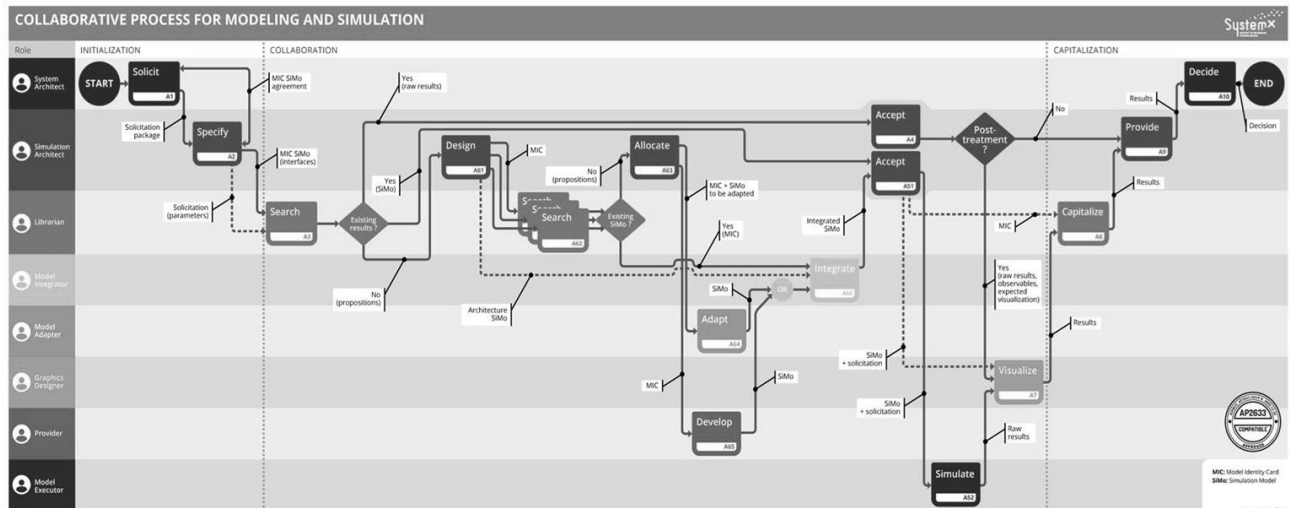


Figure 31: The added value process proposition for a collaborative design in early development phases using simulation models (Roa Castro et al. 2016)

The information objects are all the elements containing the product information, needed to fulfil the functions. All the objects needed to lead a simulation study are gathered in the Sim Artifact (Roa-Castro & Stal-Le Cardinal 2015) which is represented in Figure 32. We identified 2 main objects, the solicitation package and the simulation configuration. The first one is a single object, containing the information needed to begin the study (the initial problem, the constraints and the scenarios). Information such as the control parameters, the expected accuracy and visualisation, and the variables of interest can also be specified in this package. The second one is a combination of nine additional objects: the model itself, the SiMo Architecture (architecture of the simulation), the Model Identity Card (MIC) (Sirin et al. 2015), the integration script, the development script, the user manual, the simulation results and the verification and validation mechanisms. During the use case, the engineers exchanged 10 single simulation models, to execute six different configurations asked in the solicitation package.

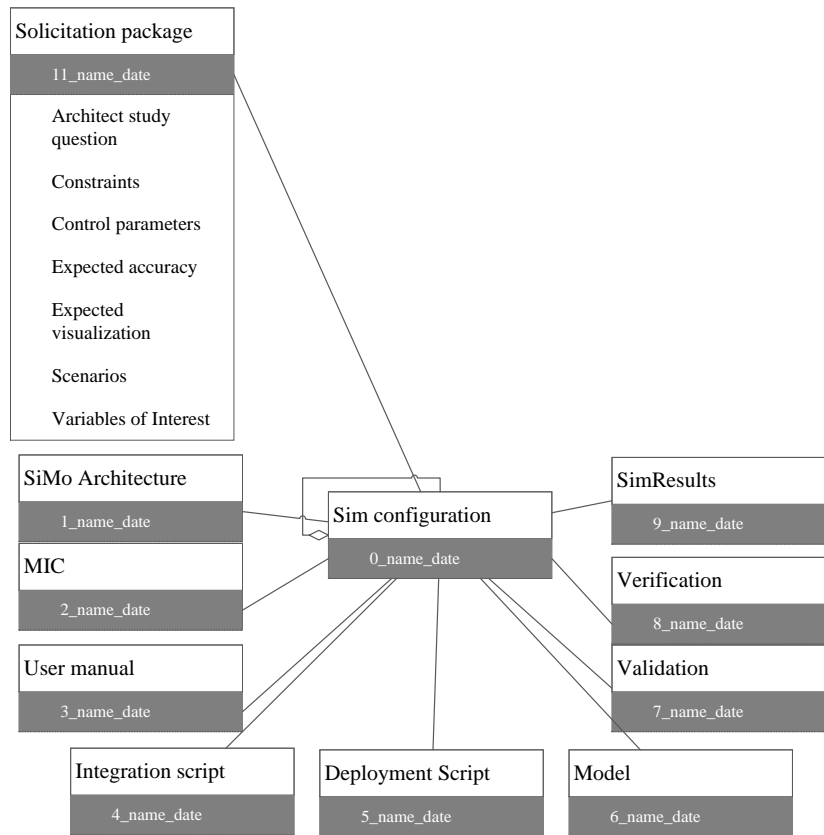


Figure 32: Data model from use case 1: The Sim Artifact

b) Use Case 2

In use case 2, we confirmed possible contentious expectations coming from the stakeholders. Indeed, performance department expects to reach the vehicle performances in time for the master process respecting the technical constraints whereas, the design department is much more focused on the layout. For example, while the performance department works on the consumption reduction, the design department may not consider it. The modelling and simulation services supports both, performances and design departments, through the realisation of simulation models. To clarify the stakeholder expectations regarding the usefulness of a collaborative STS in MBSE projects - as for the first use case - we also asked them what they should expect from the specifications of a collaborative STS for MBSE projects. Two main functions were identified. First, the system should highlight the collaboration between the participants, facilitating the understanding of those interactions. Second, it should illustrate the shared information elements needed for the collaboration.

As we mentioned in the genetic axis, this use case is focused on the junction of the performance, design and simulation *internal department process* and the design review *master phase*. During the design review phase, five activities were identified: problem diagnosis (what/where the problem is), proposal (which are the possible solutions), selection (what is the feasibility of the proposed solutions, which one is the best one?), design (design the selected solution) and evaluation (evaluate the solution regarding the original problem). Each activity is linked to at least one meeting point. The meeting points and the actors who should participate in the corresponding meeting points were identified as well. The indicators related to the technical solution are evaluated during each meeting point.

Five main information objects were identified: Initial technical definition (DT₀), Final technical definition (DT_f), Expected performance (Pe), modifications (CM_{ij}) and Problem list (Ki). The relationships between these elements will drive the logic of the actions. Thus, if the initial technical definition (DT₀) does not reach the expected performance (Pe), it is because of some technical problems (Ki). The main objective of the design review phase is to transform the initial technical definition (DT₀) by adding some modifications (CM_{ij}) into a final technical definition (DT_f) reaching the expected performance (Pe). For each problem (Ki) one or several modifications may be adopted (CM_{ij}). All the modifications proposed must be taken into account to solve the problems.

The added value process was also illustrated using the activities, information objects and actors in the same representation. However, the linearity of the representation drove us to propose a scenario representation, more adapted to the situation.

After the workshops, we concluded that the diagnosis activity is the most important in the process. The experience in the company has shown that rework task is highly demanded when not enough time is dedicated to this sub-phase. Likewise, the practice shows that the proposal and the analysis and selection activities are successful when the right people are involved at the right moment. That is why the identification of actors and meeting points is important. The design activity is based on collaborative model exchange process (use case 1 process). Finally, the accomplishment of the evaluation activity is given by the quality and impartiality of the presented results.

c) Functional axis conclusions

The observation of use case 1 allows us to affirm that the definition of the stakeholder's expectations is highly convenient as a first step. It ensures the coherence between the items of the axis. The activities and information objects definition comes at the right time. During the project, we have observed that the engineers first think about what they want to do (activities) before thinking about how to do it (objects). The discussion around the activities definition has been very enriching, especially regarding the desired description details. Lastly, the added value process was gradually built defining activity by activity, the people involved and the inputs and outputs in terms of objects. The linearity of the representation has been highlighted by the actors. However, they agree on saying that this representation is adapted as a guideline and allows the identification of possible collaborative meeting points (interaction between two or more people), but it does not completely integrate an illustration of collaborative issues.

As for use case 1, identifying at the very beginning the stakeholders expectations has also proved to be useful for later definition of the axis elements in use case 2. The information objects identification has also been very helpful for the engineer team. In addition, engineers defined some of those objects as "evolving items", as the objects to exchange and/or share during the complete process that may evolve. Following this evolution seems important for the system learning and for the improvement of the know-how. The activities identification is general at first, but then some specific aspects are explored in detail. As for the first use case, the added value process description presents the same difficulties because of its linearity. However, the description of different scenarios reinforces the illustration of collaborative issues.

Analysing both use cases results, allow us to come to the following conclusions. First, even if the stakeholders expectations, activities and information objects are completely different from a use case to another, CEDOSy method facilitates their characterisation answering simple questions such as how, who or when. Thus, the characterisation of the elements proposed by CEDOSy, is suitable to describe the MBSE dimensions. Additionally, some of those description are qualified as collaborative mechanisms such as: collaborative configuration, scenarios, relationships and data models. Second, we confirm that the stakeholders expect to reach the organisational goals through the implementation of the associated strategies. In this case, the collaborative STS for MBSE

projects, should support the design process by identifying and organising the information objects, the elementary activities and the people involved.

4.4. *Ontological axis*

The fourth and last axis of the method is the ontological axis. This axis is described in terms of the means or resources needed to execute the processes. Two kinds of resources were identified: human resources and material resources. We separate the CEDOSy elements and the applications (the use cases) as we have done for the other three axes. The top of Figure 33 is the illustration of use case 1. The middle contains the CEDOSy proposed elements and the bottom illustrates use case 2.

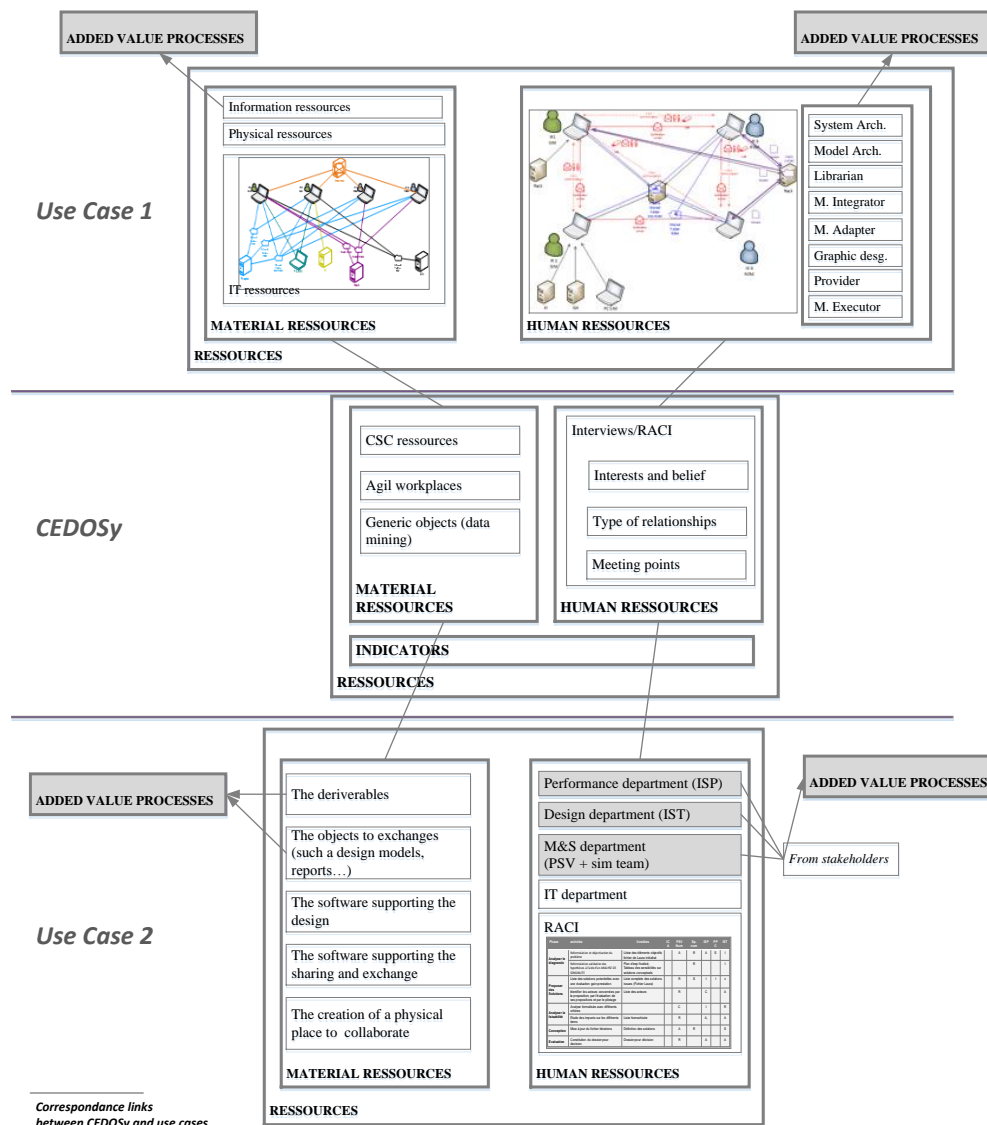


Figure 33: Ontological axis illustration of the CEDOSy implementation

The most important element of any collaboration is the people. Therefore, the stakeholders are identified as the key resource of the system. Nevertheless, they need tools facilitating the interactions among them. Both use cases present different configuration of the people involved and different kinds of tools assisting the interactions.

In terms of human resources first, we propose to complete the stakeholder description, by defining the key meeting points during the processes. Second, we propose to go deeper into the *how* question, by identifying the type of relationships among the actors (how people are organised). Third, we propose to analyse the motivation to collaborate (why) that is briefly described through the stakeholders expectations.

In terms of material means, the IT environments and platforms, the objects, and the physical places where people collaborate represent the system. Often, several computer supports respond to the same need. To avoid the redundancy between the existing supports, we propose to exhaustively identify them, and check the needs with the engineer teams. This check decreases some interoperability problems and increase the fulfilled needs.

The last items that we considered in the ontological axis is the definition of the indicators allowing to measure the collaborative performance. Contrary to OCSM method, we propose the identification of those indicators at the end. Because of the complexity of the collaboration, it would be difficult to identify the indicators earlier without a global picture of how the system works.

a) Use case 1

In the first use case, three kind of material resources were identified: 1) the IT resources, such as software, servers, e-mails, laptops and sticks; 2) the information resources, represented by the exchanged objects; and 3) the physical resources, such as the places where engineers meet each other. As an example of the IT resources, the configuration used during the project is presented in Figure 34. The configuration was supported by the personal and project laptops, the internet connection and four servers. The internet connection is represented by the upper server of the figure. The servers represents in the bottom (from left to right): the shared documents server, the Model Identity Card generation server(Sirin et al. 2015), the rack and the model server.

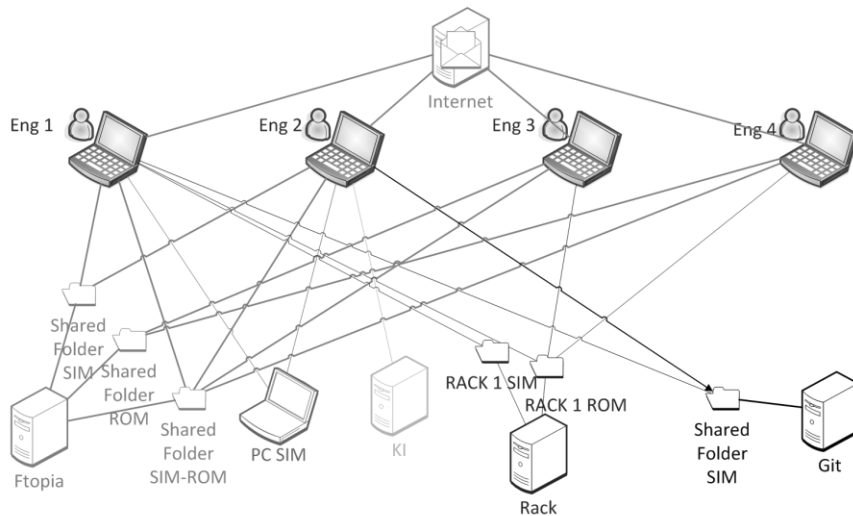


Figure 34: IT configuration

We identified the human resources as the people directly involved, and working in the systems. In sub-section 4.2 (genetic axis) we identified 5 stakeholders. Nonetheless, only three of them are active resources: the system architect, the model architect and the model supplier. These three actors will play the 8 roles identified in sub-section 4.3. Each actor can play one or several roles in function of the project.

At the end of the project, four dynamic interviews were organised aiming at understanding the relationships between the participants. Figure 35 illustrates some of the interactions. We identified some information flows going from the local computers to the shared servers (as originally planned through the architecture). However, the most of the information flows identified, were informal flows. Those flows are local-to-local information exchange. For instance, we found several e-mails sent from one people to another, or information delivered using stick devices.

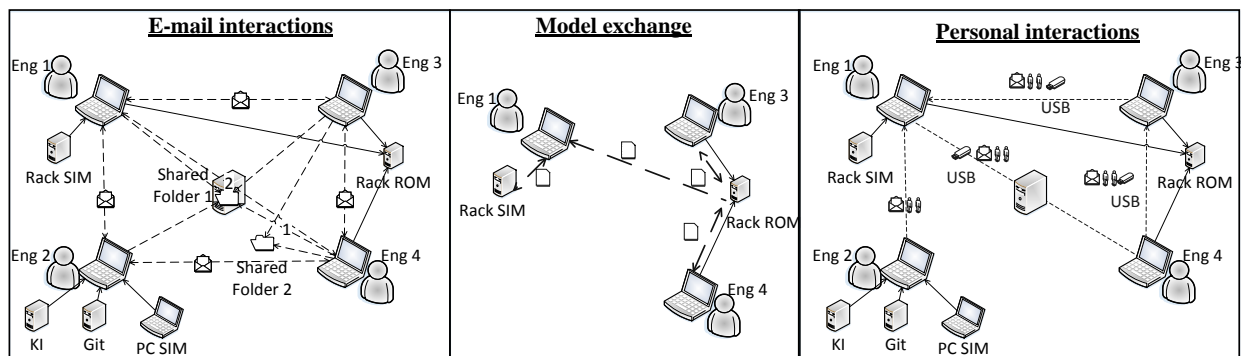


Figure 35: Illustration of some participant interactions

Use case 2

In this use case, material resources appear to be a major element to enhance and support the collaboration. Actors use them all the time to carry out their work. The material resources identified were: the final deliverables, the objects to exchange (such a design models, reports...), the software supporting the design and the software supporting the sharing and exchange. One more element was identified as a need: a physical place to collaborate. Indeed, participants do not have any dedicated place for the design reviews. A lack of material facilitating communication and collaboration activities was evidenced during the observations and afterwards, participants confirmed this need.

Contrary to use case 1, in use case 2 one more actor was identified additionally to the stakeholders: the IT department. IT department is included as a human resource since it will support the IT materials resources. In addition to human resources identification, a RACI matrix (Responsible, Accountable, Consulted and Informed) was built so as to clearly define the responsibilities of each actor.

b) Ontological axis conclusions

The filled rectangle in both use cases (added value process), link the functional axis and the ontological axis. That is, all the human resources and information objects identified interacting through the proposed process (links b and c in the global CEDOSy representation of Figure 25). They match with the stakeholders identified in the genetic axis, and they are an active part of the added value process presented in the functional axis. The description of the human resource has been done using the most adapted method to each use case (dynamics interviews in use case 1 and RACI analysis in use case 2). Both methods facilitates a general comprehension of the interactions between the actors. However, they are not detailed enough to understand actors behaviours.

In both use cases the material resources are represented by the IT configuration, the possible physical places and the information resources. Nonetheless, their representation is not the same. Use case 1 uses a graphical representation of the IT configuration, whereas use case 2 lists the IT configuration items to be taken into account. The identification of the information resources was

presented previously as the data model in use case 1 (Figure 32: Data model from use case 1) and the relations between the technical description and attended performance in use case 2.

The results of the ontological axis implementation highlight material means as a crucial elements to reach the objectives in both use cases. Likewise, the richness of the people interactions is clearly illustrated even if the methods describing them are different. Nevertheless, those descriptions do not give enough details about the interests and beliefs of the people collaborating, neither the consequences of those interests on the collaboration, nor the impact of the people organisation on the collaborative issues. Thus, the use of a method facilitating this understanding and giving more details is appropriate.

5. Proposition of foundations for the development of collaborative STS in MBSE projects

We describe below the proposition of the foundations for the development of a collaborative STS in MBSE projects for each use case. The descriptions correspond to the complete systemic view (characterised elements and their interactions). As a matter of readability, we have not included the whole system description in a single figure (such as the global representation of CEDOSy (Figure 2). Instead, we have put in square brackets the corresponding CEDOSy elements and axis for each use case, to help the reader [element/axis].

a) Use case 1

The collaborative STS supporting MBSE projects must:

- Have a positive impact on the product development process [objectives / genetic].
- Assist the development of simulation models in a multidisciplinary context [context and description/genetic axis].
 - This assistance must enhance the use of MBSE technics to improve the management of the product complexity. It must also involve the right stakeholders as early as possible [strategies/genetic axis; stakeholders expectation F1/functional axis]
 - *By assist the development of simulation models in a multidisciplinary context*, we understand that the system must assist the SA (System Architect), MA (Model Architect), MP (Model Provider), the IRT (Research Institute of Technology) and the industrial partners to play their roles[stakeholder/genetic axis],

- The assistance in the role accomplishment must be done by supporting the fourteen tasks that they need to carry all along the project phases allowing a distinction between the system level, the development level and ensuring the three main collaborative phases identified [actions; stakeholders expectations F4, F5/functional axis; phase/genetic axis].
- This assistance must support the access and the creation of the data models containing all the information needed to the model development, reuse and capitalisation providing a clearer visibility during the development process [information objects; stakeholders expectations F2, F5/functional axis].
- The system must be able to assist the entire added value proposed process by supporting the identified tasks and the access and creation of different information objects [added value process, stakeholders expectations F2/functional axis].
- The collaborative STS must support a given organisation among the actors [strategies/teleological axis; stakeholders, phases/genetic axis; added value process/functional access; human resources/ontological axis] facilitating interaction and communication [material resources/ontological axis] when exchanging, sharing, developing, reusing and capitalising simulation models [activities, information objects and added value processes].

b) Use case 2

The collaborative STS supporting MBSE design projects must

- Assist the problem solving phase and facilitate the use of MBSE technics and collaborative strategies (such as the implementation of a new organisation) in furtherance of bringing impartial results supporting the decision making process.
 - Bring impartial results should help to reach vehicle performance as fast as possible [context, strategies, objectives/teleological axis; stakeholders expectations/functional axis].
- Enhance and promote collaboration among the members of performance department and design department via simulation department services in order to support the new organisation [context/teleological axis; stakeholders/genetic axis; stakeholders expectations/functional axis].

- Be especially focused on the support of the meeting points concerning the identified stakeholders facilitating the five activities carried out during the problem solving phase, especially the diagnosis activity, as it has been highlighted as the most important in the process. Likewise, the management of the information objects exchanged, shared or created during the meeting points must be facilitated by the system as well as the assistance to the different scenarios [stakeholders, phases/genetic axis; activities, meeting points, information objects/functional axis].
- Be robust enough to support different collaborative scenarios and must be based on the necessary material resources enhancing collaboration that have been identified (such as the physical place and the current software solutions) but also on the deeper analysis of the stakeholders and their behaviours [added value process/functional axis; human and material resources/ontological axis].

6. Results and discussion

The use of CEDOSy to characterise MBSE dimensions and their interactions in both contexts (CAE-CAE and CAD-CAE) allows us to propose the foundations for the development of collaborative STS in MBSE projects presented in the precedent section. CEDOSy representation has been appreciated in both companies and has been qualified as helpful to build and understand the grounds of a collaborative STS.

We have found the necessary information in both use cases to fulfil the characterisation of all the elements proposed by CEDOSy, Gathering elements, that have not been centralised at all before, we have managed to give them a global coherence for the whole project. However, some of the proposed elements have been defined before (or after) the order advised in CEDOSy. For instance, the early stakeholder definitions in use case 1 (identified in the teleological axis instead of genetic axis, as it was part of the project strategy to work with very specific people), or the later identification of collaborative phases in use case 2 (described in the functional axis instead of genetic axis, through the meeting points definition for the different activities) are the examples that we have found. Nonetheless, we have not noticed any impact on the global description because of these earlier or later definitions of those particular elements. Thus, we can conclude that a systematic characterisation of the elements describing collaborative STS in MBSE projects is advantageous to avoid oversights, and also to build in a coherent way the foundation of the system

to develop. But, it is also opportune to leave some freedom in the identification order of the elements. Indeed, this needs to sometimes “go back” and forth in the elements definition, also proves the complex nature of the system.

Surprisingly, the inclusion of explicit collaborative policies or strategies have not been found in any of the use cases. However, both suggest the need to improve collaboration through implicit strategies, such as a new organisation in use case 1 or the early involvement of the stakeholders in use case 2.

Regarding the methods and/or tools proposed to describe some of the elements, CEDOSy is flexible enough to use the most adapted methodologies describing the elements for each context (c.f. process description, scenarios, data models, etc.). However, when describing human resources, we notice a lack of information. To fulfil this gap, we propose to study this dimension deeper, by analysing the aspects related to teamwork, communication and cooperation. Looking in the literature, we have found the FAcT-mirror method (Le Cardinal et al. 2001) whose implementation seems appropriate in this context. This framework deals with the contradictions and paradoxes existing between different stakeholders; and supports the development of structured recommendation for the co-operative actions.

The other two elements that merit to be considered in detail are the information objects and the workplaces. Regarding the information objects, we propose to develop a generic representation of the main objects. These generic representations may facilitate the information sharing between the teams and will support the capitalisation stages. Finally, concerning the places to collaborate, some such as collaborative collocated work (CCW) or agile workplaces (Joroff et al. 2003b) could be studied to encourage the establishment of a physical place to enhance collaborative activities. We recommend to make a proposition of a place supporting collaborative processes and scenarios, where people could exchange and collaborate in an appropriate environment.

The application of CEDOSy to two industrial use cases, allows us to validate the proposed elements and to identify the people as key element which needs to be studied more in detail. Indeed, in both cases people have played the central role on the characterisation of the axes since they are somehow always present in the different elements definitions. It can be, an explicit description of their roles or expectative, or an indirect representation of them through the activities that they carry out, or the objects that they develop, or the process that they perform or rather the means that they use to

do it. They are the ones who can establish the links among the different elements and the ones who define the guideline through their expectations, needs and behaviours for the development of a collaborative STS in MBSE projects. This affirmation is also confirmed by the related elements supporting each foundation (square brackets in sub-section 5). In both cases, all of the items of the foundations list imply the stakeholders or the organisation.

Finally, the results obtained from the implementation of CEDOSy allow us to improve the definition of collaborative MBSE design presented in the literature review. We conclude that collaborative MBSE design is characterised by:

- (5) The goals and profiles of people participating (simulation and design engineers)
- (6) The encapsulation of the knowledge in the simulation models
- (7) The tools and resources supporting information and knowledge treatment (e.g.: CAD-CAE)
- (8) The tasks related to design and simulation stages of the product development process.

Collaborative MBSE design covers several dimensions and factors. All of them are closely interconnected, and their sum does not represent the whole. The interconnections between the dimensions and factors influence the behaviour of the system (Chiu & Cheng-kung 2002). Therefore, Collaborative MBSE design can be considered as a complex system in the organisation.

7. Further work: CEDOSy global coherence

We have conducted further work aiming at proposing a mean to ensure the global coherence of any system foundation resulting from the application of CEDOSy. We propose to check the characterised elements by using 5W2H method (What, Who, When, Why, Where, How and How much). If the system modelling is satisfying, we should be able to answer the following questions regarding the system of interest, in the use cases collaborative MBSE design: *What are the collaborative activities? Who is collaborating with whom? Who does what? When, where, how and why do they collaborate? “How much” do they collaborate? Can we measure the collaboration? Is it efficient?* The complete list of questions concerning all the elements and their interactions is summarised in Table 11

Axis		Item	What	Who	When	How	Why	Where	How much
Teleological		Main system Objectives	x						
		Organisational strategy	x						
		Context description	x						
Genetic		Stakeholders And actors description	x	x					
		Organisational phases	x		x				
		Department phases	x		x				
		Collaborative phases	x		x				
Functional		Stakeholders Expectations	x	x					
		Activities	x		x				
		Objects	x		x				
		Processes	x	x	x				
		Scenarios	x	x	x	x			
Ontological	Material	CSCW resources				x			
		Generic objects (data mining)				x			
		Agile work places				x		x	
	Human	Meeting points		x	x				
		Kind Organisation		x		x			
		People interest and believes		x			x		
		Indicators							x

Table 11: 5W2H method to verify foundations coming from the implementation of CEDOSy

8. Conclusion and Future Work

This paper addresses the organisational complexity of the collaborative engineering design when engineers use simulation models to solve technical problems (collaborative MBSE design). We focus the attention on the collaboration between the engineering teams using CAE-CAE and CAD-CAE tools. On the one hand, the processes describing collaborative simulation (CAE-CAE) in the literature are still very general and the list of the works concerning IT aspects of the collaboration is large (the complete literature research can be found in a previous work (Roa-Castro and Stal-Le Cardinal 2014)). However, some processes describing this collaboration through the description of simulation models exchange have been proposed by the industry, such the AP 2366, FEDEP and ProSTEP. Those descriptions are a valuable initiative. Nevertheless a significant improvement could be done, especially regarding the inclusion of model reuse hypothesis and capitalisation in the process, as well as the inclusion of new roles.

On the other hand, CAD-CAE integration works have explored some holistic approaches. The research in this field identifies four key dimensions of the collaboration between both, design and performance departments (people, product, information objects and tools) (Deubzer et al. 2007; Deubzer et al. 2005), (Matthias Kreimeyer et al. 2016), (M Kreimeyer et al. 2007; Maier et al. 2009). However, the meaning of the relationships is still vague, and a systemic proposition of the elements and activities describing collaboration between engineers in this context is missing.

The literature review analysis leads us to affirm that the organisational complexity of the collaborative MBSE has not been explored enough. We conclude that no common representation, nor modelling guidelines allowing the development of collaborative systems for both CAE-CAE and CAD-CAE collaboration, have been proposed.

After comparing different modelling approaches, we propose to use the OCSM method (Organisational Complex system Modelling) –derived from the systemic approach - to model the organisational complexity of the collaborative MBSE. This approach allows us to propose CEDOSy method, which stands for Collaborative Engineering Design Organisational System. We implement CEDOSy through two industrial use cases describing the representative aspects of collaborative MBSE. The first use case illustrates the CAE-CAE collaboration, while the second illustrates CAD-CAE one.

CEDOSy takes over the systemic approach principles and assist the characterisation of the key dimensions found in the literature describing collaborative MBSE. It also supports the design of collaborative Socio Technical Systems (STS) in a MBSE projects by first, proposing the necessary methods and tools facilitating the characterisation of each MBSE dimension and second, by defining their interactions.

Through the implementation of CEDOSy, we have been able first, to validate the proposed elements characterising the collaborative MBSE dimensions and their interactions, answering the two first research questions (How can we characterise the MBSE dimensions proposed in the literature? How can we define the interaction among them?). Second, to propose the foundations for the development of collaborative STS in MBSE projects in both use cases, which allow us to answer the third research question (How can we include the social aspects of the organisation to support the development of collaborative systems while assisting engineering design?). Indeed, the results also highlight the identification of stakeholders as the key element of the collaboration,

given that they are the ones who can establish the links among the different elements and the ones who define the guideline through their expectations, needs and behaviours for the development of a collaborative STS in MBSE projects. And third, we also have been able to improve the definition of collaborative MBSE design presented in the literature review.

Finally, the use of CEDOSy has been recognised by the companies as a valuable initiative to first create a common representation of collaborative STS for MBSE projects, and second, to take a step forward in the development and implementation of collaborative STS contributing to the company objectives. This representation is important for them, because no model describing the current situation exists. Likewise, the establishment of foundations are key since no STS supporting MBSE collaboration exists today in the studied companies. The development of a system adapted to their own needs has been pointed out as a business priority.

Future work should consider a deeper study of the actors behaviours and relationships as suggested in results and discussion section (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.). Likewise, the identification of the activities, information objects and means assisting collaboration has been identified as crucial to understand the relations among the actors. These elements, their interactions and their impact on the collaboration also need to be analysed more in detail. In addition, in future work we would like to carry out more implementations of the model in other design domains. Furthermore, we would like to use the proposed foundations to help developing efficient collaborative STS in the company, such as collaborative rooms, activities and documents (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.; Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.). Finally, the proposition of some indicators measuring collaboration efficiency of the system will be suitable.

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Paper # 2

Added value process for collaborative early design using simulation models in aeronautics and automotive industries

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Abstract: *The research presented is focused in the modelling of three main features in collaborative design using simulation models (M&S): Actors, activities and objects. To represent these features, an added value process proposition for a collaborative design in early phases using M&S was suggested. The new process was implemented and evaluated during a project at the IRT SystemX having Renault and Airbus Group Innovations industries as a partners of the project. The results suggest the proposed representation as highly adapted to the problem and point out the actors as the key element on the collaborative design.*

Key words: *design process, collaborative design process, collaborative simulation, process industrial application, process modelling*

1. Introduction

Engineering process modelling have been classified as a significant activity in most major companies around the world, making this methodology a crucial part of the company's management (M.A. & Wilson 1996). Vehicle industry is not the exception. Process approaches have been largely applied to manufacturing and production phases. Then, more recently, these approaches started to be applied in engineering design phases. During the design phases, the use of simulation models in this industry has grown in importance in the last decades. These techniques could be extremely accurate, bringing a quality/cost solution to test phase problems. The passing through a numerical era, where simulation models are used as the basis of the development process can often be referred to as a Model Based Systems Engineering (MBSE).

INCOSE defines MBSE as the formalised application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases (INCOSE 2007). This approach demands as well a new organisation around the simulation models. Our research aims at understanding how people interact thanks to the models, and how they obtain the results in a context where team are large, spread and sometimes diverging objectives. In others words, how people collaborate in the design phases using simulation models.

In previous research, (Roa-Castro & Stal-Le Cardinal 2014a), (Roa-Castro & Stal-Le Cardinal 2015), the main features of the collaborative design using simulation models were identified. Nevertheless, no model exists today describing all the feature for a collaborative design in M&S context. The research presented in this paper is part of a larger effort on collaborative design modelling, and is focused in the modelling of three main features in collaborative design: Actors, activities and objects. To represent these three features, an added value process proposition for a collaborative design in early development phases using simulation models is suggested.

Section two presents the action-research methodology used in this paper, starting from industrial problems and literature gaps, passing through the added value process proposition, its implementation and later feedback. The observations of the industrial practices and the literature review are exposed in section three and four. Sections five to seven introduce progressively the added value process proposition, its implementation and its evaluation. Finally, conclusions and future work are presented in section eight.

2. Methodology

This paper follows a methodology in five steps. First, the observations in the industry pointed out the problem. Then, a literature review underlined the gap regarding the collaborative design process for simulation models, and suggested the need of guidelines in this context. After both, problem and literature analysis, an added value process for a collaborative design in early development phases using simulation models was proposed. Later, the implementation of the process in a project context was performed. Finally, a feedback regarding the newly implemented process was gotten through dynamics interviews. A complete view of the methodology is presented in Figure 36

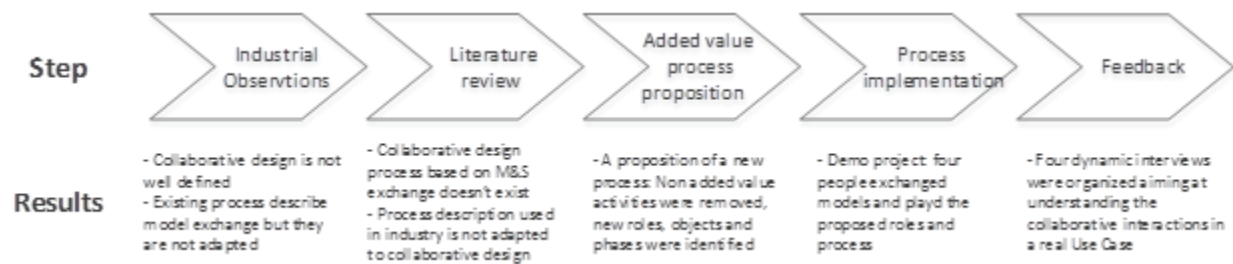


Figure 36: Methodology

3. Industrial observations

The industrial observations come from aeronautics and automotive industries. Two kinds of observations were done:

- (1) Theoretical observations: Based on the internal documentation for model exchange.
- (2) Operational observations: Based mostly on workshops.

Theoretical observations correspond to the analysis of industrial documentation about the support of model exchange. The outline of the guidelines is based on roles, process and model description. In total, eight main roles, three main stages containing about 30 detailed stages and ten documents to exchange are identified. Analysing the roles, the stages and the documents, some facts can be highlighted:

- Some stages have undefined outputs
- All the described roles are not used in the process description
- All the described documents are not used in the process description, one of them concerning interfaces agreement.

- Additional undescribed supports are used but not documented
- No capitalisation stage is described during the process
- The process considers only the model development situation, missing the re-use cases when a model already exists.

Operational observations aim at illustrating the *As-Is* situation. The situation studied refers to the engineer teams using simulations models in order to respond to a request. After analysing the situation through ishikawa and five why's methods, a representation of the current situation was done in participation with company's engineers. The representation uses a flowcharts. Situations introducing a way back in the process were identified and included into the diagram as a return flow using an arrow. The situations presented below were pinpointed during two workshops. Each workshop took two hours, and sixteen engineers were participating.

- Architecture changes are often requested during the simulation process. These changes, concerning the architecture evolution are difficult to take into account with the current process.
- Often simulation teams need to request for an additional information regarding the environment where their models supposed to be used.
- When the assembly of the models takes place, the accuracy of the models is not appropriate. This inaccurate results often lead to rework tasks as well as other imprecise specifications during the model request stage. In general, a better preparation upstream of the model request, is identified as an important need.
- A centralised vision of the entire model seems to be missing. As a result, a lack of organisation aiming at the models convergence emerges.

4. State of the art

Additionally to AP2633 (Airbus 2005), two other industrial initiatives propose model exchange processes: FEDEP (Department of Defense 1999) and ProSTEP (ProSTEP 2014). On the one hand, FEDEP is the acronym used for Federation Development and Execution Process. FEDEP document describes a high-level process where the activities are related to high level architecture federations. Nevertheless, FEDEP documentation does not include any role in its process and it is mainly focused on task and documents identification. On the other hand, ProSTEP iViP Recommendations document aims at orchestrating different models of manufacturers and suppliers. ProSTEP

initiative offers an interesting break down structure regarding the product lifecycle and different scenarios for joint product development phase. Regarding this phase, a significant description of the IT needs have been done. The ProSTEP reference process identifies three roles (Partner A, Partner b and All), three phases, thirteen activities and five elements of the behaviour model specification. Nevertheless, the roles identified are still general and the outputs of each activity are not included in the process description but in other documents.

Some academic works propose approaches much more related to knowledge exchange by standardizing the simulation model interfaces. Sirin et al. (Sirin et al. 2015) suggest the standardisation of the model interfaces through a Model Identity Card (MIC). This work identifies as well three main roles in a collaborative design based on simulation models context: System architect, model architect and model provider. Another research in a similar context is presented in the work done by Badin et al. (Badin et al. 2011) where KCMModel methodology (Knowledge Configuration Model) is introduced. The purpose of the KCMModel is to Capitalise, Trace, Re-use, and ensure the Consistency (CTRC) of technical data shared by several experts model, especially in the upstream step of design process. Other collaborative approaches mention the importance of the process but are much more based on user interfaces and IT improvements during the simulation models exchange (Jun et al. 2008), (Freedman et al. 2015).

Looking in the wider scope of collaborative design process in the literature, no commonly method, used specifically for collaborative design, was found. Though, both, traditional and relatively new process modelling approaches are used. Two interesting new approaches are Cooperating Correlative Map Based on Activity (CCM_A) and the Collaborative Architectural Design Processes. The CCM_A process modelling method (Cui et al. 2009) takes into account some of the important features of the collaborative design. Nevertheless, the roles and the interaction within the stakeholders are difficult to interpret. The Collaborative Architectural Design Processes is characterised by a collaborative engagement of all stakeholders. This approach structure different design tools and design events, as walkthroughs and design games, aiming at promoting creativity and facilitate common understanding of the design tasks (Binder et al. 1998).

To conclude, literature proposes different process modelling methods and different approaches to study collaborative design. However, none method is exclusively dedicated to collaborative design using simulation models. In addition, only very general processes describing Modelling and

Simulation (M&S) specific interactions in the literature exists today. However, some process describing M&S exchange have been proposed by the industry, such the AP 2366 by Airbus Group Innovations, FEDEP and ProSTEP. Those process descriptions are a valuable initiative nevertheless a significant improvement could be done, especially regarding the inclusion of hypothesis of model reuse and capitalisation and the roles played during the process.

5. Added value process proposition

5.1. The process modelling method

Methods commonly associated in the literature to the keywords design process, modelling methods, and process modelling are: the flow charts, the IDEF, the Critical Path Method (CPM), the Design Structure Matrix (DSM), the Petri-net, the Data flow diagram (DFD), the Role activity diagram (RAD), the Business Process Modelling Notation (BPMN), the Business Use Cases (BUC) and Business Object Interaction Diagram (BOID) among others (Huang et al. 2003), (Wang et al. 2006), (Yao et al. 2006), (Aldin & De Cesare 2009), (Perrot 2008a). The design process modelling methods mentioned before have different characteristics and are useful in certain cases. In order to choose the most appropriate representation for our problem a comparison of different methodologies is presented in Table 1.

Collaborative design features using simulation models have been identified in previous work (Roa-Castro & Stal-Le Cardinal 2014a), (Roa-Castro & Stal-Le Cardinal 2015), (Roa-Castro et al. 2015) and also in others researches (Freedman et al. 2015), (Wang et al. 2015). A synthesis of the features is presented below:

- Lifecycle and stages: A basic time notion
- Simulation artefact: Includes simulation models to be exchanged as well as all the documents linked with the model (interfaces definition, scenarios, hypothesis, requirements, etc.)
- Stakeholders: Stakeholders and actors are included in this categories
- Activities: Succession of activities to achieve a simulation having different contributors
 - Parallelism and iteration: Characteristics of the activities
 - Decision: The final objective of any collaboration is to make a decision. At the moment the decision will be considered as an action

- Traceability-reuse: Models can be reused when the modification is easier to handle than a new development. In addition, author information and model records are crucial in model exchange.
- Trade-off points: Different interest from different stakeholders
 - IP constraint: Intellectual properties constraints linked to the use of models. Can be considered trade-off point.
 - Multidiscipline: People coming from different backgrounds working together. Can be considered as a trade-off point.
- Resources: Material resources needed for the activities
- Environment/context: Organisational context (e.g.: how people are organised, what is the company policy)

A comparison regarding seven features of collaborative design using simulation models is presented in Table 1. After the evaluation of the different characteristics, no method completely fulfils the needs regarding collaborative design for M&S modelling. In addition, collaborative process studies, presented in section four, tackles mainly the activities, the documents and the roles involved during the model exchange. As a result, in a first instance this work will be mainly focused on the information flow (Sim Artefact), activities and roles. Then, in a further research a more complete representation will be studied. Regarding these three criteria, three representations seem to be appropriated: IDEF, RAD and BPMN. After several attempts using the three methods to represent information flow, activities and roles, a mix of the three seems to be the most appropriated modelling process representations for our case.

Table 12: Comparative table. Process modelling representations Vs Collaborative design for M&S features

	Lifecycle and stages	Sim Artefact	Actors	Activities	Trade-off point	Resources	Context	Score
Flowcharts	+			++				3
IDEF	+	++	+	++	+	++		9
CPM	++			+				3
DSM		+	+	+		+		4
Petri-net	+			+				2
DFD	+	++		++				5
RAD		+	++	+	+	+		6
BPMN	++	+	+	++	+	+		8
BUC			+	+			+	3
BOID	+		+	+	+			4

5.2. The added value

The collaborative design process for simulation models proposed in this paper contains fifteen activities, eight flows and eight data roles. Three roles among the eight presented are the proposed roles by Sirin et al. (Sirin et al. 2015)(System Architect, Model Architect, Model Provider) as well as one of the data flows (Model Identity Card).

The process starts by a request (solicitation in Figure 2) from the System Architect. This request is often a question, such as: What if a new technology is introduced in the system? This request is followed by a solicitation package (first information flow), where other important elements are presented, for instance, the scenarios to be studied, the hypothesis, the possible architecture to be studied etc. All this information is delivered to the model architect. He will technically specify the simulation architecture(s). Then a check loop with the system architect is done in order to verify the needs. This step is very important in order to avoid the rework tasks later in the process. The final agreement will be formalised using a MIC Simulation model (Simo) agreement. The MIC Simo agreement is a high level Model Identity Card (Sirin et al. 2015) for the global simulation.

Then the model architect will define every interface within the architecture elements by using a MIC (MIC Simo interfaces in the diagram). The next step is the search. The search step is essential in the process. Contrary to industrial existing process, in the present research we assume that the enterprise can already have the models or the results. As well as the verification of the needs, the

search activity avoid rework tasks. The search is done by the librarian role. At that moment four possible scenarios could happen:

- (1) The architecture of the simulation and its raw results exist already. In this case, the raw results are transferred to the model architect who will see if the results need a post-treatment or not.
- (2) The architecture to be simulated exists but there are no raw results available. In this case, the simulation model is transferred to the model architect who will contact the model executor to run the simulation. Then, the graphic designer will be requested to make the post treatment (Visualisation).
- (3) The architecture to be simulated does not exist but the subsystems models compounding the architecture exist. Then the model integrator will be requested to integrate the subsystems. After integration, the model architect will ask the execution of the simulation and visualisation of the results.
- (4) The architecture to be simulate does not exist and the subsystems models neither. In this case, the model architect will ask to adapt or develop new models to the model adapter or model provider. In both cases, after development or adaptation, the model integrator will be requested to integrate the subsystems. The model executor to run the simulation. And he graphic designer to make the post treatment.

In all the cases, after post treatment, a capitalisation will be requested to the librarian. The capitalisation activity is key in the whole process. Without it, every situation will be automatically treated as the situation number four mentioned above. A complete view of the added value process proposition for a collaborative design in early development phases using simulation models is presented in Figure 37

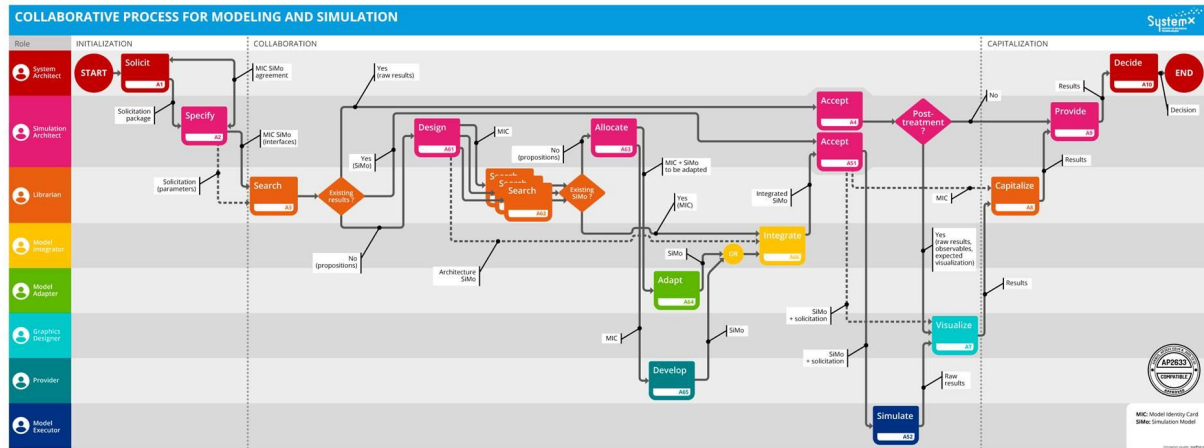


Figure 37: The added value process proposition for a collaborative design in early development phases using simulation models

The proposed process contributes to an added value solution at three different levels:

- Operational level: At the operational level, the suggested process can be considered as an improved input for the vehicle industry. This new input has a major focus on the preparation phases, trying to converge the actor's perspectives as soon as possible and avoiding numerous changes during the process. The new process avoids the rework tasks at the development level and fulfils the gap concerning capitalisation activity, which is a primordial need (Roa-Castro et al. 2015). In addition, the interfaces definition is addressed all along the process by using Model Identity Card formalism.
- Three main improvements regarding the existing guidelines can be highlighted in Figure 37:
 - Eight roles are defined and used in the process. Additionally, the roles proposed in Figure 2 are compatible with the current industry guidelines.
 - A new task sequential logic for model exchange is suggested.
 - Information flow between the tasks has been identified.
- Tactic level: A clear vision of how and who does what is given at management level. Likewise, people involved in the process have a larger vision of how their work is valuable for the organisation. In addition, the missing capitalisation stage in the guidelines, proposed in the new process, could improve the knowledge management in the organisation.
- Strategic level: The new process is compatible with the existing industry process mentioned in the state of the art. This process can be easily integrated in the organisation and match

with the others process. Furthermore, the hypothesis of model reuse proposed in the process could enhance the know-how of the organisation and could eventually reduce the time of development during the design.

6. Process Implementation

The process implementation took place in the Future@SystemX project. During Futur@SystemX four people exchanged models and played the proposed roles and process. This project took place between December 2014 and February 2015 at the Research Institute of Technology IRT SystemX. They exchanged 10 single simulation models, for a total of 6 different configurations of the global simulation. At the end of the project, four dynamic interviews were organised aiming at understanding the collaborative interactions in a real Use Case.

Figure 38 shows the process implementation. The use case deals with the thermic aspects of the cabin in the airplane. There is an air conditioner system (Environment control System ECS) in the cabin, and the question is: what kind of control model is better to use between two options (On/Off controller or PID controller)? The question is given during the solicitation stage. In this stage, other elements such as flight profiles and cabin architecture are provided. After an agreement between the system architect and the model architect, the specifications are provided. Those specifications establish the general simulation architecture to be studied. The elements composing the architecture are the cabin, the regulation system and the ECS system. Likewise, the elements of the solicitation package are established: the objectives (temperature comfort), the item to be observed/measured (temperature mean) and the scenarios (pressurization and temperature).

At the search stages, no result for a precedent simulations were found. Then, the design of each sub-system item was done using a Model Identity card (MIC). In total, six subsystems were described: an ECS, two kinds of control models (On/Off and PID) and three cabin models (surrogate model, 2D model and a nodal network model). After a second search (this time at sub-system level), one model has been found and it needed to be adapted (cabin surrogate model) the rest of the models were not found in the storage system, then a development stage was necessary. Once the models were ready, the integration and simulation phases took place. By combining the models, six different reconfigurations of the architecture were integrated and simulated. Finally, the results were visualized using the curves to compare the results. At the end all documents and models exchanged during the process were capitalised. The Results were useful and the decision

could be done. The preferred configuration was PID as a control model, surrogate as a cabin model and of course the ECS model.

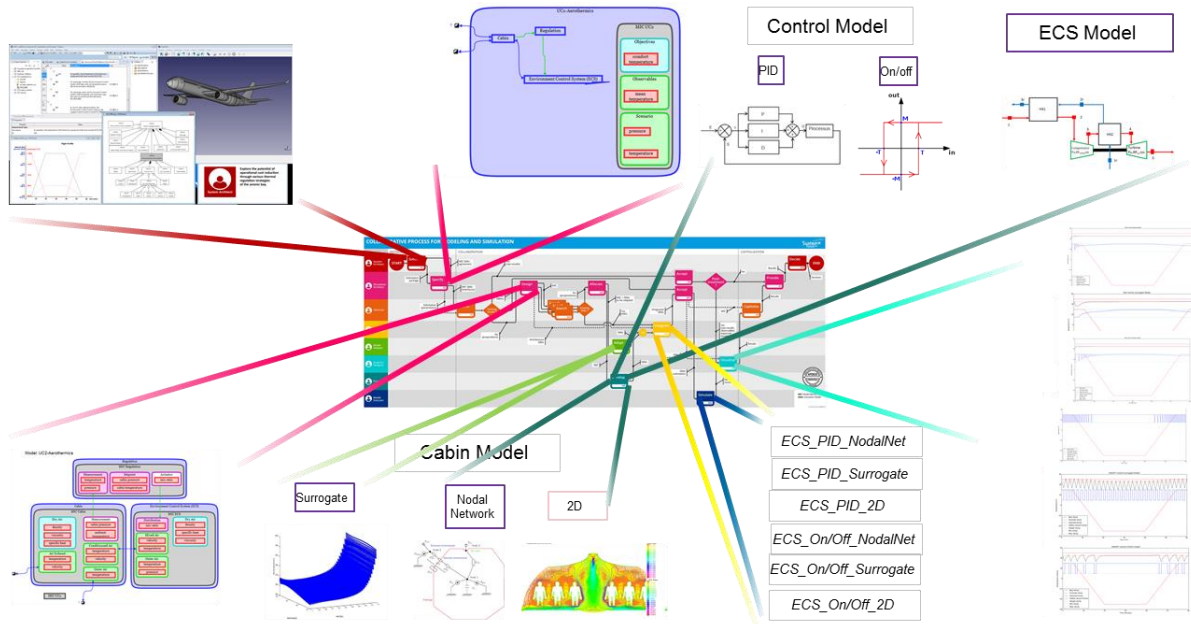


Figure 38: Process Implementation Illustration

7. Feedback

At the end of the project four dynamic interviews were organised aiming at understanding the collaborative interactions in a real Use Case. The results suggest some clues regarding the link between some of the collaborative features studied in this work: the stakeholders and actors of collaborative simulation process, the process itself (activities sequence), the Objects to exchange/share during the process and the tools supporting it (resources).

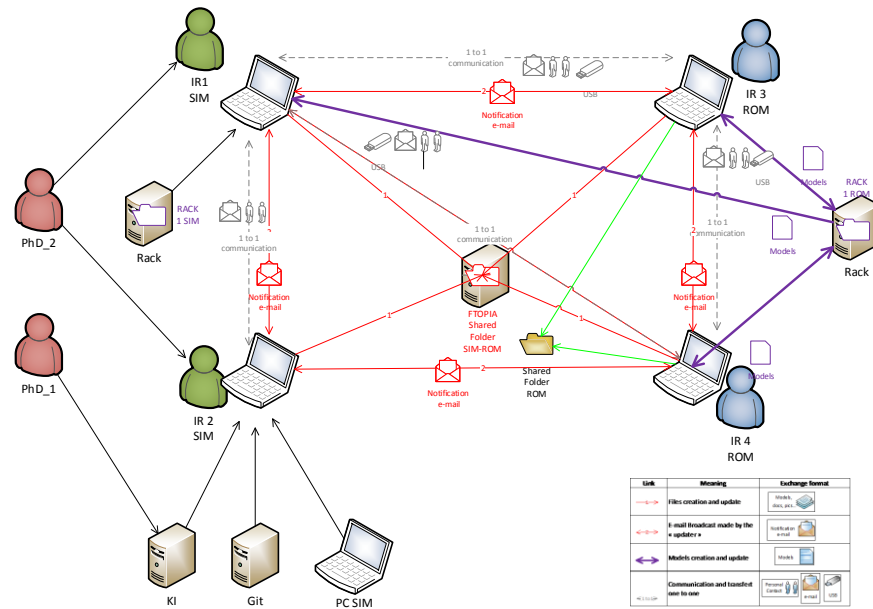


Figure 39: Interactions between actors at Futur@SystemX

The interaction between the actors and the object exchanged are represented in Figure 39. This representation illustrates another view of a collaborative design situation and is one of the results of the interviews. In the diagram, the IT elements, the team members and the exchanges objects are represented. The arrows between the character figures symbolize the interactions between the engineers working in the project. The arrows contain the exchange format of the documents as well. The colours and the ends have different meanings. For example, a red arrow with only one end represents the files creation and updates in the server. A red arrow with two ends, represents also an update but in a broadcast communication between the team members. Purple arrows with double ends represent the simulation models creation and update. And the black arrows represent communication one to one.

Regarding the three main elements studied in the process: the sim artefact, the actors, and the activities some improvements are presented below:

- The Sim Artifact (ensemble of exchanged objects): The proposed objects seem to be appropriate, all of them were used. MIC object seems to be appropriate to model exchange, nevertheless, since this object has been developed for a specific company, some parameter are still very specific to it. Though, a difficulty related to the parallel work in the same model was highlighted. The sharing of an intermediate model looks delicate. This problem generates several intermediary files and transfers. Defining the best length of the milestones

and the appropriated maturity level of the object to be shared could be helpful to solve this problem. Moreover, a platform for the documents management is necessary. PLM solutions can be a good alternative if the appropriate parameters and data model are used. Regarding the simulation models, other solutions must be explored.

- The actors: All the roles were played by someone during the project and no missing role were identified. However, a more specific role definition would be appropriate. This description could include some information regarding their rights, links, objectives, etc. Even if the representation is not completely adapted for representing the whole characteristics and complexity of the collaboration, it is very helpful to understand the chosen aspects such as task, exchanges and linear vision. In a future research more complete model will be suitable. This model must either expose as much as possible collaborative features at the same time or have different views. Finally, the implementation of the process brought to light the important part of human behaviour in the collaborative problem as well. Most of the time, people collaborate because they want to and not because they have to. This raises a new research question: What are the factors motivating people to collaborate in this context and how can we measure them?
- The Actions: The representation was appropriate for the actions. Everyone understood their role and tasks very easily. The interfaces with other people are less evident to understand since one person can actually play different roles. The coordination tasks played a crucial role and they are not indicated as a task in the process, because most of the time coordination tasks arrive between the actions. In general, the project used the proposed guideline without any particular problem, but they use several parallel and iterative paths which is normal in design process, but is not represented in the process. As a guideline, the process seems to be adapted if everyone collaborates.

8. Conclusions and future work

The suggested process is an added value solution proposition to the current industrial needs and to the literature gap. The process modelled three of the main characteristics in collaborative design: Actors, activities and Sim Artefact (objects).

The proposed process contributes to an added value solution at three different levels in the organisation: the operational level, the tactic level and the strategic level. At the operational level,

the new process avoids the rework tasks at the developing level and fulfils the gap concerning capitalisation activity. In addition some recommendations to industrial guideline are suggested. At the tactical level, a clear vision of how and who does what is given at management level. Likewise, people involved in the process have a larger vision of how their work is valuable for the organisation. At the strategic level, the process can be easily integrated in the organisation and match with the other process. Furthermore, the hypothesis of model reuse proposed in the process could enhance the know-how of the organisation and could eventually reduce the time of development during the design.

After implementation and evaluation of the process, we conclude that collaboration in M&S activities is not a linear problem at all, but the proposed representation is highly appropriated to improve global comprehension of the objectives and the context understanding in the first instance. Concerning the actions, process representation describe them satisfactorily in terms of task and flow. Concerning the Sim Artefact, the proposed objects seems to be appropriate, all of them were used. Nevertheless, some formats are still specific to a company and need to be improved. In addition, links between the object deserve to be studied as well. Finally, concerning the actors, no missing role were identified. However, a more specific role definition would be appropriate. The implementation of the process brought to light the important part of human behaviour in the collaborative problem as well, pointing out the actors as the key element on the collaborative design and raising a new research question: What are the factors motivating people to collaborate in this context and how can we measure them?

Further research will explore on the adaptability and the flexibility of the process. And will mainly focus on a model with more collaborative features, based in the interaction between the actors and their motivation to collaborate. In addition, a data model describing the links between the different objects will be included.

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Paper # 3

Crossing Games Theory and FAcT-Mirror methods to improve cooperative MBSE design projects

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Abstract: Collaborative MBSE (Model Based Systems Engineering) design has been recently introduced in the literature as a way to face the new organisational needs introduced by the use of MBSE technics. However, the research carried out in this paper shows that the nature of the relationships between the people in MBSE design project context are more cooperative than collaborative. This study aims at understanding and improving cooperative MBSE design projects from the Games Theory perspective. We propose a coupling method between the Non-Cooperative Games Theory (NCGT) and the FAcT-Mirror methods to understand and improve this cooperation. The results show how the use of the coupling method facilitates the industrial implementations of both, NCGT and FAcT-Mirror method to analyse real situations. Furthermore, the application of the proposed method to two industrial projects to study transversal relationships, shows how the method assists the improvement of the cooperation in MBSE design projects. In addition, the results of the implementation allow us to conclude that transversal relationships in MBSE cooperative design projects are driven by information sharing. Finally, we demonstrate how this cooperation could be improved.

Key words:

1. Introduction

The application of modelling technics to product development, also known as MBSE (Model Based Systems Engineering), has become very popular during the last years. The popularity of MBSE approach has increased in an accelerated manner, among others, because of its efficiency to handle the high amount of knowledge and information required in new product development. Indeed, MBSE approach aims at applying modelling technics to support system requirements, design, analysis, verification and validation activities during the different life cycle phases (INCOSE 2015).

Although MBSE approach assists the management of the product complexity, it leads the companies to lean on new technologies and to find more adapted approaches to manage the new organisational needs that these new methods and technologies bring with them. Collaborative approaches have been introduced as a way to face these new organisational needs. Even if several studies on organisational collaboration exist in the literature, the number of studies analysing the cooperation among the actors related to the use of emerging methods such as MBSE (Model Based Systems Engineering) is reduced.

This study seeks to understand and improve cooperative MBSE design projects from the Games Theory perspective (sometimes known as collaborative MBSE or collaborative engineering in the literature). By collaborative MBSE design we understand the collaboration between a group of people when they use simulation model technics to solve design problems (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.). However, after studying further the relationships between people in this context, we conclude that the nature of these relations must be mostly cooperative. We propose a coupling method between the Games Theory (Von Neumann & Morgenstern 1953) and the FAcT-Mirror (Le Cardinal et al. 2001) methods to understand and improve this cooperation. Thus, two main questions drive this research:

- How can we characterise cooperative MBSE design in project context using a Games Theory perspective?
- How non-cooperative games can assist the improvement of cooperative MBSE design in this context?

To gather the information needed to set the game, we use and adapt the FAcT-Mirror method in two French companies during vehicle development projects. Then, we use the proposed coupling method to set a non-cooperative game and find its *Nash equilibrium* which from a Games Theory perspective does not mean competition. Indeed, the non-cooperative games are interested in the agent actions modelling more than the abstraction of the coalitions that those agents could form (cooperative game theory) (Chatain 2014).

The rest of the paper is organised as follow: in section 2 we present a literature review, where we first mention some works addressed to collaborative MBSE, then we review collaboration and cooperation definitions and finally we succinctly introduce the Game Theory and FAcT-Mirror method. Section 3 presents the FAcT-Mirror method in detail and the proposed coupling method. In section 4 we present the results obtained from the industrial implementation of the FAcT-Mirror and coupling methods. In section 5 we present the NCGT and the proposed game, that uses the results obtained in the preceding section. A deeper analysis of the games results is presented and discussed in section 6. Finally, the limitations and future work are presented in section 7 and the conclusions in section 8.

2. Literature review

Nowadays, using MBSE approaches to speed up the product development process in the industry, is more and more common. Modelling and simulation technics related to this approach, have been recognised as an element supporting collaboration (Kleinsmann et al. 2012) mainly because of the graphical illustration that those models provide to engineers and designers. Nonetheless, introducing those technics leads to other collaborative issues to address, such as information sharing boundaries or intellectual property constraints (Lee & Kim 2014). Furthermore, collective human endeavours and cooperative behaviours are also emphasized as a key aspect to explore (Lu et al. 2007), (Teichert 1993). Consequently, collaboration between different teams in the product development process is a strategic need along the industrial life cycle (Laborie 2006).

In spite of previous product development researches on the one hand, and collaboration researches on the other hand, collaborative design appears long after in the state of the art. Nowadays, numerous researches on collaborative design can be found in the literature. However, only a few number of them address collaborative MBSE design. In addition, most of those works are centred on the proposition of collaborative IT tools (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.),

although some works studying other characteristics – such as process, data and stakeholders definition - related to this collaboration exist, (Kleinsmann et al. 2007), (Kleinsmann et al. 2012). Nonetheless, we have not found any research addressing cooperative behaviours among the actors in MBSE design projects.

2.1. Collaborative MBSE Vs Cooperative MBSE

We have found that the terms cooperation and collaboration are sometimes used as synonyms whereas the literature indicates that their meaning are different. We summarise cooperative and collaborative characteristics in Table 3 according to the literature insights. In general, cooperative and collaborative relationships are always presented as people interacting through different activities implying coordination, synchronisation and communication actions among them. However, even if cooperation and collaboration share these actions, they can be differentiated by other elements proposed in the literature. We use the 8 elements proposed by Mattessich and Monsey individually (Mattessich & Monsey 1992) - instead of their grouped proposition - to give details of cooperation and collaboration characteristics. In addition, we have added a new element (sharing of knowledge, expertise or ideas) and updated another one (**common goal** definition).

Table 13: A summary proposition of collaboration and cooperation characteristics coming from the literature and a comparison with industrial observations of MBSE projects

Characteristics		Coop	Coll	References.	MBSE design projects	
					Chracteris.	Observations examples
<u>Common goal</u> (Vision)	Defined		X	(Bedwell et al., 2012), (Chiu & Cheng-kung 2002), (Ostergaard & Summers 2009), (Kvan 2000a), (Wood, 1991), (Mathew, 2002), (Mattessich & Monsey 1992)		We have observed that people only have a partial vision of the project, which encourages them to perform their tasks on their own and consequently impede the establishment of a common goal.
	Undefined	X			X	
Knowledge assets/expertise/ideas	Join		X	(Chiu & Cheng-kung 2002), (Wood, 1991), (Ostergaard & Summers 2009), (Mathew, 2002)		A centralised model repository does not exist today. Models are developed several times because their reuse is difficult
	Separate	X			X	
Relationship	Informal	X		(Mattessich & Monsey 1992), (Kvan 2000a), (Wood, 1991)		The hierarchical relationships and the relationships between the project leader and the members are formal. Nonetheless, the relationships among the rest of the team members are still informal
	Formal		X		X	

Common structure (roles, planning.)	Defined		X	(Mattessich & Monsey 1992), (Kvan 2000a), (Wood, 1991), (Bedwell et al., 2012)		When the project is launched the planning, the WBS (Work Breakdown Structure), the roadmaps and all the information related to its organisation is well defined and structured. However, as time goes on, this information is not necessarily updated. The boundaries of the design tasks become less clear and overlaps occur more frequently
	Undefined	X			X	
Communication channels	Structured		X	(Mattessich & Monsey 1992)		Companies offer different communication channels to support the interactions among the project members. Still, most of the time the team members end by using their e-mail
	Unstructured	X			X	
Authority	Common		X	(Mattessich & Monsey 1992), (Kvan 2000a)		Because of the matrix organisation team members have two authorities. The first one is shared: the project leader, whereas the second one is not: department chief
	Separated	X			X	
Shared Risk/Responsibilities	Yes		X	(Mattessich & Monsey 1992), (Kvan 2000a), (Chiu & Cheng-kung 2002), (Von Neumann & Morgenstern 1953), (Semsar-Kazerooni and Khorasani, 2009), (Crujssens et al., 2007)		As the members perform their tasks on their own, each person is responsible for the consequences of his/her own tasks
	No	X			X	
Resources	Common		X	(Mattessich & Monsey 1992), (Kvan 2000a), (Chiu & Cheng-kung 2002), (Ostergaard & Summers 2009),		The design and development resources still belong to the department and not to the project. Thus project members do not necessarily share it
	Separated	X			X	
Rewards	Common		X	(Mattessich & Monsey 1992), (Kvan 2000a), (Von Neumann & Morgenstern 1953), (Semsar-Kazerooni and Khorasani, 2009), (Crujssens et al., 2007)		The rewards that people participating in these projects obtain do not come from the project but from the department. These rewards (such as pay raise) are personal and they are not associated to the project achievement only but to their year performance in general.
	Separated	X			X	
Time	Long term		X	(Mattessich & Monsey 1992), (Kvan 2000a)		The observed projects concern the development of a product of the company. These developments are usually planned for the short and mid-term.
	Mid-term				X	
	Short term	X			X	

We have noticed that all the definitions found in the literature call on a common goal definition as the basis of any collaboration, differentiating collaboration from cooperation where people aim at maximising their own objectives. However, this feature is not mentioned in this way in Mattessich and Monsey work. It is rather referred to as shared vision. We propose to refer to *common goal* as

a result of this literature review. Likewise, we have found a new element related to knowledge sharing. As presented in the previous paragraphs, literature reveals that mobilising knowledge enables collaborative activities to be successful. Actually, the mentioned works note that people mobilise different kind of knowledge, such as ideas, expertise or know-how to achieve a defined common goal.

Regarding the rest of the elements, we observe that in collaborative relationships people have a common and defined structure coming from collaboration itself. Additionally to the structure, people collaborating also share the authority, the risk, the resources and the rewards. They communicate through structured communication channels and their interactions often imply long term relationships. Contrary to collaborative relationships, people do not necessary share the same structure, authority, risks, nor rewards, in cooperative relationships. Their communication channels could be more informal and their interactions are the result of short, or mid-term relationships. Based on these characteristics, we can define collaborative and cooperative relationships as follows:

Collaborative relationships: Organisation of two or more people who work together to achieve a common goal. They are organised through a common defined arrangement (but not imposed), supported by structured communication channels where the authority is shared along with the risk, resources and rewards. These interactions are often the results of long-term relationships but they are not restricted to it.

Cooperative relationships: Organisation of two or more people who work together without necessarily having a common goal to achieve. The organisational structure is not necessary the same and it can often be an imposed one. The people usually interact through informal communication channels. The interactions are mostly short and mid-term where neither the authority, the risks nor the rewards are shared. They are often the results of long-term relationships but they are not restricted to them.

Comparing *cooperation* and *collaboration* columns of Table 13 to the *MBSE design project* column, representing the French company's cases that we expose in this paper -and that we have been observing for three years- we notice that the collective accomplishment of the project achievement cannot be considered as goal. Among others, because there is no common reward, nor common risk or common resources. If the project succeeds (or fails), design engineers will not get

a reward (or penalty), contrary to the high level managers that may be confronted with this kind of system. In fact, they are often interested in obtaining personal rewards that their department manager may offer them (matrix organisation). We also can consider that the risk is not shared among all the project members because if by any chance a bad product is developed, the entire team will not suffer the consequences. On the contrary, high level managers are called to accept responsibility. Finally, we observed that the modelling and simulation resources are still assigned at the department level and not at the project level, thus the project members do not share the same resources from this point of view.

Regarding the authority, the relationship and the common structure characteristics, MBSE design projects are situated in between cooperation and collaboration. The authority is still the hierarchical manager at each department level even if a common project manager is designated. The relationships among the project members are mostly informal mainly because of the project organisation remains detailed only at the highest level. Thus, the common structure regarding the roles definition is not clearly set up either. Although this missing definition, other common structures such as the planning project are well defined. Finally, MBSE projects are mostly mid-term or short term in the vehicle industry. These statements suggest that in a MBSE design projects, we need to study the cooperation among the actors more than the collaboration. As literature suggests that cooperation is needed to collaborate, improving cooperation among the actors will also improve some collaborative aspects of their relationships.

2.2. Modelling cooperation: The Games Theory and the FAcT-Mirror methods

We have found several modelling methods adopted to describe collaborative MBSE - as literature used to employ collaborative MBSE instead of cooperative MBSE -, but those methods are mostly descriptive (process modelling or systems modelling, DSM) and they do not allow a deeper analysis of the actors relationships (Roa Castro et al. 2016). However, among the methods proposed in the literature, the Games Theory appears as the most appropriate method to analyse cooperation. Thus, we focus on this paper in the exploration of the application of the Games Theory (GT) approach to analyse cooperative interactions among the members of MBSE projects.

Games Theory comes from the analysis of economics problems regarding conflicts of interest. The theory proposes a mathematical analysis of these problems by studying cooperation issues for a given situation between decision makers (Myerson 1991). To study cooperation, two main fields have been established in Games Theory: Non-Cooperative Game Theory (NCGT) and Cooperative Game Theory (CGT). While NCGT is interested on the agent actions modelling, the CGT is focused on the abstraction of the coalitions that those agents could form (Chatain 2014). Since we are interested on the actor level behaviours, in this paper we use NCGT (focus on individual actions modelling) to model those behaviours and understand the possible cooperation. NCGT states the problem by assuming that a customer desires to obtain a maximum of utility or satisfaction and an entrepreneur maximum profits. The mathematical analysis attempts to find a description of the endeavour of the individual to obtain a maximum of utility (Von Neumann & Morgenstern 1953). Even if the Games Theory has been developed for economics, its applications to conflict of interest situations in other domains is very common nowadays. However, few works using this theory on collaborative MBSE design exist in the literature. What we have found is mostly related to the trade-offs between different design options, (Lewis & Mistree 1997), (Xiao et al. 2005) more than the analysis of the actors itself.

As the Games Theory is based on the careful analysis of everyday representation of economics facts, we base our research on the detailed analysis of the problem solving situations in MBSE design projects. To set the game three elements are needed: the set of players $\{P\}$, the set of strategies $\{S\}$, and their respective pay-offs $\{x\}$ (or utility functions depending on the pay-off $\{U(x)\}$). Each player has a defined set of strategies to play (the actions describing the manifestation of his will). The pay-offs are the gains or losses that a player receives when choosing a certain strategy, given the strategies played by the other players (Von Neumann & Morgenstern 1953). The use of the Non-Cooperative Game Theory in MBSE design projects is useful to understand why and when a player chooses a certain strategy more than another, and when the players keep a chosen strategy. Indeed, if they have nothing to gain by changing strategies: this situation is called the Nash equilibrium. The analysis of those equilibriums is favourable to find mechanism or incentives promoting cooperation among the players.

To define the set of strategies and pay-offs, it is necessary to know as much as possible about the behaviour of the player in a given situation. However, it is extremely difficult to interpret the

observations of everyday situations to constitute the set of strategies and pay-offs. To succeed in this interpretation, the FAcT-Mirror method (Le Cardinal et al. 2001) suggested in the literature seems appropriate since it proposes the elements facilitating the description of these situations. FAcT-Mirror method describes relationships between people in terms of Fears (F), Attractions (Ac) and Temptations (T) -elements that are easier to identify than strategies and utility functions- and is based on the prisoner's dilemma Games Theory example. The relation between the standard prisoner's dilemma example and the FAcT-Mirror method is presented in Figure 40.

Table of revenue for the prisoner's dilemma			FAcT-Mirror method relationship with prisoner's dilemma revenues
Actor 1 \ Actor 2	Co-operative	Non-cooperative	
Co-operative	R' (=3) R (=3)	T' (=5) S = (0)	$T > R > P > S$ P-S = Fear of being betrayed Risk to lose more if they co-operate R-P = Attraction of achieving mutual co-operation Win R or do not lose P T-R = Temptation to betray the other Extra win thanks to betrayal
Non-cooperative	S' (=0) T (=5)	P' (=1) P (=1)	

Possible behaviours: co-operation; non co-operation (or defection)
 Revenues R, R' reward to mutual co-peration
 T, T' payoff due to unilateral betrayal
 S, S' corresponding payoff (sucker's payoff)
 P, P' loss du to mutual non co-operation

Figure 40: Table of revenue for the prisoner's dilemma and FAcT-Mirror method relationship (Le Cardinal et al. 2001)

G. Le Cardinal et al. (Le Cardinal et al. 2001) defines FAcT regarding the revenues of prisoner's dilemma as follows. First, the *Fear* of being betrayed and suffering the consequences corresponds to the difference between loss and the "sucker's" pay-off ($P-S$). Second, the *Attraction* of achieving mutual co-operation corresponds to the difference between the rewards and the losses ($R-P$). Last, the *Temptation* to betray the other corresponds to the difference between the revenues from betrayal and the rewards from cooperation ($T-R$).

However, the proposed steps in the FAcT-Mirror method require a significant amount of time of the actors involved in the study, which may hinder industrial implementations. Thus, a way to shorten the time needed is suitable. One way to shorten this time to set a game back (which could replace some steps of the method). Nevertheless, the way to set a game back is not defined in the current method description. Therefore, we propose a coupling method establishing the relations between FAcT and the strategies and pay-offs needed to set a non-cooperative game. The definition of the non-cooperative game allows us to understand participant's behaviours and relationships in

MBSE design projects. We present the FAcT-Mirror method and the proposed coupling method in section 3 and the non-cooperative game in section 4.

3. FAcT-Mirror Method and proposed coupling method

The objective of the FAcT-Mirror method (Le Cardinal et al. 2001) is to find recommendations improving the relationships between the actors or, in game theory terms, to find the mechanism and incentives enhancing players cooperation.

To define the set of fears, attractions and temptations, five main stages are proposed in the method (Figure 41). First, all the concerned actors should agree on the problem which concerns all of them (this is the situation that needs to be improved). Second, they should express all their fears, attractions and temptations regarding the other actors (but also regarding themselves). All this information is gathered in a matrix, where each cell represents the relationship between two actors, and is filled with the fears, attractions and temptations describing it. Third, all the participants are invited to evaluate the degree of importance of all the fears, temptations and attractions in the matrix. Once all the items are evaluated, a global mark of each item is obtained by calculating the average of all the participant marks. From this point forward, only the most important items are considered. Fourth, the participants should classify the items into 5-10 “unavoidable themes”. Fifth and last, the elaboration of the recommendations is done by asking to the actors how to suppress, reduce and limit the fears and the temptations and how to realistically obtain what has been expressed as an attraction. A summary of the principal stages of the FAcT-Mirror method is presented below.

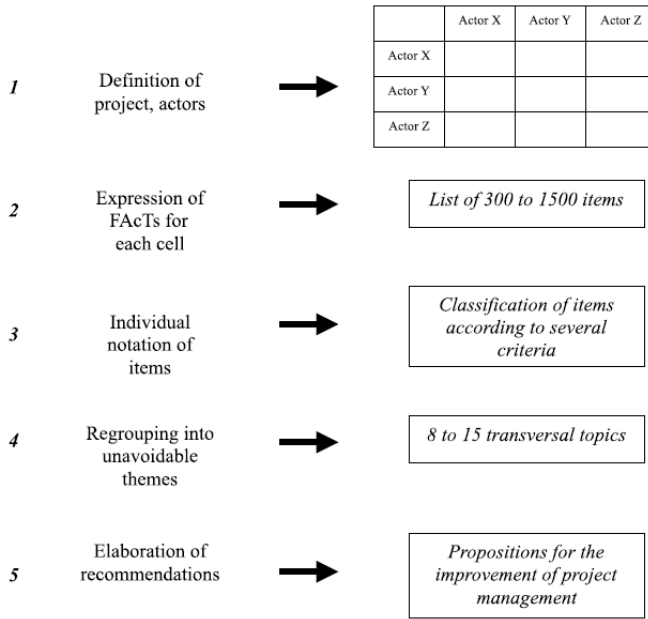


Figure 41: summary of the principal stages of FAcT-Mirror method (Le Cardinal et al. 2001)

In order to improve cooperation among the actors in a MBSE design projects, we have applied the FAcT-Mirror method to two different industrial contexts. By applying the method we have found drawbacks in the third step (the evaluation of the items). Likewise, we have found some difficulties to gather all the participants to carry out steps four and five. To face those problems, we propose a coupling method improving the mark and grouping protocol suggested in FAcT-Mirror method and facilitating the transition to set a game. We present in Figure 42, a summarised version of the coupling method proposed.

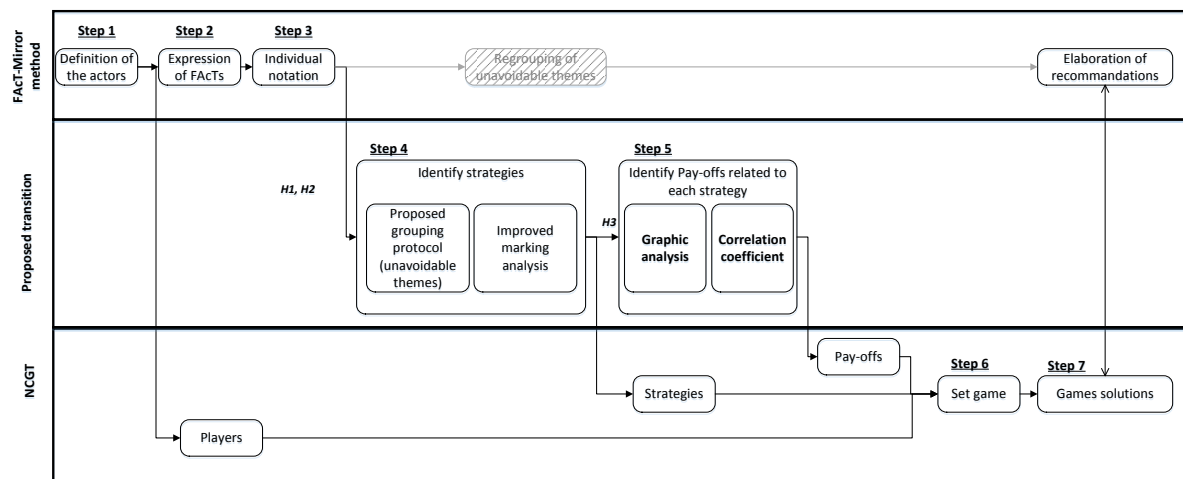


Figure 42: A summarised version of the coupling method proposed between FAcT-Mirror Method and Games Theory Inputs

The top row of the figure, contains the five main stages of the FAcT-Mirror method. The bottom row contains the inputs needed to set a game in NCGT. The row of the middle contains our propositions to couple both methods and the three hypothesis under which these propositions have been done (H1, H2, H3). We use the first two steps of the FAcT-Mirror method, to establish the inputs of the game. These inputs corresponds to the observations of the reality through a list of Fears, Attractions and Temptations. All the arrows in the figure represents the information flow among the different elements to get to solution. In the next sub-section we present the proposed transition from FAcT-Mirror method to Games Theory formalism

3.1. Proposed transition: From FAcT to GT

As explained in section 3, FAcT-Mirror method suggest a characterisation of the different relationships in terms of fears (F), attractions (Ac) and temptations (T) (Figure 43 (a)). To go back to the Games Theory format, we need to find the strategies (S) played by each actor (player) and their pay-off (U) (Figure 43 (b)).

Hypothesis 1: As FAcT-mirror is based on the Games Theory, we can assume that the set of fears, attractions and temptations describing each relationship are equivalent to the set of strategies and pay-offs for each couple of actors. c.f.: Figure 43 (c).

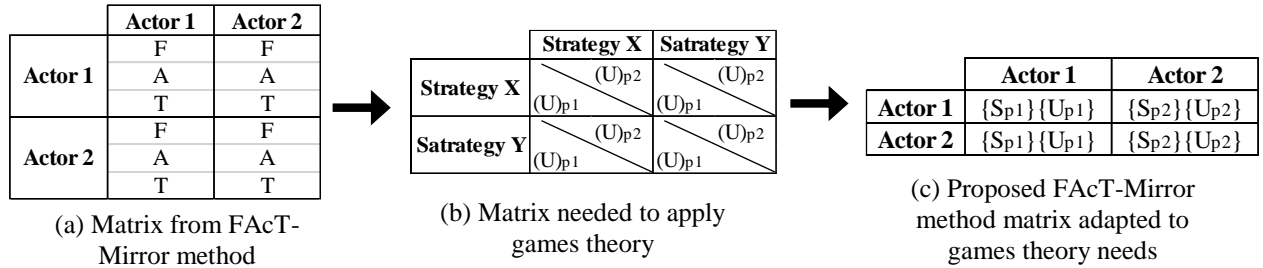


Figure 43: From FAcT-Mirror matrix to games theory matrix

Once we assume that the set of FAcT represent the set of strategies and pay-off, we need to know which of those fears, attractions and temptations are strategies and which ones are pay-offs. Thus, our second hypothesis is:

Hypothesis 2: As fears and attractions are feelings, and temptations are potential actions, we define the group of temptations of an “unavoidable theme” as the group of strategies and the group of fears and attractions as pay-offs.

The use cases study in this research allow us to we identify three kinds of relationships existing within the company in the French vehicle industry. The hierarchical relationship (e.g. manager-employee), the transversal relationship (e.g. internal client-supplier departments in a project organisation) and the competitive relationship (e.g. two departments promoting different technologies for the same system). We could not manage to get enough data regarding the competitive relationships. Thus, in this research we focus our attention on the transversal relationships since the cooperative stakes without the presence of an authority (hierarchical relationships) seems significant. Looking at understanding that relationship, we need to identify its dominant strategy (Stage 4 of Figure 42), and the set of pay-offs associated to the strategy for each actor (Stage 5 of Figure 42)). To find the dominant strategy of the relationship and to associate it to the pay-offs we have analyse the data from the industrial observations.

3.3.1. Strategies identification

The identification and evaluation of the F, A and T resulting from the industrial observations represent a significant amount of data. FAcT-Mirror method estimates the number of statements between 200 and 1000 according to the problem and the time spent on the problem. To exploit this data, we suggest a grouping protocol that can be used when all the participants cannot complete this activity. Likewise, to identify the most important “unavoidable themes” (group of strategies) we propose and improved mark analysis. The proposed grouping protocol and mark analysis are explained below.

Proposed grouping protocol

We advise the use of text analysis method. The use of this method allows the suggestion of a first version of the grouping to the participants, who can directly validate or modify. This proposition is more time consuming for the person leading the workshops, but less time consuming for the company and the participants, which can make FAcT-Mirror method more attractive for industrial applications.

Improved marking analysis

FAcT-Mirror method proposes to use an average to rank the items. This measure seems appropriate when the number of participants is significant to obtain a representative result. However, for small groups, this measure is less appropriate to find the central tendency because of the effect of the

extreme values. Therefore, we propose to calculate the average, but also to take into account the standard deviation and the 4 or 5 quantiles (quartiles or quintiles) to be sure that at least 75% or 80% of the participants mark the item above a certain value. Thus, we can be sure that the majority of participants agree on that measure.

3.3.2. Pay-offs identification

Figure 6 is a graphic illustration of an analysis of the transversal relationships. The analysis is performed with an example taken from one of the industrial observations, for which eight “unavoidable themes” have been found after applying the FAcT-Mirror method (c.f: Figure 47). For each “unavoidable theme”, we calculate the number of the Fears, Attractions and Temptations (frequency) and their respective marks. Then we graphically analyse these measures. This analysis is used to obtain the main unavoidable theme driving the strategies.

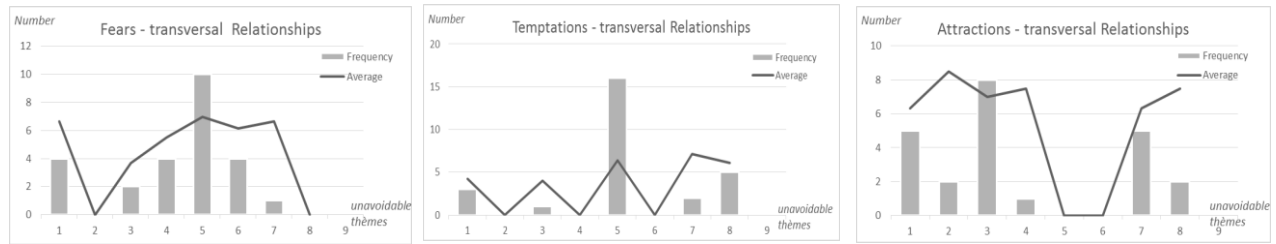


Figure 44: Example of strategies and pay-offs analysis

For example, to find the main strategy driving transversal relationships, we first calculate the temptations average mark and frequency, for each of the eight “unavoidable themes” (chart of the middle in Figure 44). We take into account both, mark average and frequency to cross-check the importance of the theme. Then, we proceed in the same way for the fears and attractions. In the example, we can see that the “unavoidable theme” five (*creation of an information sharing and exchange policy*) drives the strategy of the transversal relationship.

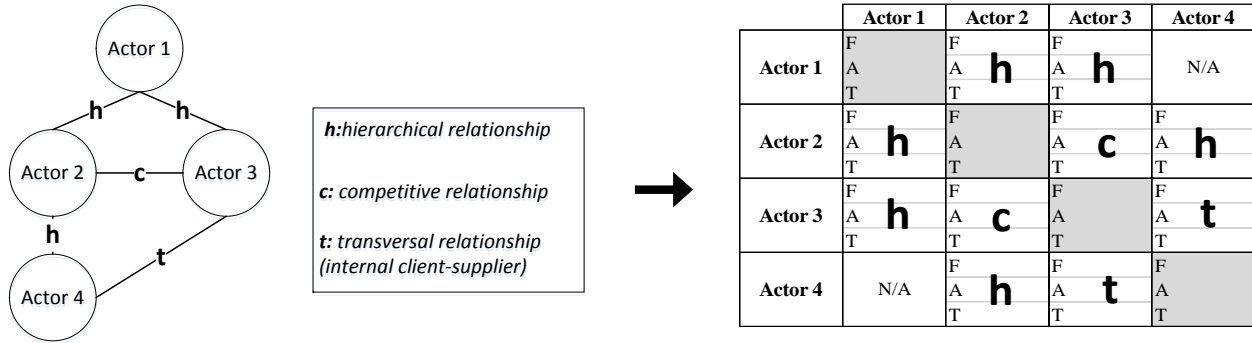


Figure 45: Relationship of interest and its identification in FAcT-Mirror matrix

Analysing the fears and attractions respective graphics, we can see for example that the most important fears are those related to theme five, whereas the most important attractions are related to themes one, three and seven. We can also see that the Fears related to the themes four and six have an important score but the graphic representation alone, is not enough to assert their correlation to temptation five. To be sure of these relationships, we need an additional point of view. We have first thought of using Pearson coefficient, it cannot be used in our case because it measures a distance between two variables. We turned to the Jaccard index, also known as the similarity Jaccard coefficient, used for binary variables.

The Jaccard index is defined by the following mathematical formula:

$$J = \frac{|A \cap B|}{|A \cup B|} = \frac{|A \cap B|}{|A| + |B| - |A \cap B|}$$

Let's consider two objects A and B, each with n binary attributes that can be either 0 (absence) or 1 (presence). Their attributes are gathered in Figure 46 (a)

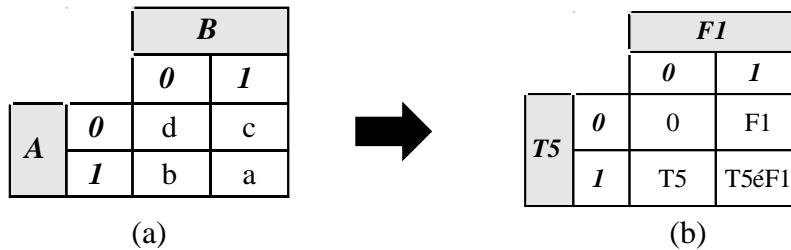


Figure 46: Example of Jaccard index attributes

The Jaccard index between A and B can be expressed as follows:

$$J = \frac{a}{a + b + c}$$

Going back to our case and to give an example, we consider the objects T5 and F1. Proceeding in the same way as for objects A and B, their attributes are placed in Figure 46 (b). Thus, the corresponding Jaccard index between T5 and F1 is given by the number of fear of the “unavoidable theme” one (F1) when a temptation of the “unavoidable theme” five exists (T5), divided by the total number of F1 plus T5

$$J = \frac{T5 \text{ é } F1}{T5 + F1 + c}$$

To use it in the case of Figure 46, we normalise the frequencies denoting the presence by 1 and the absence by 0 of the different Fears and Attractions, and calculate the Jaccard indexes between them and T5 (c.f. Table 15). These results, confirm on the one hand the relation between temptations 5 and attractions one, three and seven, and on the other hand, between temptations 5 and fears one and five. These unavoidable themes drive the strategy of the transversal relationships on a second level.

UC2																
	A1	A2	A3	A4	A5	A6	A7	A8	F1	F2	F3	F4	F5	F6	F7	F8
T5	0,6	0,4	0,7	0,2	0	0	0,7	0	0,8	0	0,4	0,3	0,7	0,4	0,2	0

Table 14: Example of Jaccard index results from use case 2

This kind of analysis, allow us to find the set of data needed to set a game: the strategy (T5) and the pay-offs (+A1, +A3, +A7, -F1,-F5) between two actors in a transversal relationship. As those elements are not quantitative, we are not able to define how much an attraction or a fear will influence the pay-offs. Nonetheless, we can affirm that an attraction increases the pay-off, and a fear decreases the pay-off.

Hypothesis 3: *We consider that each attraction and fear associated to a given strategy could increase or decrease from one unit the pay-off of the actors or have simply no effect on the pay-off.*

In the next section, we present two industrial use cases that allow us to obtain the set of strategies and pay-offs characterising the game.

4. FAcT-Mirror industrial implementations: the inputs for the game

We carry out steps one to four of the FAcT-Mirror method in a project context at the French car manufacturer Renault (use case 1) and at the French Research Institute of technology IRT SystemX (Use case 2). We use both cases to study and compare transversal relationships (“t” in Table 15). The results obtained from the implementations supply the necessary information to set the game presented in section 5.

4.1.General information

We summarise the general information of both use cases in Table 15. This information includes the number of participants, the number of departments where the participants come from, the number of FAcT that have been found and the number of workshop needed.

Use case 1		Context	Organisation studied
Participants	9	<p>The relationships analysis corresponds to the design review phase of the project. During this phase, performance department and design department have contradictory objectives (e.g. design department pushes forward the vehicle design no matter what the consumption is, whereas performance department pull forward the consumption reduction). The simulation department role is to assist both department proposition through simulation models results. Thus, the relationships between simulation department members and design and performance department are <i>internal client-supplier</i> relationships</p>	
Departments	3		
Fears	109		
Attractions	69		
Temptations	78		
Workshops	6		
Use case 2		Context	Organisation studied
Participants	5	<p>The relationships analysis corresponds to the design development phase. During this phase the simulation department should provide simulation models to the system department. The relationship between both departments is also defined as an <i>internal client-supplier</i> relationship</p>	
Departments	2		
Fears	83		
Attractions	72		
Temptations	80		
Workshops	4		

Table 15: Use cases general information

4.2.FAcT results

We present some examples of FAcTs that we have found in both use cases. We introduce in Table 16 some examples related to use case 1 (Renault). Fears 65 and 71 illustrates a typical client-supplier relationship. The supplier (in this case the simulation department –ISCAE and SMSN-) is afraid to have to do more than agreed on the contract, for instance, develop more functions or execute more simulations. While F65 and F71 are common to the two actors representing simulation department, F103 is only related to a junior profile (SMSN), indeed, being afraid to make a technical mistake in their development, generates also other fears as being rigorously judged by his client and superiors. Regarding the attractions A15 and A34, on the one hand, they are mostly related to the personal fulfilment and self-learning. It is interesting to confirm that people behaviour is not only driven by his tasks but also by other influencing factors. On the other hand, A13 and 36 are related to obtain the necessary means (in this case information) to carry out a specific task. In the same way, A39 concerns the recognition that could be obtain as a result of a good job. Finally, analysing the temptations we can see that T10, 11 and 30, 31 are the same. It is because the performance department (PPC) and the simulation department (IST) are in competitive relationship and they both want to use simulation models to “justify” their ideas. Furthermore, as performance and design department must pass through simulation department manager (ISCAE) to do a request, sometimes, they are tempted to address their request directly to the people developing their models (SMSN) bypassing their manager.

Use case 1

Type	No	Item	Btw
F	65	Being requested for more obligations than what he is supposed to do	ISCAE-PPC
F	66	Underestimating the time needed for the accuracy requested	ISCAE-IST
F	71	Being requested for more obligations than what he is supposed to do	ISCAE-IST
F	103	Being afraid of making mistakes because of his short experience	SMSN-PPC
A	13	Getting the necessary elements to take a decision (or to propose a preferred solution)	PPC-ISCAE
A	15	Obtaining the satisfaction given by the work done	PPC-ISCAE
A	34	Learning about the architecture of the system	ISCAE-PPC
A	36	Getting a clear problem statement	ISCAE-PPC
A	39	Showing his capabilities and impartiality by using factual results	ISCAE-IST
T	10	Being too directive in order to find an expected solution (steer the study)	PPC-ISCAE
T	11	Influencing the perimeter to be studied	PPC-ISCAE
T	20	Bypassing the ISCAE	PPC-SMSN

T	30	Being too directive in order to find an expected solution (steer the study)	IST-ISCAE
T	31	Influencing the perimeter to be studied	IST-ISCAE

Table 16: Example of FAcT from Use Case 1 (Renault)

The FAcT examples of use case 2 are presented in Table 17. We notice that fears are similar to those associated with the request of more tasks than initially agreed (F71 in use case 1 and F72 in use case 2). However, we give other examples of fears such as those related to the apprehension of not having the right information to accomplish a job (F56 and F50). The attractions presented in Table 17 are also related to the personal learning and the recognition. As for the fear T20 of use case 1 (bypassing the manager), the temptations T40 of use case 2 are also representative of the longing to address a request directly to the people developing the models (MP in use case 2) without the manager advice (ChMP). What we observe in this case is that those requests emerge as a way to save time by bypassing the manager (use case 1). Finally, T43 and T64 are temptations related to the information sharing. In this use case we notice that people are tempted by sharing less information than needed or asking for more information than needed. Those temptations could explain why people are afraid of not obtaining the right (or enough) information. In fact, they know that sometimes they do not share suitable information (F56 and F50).

Use Case 2			
Type	No	Item	Btw
F	56	Not obtaining the requirements clear enough to accomplish the work	ChMP-MA
F	50	Obtaining an inappropriate result (or incomplete results: It means a rework of his (MA) part)	MA-MP
F	72	Being requested for too many modifications	MP-MA
A	37	Learning about the subsystems and new technologies	MA-MP
A	64	Being recognized for his work	MP-MA
T	40	Not implying the ChMP in the model(s) decision(s)	MA-ChMP
T	43	Underestimating the information to be shared to make the model	MA-MP
T	64	Asking for more information than needed	MP-MA

Table 17: Example of FAcT from Use Case 2 (Research Institute)

After expressing FAcT, participants proceed to the evaluation of the elements. Each fear, each attraction and each temptation is evaluated from 1 to 10 according to the FAcT-Mirror method explained in section 3. The evaluation is used to identify the “unavoidable themes”. According to the regrouping protocol proposed in sub-section 3.1, nine “unavoidable themes” are identified in both use cases. We use the right side table in Figure 47 them and the left side chart to represent the

average and the frequency obtained for each “unavoidable theme” in each use case. Likewise, we present in Table 18 the two most important of them and their related key words.

No	Unavoidable theme	Key words
1	Career recognition and roles definition	act as; apprehension; be considered; be judged; be recognized; be selected; career improvement; contestation; credibility; fool Imposture feeling; indispensable; "is not my fault"; "is not my job"; mislead; show; success
5	Creation of an information sharing and exchange « policy »	"ask for more information than needed"; ambiguous; bias; clear; client's needs; concreate facts; hidden; inappropriate; incomplete; influence; insufficient; lie; modifications; marge; narrow; necessary elements; over/under : complexity; over/under : estimate; problem statement; over/under : simplify; over/under : specified; orientate; secretive; sharp facts

Table 18: Example of key words of unavoidable themes 1 and 5

The “unavoidable theme” 1 concerns all the fears, attractions and temptations related to the career recognition and role definition. The key words used on the description of the FAcT belonging to that “unavoidable theme” shows the concerns of the actors towards their colleagues but mainly their superiors. The “unavoidable theme 5”, is the creation of an information sharing and exchange policy. Indeed, information sharing is the topic that has been the most discussed during the workshops. It is not only because a clear definition of the information to share is missing, but also because the current means hinder the sharing and exchange. In addition, the margins used all along the product development process get the situation worse, discouraging the transparency of the information and increasing the biased purposes.

The marks of each theme and their frequency are presented in Figure 47. Both use cases data is represented by bars and curves, respectively grey for use case 1 (UC1) and black for use case 2 (UC2). Bar diagram represent the number of elements (fears, attractions or temptations) corresponding to an “unavoidable theme” while the curves represent the average obtained from their evaluations. As mentioned in previous paragraph, the results show that “unavoidable themes” one and five are the most important for the participants. They are not only the highest rated, but they also represent almost half of the total FAcT in both use cases (111/256 for use case 1 and 105/239 for use case 2). It is important to mention that as researchers we may have had an impact on the grouping of the *unavoidable themes* since we have used the list of FAcT coming from Use case 2 as a guide in Use case 1 to help the participants to express their own FAcT. Nonetheless we consider that we have not had an impact on the notation of the items. Thus, the results are then quit surprising to us because in both use cases we have found more or less the same order of magnitude for the unavoidable themes.

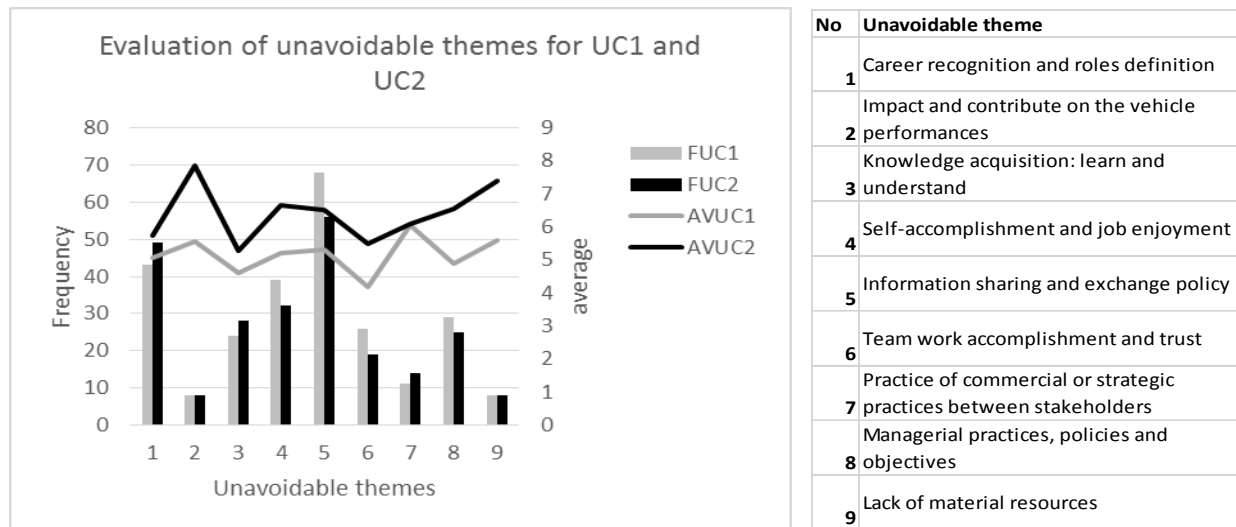


Figure 47: Unavoidable themes

As we explain in sub-section 3.1, we focus our attention on the transversal relationships. The chart in Figure 48 illustrates the FAcT driving transversal relationships in both use cases, In use case 1(UC1) on the one hand, transversal relationships are mainly driven by the “unavoidable theme” five, however, unavoidable themes one and six are also significantly present. In use case 2 (UC2) on the other hand, the transversal relationships are clearly driven by the “unavoidable theme” five. As this particular theme drives the transversal relationships of both use cases, we decide to choose it as the main “unavoidable theme” driving this kind of relationships in order to set the game presented in the next section.

5. The game

The game proposed in this section aims at understanding and describing some behaviours in MBSE design projects through the use of NCGT (Non-Cooperative Games Theory). The strategies and

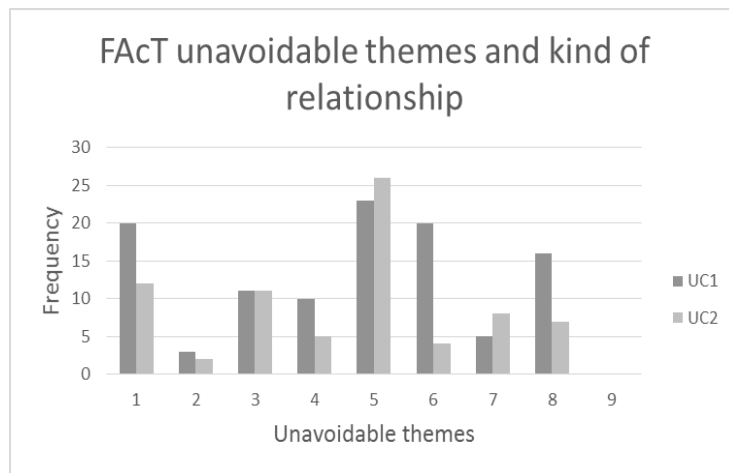


Figure 48: FAcT for transversal relationships for both use cases

payoffs come from the results of FAcT-Mirror implementation presented in section 4 and from the hypothesis 1 to 3 presented in sub-sections 3.1 and 0. The game is driven by a Maxmin criteria where the goal of each player is to maximize its minimum payoff, by choosing the best response (strategy) depending on the other players choice.

Formal definition (Von Neumann & Morgenstern 1953), (Chen 2011): We consider a game Γ , with a n finite set of actors $\{1, 2, \dots, n\}$ and \mathcal{A} finite set of possible actions. The game is defined by a sequential and fixed number of moves denoted χ with a chronological order prescribed by $q(\cdot)$. The function $\alpha(\cdot)$ provides the action leading to any non-initial node χ from its immediate predecessor. $p(\chi)$. $H(\cdot)$ is the function assigning each node χ , to an information set. $\mathcal{H}(\chi)$. $\iota(\cdot)$ assigns each information sets \mathcal{H} to the player moving at decision nodes. $q(\cdot)$ denotes the probability to move from a node to another. Finally $u(\cdot)$ is the utility function assigning a collection of payoffs to a player reaching a node.

$$\Gamma \equiv \{ \chi, \mathcal{A}, n, q(\cdot), \alpha(\cdot), \mathcal{H}, H(\cdot), \iota(\cdot), \rho(\cdot), u(\cdot) \} \quad \text{Game formal definition}$$

- $q: \chi \rightarrow \{ \chi \setminus \emptyset \}$ function assigning chronological order of the moves
 $\alpha: \chi \setminus \{x_0\} \rightarrow \mathcal{A}$ function assigning the action leading from non-initial node to its predecessor
 $H: \chi \rightarrow \mathcal{H}$ function assigning the node to the information set
 $\iota: \mathcal{H} \rightarrow n$ function assigning the information set to the player
 $\rho: \mathcal{H} \times \mathcal{A} \rightarrow [0,1]$ probability function to move from one node to another
 $u: T \rightarrow \mathbb{R}$, where $T \equiv \{ x \in \chi: q^{-1}(x) = \emptyset \}$ Utility function: Function assigning the collection of pay-offs to each player for each reached node

In other words, to set a game we need to define, the number of players, the set of strategies - moves defined by several actions - describing how the player will act in each circumstance and the collection of pay-offs assigned when a player chooses a particular strategy S_i (Strategy i of a player) given the strategies of the other players S'_{-i} :

The players: Let assume $P_n, n = 2$ the number of players of the game. We define P_1 and P_2 as two players linked by a transversal relationship. In our case and as they work for the same company, we assume that their relationship is an internal client/supplier relationship. P_1 represents the supplier department, whereas P_2 represents the client department.

The strategies: On the basis of the information sharing and exchange policy (“unavoidable theme” 5), we identify three main strategies (or behaviours) that P_1 and/or P_2 may consider when sharing or exchanging information. They are derived from the analysis of the key words related to the theme. Let set $i = 3$, the number of strategies S_i . $\{S_1, S_2, S_3\}$ the strategies played by P_1 , and $\{S'_1, S'_2, S'_3\}$ the strategies played by P_2 . We present the set of strategies in Table 19.

Strategies	Key Words of “unavoidable theme” five: information sharing and exchange policy
S_1, S'_1 : catch as much information as possible	ask for more__ than needed; client’s needs; marge
S_2, S'_2 : Hide as much information as possible (by over complexifying or over simplifying)	Ambiguous; bias; hidden; inappropriate; incomplete; influence; insufficient; lie; marge; narrow; over/under: complexity; over/under : estimate; over/under : simplify; over/under : specified; orientate; secretive

S3, S'3: Give/show a clear and transparent information	Clear; concrete facts; necessary elements; problem statement; sharp facts
--	---

Table 19: Game strategies

First if a player (P_1 or P_2) chooses strategy one (S_1, S'_1 respectively), his aim is to obtain as much information as possible. With this strategy, he gathers a considerable amount of information in order to have a deeper understanding of the client system (needs, margin, etc, ...). Second, if a player (P_1 or P_2) chooses strategy two (S_2, S'_2 respectively), he prevents the other player from having access to the information he has. For instance, he could present ambiguous purposes or even give incomplete information. He could also increase the margins of his systems. Lastly, if a player (P_1 or P_2) chooses strategy three (S_3, S'_3 respectively), he takes a stance on transparency to the other player. When the other player asks him, he gives clear problem statements and provides necessary elements to their questions.

The pay-offs: As explained in sub-section 3.1 and 0, we define the pay-offs by identifying the fears and attractions related to the temptations of an “unavoidable theme”. The Jaccard index results showing the relationships between the temptations of the “unavoidable theme” five with respect to the fears and attractions is presented in Table 20 for both use cases.

		A1	A2	A3	A4	A5	A6	A7	A8	A9	F1	F2	F3	F4	F5	F6	F7	F8	F9
UC1	T5	0,5	0,3	0,8	0,2	0	0	0,7	0,2	0	0,7	0	0,3	0,5	0,8	0,3	0,2	0	0
UC2	T5	0,8	0,2	0,7	0	0,8	0,2	0,2	0	0	0,8	0	0,2	0,8	0,2	0,7	0,2	1	0

Table 20: Jaccard index results. Correlation between "unavoidable theme" five temptations, fears and attractions

In both cases, the temptations are driven by the attractions A1 and A3 (Career recognition and knowledge acquisition respectively), we assume that the longing to obtain enough information has a positive impact on the career improvement. For example, this information could influence the decision making process impacting the career recognition (good or bad decisions taken during the project). Likewise, the knowledge acquisition represents in both cases a significant stake since the adequate use of the right information helps in the knowledge creation process (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.). We present the value of all the pay-offs in Figure 49.

Surprisingly in use case 1, no attractions linked to the information sharing (A5) and concerning the transversal relationships are found (*Jaccard Index* in Table 20 = 0). Nonetheless in use case 2, procuring clear information is an attractive point in these relationships, which is confirmed by the Jaccard index results of Table 20. In opposition to these results, the fears linked to the information

sharing (F5) are significant in use case 1 but they are not in use case 2. This fact can be explained by the context of the project, and the fact that in UC1 these relationships concern mainly the *Model architect* (see organisation to study for UC1 in Table 15), who plays a mediator role and assumes an important responsibility in the development. While in use case 2, this responsibility rest on ISCAE role (see organisation to study for UC2 in Table 15) more than SMSN role who is only focused on the development. However, it seems logic to take into account both (A5 and F5) for the pay-offs definition since they have been classified in the “unavoidable theme” five.

Concerning A7, F6 and F8, we confirm their relation regarding T5 only in one of the two use cases. Thus, we do not take them into account in this game. Nonetheless, collecting more data in the future could allow us to recognise them as a shared feature for the transversal relationships. Finally, we also take into account F1 (opposite to A1) as the fears of not being recognised or being recognised badly with regard of the obtained and shared information) and F4, as the fears of not being satisfied with the accomplished job.

The game: Let’s consider a non-zero-sum non-cooperative game with two players P_1 and P_2 linked by a client-supplier transversal relationship. During an information exchange situation, three main strategies are considered: S_1 , S_2 and S_3 . The utility function of each couple of strategies (S_i, S'_i) is defined by the difference of their related attractions and fears $\{A_1, A_3, A_5, F_1, F_4, F_5\}$, previously summed as expressed as follows:

$$U(A_i, F_j) = \sum A_i - \sum F_j \quad i=1,3,5; j= 1, 4, 5$$

Following *Hypothesis 3* presented in sub-section 0 gives:

- $A_i = 1$, increment of the utility function from one unit.
- $A_i = 0$, no impact on the utility function from one unit.
- $A_i = -1$, decrement of the utility function from one unit.
- $F_j = 1$, decrement of the utility function from one unit.
- $F_j = 0$, no impact on the utility function from one unit.
- $F_j = -1$, increment of the utility function from one unit.

We present in Table 21 and Table 22 the construction of the utility function values. All the possible combinations are mentioned below.

- If P_1 plays S_1 and P_2 plays S'_1 , they both aim at catching as much information as possible, which makes them feel that they are gathering suitable information (+A5) to generate new knowledge (+A3) and improve their career as explained in the pay-offs paragraph. In this way, F1 and F5 are decreased (-F1 and -F5), as well as F4 (job satisfaction) since the information gathered makes them feel they have done the maximum effort to obtain the right inputs.
- If P_1 plays S_1 and P_2 plays S'_2 , then the attractions of P_1 decreases since he is not able to catch any information as P_2 hides it on purpose (-A1, -A3 and -A5) whereas his fears (F1 and F5) increases. However, F4 does not change since he does his best to get the information without success. In this situation, the attractions of P_2 stay unchanged because even if he is not getting any information, he is not losing either. Nevertheless, seeing that P_1 tries to catch his information, his fears increase. Additionally, when the opposite situation occurs (P_1 playing S_2 and P_2 playing S'_1), the values are reversed.
- If P_1 plays S_1 and P_2 plays S'_3 , all the attractions of P_1 increase whereas his fears decrease. On the contrary, all the attractions of P_2 decrease whereas his fears increase. In this situation, P_1 succeeds on all his objectives while P_2 feels dispossessed of his knowledge and information. Similarly, when the opposite situation occurs (P_1 playing S_3 and P_2 playing S'_1), the values are reversed. Here is one of the important limitation which explains the *Hypothesis 3*. Comparing the utility function values for P_1 when he chooses S_1 , he wins the same no matter if P_2 chooses S'_1 or S'_3 although, we are conscious that he is probably getting more useful information when P_2 plays S'_3 .
- If P_1 plays S_2 and P_2 plays S'_2 , both hide as much information as possible. A1, A3 and A5 decrease while F1 and F5 increase. However, F4 decreases since the players do not feel dispossessed of their information.
- If P_1 plays S_2 and P_2 plays S'_3 , then the attractions and fears of P_1 related to career recognition (A1, F1) do not change because even if P_2 gives access to his information (S_3), P_1 is not in a gathering position but rather in a protection position. However, as he feels that his information is protected (feeling of accomplishment), A3 and A5 increase and F4 and F5 decrease. Similarly, when the opposite situation occurs (P_1 playing S_3 and P_2 playing S'_2), the values are reversed.

- If P₁ and P₂ plays S₃, the attractions A₃ and A₅ increase because of the transparency of the interactions, but the attraction A₁ decreases because of the fear of being judged by the superiors, even if the other player will appreciate the position adopted. Likewise, the fears F₁ and F₄ increase because of the same reason, whereas the fear F₅ decreases thanks to the information exchanged.

Table 21: example of summarised information for the construction of the game matrix

S3: Give/show a clear and transparent information	S'3			
	Player 1 uses Strategy S3		Player 2 uses Strategy S3	
	Attractions label	Fears label	Attractions label	Fears label
	Pay-offs coming from each attraction for player 1	Pay-offs coming from each fear for player 1	Pay-offs coming from each attraction for player 2	Pay-offs coming from each fear for player 2
	Utility function for player 1: Attraction - Fears		Utility function for player 2: Attraction - Fears	

Table 22: Games matrix

	Strategy 1'	Satstrategy 2'	Satstrategy n'
Strategy 1	\sum Pay-offs (Player 2)	\sum Pay-offs (Player 2)	\sum Pay-offs (Player 2)
Satstrategy 2	\sum Pay-offs (Player 1)	\sum Pay-offs (Player 1)	\sum Pay-offs (Player 1)
Satstrategy n	\sum Pay-offs (Player 1)	\sum Pay-offs (Player 1)	\sum Pay-offs (Player 1)

"Unavoidable theme" 5: Creation of an information sharing and exchange policy

As a player *i* will catch, hide or share the information in order to improve my career, increase my knowledge and improve my own vendor or client strategy. However, depending on the other player strategies, I'll be afraid do not obtain the right information and loss my credibility regarding the others stakeholders

						S'1										S'2										S'3												
S1: catch as much information as possible	P1 S1					P2 S'1										P1 S1					P2 S'2					P1 S1					P2 S'3							
	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5								
	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	-1	-1	-1	1	0	1	0	0	0	1	-1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	1	1	1	
	6					6										-5					-1					6					-6							
S2: Hide as much information as possible (by over complexifying or over simplifying)	P1 S2					P2 S'1										P1 S2					P2 S'2					P1 S2					P2 S'3							
	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5		
	0	0	0	1	-1	1	-1	-1	-1	-1	1	0	1	-1	-1	-1	1	-1	1	-1	-1	-1	1	-1	1	0	1	1	0	-1	-1	-1	-1	-1	-1	1	1	1
	-1					-5										-4					-4					4					-6							
S3: Give/show a clear and transparent information	P1 S3					P2 S'1										P1 S3					P2 S'2					P1 S3					P2 S'3							
	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5	A1	A3	A5	F1	F4	F5		
	-1	-1	-1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	1	1	0	1	1	0	-1	-1	-1	1	1	1	1	-1	-1	1	1	1	1	-1	
	-6					6										-6					4					0					0							

Figure 49: Creation of a MBSE design non-cooperative game

We present in Figure 50 (a) the summarised version of the proposed game. We also present in the part (b) of the figure, the analysis of *the best response strategy*. We notice that S_1 is the best response when the opponent plays strategy one or three; however, strategy two is the best response when the opponent plays strategy two. Then, playing a game with open information (strategy three) is never the preferred solution, no matter what the opponent chooses. In part (c) of the figure, we present the chart corresponding to the best response functions for P_1 and P_2 . We indicate with the black points the two possible Nash equilibrium of the game. Those are the solutions (S_1, S'_1) and (S_2, S'_2) .

Changing the values of the pay-offs, changes instantaneously the Nash equilibrium of the game. For instance, If we suppose the adoption of a different management policy, where information sharing is not judged nor penalised, we could relax A1, F1, and F4. We could decrease the A1 for strategies S_1 and S_2 , and increase it for S_3 to encourage this sharing. Likewise, F1 and F4 could be decrease for S_3 . Then, the equilibrium moves from (S_1, S'_1) and (S_2, S'_2) to (S_1, S'_1) only as illustrated in the top side of Figure 51. Trying to enhance the information sharing an exchange we increase from two units A3 and A5. This is the case if the shared information and the obtained knowledge is much more significant than the others attractions or fears. Which makes appears (S_3, S'_3) as an equilibrium (see bottom side in Figure 51). However, (S_1, S'_1) stills appears as an equilibrium. Indeed, if players start by playing S_1 or S'_1 , (S_1, S'_1) is the only equilibrium, whereas if they star by S_2 or S_3 the Nash equilibrium is (S_3, S'_3) . Those results seems to indicate that catching information strategy (S_1, S'_1) is too forceful, and it could block any cooperation between the players, from an information sharing point of view.

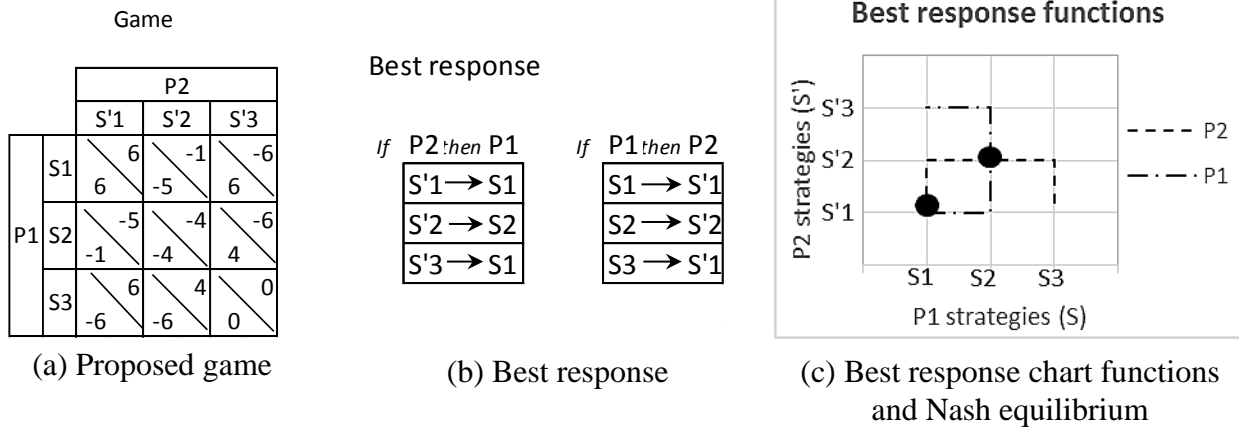


Figure 50: Nash equilibrium

The involvement of new management policies making the information sharing more flexible among the departments seems pertinent, as they could decrease the fears related to the superiors opinions and job accomplishment. Likewise, the implementation of information sharing resources ensuring a secure sharing and exchange process while enhance the new knowledge development could significantly increase the attractions A3 and A5, while reducing F5, which could turn the pay-offs balancing the equilibrium towards (S_3, S'_3)

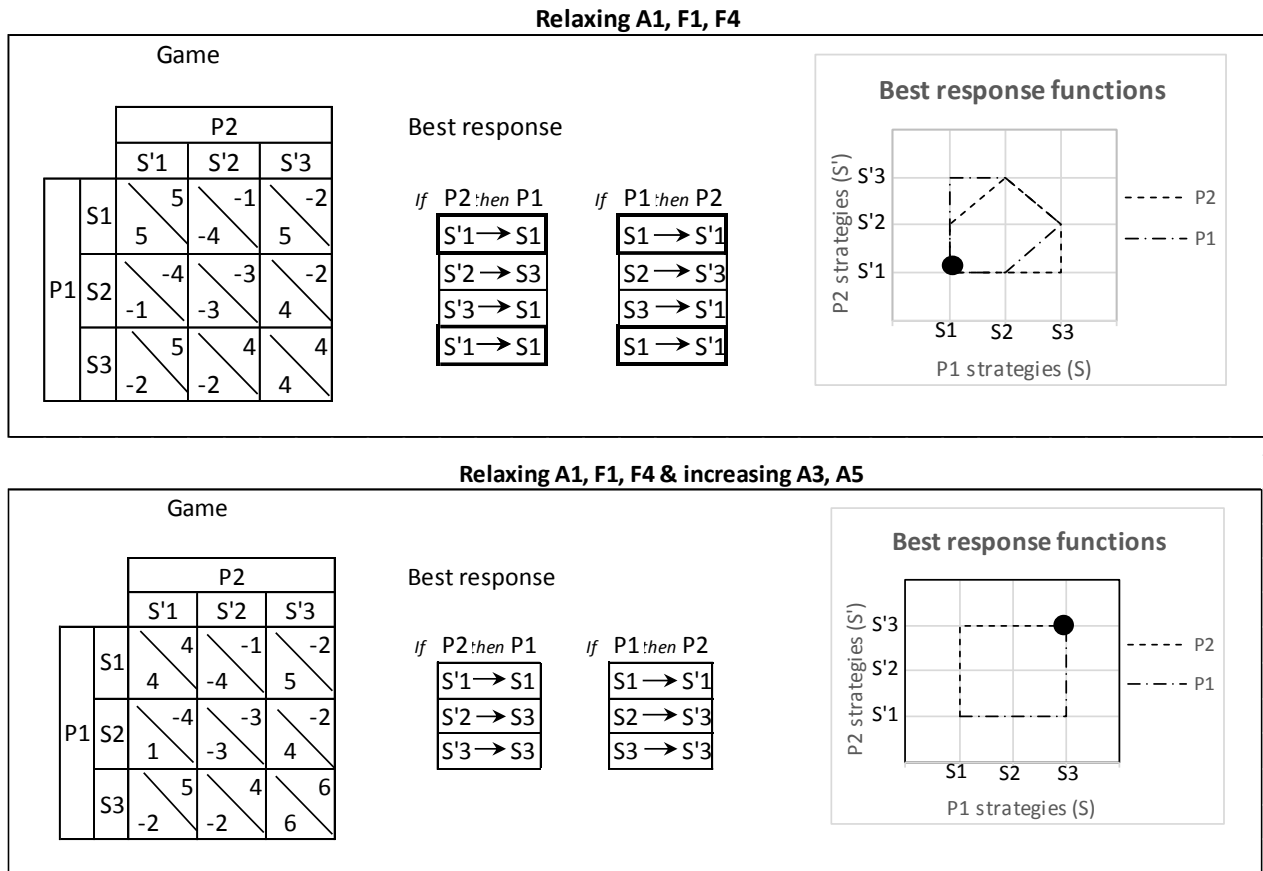


Figure 51: Examples of Nash equilibrium moving

6. Results and discussion

The first contribution of this research is the proposition of cooperative MBSE design projects instead of collaborative MBSE design terminology. The analysis of the literature and the current industrial observations allow us to make this proposition for the project context. We consider that people are organised in a cooperative mode more than in a collaborative mode mostly because of the specific features characterising project organisation. In fact, regarding the cooperative and

collaborative characteristics presented in Table 13, we remark that in cooperative MBSE design projects, no common goal is defined, the authority of the members working in the project is spread even if a project manager is designated (members from different departments working together with different managers), the risk is not shared, the resources and the rewards are separated, the relationships are mostly informal and the common structure of the project is not defined for the different levels of the project. Contrary to the project organisation, the vertical organisation of the company presents more features indicating the possible establishment of collaboration among people, which is rather surprising given the hierarchical nature of the relationships characterising vertical management. For example, for a given department people share the authority and the rewards (e.g. the manager of the commercial department sharing the group commissions among his team). Likewise, the relationships are formal as well as a common structure for the department is defined (e.g. the organisation charts). Finally, people work under long term objectives (such as career evolution) more than short term ones (length of the project).

The second contribution of the paper is the coupling proposition between FAcT-Mirror method and NCGT (way back from FAcT to NCGT) under the three hypothesis presented in section 3. This proposition includes the suggestions of a new marking and regrouping protocol, where a list of key words identified (and reusable for others applications) may facilitate the implementation of the FAcT-Mirror method in the companies when some external constraints such as reducing time with the participants or the impossibility to gather all of them are imposed. Likewise, the three hypothesis proposed to facilitate the coupling of the methods, will also favour the industrial implementations since it reduces the time needed with the participants. However, it does not mean that the participants are not involved. It also gives more freedom/independency to the researcher as he just needs the list of FAcT and their respective marks, to confirm his propositions to the participants.

Third, we identified three kinds of relationships existing within the company in the French vehicle industry: the hierarchical relationship, the transversal relationship and the competitive relationship. Then we used the FAcT-Mirror adapted method and the NCGT to study the transversal relationships. The results of the adapted FAcT-Mirror method implementation allow us to characterise the transversal relationships, in a project context, as mainly driven by strategies related to the information sharing. Three main strategies regarding the information sharing are identified.

The first strategy is related to the information procurement and we call it *S1: catch as much information as possible*. The second strategy describes the protection of the information and we call it *S2: Hide as much information as possible*. Finally, the third strategy is the opposite of the first one; it characterises the accessibility of the information and we call it *S3: Give/show a clear and transparent information*. In this research, we study the transversal relationships only. And that is the reason why only the “unavoidable theme” five have been analysed. However, it is possible to obtain a greater number of recommendations if the objective is less specific (kind of relationship between two actors). For instance, if the topic of interest is the entire group of actors, then the nine unavoidable themes could be analysed in the same way: finding the fears and attraction related to each “unavoidable theme”, the strategies describing it and their pay-offs matrix.

Fourth, we use NCGT facilitates the understanding of the actors behaviours and preferences. For instance, the strategy *S1: catch as much information as possible* emerges as the predominant strategy, which always drives the Nash equilibrium to itself. The analysis of the proposed game, through the modification of the pay-offs of the fears and attractions, demonstrates how the Nash equilibrium, could be moved from S_1 to S_3 . Two solutions decreasing the fears related to the information sharing and increasing its attractions are proposed. These solutions can be also interpreted as the recommendation of the FAcT-Mirror method. The first one is the involvement of new management policies focused on the benefits of the information sharing more than the inconvenient. The proposed game illustrate how this kind of policies are pertinent to decrease the fears related to the superiors opinions and job accomplishment and transform them into attractions. Furthermore, the implementation of information sharing resources ensuring the safety of the shared and exchanged information and enhancing the knowledge development also increase the attractions and reduce the fears. Assuming that those increments and reductions are more significant for the actors, the Nash equilibrium of the game is moved towards (S_3, S'_3) .

In summary, the use of the first three steps of the FAcT-Mirror method considerably facilitates the transition between the reality (observations) and the inputs needed to set a game. Then, the transition between the inputs and the game is done thanks to the proposed coupling method. The method enables to set a non-cooperative game. Its solution and analysis lead to the identification of some propositions (mechanisms) improving cooperation among the actors. The use of the proposed coupling method is mainly helpful in two situations. First, when a game needs to be

established but the bridge between the reality and the mathematical model is difficult to define. Second, when it is not possible to carry out the totality of the steps of the FAcT-Mirror method (e.g.: time reduction or limited actors availability).

To conclude, the coupling of the method allows us to respond to the first research question: How can we characterise cooperative MBSE design in project context using the Games Theory perspective? Likewise, the use of NCGT facilitates first, the understanding of the actors behavioural decisions and endeavours. Second, it simplifies the analysis of the situations (through the different Nash Equilibrium solutions) to improve cooperation by addressing the main concern (“unavoidable theme”) in the relation. And third, it helps to state the propositions that could modify the preference on the actor choices, and that could move the equilibrium towards the transparency information strategies. Thereby, we respond to the second research question: How non-cooperative games can assist the improvement of cooperative MBSE design in this context? Indeed, the identification of the found solutions and their future implementation will assist the improvement of cooperative MBSE design projects. Those findings are in consistency with the literature, that also points out the importance of the clarity of the information exchanged in the design context (Babcock Gove 1981), (Oliver et al. 2004).

7. Limitations and Future work

The first limitation to mention is the statement of the three proposed hypothesis. Indeed, the coupling method is usable only if the three are fulfilled. Nonetheless, as the FAcT-Mirror method comes from the NCGT, the hypotheses are completely coherent and this limitation should not affect other implementations.

Another limitation is the time required. Even if the coupling method reduces the time spent with the group of actors to study, the analysis proposed is still time consuming for the researcher, though some automations could be considered. For example, the use of some simple algorithms assisting the mark and re-grouping protocol. As well as the automatic creation of correlation tables and games matrices.

Regarding the propositions and solutions found, they come from subjective inputs (feelings of the actors). Of course, it could be interpreted as a vague mechanism to make propositions that at the end are not founded. Nonetheless, we consider that the subjectivity of the inputs represents the appropriateness of the proposed solutions. Indeed, even if the inputs are subjective and not

absolute, they represent the reality of a given situation. Thus, although the proposed solution cannot be directly applied as it is in any other context, the method to find a solution is. To conclude the limitations, it is important to say that the use of the method will not give a complete representation of the human being behaviour, in fact, that was never our intention, but instead, it will assist the analysis and understanding of specific cooperative aspects.

Concerning the future work, as mentioned before, FAcT-Mirror method provides very rich and numerous inputs, which is very positive. However, as the analysis of these information is very time consuming, we focus our attention on the cooperative aspects of the transversal relationships. In consequence, more analyses could be done . One example of analysis that could be carried out with the current information, is the characterisation of the relationships with oneself as the FAcT-Mirror method offers the opportunity to analyse it (represented by the FAcT situated in the diagonal of the matrix. c.f: Figure 45). A generalisation of these relationships by them self is probably not the most interesting analysis since they remain personal and applicable at the individual level. But, if the identification of some recurrent features is possible, then those features could be included in the analysis of the others relationships, and then the results could be compared. Likewise, although the hierarchical relationships do not involve an important number of cooperative stakes, it study could be interesting in other management contexts. Regarding the transversal relationships, including the attractions and fears that are not common to both use cases (A7, F6 and F8) and comparing the results could be interesting. Likewise, instead of gathering all the information to triangulate, each use case could be analysed by separated.

On the contrary to the transversal relationship, the limited sample for the competitive relationships, did not allow us to propose a characterisation of them as we did for the transversal relationships. Thus, obtaining more information in order to fulfil this gap should allow this characterisation. Similarly, repeating the FAcT-Mirror method to collect information from other projects within the company could be convenient to verify if the strategy stays the same or not. Likewise, the application of the method in other contexts or industries could be also appropriate to analyse the differences. Those analyses may assist the definition of a more general tendency for each kind of relationship.

Finally, in regard to the proposed games, other forms of games such as cooperative games and biform games can be explored. Cooperative games exploration will assist the exploration of the

possible coalitions between the actors, while biform games (Chen 2011) could gather both analysis (cooperative and non-cooperative). Thus, we could for example analyse in a first time the cooperation among the actors (as we have done in this paper) and then, based on in this results propose some possible coalitions among them and analyse from this point of view the new cooperation.

8. Conclusions

The research presented in this paper aims at understanding and improving cooperative MBSE design projects from the Games Theory perspective. To succeed, we first propose the concept of cooperative MBSE design projects instead of collaborative MBSE design after analysing cooperation and collaboration in the literature. Then, we address the two main questions driving this study: how can we characterise cooperative MBSE design in project context using the Games Theory perspective? And how non-cooperative games can assist the improvement of cooperative MBSE design in this context?

To answer the first question, we propose the coupling of the FAcT-Mirror method and the Non-Cooperative Games Theory (NCGT). The use of FAcT-Mirror method and the proposed coupling method is useful to translate the reality (observations) into a non-cooperative game. Then, to answer the second research question we propose to analyse transversal relationships using a non-cooperative game. The proposed game assists the understanding of some of the actors choices and by the analysis of their Nash equilibrium, some proposition improving cooperation have been drawn.

The transversal relationships analysis results show that MBSE cooperative design projects are driven by information sharing. The solutions proposed to improve cooperation include the implementation of new management policy and the implementation of information sharing resources. The obtained results confirm that NCGT can be used as a tool to understand cooperation among the actors. Likewise, the coupling of the methods is useful to face real world constraints like having a restricted access to the participants.

Even if the use of the coupling methods reduces the time spent with the participants, it is still time consuming for the researcher. Some improvements are proposed in the *limitations* section. Likewise, even if the proposed games (and those that could be proposed from the implementation

of the coupling) are not a complete and detailed representation of the human behaviour, it facilitates the understanding of certain aspects.

Future work will be concentrated on the exploitation of the current data, and the impact of oneself relationships in the obtained results. The collect of more information in order to triangulate (within the company regarding other projects, and between companies) is suitable as well as its implementation in other contexts. Furthermore, the analysis from a cooperative Games Theory perspective and biform games perspective is also an interesting perspective to follow.

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Paper # 4

Developing sociotechnical systems for collaborative design review Part I: Guidelines proposition and application to the vehicle industry for the development of collaborative environments

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Abstract : *The technical Design Review (TDR) phase is considered as a vital control point during the design process. Its purpose is to ensure the choice of the most satisfactory design meeting the requirements. The researches on the literature and the industrial challenges, allowed us to identify several interests on bringing collaborative support to the TDR. This paper presents a guidelines proposition to develop collaborative environments, conceived from a sociotechnical systems (STS) perspective. These guidelines are not only adapted to the TDR but also applicable to other design situations. We applied them to an industrial use case in the vehicle industry. The results show the appropriateness of the guidelines to develop collaborative TDR environment and to improve the overall design process.*

Key words: *collaborative design, computer supported design, engineering design, sociotechnical systems (STS), design practice*

1. Introduction

Design activities require high level of integration during the process development. From the client needs to the product disposal, several phases such as requirements definition, concept development, detailed design and verification and validation are carried out through different activities (NASA 2007). The transfer of the information between those activities needs to be coherent and should ensure the information integration at different project levels. Technical Design Reviews (TDR) assist the integration and the verification activities by bringing an effective solving problem approach that allows the participants to agree on the proposition of new design solutions. TDR take place between concept development and the detailed design phases. In the new product development context, a high integration is required because of the technical complexity of the products, but also because of the complexity of the organisation.

On the one hand, technical complexity is related to the integration of a large number of components, systems and sub-systems. On the other hand, organisational complexity is associated to the diverse and numerous people required to the development. So as to reach a successful product development, a strong coupling between both complexities is necessary. In addition, product development is subjected to different market pressures, such as cost reduction, environmental effects minimisation, client satisfaction increment, lead times reduction, etc. To orchestrate the technological and organisational complexities under the market pressures, collaborative approaches emerge as a solution. Collaborative Engineering (CE) is part of the collaborative approaches aiming at improving engineer processes. Nowadays, the number of studies in Collaborative Engineering Design (CED) is increasing significantly (Deubzer et al. 2007).

In a previous work (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.), we have proposed CEDOSy (*Collaborative Engineering Design Organisational Complex System*) model. CEDOSy facilitates the understanding of the collaborative context by identifying and linking the dimensions of CED (*Collaborative Engineering Design*). Among the established dimensions, the material resources have been identified as an essential element to support collaboration. Likewise, the use of a Sociotechnical System (STS) approach supporting the interrelations and establishing the coherence between those resources and the organisation (people) has also been determined as key aspect promoting collaboration. The research presented in this paper concerns the development of diverse

elements supporting CED. This is the application of collaborative engineering to product design, what is usually called Collaborative Computer Supported Design (CCSD) (Shen et al. 2008b), or more general CCSW (*Collaborative Computer Supported Work*). However, in order to go further than computer support, we use a STS approach found in the literature as *Agile Work Places* (Joroff et al. 2003b) to support CED. We focus this work on the collaborative support of a particular design phase: the technical design review (TDR).

We summarise the problem addressed and the concepts and approaches used in this research in Figure 52.

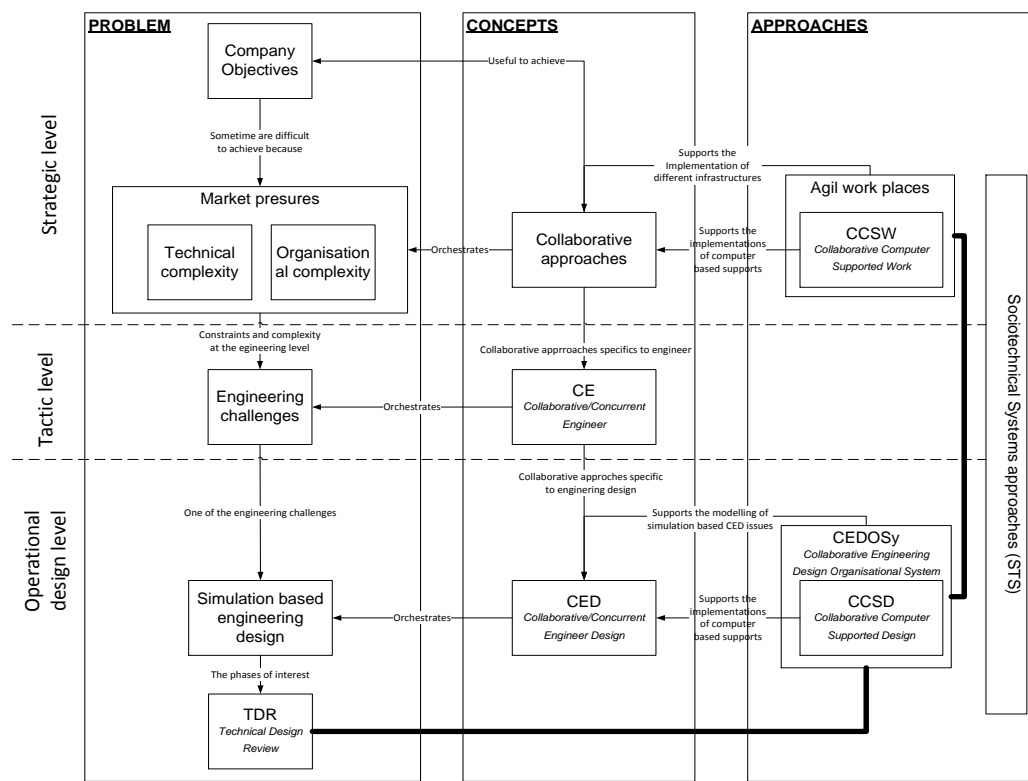


Figure 52: General view of the problem addressed and the concepts and approaches used in this research

In general, the design review phase is considered as a vital control point. Its purpose is to ensure that the most satisfactory approach, plan, or design has been selected and/or that the item to be produced meets the specified requirements (NASA 2007). Design review is also viewed as an essential activity formally conducted to ensure a smooth transition from one phase to another (Huang & Jiang 2002). As it is mentioned in its designation, the Technical Design Review (TDR), is related to technical aspects of the product. Technical design reviews are one of the typical

scenarios of Collaborative Engineering (CE), because of the number of teams involved, their spread locations and their multiple backgrounds.

The literature on TDR is very limited. In 2002, G.Q. Huang (Huang 2002) carried out a comprehensive research and found several publications mentioning DR (Design Review) as a crucial phase during the design process. Among these publications, they highlight the ISO9001 standard. This standard designates DR as a mandatory in the product development. However, the extent of coverage is rather brief. More recently, in 2007, G. Huet et al. (Huet et al. 2007) proposed several meeting analysis tools to study DRs. In the same year, the NASA Handbook dedicated several pages to design review phases. Nowadays, a gap on TDR still exists, and the industrial needs for a collaborative computer supported TDR is increasing.

The researches on the literature and the work done in collaboration with our industrial partner, a French car manufacturer, allowed us to identify several challenges on bringing collaborative support to the technical design review. The most important challenges from the industrial point of view are the identification, resolution and improvement of collaborative issues among the members doing the TDR, in order to meet the strategic objectives of the industry in terms of time, cost and delay. From an academic point of view, this research contributes to the gap fulfilment on DR studies and follows the research line on Collaborative Engineering (CE).

We believe that the application of *agile work places* and *CEDOSy* approaches enables the implementation of collaborative means during the TDR. The implementation of the appropriate means will have a positive impact on the global improvement of the design process.

The bold connectors in Figure 52 establish the driving threads of the research presented in this paper. In this research, we focus the attention on the means supporting TDR. We propose a group of guidelines implementing *agile work places* and *CEDOSy* approaches. Their goal is to support the design of a collaborative environment and their use shows how an appropriate implementation of those approaches can minimise both, collaborative and misunderstanding problems.

The two main hypothesis driving the research presented in this paper are:

- *The minimisation of collaborative problems, has a positive impact on the TDR process, and consequently on the global design process*

- *A lack of an appropriate environment leads to collaborative problems, having a negative impact on the TDR process, and consequently on the global design process*

This paper is organised as follows: section 2 introduces a literature review on collaborative engineering design support. Section 3 presents the guidelines proposition to develop collaborative environments. An application of the guidelines through a vehicle industry use-case is presented on section 4. The results and conclusions are summarised in section 5. Finally, section 6 presents the perspectives and future work.

2. A literature review on CED support

We separate the literature review presented in this section into three sub-sections. We start presenting the work done on Collaborative Collocated Work (CCW) and Collaborative Computer Supported Work (CCSW), then we introduce the agile workplaces approach and finally we mention some examples of agile workplaces implementations.

2.1.CCW and CCSW

Collaborative Collocated Work, also known as CCW, addresses interactions and collaborative issues between team members. Its objective is to provide means to enhance team work when the members of the team are gathered in the same place. A significant number of companies have adopted this approach during the 90'S. For instance, Boeing company, ensured teamwork by collocating the most part of them in the same building, to facilitate meetings, discussion and coordination (Poltrack & Engelbeck 1999).

The globalisation of manufacturing products, brings new constraints to the collaborative issues. This constrains make CCW approach less appropriate to face nowadays context. Today, engineers work simultaneously in multiple tasks, diverse products and different teams. They are framed by the same global company processes and they share an enormous amount of information. This context makes the collocated work difficult to carry out. Even if CCW is still relevant to improve collaboration, new approaches such as CSCW supporting also non collocated situations have emerged. CSCW stands for Computer Supported Collaborative/ Coopertaive Work. This approach aims at supporting new collaborative work using computer-based systems (D'Souza & Greenstein 2003). In spite of the approaches proposed by the literature and the applications, we only found one guidelines proposition for the development of virtual environments for collaborative design

(Vosinakis et al. 2008). However, these guidelines are more requirements checking than an explicit protocol guiding the development of such environments.

CSCW research gives also some highlights to understand work practices in a complex collaborative context (Davis et al. 2006). The application of the CSCW to design is called Computer Supported Collaborative Design (CSCD). CSCD reflects the process of collaborative design within the entire lifecycle of the product (Shen et al. 2008a).

2.2. Agile Workplaces

CCW and CSCW approaches are useful to understand how collaborative work can be supported by computer technology. However, these approaches do not consider the need of physical place to collaborate, neither the interaction between the technologies, the place and the people. Joroff et al (Joroff et al. 2003b) propose a sociotechnical approach including the notion of *workplace* as another solution to improve team collaboration. Agile workplaces approach claims that the environment affects organisations and the people in their work (Morgan & Anthony 2008). This affirmation confirms the need to improve the place where people work. Workplace improvement is not only focus on the “required physical accommodation” but they also aim at raising flexibility and upgrading communication (Morgan & Anthony 2008). In this spirit, the concept of agility is crucial to propose a suitable workplace. Agility turns the workplace concept into an *agile workplaces* approach.

The agile workplaces approach proposed by Joroff and al. (Joroff et al. 2003b) introduces the term agility as the ability to respond effectively and rapidly to quick change and uncertainty. In the industrial context, agility becomes the ability of adopting the emergency disturbance as a usual and fundamental condition of the behaviour of the organisation (Becker 2001). Agile workplaces practices guarantee the alignment of work, where an appropriate place to work becomes a priority. As well as CEDOSy approach (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.), the agile workplaces approach highlights the importance of some of the dimensions of collaborative engineering design. Both approaches make a special focus on the links between people, work and place. In addition, they include those links as a part of the work itself.

2.3.Existing agile workplaces implementations

Several examples of implementations can be found in the industry. However, we focus on two general examples of an agile workplace. The first one is the war room and the second one is Teamspace.

“The War Room is used as a strategic planning and a competitive intelligence tool” (Shaker & Rice 1995). It is considered as a place where people meet to work on the achieving of a common goal. A war room provides a solution of information management, sharing and visualisation. The walls are organised on sections and panels corresponding to different topics, and the information flow on those walls respects a rational approach. Teasley et al. demonstrate on their research (Teasley et al. 2000) that work in a war room doubles the productivity of the team. This improvement is the result of bringing accessibility to the information and assistance to coordinative tasks.

The second example is the Teamspace prototype produced at GeorgiaTech (Richter et al. 2001). The prototype is a collaborative workspace, developed during project joined by IBM and Boeing. The collaborative workspace enables the management of collaborative processes and the maintenance of “shared artefacts in distributed projects” (Richter et al. 2001). Teamspace can support collaboration between different teams in the company.

3. Collaborative workplace: The guidelines proposition

In order to assist the development of a suitable collaborative support, we have integrated the Agile Work Places approach (Joroff et al. 2003b) to CEDOSy model (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.). As a reminder, CEDOSy identifies CED dimensions and the link in between. Among the established dimensions, the material resources have been identified as an essential element to support collaboration. In this context, the Agile Work Places approach proposed by Joroff et al. is presented as a mean to develop material resources supporting TDR (technical design reviews).

Joroff et al. propose a five-step framework for workplace-making: Situation awareness, process design, artefact design, design making and evaluation. Situation Awareness is identified by observing and mapping the current work, working with the participants and diagnosing the current problems. Process design aims at creating alternatives and implement strategies of change. Artefact design is the design of the actual workplace itself and the generation of new ideas. The design

making, aims at identifying the elements of the new workplace and its support elements. And finally, the evaluation step is used to assess the work place and work practices.

The collaborative environment guidelines proposed in this paper materialise the process design, artefact design, design making and evaluation activities. Six guidelines are defined to assist the appropriate dimensioning of a collaborative environment. By appropriate we mean that the workplace should support the totality of the activities carried out during the TDR and it should be based on the behaviour of the organisation. The six proposed guidelines are: the scenario description, the stamping of the activities (according to a proposed list), the listing of the user needs, the functions cross-checking and the dimensioning of the environment elements. We present each of the six guidelines from sub-section 3.1 to sub-section 3.6

3.1.Guideline 1: Scenario description

The importance of the choice regarding the level representation has already been discussed in the literature. Wynn et al. (Wynn et al. 2007) discuss the importance of an appropriate level of modelling detail. Likewise, Clarkson and Eckert (Clarkson & Eckert 2005) affirm that no modelling framework is available at present, to capture the entire richness of design process. However, some frameworks such as IDEF, DSM and Signposting are useful to model partial views or specific features of design processes. We tried to use IDEF framework to model TDR process more in detail. We arrive to the same conclusion than the authors, the representation of the iterative activities is difficult to attempt. To solve this issue, we propose to represent the TDR via scenarios.

We propose to represent the basic scenario through UML activity framework. We do not advice IDEF framework in this case because of the amount of information that is represented at the same time (Inputs, outputs, control and mechanisms). This representation is not appropriate either for the communication towards TDR participants, nor for the analysis of the TDR infrastructure. The template used for the scenario representation contains horizontal, vertical swim lanes and rectangles. The horizontal swim lanes serve to identify the participants. The vertical swim lanes delineate the stages of the TDR. The rectangular shapes symbolise the activities carried out in each

stage for each group of participants. An illustration of a scenario representation is presented in the use case (c.f. Figure 54).

3.2.Guideline 2: Stamping the activities according to the proposed list

A classification of the actions carried out during the TDR is done according to fourth criteria: industrial observations, the exchange roles describing DR activities (Huet et al. 2007), the social action framework (Ngwenyama & Lyytinen 1997), and the aspect of knowledge (PAUL 2006). Stamping the activities of the scenario according to the proposed list will group the activities and facilitate the user needs identification. This will also be helpful in the future quantification of the required ITCs (Information and Communication Technology) elements to support the activities.

To propose the action classification, we have identified an exhaustive list of actions coming from the industrial observations. The industrial observations included 3 industrial interviews and 25 TDR attendance. We have identified 21 different activities during the observations. Then we have grouped the list of actions observed during the TDR according to the exchange roles proposed by G. Huet et al. (Huet et al. 2007) and we have classified it according to the social framework design objects proposed by Vosinakis et al. (Vosinakis et al. 2008) and according to the three aspects of knowledge management for collaborative activities proposed by Paul, D.L. (PAUL 2006).

On the one hand, G. Huet et al. (Huet et al. 2007) propose six core *exchange roles* describing DR activities as a part of the meeting analysis tool *MCT*: exploring, evaluating, clarifying, informing, debating and decision making. Among the six *exchange roles*, we have used the first five, since we consider the decision making as the global output of the TDR. We have grouped the 21 observed activities into the five exchange roles. However, after analysing the social framework proposed by Vosinakis et al. presented below, we have split the *exchange roles* exploring and clarifying into three more specific activities (for each one) as to the design objects supporting these activities are different.

On the other hand, to understand the social framework design objects proposed by Vosinakis et al. (Vosinakis et al. 2008) is necessary to mention the action theory and social framework. The social

action theory (also known as theory of communicative action) (Habermas 1984) outlines a set of social action categories supporting everyday activity. The social action framework proposed by Ngwenyama & Lyytinen (Ngwenyama & Lyytinen 1997) is based on Habermas's theory. It applies Habermas's concepts as design categories to analyse groupware environments. Finally, Vosinakis et al. (Vosinakis et al. 2008) proposed a list of design objects for each action category. Some examples of design objects for each action category are:

- Instrumental action: sketches, mock-ups, prototypes
- Communicative actions: meetings, mail and presentations
- Discursive actions: high-level descriptions, method to design and methods to evaluate
- Strategic actions: negotiation and expert opinions for.

According to our experience observing and analysing design activities, the categories and the objects proposed by Vosinakis et al. (Vosinakis et al. 2008) seem appropriate to describe the design actions. However, concerning the TDR activities carried out during the meetings, instrumental actions can also be considered as a kind of communicative action because, the participants use the objects proposed in this category (mock-ups, sketches ...) to give better explanations to the other participants. This fact is not surprising given that TDR is focused on the requirements validation more than the development activities itself.

Finally, Paul, D.L. (PAUL 2006) affirms that collaborative activities involve some combination of knowledge transfer, knowledge discovery, and knowledge creation. He defines knowledge transfer as any action that can contribute to disclosure, dissemination, transmission, and communication of knowledge. Knowledge discovery is defined as the new understanding through the integration of pre-existing knowledge or information. Finally, knowledge creation refers to the development of new knowledge.

The literature insights presented before, plus our experience on TDR industrial observations allow us to propose a classification of the TDR activities. We conclude that they can be grouped by the five *exchange roles* and they can be classified into oral communication activities and visual communication activities. The matrix used for the groping analysis is presented in ANNEX 2 (Table 30). The oral communication activities involve the three kind of knowledge, while the visual

communication activities imply mostly knowledge transfer activities and sometimes knowledge discovery. Even if some of the TDR activities can be classified as Instrumental and discursive activities, when those activities are carried out, their final objective is either the knowledge transfer or the knowledge creation. It means that these activities are used as communication means.

Based on the literature analysis and on industrial observations, we propose eleven generic activities characterising TDR. The proposed activities comes from a second grouping analysis presented in Table 31 and Table 32 of the ANNEX 2. Among the eleven activities, two of them correspond to oral communication activities, seven of them to visual communication activities and the remaining two are the readiness activities. Readiness activities have not been mentioned in the literature yet. However, we have decided to include them, not only because they are required to setup any TDR, but also because readiness has been highlighted as an important TDR success factor (NASA 2007). We present in **Erreur ! Source du renvoi introuvable.** the proposed eleven generic activities characterising TDR.

Two simple readiness activities were identified: system and files setup. The system setup refers to the system configuration and the eventual activities needed to get the system to be ready to use. The documents setup refers to eventual resources needing a significant amount of time to get ready during the TDR.

The proposed oral communication activities are: presentation and discussion. The presentation activity is usually well planned and is carried out by one or two people whereas the discussion activities are more spontaneous and less organised. These activities transfer and create an important amount of information and tacit knowledge. It is important to ensure the correct transmission of the information to avoid the tacit knowledge loss.

Finally, the visual communication activities proposed are: video interactions, screen sharing, point out, run simulations or mock-ups, modify documents, sketch on board, over-sketch initial designs. These activities are strongly based on the literature evidence regarding the use of prototypes, sketches and other artefacts during the design process that match with the industrial observations.

In fact, several works have proven the importance of those artefacts during the DR. For instance, Groen et al. (Groen, McNair and Paretto, 2016) have established that the use of artefacts moderate and structure the relationships among the designers, facilitate the mutual understanding and have an impact on the innovation. Likewise, Ferreira et al. (Ferreira, Christiaans and Almendra, 2016) affirm that these artefacts are the expressions of the thought increasing the richness of the DR. We explain each of the seven visual communication activities below:

- Video interactions: these activities often give the context information to the participants remotely connected. It is also helpful to transmit some information when participants refer to objects different from those shared in the screen.
- Point out activity: This activity was one of the surprising activities to be presented as a kind of activity. Even if this activity seems to be too specific for being a class of activity, during the observations we noticed that participants point out more than fifty percent of the time during a TDR. However, participants do not make sure that other people can see what they are pointing out.
- Screen sharing: Screen sharing is doing hundred percent of the time during TDR. It is the most popular visual activity improving both knowledge transfer and creation.
- Running simulation and mock-ups: As TDR is an evaluation phase during the design process, the design itself does not take place during the TDR but before. However, the design results are presented during the review. Which often implies significant computer resources
- Modify: File modification activities could take place during the TDR. Nevertheless, as the TDR time slot is reduced, important modifications are carried out between two TDR.
- Board sketching: board sketches or writing are also used as a communication mean allowing knowledge transfer and discovery.
- Over-sketch: this is another surprising activity of the listing. During TDR sketches and over-sketches are tacitly distinguished. People use over-sketches to start the modification that will be carried out between TDR and to ensure that the understanding of all participants is the same.

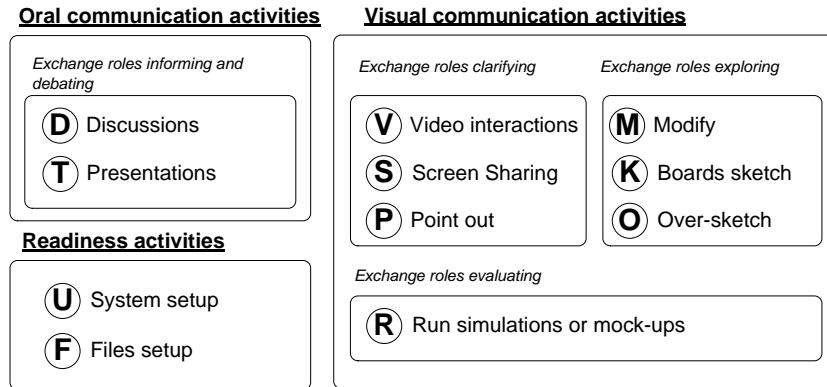


Figure 53: Proposition of TDR collaborative generic activities

The detailed level of the *proposed generic activities* allows to include in this classification the DR acts recently discussed in the literature such as the *Artifact Acts* (e.g.: Illustrate/explain and explore/discuss) (Groen, McNair and Paretti, 2016) and the interaction dynamic notations (IDN) (Sonalkar *et al.*, 2016), which are much more detailed (e.g.: move, question, support, block...).

3.3.Guideline 3: Listing the user needs as a functions of the system

After describing the scenario and stamping the activities, the next step is to identify the user needs in terms of the functions of the system. The list of functions should be based on the observations of the designer but also on the interaction with the users. It is important to include the user expectations in the list. For this step we advise to use a functional analysis through the APTE formalism (de la Bretesche 2000). This formalism proposes to represent the system to be developed and the components having an important impact on the system. These components are called *environments* as they take environmental aspects into account. We have identified the collaborative workplace as the system to be developed. And four main categories of environments: the participants, the physical means, the IT means and the information and knowledge to be shared. The identification of the specific elements of each category should be conducted within a brainstorming process including the different stakeholders. Involve the different stakeholders in this process is a relevant instrument to support innovation and to assist to establish a common view of the system to be developed (Schumacher 2011).

3.4.Guideline 4: Cross checking the activities and the functions

To reduce the redundancy and to avoid the lack of functions it is important to verify that each activity is at least covered by one function (Check between guidelines one and two concerning guideline three). If several functions cover the same activity, it is also possible to merge several functions.

3.5.Guideline 5: Dimensioning the elements of the environment

The second to last step is the dimension of the elements supporting the collaborative environment. We propose a list of elements to quantify. The list can be easily filled in and transformed into the collaborative workplace specifications.

We based the proposition of the list on the results of the activities analysis. It allows us to focus on the support of communication activities to ensure knowledge transfer, knowledge creation and knowledge discovery. To find the good elements supporting collaborative environment, we analysed the activities proposed regarding ITC characteristics (Information and communication technologies) in different coordination modes (Raposo et al. 2001).

We evaluate the four main characteristics of ICT systems (access, store, transfer and manipulation) regarding the proposed activities. Each evaluation gives us a list of elements that can be directly quantified. This quantification can be translated directly into the specification of the collaborative environment. For the characteristics access and manipulation, we also evaluate the coordination mode: synchronous, asynchronous, concurrent or not concurrent. By synchronous, we understand that one or more elements need to be shared at the same time. While in asynchronous mode, the elements do not need to be shared at the same time. By concurrent, we understand that a number of people use the same resource at the same time. While in a non-concurrent collaboration people does not share the same resource at the same time.

We present in Table 23 the elements to quantifying each activity for each characteristic. The quantification of those elements will facilitate the definition of the specification of the environment. For instance, if we quantify the elements regarding the video interaction, we will be able to define

the number of devices needed (microphones, cameras, speakers, headphones), the internet width-band and the storage capacity. More examples are presented in the use case.

ICT characteristics Communication activities	Access		Store	Transfer	Manipulation		
	Sync	Async			SynC	SynNC	Async
Discussions	<div>For each activity and each characteristic define:</div> <div><ul style="list-style-type: none">○ Number of people involved in the activity (min and max)○ Shared/exchanged objects: extension, size (min and max), storage time and location○ Tools used:○ Software○ Internet needs: Waiting time acceptance and Delay time acceptance</div>						
Presentations							
Video Interactions							
Screen sharing							
Point out							
Runsimulation/mock-up/prototypes..							
Modify							
Boards sketch							
Over-sketch							

Table 23: Elements to dimension the environment

3.6.Guideline 6: Feedback and evaluation

Feedback is given by the users all along the steps because the definition of several aspects needs the user's information. However, once the final specifications are completed, at least one meeting, gathering all the stakeholders (designers, TDR participants and ICT department) is suitable. We propose two evaluations of the workplace: a qualitative evaluation and a quantitative evaluation. The qualitative evaluation aims at measuring user acceptance and satisfaction. The quantitative evaluation aims at quantifying the improvement of the design process.

To design the qualitative evaluation we propose a survey using the qualitative dimensions proposed by B.E. Hayes (Hayes 1998): correctness, reliability, usability, maintainability, testability, portability, interoperability, intra-operability, flexibility and overall satisfaction of the collaborative workplace. To evaluate the correctness of the system, we ask the users for their satisfaction regarding the functions of the environment. For the rest of the dimensions we address between one and three questions. For all the questions we use a Likert scale to evaluate the degree of satisfaction. The proposed survey is presented in Table 24.

The template of the evaluation proposed in Table 24 is important to ensure a complete loop in the design of collaborative environments. The user experience is essential to improve the system and furthermore, it is necessary to verify the compliance of the environment regarding the user needs. If a non-compliance (bad evaluation) happens, the use of evaluative dimension (left column in Table 24), will allow the adjustment of specific dimensions of the environment. This kind of evaluation could also facilitate a progressive evaluation of the system while waiting for the results of a quantitative evaluation, as the last one needs a long period of time after the environment implementation.

To design the quantitative evaluation, we propose to estimate the profit in term of cost. To estimate the cost saved, we propose to calculate the number of loops saved during the design process. As we mention in *step a*, design process is iterative. Each TDR represent one iteration need to reach the requirements. The collaborative environment improves collaboration between members and favours the problem solution phases. This environment should reduce the number of TDR needed to reach the requirement. Then by calculating the number of TDR saved, we can deduce the number of men/hours saved, and then, the cost saved by the enterprise.

Dimensions	Questions	Possible Answers				
Correctness	I am able to complete my TDR job in the collaborative environment?	I can't complete my job at all	25% of my job	50% of my job	75% of my job	100% of my job
	Does the environment (function 1, 2....)	The environment does not accomplish the function at all	25% of the function is accomplished	50% of the function is accomplished	75% of the function is accomplished	The environment accomplish 100% of the function
Reliability	Does the environment allow me to perform functions accurately?	It does not allow me	It allows me 25% of the time	It allows me 50% of the time	It allows me 75% of the time	It allows me 100% of the time
Usability	Was it easy to learn how the system operates?	Very difficult	Difficult	Neutral	Easy	Very easy
	Can I easily get what I need from the environment?	Very difficult	Difficult	Neutral	Easy	Very easy
Maintainability	How often the environment present the failure?	Always	75% of the time	50% of the time	25% of the time	Never
	Am I able to understand where the errors come from?	Very difficult	Difficult	Neutral	Easy	Very easy
	Am I able to fix an error easily?	Very difficult	Difficult	Neutral	Easy	Very easy
	Am I satisfied with the delay of response of the ICT department?	Very unsatisfied	unsatisfied	Neutral	Satisfied	Very satisfied
Testability	Am I satisfied with the time need to test and establish the voice connection?	Very unsatisfied	unsatisfied	Neutral	Satisfied	Very satisfied

	Am I satisfied with the time need to test and stablish the video connection?	Very unsatisfied	unsatisfied	Neutral	Satisfied	Very satisfied
	Am I satisfied with the time need to test and stablish the screen sharing connection?	Very unsatisfied	unsatisfied	Neutral	Satisfied	Very satisfied
Portability (nous adaptability)	Is the system appropriated to different subject addressed during the TDR?	Very inappropriate	inappropriate	Neutral	Appropriated	Very appropriated
	Is the system easily adaptive to the number of participants?	Very difficult	Difficult	Neutral	Easy	Very easy
Interoperability	Has the environment present any interoperability problem?	Always	75% of the time	50% of the time	25% of the time	Never
Intra-operability	It is simple to make communicate the systems component between them?	Very difficult	Difficult	Neutral	Easy	Very easy
Flexibility	If I need to change the regular operational mode. Can I it change easily?	Very difficult	Difficult	Neutral	Easy	Very easy
Overall satisfaction	Am I satisfied with the environment?	Very unsatisfied	unsatisfied	Neutral	Satisfied	Very satisfied
	Does the environment meet my expectations?	No it doesnot at all	It meets 25% of my expectations	It meets 50% of my expectations	It meets 75% of my expectations	It does a 100%

Table 24: Proposition of qualitative survey template to evaluate collaborative environments

4. Industrial Use Case

The industrial use case took place at the vehicle manufacturer Renault. The use case aims at providing a collaborative workplace to the participants of the technical design review (TDR). The importance in the literature of TDR is well known, the reviews help to develop a better understanding of the task among the project participants, to open communication channels, to alert participants to the problems, and to open avenues for solutions (NASA 2007).

TDR at Renault are essential in the design process. Each TDR is part of the problem solving phase, where a given design is evaluated regarding the expected performances and requirements. When the design does not attempt the performance nor the requirements, a solution is necessary. The process to find the right solution, satisfying all the involved departments is the basis of the TDR.

Several TDR are carried out during the design process at Renault, from the early design phases to the final design. The case study presented in this section takes place during the TDR of the late design phases: preliminary and final design. During these phases, collaborative stakes have a particular interest for the company because three different departments need to work together: design department, performance department and simulation department. Design and performance

departments use simulation models to evaluate the developed item. This is a typical application of CAD-CAE collaborative problem.

The vision of the product from the design and performance teams is biased by their perimeter. TDR process gives a central and complete view of the product integrating the aspects developed for each team through simulation models. TDR should not be considered just as a meeting to share ideas and resolve issues (NASA 2007). Thus, TDR allows the project to establish baseline requirements, plans, or design through the review of technical approaches, trade studies and analyses. An efficient support of TDR will ensure compliance with systems integration requirements, via objective evaluations through mock-ups and simulation models. The correct analysis of the evaluations results, will allow the development of suitable solution.

In the use case presented in this section, we apply the collaborative workplace guidelines proposed in section 3. The aim of the use case is to show how to build a new physical environment in the company to support TDR. We start by the description of the current problems and situation in the company. Then, we present the step by step application of the guidelines from sub-section 4.2 to 4.7.

4.1.Description of the current situation

In the current situation each participant attends to the TDR in person or via Skype for business. The person leading the TDR shares a presentation via skype, or sends it in advance via e-mail. Another person writes down the minutes all along the meeting. However, no one can see the content of the minutes until the future mail delivery. During the TDR, the presenter is switched several times. Some people present digital mock-ups or simulation results screen shots. Most of the time, people prepare the screenshots in advance, because of the slow data transfer of the current solution. At the end of the TDR, the participants agree on a list of solutions, to be explored. In the next TDR, they will evaluate the impact of the solutions and they will choose the best one.

We have observed that participants find difficulties to understand each other when they discuss some technical aspects with participants that are not from the same department. The participant which is speaking has some troubles to explain him/herself via his/her voice or using one or two images. Often, they connect their laptops to their remote post to run some simulations, or to show some 3D models. However, this operation is time consuming. We also observed a source of

conflicts between design and performances teams. The conflicts are often due to the disagreement between the objectives of both departments. For instance, design department will request a specific shape for the client, whereas that shape will increase the global consumption, and then decrease the product performance. It is difficult for the performance team to understand why the shape is important without a global mock-up of the product. Likewise, it is difficult for the design team to understand the impact without the simulation models. A suitable environment or infrastructure will facilitate the technical discussion (Huang 2002). It is also recognized by the literature, that to support collaborative design, information and communication technologies are used to increase the capabilities of the individual specialists, and enhance the ability of collaborators to interact with each other and with computational resources (Shen et al. 2008a).

4.2. Scenario description

As proposed by the guidelines, we use the UML activity framework to describe the TDR scenario at Renault. The TDR scenario description is presented in Figure 54. The horizontal swimlanes serve to identify the participants of the TDR. In spite of the participation of the three departments mentioned before (design, performance and simulation), each swimlane does not represent a department. The observations showed that activities performed by design department and performance department during the TDR were the same. They only participate by showing some images or models to defend an argument. On the contrary, we observed that simulation department needed to be split into two swimlanes. Indeed, the leader of the TDR belongs to the simulation department. We noticed that the activities carried out by the leader are quite different from those performed by the rest of the team. The vertical swimlanes delineate the stages of the TDR. Seven stages were identified: data setting, system starting, communication set up, TDR opening, results presentation, problem discussion, and conclusion and closing.

The rectangular shapes symbolise the activities carried out in each stage for each group of participants. After assisting a several TDR (25) we have been able to propose the TDR scenario description presented in Figure 54. We have observed that most part of the time is dedicated to stages: results presentation and problem discussion. In addition, the most part of the actions carried out during those phases are an iterative effort to get participants to understanding what the interlocutor want to express.

4.3. Stamping the activities according to the proposed list

By stamping the scenario presented in Figure 54, the central activities of the TDR are naturally highlighted. For example, we can see how the displaying activities are presented all along the main phases of the TDR and how they are used as a communication mean. In fact, the stamps show the wealth of these collaborative activities. A simple displaying activities implies discussions, but also several visual interactions such as, sketching, pointing out or running simulation models. Likewise, the duplication of the same activities through different group of actors and the looping arrows (coming in and out of these boxes) shows the iterative character of the design process.

The stamping process also allow us to distinguish between the preparation phases and the main phases of the TDR (opening, results presentations, problem discussion and conclusions). We also have observed that during the results presentation and problem discussion activities, almost all the participants perform all the collaborative activities, except for the coordinator (simulation department leader in the figure), who is assigned to some specific tasks. This fact, also reveals the complexity of the collaboration between the actors. Everyone wants to participate by exhibiting his/her arguments almost at the same time.

Finally, we notice that discussion activities (D), video interaction activities (V) and presentation activities (T) are never alone. These activities are often in company of some other activity such as sketching or screen sharing or simulations running. This is probably because of the need of participant to justify their choices and/or decisions.

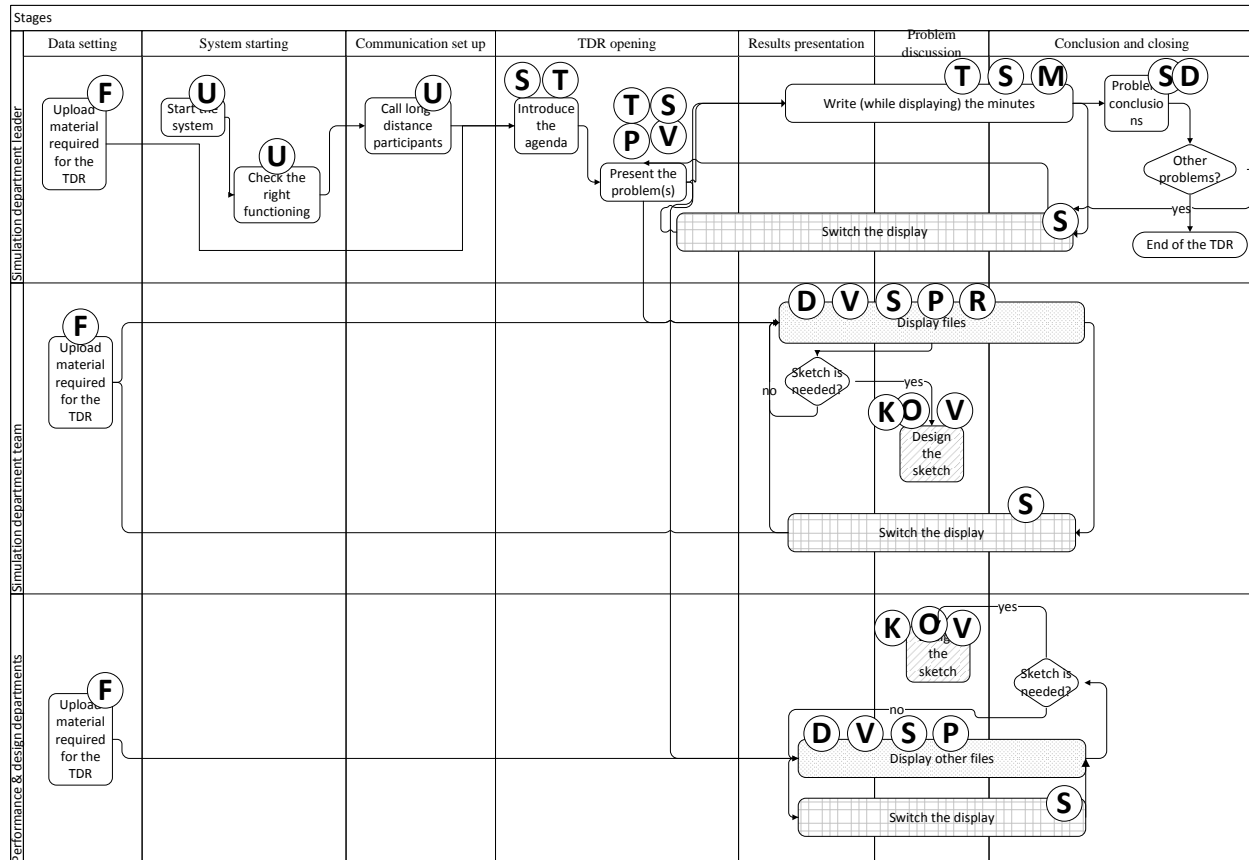


Figure 54: TDR scenario representation at Renault

4.4. Listing the user needs as functions of the system

To list the user needs we use a functional analysis. The functional analysis has been carried out through the APTE formalism (de la Bretesche 2000) as suggested by the guidelines. As proposed in guideline 3, we represent the collaborative workplace as the system to be developed, and four main environments of the system - IT means, physical means, participants and information/knowledge -. In Figure 55. The specific elements identified for each category are:

- TDR participants at Renault : design department, simulation department and performance department
- IT means: simulation software, visio conference tool and office software applications
- Physical means: hardware (such as laptops, board or screens) and room objects
- Information and knowledge: models, know-how, skills and TDR documentation

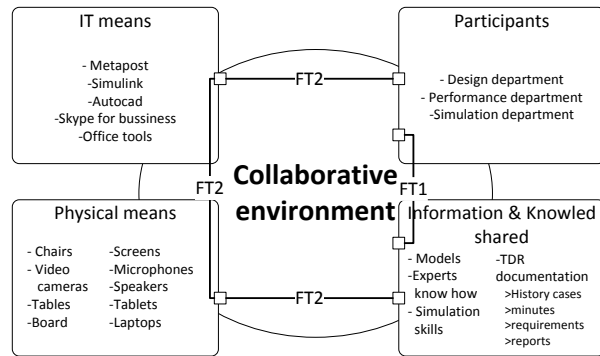


Figure 55: Use case functional analysis: APTE formalism

The two main functions of the system (FT1 and FT2) are presented in Table 25, they concern the support of collaborative activities and the information sharing among the participants though IT and physical means. We have identified both, transfer functions (FT) and constraints function (FC). Transfer functions include at least the interaction of two environments through the system, while constraint functions are generated only by one environment. Transfer functions represent the environmental expectations while constraint functions represent the constraints imposed by the environment (de la Bretesche 2000). A total of 15 functions (leading to 24 technical specifications) have been identified during the use case. Some examples of the functions identified are presented in Table 25. This analysis allows us to identify the functions that the system should guarantee. The set of functions represent also the user's needs.

4.5. Cross checking the activities and the functions

In order to ensure the completeness of both, activities and functions. Each category of activity should be related at least to one function. An example of the cross-check done for the use case is presented in Table 25. This example shows the higher level functions – more detailed functions have been proposed in the internal documentation but they are not shown here -. For instance, *FT1: The system must support collaborative activities between all participants in order to make decisions, based on shared information* needs to be more detailed. We propose a function for each collaborative activity identified. As a result, one of the proposed detailed function is: *FT1.6: The system must support the point out actions carried out by the participants.* or *FT1.6.1: The system must allow to all the participants to see what is pointed out by any other participant.* Finally, the cross-check is also warning mean. When a row and/or column is empty or almost empty, a deeper analysis is needed. For example, column 10 *System Setup* is only supported by the maintenance

function FC4. However, only an appropriated maintenance will not support the daily setup of the system. Then a function supporting this need is suitable.

	Discussions	Presentations	Video interactions	Screen sharing	Run simulation or mock-ups	Point out	Modify	Boards sketch	Over sketch	System Setup	Files Setup
Function/Collaborative activities	1	2	3	4	5	6	7	8	9	10	11
FT1. The system must support collaboratiive activities between all participants in order to make decisions, based on shared information.	x	x	x	x	x	x	x	x	x		
FT2. The system must allow information sharing, in real time, in the room and with other distant sites.	x	x	x	x	x			x	x		x
FC1. The system must ensure a simultaneous display			x	x	x			x	x		
FC2. The system must ensure rapidity in managing displays.			x	x	x			x	x		
FC3. The system must able the realization of sketches in collaboration.								x	x		
FC4. The system must be able to be maintained.										x	

Table 25: Systems functions and cross check

4.6.Dimensioning the elements of the environment

We use the table of quantification proposed in the guidelines (c.f. Table 23) to quantify the elements needed to build the environment. We present discussions and screen sharing activities to illustrate two examples in Table 26.

To illustrate the dimensioning of the elements regarding the discussions activities, we can consider the following example. Attributes concerning synchronous accessibility allow us to see how many people will be connected at the same time, if voice recording is needed or not, and the tolerance in terms of communication delay. These parameters allow us to build the specification of the system (the number of microphones, headphones and speakers needed and the width band). Then, we can see in Table 26, that no attribute concerning the asynchronous accessibility was required in the use case. However, voice recording could have been an example for this kind of attribute. Indeed, voice

recording is asynchronous since people can access to the records afterwards. Likewise, no store attributes nor transfer attributes were identified since there is no asynchronous access concerning the discussions. Finally, the manipulation attributes concerning Synchronous and Concurrent (SynC) discussions can also be defined as attributes needed when several elements are shared at the same time (Synchronous) and handled by several participants (concurrent). For example, if participants need to have a discussion at the same time (synchronous) and several participants should be allowed to take the control of the system at the same time (concurrent), this situation will originate different specifications than if only one participant (no concurrent) is allowed to have the control of the system.

Fulfilling the table for all the activities assist the identification of all the features needed by the collaborative environment. The exhaustiveness of the table aims at bringing the appropriate elements to the designer of the environment to reflect and consider different possible situation. The table can be fulfilled by the designer or by the user. However, it will be better if they can fulfil the table together (“two heads are better than one”). The use of the table does not exempt the development of an environment with missing elements, and at the same time not using it entirely, does not mean a failed development. Nonetheless, its use reduces the risks of missing something which in industrial context means time and money.

In the use case, for each specification the participants have defined also the importance of the requirement (must or want) in order to take into account the budget constraints.


Communication activities	Access		Store	Transfer	Manipulation		
	Sync	Async			SynC	SynNC	Async
Discussions	Min and max total number of participants to be connected: 3-12 Software used for voice transfer of all participants: skype for bussiness, phone Internet connexion: delay accepted: 1 second Fluidity of the communication: Must	Voice recording (Yes or No). NO	<i>If yes:</i> <i>Size of the records</i> <i>Storage time</i> <i>Participant having access</i>	NA	# of participant allowed to manage the call: 1	Si # of participant allowed to manage the call = 1 	NA
Screen sharing	Number of remoted connected people involved during the sharing activity: 0-10 Number of "present" people involved during the sharing activity: 3-12 Number of elements to share during the meeting: 3-10 Extention of the elemnts: office: .doc, .xls.ppt. Pdf simulink: .slx Tools: screen, laptops Internet connexion: delay accepted: 2 seconds Fluidity of the sharing: must Elements size: 30K-3Gb	NA	Elements size: 30K-3Gb Storage time: 1 month after TDR date Storage location: TDR Shared forder : //H:\PROJET TEO - SIM\Misc	NA	# of participant sharing documents in the room: 4-6 # of participant sharing documents remotely connected: 0-2		Number of elements to be manipulated lately: 3-10 Extention of the elemnts: office: .doc, .xls.ppt. Pdf simulink: .slx Software: office, simulink

Table 26: Use case examples of quantification

4.7. Feedback and evaluation

At the end of the process we have carried out three extra meetings with the stakeholders of the environment to ensure the coherence and the completeness of the specifications. Then we estimate a quantitative evaluation of the system. The engineers assess that collaborative facilities allow them to save at least one iteration during the TDR phase. This is instead of need ten TDR they will need only nine to solve the problems. Save one TDR means two men/hours for each participant. In average, 10 participants assist to a TDR in the company. Which allow as to save 20 men/hours every 10 TDR. When we estimate the savings in a year (the company predicts about 1000 TDR/year), the number of men/hours saved is 2000 men/hours.

The company already accept to invest in the construction of the collaborative environment. However, due to the administrative procedures, the environment will be operational at the end of 2016. Consequently, we have not been able to carry out the qualitative evaluation across the participants using the environment.

5. Results

Several challenges on bringing collaborative support to the technical design review have been highlighted in both, industry and literature. In spite of the importance of those challenges, except for the NASA handbook (NASA 2007), no work addressing them has been found. Nonetheless, we have found several works addressing general collaborative issues at more general design level. Some examples of the most known approaches are Collaborative Collocated Work (CCW) and Collaborative Computer Supported Work (CCSW) but they are mainly focused on computer support.

More recent researches in STS domain, such as the works introducing *Agile Work Places* (Joroff et al. 2003b) and *CEDOSy* (Roa-Castro, Stal-Le Cardinal, Callot, et al. n.d.) approaches, propose a more holistic view of collaborative issues. The implementation of those approaches to the TDR context, allowed us to propose guidelines for the development of collaborative environments and to apply them to an industrial use case. Six guidelines have been proposed aiming at the design an appropriated TDR environment: scenario description, stamping the activities according to the proposed list, listing the user needs as functions of the system, cross checking the activities and the functions, dimensioning the elements of the environment, feedback and evaluation.

The main contribution of the scenarios description is the workplace development driven by the organisational behaviour. Indeed, this starting point assist an actor based development since the actions carried out by the actors should be supported by the workplace. The scenario representation also facilitates the representation of several situations, the comparison between them and a potential generalisation. For instance, at the beginning of the use case, we have sketched several scenarios in order to obtain as much information as possible. However, after analysis, we have observed that TDR events were similar, and the special features could be taken into account later, during the quantification process.

The use of the stamps in the scenarios is disclosed useful to understand and to represent the complexity of the design process. We also notice that the bigger number of stamps is used for the same activity, the bigger is the possibility that the activity needs an important number of resources for being supported. In addition, we have observed that those activities are also revealed as the main iteration points during the TDR. They can be identified as the main iteration points in terms of number of iteration but also in terms of involved participants. The list proposed to stamp the collaborative activities supports considerably the use case. We use all the proposed activities and the list covered the use case scenarios. However, we are conscious that it can be enlarged.

The functional analysis allows us to specify the user needs, but it also allow us to identify the knowledge shared and exchange through the system, as a new key element to improve collaboration. The transfer and capitalisation of this knowledge have been object of a second paper, presented in the second part of this research (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.). The cross check ensures the transition between the user needs and the ICT needs. Then, the proposed elements to quantify the ICT elements guarantee an extensive description of the possible collaborative scenarios (e.g. : number if people participating, kind of information exchanging, etc...). It also facilitates the translation of these scenarios and needs into specifications.

Finally, the feedback and evaluation step ensures the global coherence of the environment and the fulfilment of the user's needs. It is also a helpful mean to evaluate the user's satisfaction and the improvement on the overall design process. These results are in accordance with other research claiming that the improvement of the workplaces has a positive impact on the efficiency and productivity (Morgan & Anthony 2008), (Joroff et al. 2003a), (Teasley et al. 2000).

The initial industrial observations and the obtained results allow us to validate the first hypothesis driving this research: *A lack of an appropriate work environment leads to collaborative problems and consequently on the global design process*. Indeed, several elements of the collaborative environment assisting information sharing help to overcome the difficulties observed regarding the understanding between participants. Likewise, the second hypothesis - *The minimisation of collaborative problems, has a positive impact on the TDR process, and consequently on the global design process* - is supported by the results of the implementation. The quantitative evaluation of the system suggests that one TDR design loop is saved thanks to the environment, which means 2000 men/hours saved per year. Then, we conclude that the use of an appropriate work environment improves the global design process by decreasing collaborative issues and misunderstanding.

These results also supports the literature insights regarding the social nature of the design process (Sonalkar *et al.*, 2016), (Tolbert *et al.*, 2016) and bring new insights regarding the articulation among the design research and the industrial applications

6. Conclusions and Perspectives

This paper presents a six guidelines proposition aiming at the development of collaborative design review workplaces. The proposed guidelines are helpful especially in the TDR context but applicable to other design situations. The resulting workplaces could be also conveniently adaptable through a proposed qualitative evaluation. We implement two STS based approaches - Agile Work Places (Joroff *et al.* 2003a) and CEDOSy (Roa-Castro, Stal-Le Cardinal, Callot, *et al.* n.d.) -to address collaborative TDR issues. A literature review on collaborative engineering design supports has been done. However, researches on this field have not addressed the TDR phases neither an explicit protocol to develop collaborative workplaces which encouraged us to propose guidelines adapted for the development of a TDR environment.

The two main hypothesis that have driven the research presented in this paper are:

- *The minimisation of collaborative problems, has a positive impact on the TDR process, and consequently on the global design process*
- *A lack of an appropriate environment leads to collaborative problems, having a negative impact on the TDR process, and consequently on the global design process*

Both hypotheses have been validated through the results, allowing us to affirm that the use of an appropriate work environment improves the global design process by decreasing collaborative issues and misunderstanding.

We conclude that the use of the guidelines facilitates the development of the collaborative environment and improves the overall design process by reducing the number of iteration needed to solve the problems discussed during the TDR. In addition, the guidelines respect the nature of the organisation by driving the development of the workplace on its behaviour. Nonetheless, even if an appropriate environment is set up, it is not necessarily enough to take the right decision at the end of the TDR. We have noticed that the transfer and capitalisation of the information discussed during the review is missing. Each new problem considered during the TDR is a new beginning. In general, the historical records are not documented and the knowledge transfer is imprecise. A suitable capitalisation and knowledge transfer process is required. These observations open a second research hypothesis, that we address in the second part of this paper (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.).

To conclude, the short term perspectives of this work are focused on the qualitative evaluation of the implemented environment at Renault and the future implementation in other contexts. Nevertheless, several long term perspectives have been identified after all, like the examination of the recording methods allowing the participants to be more focused on the discussion than notes writing. Likewise, we are still working on some metrics allowing to measure the impact of the collaborative solutions at different levels in the company. Finally, another interesting point to explore will be the adaptation of the guidelines to other design situations and its generalisation.

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Paper # 5

Developing sociotechnical systems for collaborative design review Part II: Guidelines proposition and application to the vehicle industry for the development of capitalisation supports

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Abstract: *This paper presents a guidelines proposition to develop collaborative supports for Technical Design Review (TDR). The proposed guidelines follow a sociotechnical systems (STS) approach and are supported by specific data elements. The suggested data elements are the result of the juxtaposition of three key concepts for collaborative design: capitalisation steps, success TDR criteria and collaborative mechanisms and methods. An implementation of the guidelines is illustrated through an application in the vehicle industry. The results allow us to conclude that the implementation of an appropriate capitalisation support improves collaboration through TDR participants. The guidelines and the data elements proposed.*

Key words: *collaborative design, design knowledge, computer supported design, engineering design, sociotechnical systems (STS).*

1. Introduction

Today, globalisation circumstances impose important market and customer pressures to the industry. On the one hand, companies must reduce their expenses and the time to market in order to remain competitive. On the other hand, they should develop more innovative products to respond to their client's needs. These pressures increase both, product and process complexity within the organisation. Collaborative Engineering Design (CED) approaches have emerged during the last decades as a part of the practices assisting the management of new complexities. The work presented in this paper aims at proposing guidelines to develop capitalisation supports during the engineering design process in order to improve collaboration between actors. The guidelines are addressed to a particular design phase: the TDR (Technical Design Review). A more detailed view of the positioning of this research regarding STS and CED works can be found in PART I of this work (ref us PART I)

We focus our attention on the TDR because of its importance in the design process. TDR is often positioned between preliminary design and final design phases. The importance of the TDR resides in its effectiveness to solve design problems and to present new solutions reaching the requirements. Indeed, several publications mention design review phases as a crucial phase in this process (Huang 2002), (NASA 2007). Looking for TDR knowledge capitalisation in the literature, we have found a relevant work proposing three meeting analysis tools called *TCS*, *MCT* and *IMT* (Huet et al. 2007). The first one aims at analysing meetings discourse through an intelligent segmentation of the transcriptions. The second one proposes a meeting capture template, and the third one proposes an information mapping technic. These propositions are very pertinent for the analysis of the DR. Indeed, in the first part of this research (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.) we have used some of the *MCT* insights. Even if these propositions support the analysis of the exchanged knowledge during the TDR, they do not provide a capitalisation support assisting it. Actually, no capitalisation support assisting TDR reviews have been found in the literature, even so the literature confirms the importance of historical information supports as a success criteria in the reviews (NASA 2007). In addition, industrial observations done for this research at Renault reinforce the need to bring a capitalisation support to the TDR process.

Even if the works mentioned before endorse the analysis of the exchanged knowledge during the TDR and confirm the complexity of the cognitive process related to the design thinking, they do

not provide a capitalisation support assisting it. Actually, we have found a gap in the literature concerning the design of capitalisation supports assisting TDR, even so the literature confirms the importance of historical information supports as a success criteria in the reviews (NASA, 2007). In addition, industrial observations done for this research at Renault reinforce the need to bring a capitalisation support to the TDR process.

In Part I of this research (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.) we characterise the TDR activity mostly as knowledge transfer activity. The guidelines for collaborative environments proposed in the same paper facilitate the knowledge transfer among the participants during the TDR. Nonetheless, as part of the conclusions presented in Part I, the need of a support assisting the knowledge transfer in between TDR was introduced. In the present paper we introduce a guidelines proposition in order to , first, facilitate the transition of tacit knowledge into explicit knowledge and second, enable the explicit knowledge transfer through the TDR. The main objective of the guidelines is to ensure lasting collaboration while supporting the Technical Design Review process. We expect that an appropriate capitalisation and knowledge transfer support will enhance collaboration between the TDR members. The guidelines proposition is based on both: collaborative mechanisms improving common understanding and knowledge capitalisation principles.

Two main hypothesis drive the research presented in this paper:

- *The minimisation of the misunderstanding problems improves the collaboration in the TDR context*
- *We can reduce the misunderstanding problems through an appropriate capitalisation and knowledge transfer support.*

This paper is organised as follows: a literature review on knowledge management and capitalisation is presented in section 2. Section 3 introduces the guidelines proposition to develop capitalisation supports. An application to the vehicle industry is illustrated in section 4. Section 5 presents the results and conclusions. And, finally, section 5 summarises the conclusions and the future work.

2. A literature review on knowledge management and capitalisation

The current signification of the term Knowledge management (KM) appears for the first time in the 80's (Sveiby & Lloyd 1987) (Wiig 1988). However, KM field of study starts to become common in the academia during the 90's, with the Nonaka and Takeuchi work (Nonaka & Takeuchi 1995). Even if KM seems a young field of study, the knowledge issues have been studied since the antiquity (Robin 1970). Today, the importance of KM studies are not only related to human resources management and competences, but to the "added-value creation" resulting from the good knowledge governance (Grundstein 2000) and from the usage of the knowledge among different co-workers (Baird & Henderson 2001).

More recent studies, focus their attention on more specific KM issues. With the arrival of new organisational theories, the perception of the knowledge within the organisation has evolved. The link between the organisation and the KM appealed numerous researchers. K. Wiig (Wiig 1997) wrote about how KM helps companies act intelligently. Then, Davenport and Porsak (Davenport & Prusak 1997) have positioned the knowledge as part of the capital of the organisation. These works have probably motivated Nonaka et al. (Nonaka et al. 2001) to introduce "knowledge assets" concept, which they define as "the firm-specific resources that are indispensable to create values to the firm". Later, others authors (Maier 2007), (Baird & Henderson 2001) define KM in the organisational context as a "resource of the organisation that can be associated to the organisational learning and to the organisational memory".

Different kinds of knowledge have been studied in KM and organisations field. Nonetheless, in this research we focus the attention on both: the transition from tacit knowledge to explicit knowledge, and the capitalisation and transfer of explicit knowledge. Nonaka & Takeuchi, Grundstein and Oladejo et al. (Nonaka & Takeuchi 1995), (Grundstein 2000), (Oladejo et al. 2010) have already studied the importance and the concepts allowing the transition from tacit knowledge to explicit knowledge and vice versa. In the knowledge spiral Nonaka & Takeuchi propose socialisation and externalisation as means to make the transition between the two types of knowledges. These works give us the insights to look for methods allowing the socialisation and externalisation practices in the TDR context.

Some methods allowing this transition have been found in the literature. D. Penuic (Penciu 2012) presents a large review of these methods in her thesis, including: semantic representation, ontologies, descriptive logic, and annotations. In the organisational context, where data, information and knowledge are often mixed, the Ackoff model (Ackoff 1989) has been largely used to understand the transition. This model is helpful to distinguish between the three elements (data, information and knowledge). Indeed, they are represented by a pyramid, having in its base the data and the knowledge on the Top. Our interest regarding the technical design review (TDR) is to translate the tacit knowledge into explicit knowledge or information, and then into data that can be capitalised.

Grundstein (Grundstein 2000) defines knowledge capitalisation as a storehouse of knowledge used and produced by the company that contributes to increasing the company's capital. In general, authors agree on the importance of knowledge sharing and capitalisation in the company for its future reuse (Oladejo et al. 2010), (Renaud et al. 2004) . Based on the lecture of knowledge capitalisation studies, we conclude that knowledge capitalisation methods are enablers to: formalise the knowledge, capture and use the knowledge, clarify problems, increase proficiency, increase the comprehension of complexity, accelerate quick modifications, find better solutions and increase innovation.

Our purpose is to translate and capitalise the knowledge needed during the TDR in order to improve collaboration. Two interesting researches using KM to improve collaboration have been found. The first one, is a research in telemedicine domain (PAUL 2006). This research refers to collaborative elements improving knowledge transfer, knowledge discovery and knowledge creation. The second one, is a study on collaborative design where the influencing factors for creating shared understanding between actors in multidisciplinary design teams have been identified (Kleinsmann et al. 2007). Nevertheless, no research aiming at improving collaboration through KM practices in TDR have been found in the literature.

The proposition of guidelines for the development of capitalisation supports presented in the next section ensures the knowledge transformation principles mentioned before. In addition, it ensures

the collaborative practices improving knowledge sharing proposed by Kleinsmann et al. (Kleinsmann et al. 2007) and take into account the NASA success criteria for the TDR (NASA 2007).

3. Collaborative capitalisation guidelines

The proposition of the capitalisation guidelines is based on:

- The Industrial observations concerning knowledge transition (tacit to explicit)
- The Analysis of the transition and capitalisation needs regarding the literature.

This proposition fulfils both, the industrial needs and the gap in the literature. Industrial observations are presented in sub-section 3.1. The needs analysis is introduced in sub-section 3.2. Finally, the capitalisation support guidelines are proposed in sub-section 3.3.

3.1.Industrial Observations

To understand how the knowledge transition (tacit to explicit) occurs in the TDR, we have observed TDR interactions and exchanged documents during the entire phase. According to Davenport and Prusak (Davenport & Prusak 2000) the knowledge is not only present in the documents or in the repositories of the company, but also in its routines, practices and standards. Therefore, the observations are an essential input for this research. The industrial observations have been done at Renault. In total, we have assisted to 25 TDR, we have analysed eight kind of documents and we have interviewed 7 engineers manipulating the documents.

We describe the current situation in Figure 56. We synthesise the knowledge transfer activities in TDR 1 and TDR 2 rectangles (a detailed description of all the activities carried out during the TDR can be found on Part I of this work (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.)). Regarding the knowledge spiral proposed by Nonaka & Takeuchi (Nonaka & Takeuchi 1995), we catalogue these activities as socialisation practices. Socialisation practices are the first step to start a transition from tacit knowledge to explicit knowledge. The documents sharing activity is represented by the exchanged documents (rectangle of the middle in Figure 56). we catalogue this activity as an externalisation practice. Which is the second step for the transition. Those practices represent also

the transition between knowledge, information and data (Ackoff 1989). We use the left rectangle in Figure 56 to represent the knowledge creation activities taking place between two TDR. These activities aim at solving the problems identified during the first TDR in order to reach the requirements. At the end of the TDR, tasks are split and the concerning participants should socialise and externalise the solution in the next TDR.

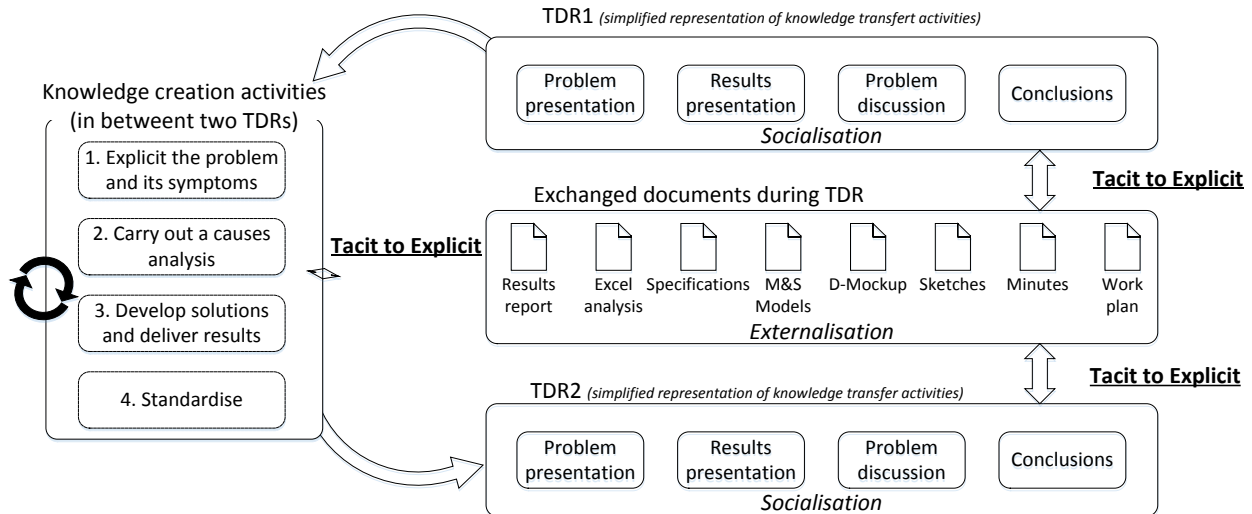


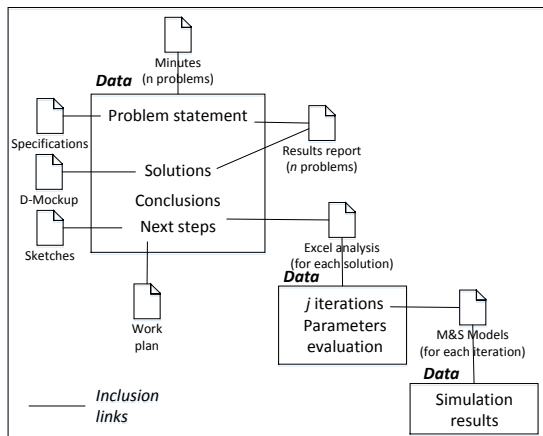
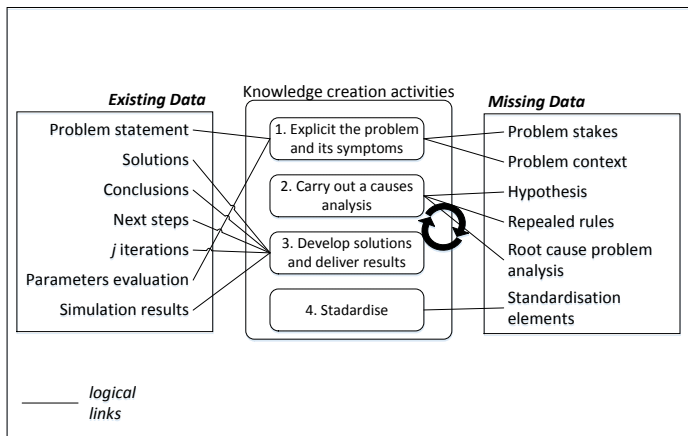
Figure 56: Industrial observations: current situation description

The current externalisation through the documents allows knowledge transition. We notice that, TDR participants are used to computerise all the information. They transform the information into files. Even the oral exchanges during the meetings are either transcribed in the minutes or photographed (if the board is used). However the content of the documents is not standardised, which leads to a lack of information in function of the person in charge of the document. In addition, the knowledge creation activity is not supported by the externalised data as it should. Consequently, several loops are needed to find the appropriate solutions. These loops are represented in Figure 56 by the cyclical arrows at the left of *knowledge creation activities* rectangle. The engineers contributing to the workshops and interviews agree on the fact that today, finding the right CM is still a very trial-and-error process. These observations are in accordance with the literature on engineering design process which presents the iteration as inherent characteristic of the design process (Wynn et al. 2007). Even if some iteration tasks are useful in the design process (Costa & Sobek 2003) the rework task need to be removed, and the challenge in the modelling iteration needs to be addressed. The use of a capitalisation support can also tackle those

problems by: standardising the data to be externalised, offering a guide to the problem analysis and providing the historical information about the past developed solutions.

Using the exchange documents identified, we analysis its content and the needs regarding the knowledge creation activities. We illustrate the documents content analysis in Figure 57. First, we identify the data contained in each document (Data Analysis part I in the figure). Then, we illustrate the data duplication among the document on the left side of Figure 57 (data analysis part II). No document contains the totality of the data. However, the minutes is the document containing most of the information and its format is very similar. No template is established. It is up to leading member to decide the guidelines of the day. Both, lack of guidelines and historical support are closely linked. In fact, the capitalisation process is a “heritage view” (NASA 2007) for the vehicle construction. Without appropriate guidelines, the capitalisation of the information requires a lot of work.

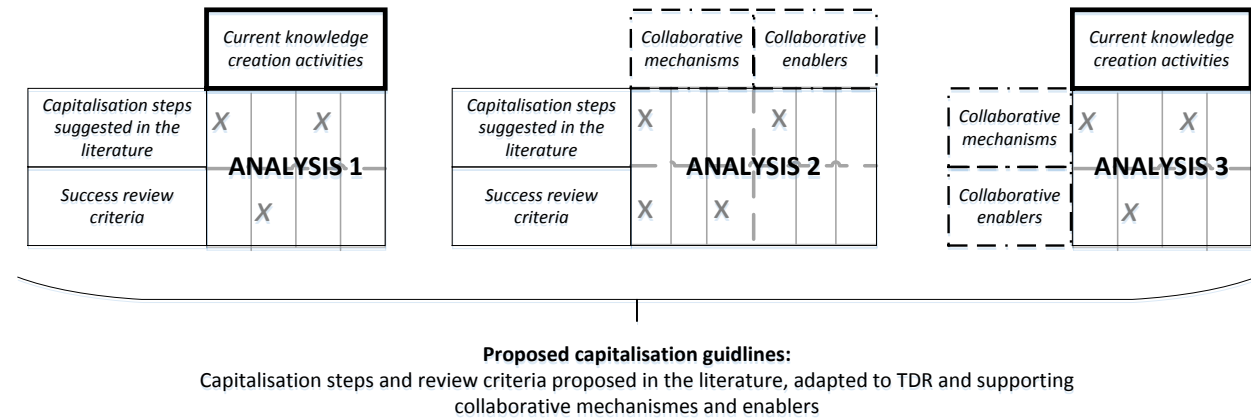
Second, we observe that short time is dedicated to the cause analysis. Most of the time is allocated to development activities. This observation is consistent with the document analysis. On the right side of Figure 57, we can observe that most of the documents are dedicated to the development phase, and no official document exists for the cause Analysis. Comparing the existing data regarding the knowledge creation needs (right side of Figure 57) we are able to identify the missing data. This data corresponds to information shared during and between the TDR that we have not found in the existing documentation. Indeed, we observe that senior members of the TDR, often call on the experience to mention similar cases and the CM proposed at the time. However, no historical support of past solutions exists today.

DATA ANALYSIS PART I**DATA ANALYSIS PART II****Figure 57: Data analysis part I and II**

The scattered data, the lack of uniformity between the documents, all the missing capitalisation system and the process driven more by problem solving than problem analysis, deteriorate collaboration and slow down the design process significantly.

3.2. Current TDR elements and literature

Aiming at improving collaboration through capitalisation activities, we look for the capitalisation steps suggested in the literature and we compare them to the current TDR knowledge creation activities at Renault. We also compare those activities to the success criteria of a review. Then, we analyse the existence of collaborative mechanisms and enablers in the current activities. Finally, we identify the capitalisation steps and the success criteria linked to those mechanisms and enablers. We illustrate the methodology used for the analysis in Figure 58.

**Figure 58: Analysis methodology**

Starting by Analysis 1 (left table in Figure 58) we study the current knowledge creation activities regarding the six main capitalisation steps suggested in the literature (Grundstein 2000), (Oladejo et al. 2010), (Renaud et al. 2004). We summarise in Table 27 the existence (check mark), the lack (cross mark) and the analysis of each of the six steps suggested in the literature, regarding the current knowledge creation activities at Renault (c.f: knowledge creation activities 1 to 4 in Figure 56 and Figure 57)

Step #	Capitalisation steps suggested in the literature	Current knowledge creation activities				Analysis
		1	2	3	4	
1	Extraction/Elicitation: Knowledge must be externalised. [2], [3]	✓	☒	N/A	N/A	Today, an externalisation of the knowledge is done, but the externalised information is not enough to identify at the first attempt the right problem causes. A deeper cause analysis is needed
2	Location: knowledge must be must be selected, identified, located, characterised and classified. [1], [2]	✓	☒	N/A	N/A	Knowledge selection and classification is not done at the beginning of the process but at the end, when several solutions have been tried. This is a very time consuming approach. The selection and classification should be done right after the externalisation
3	Preservation/Modelling/Representation: Knowledge must be conceptualised, formalised, conserved and structured. [1], [2], [3]	☒	☒	✓	☒	Modelling and representation are activities are the most developed during the TDR. Engineers concentrate the most part of their attention on those activities. However, no preservation phase exist today since no capitalisation activity is encouraged
4	Storing: Knowledge must be stored and temporal attributes must be used. [3]	☒	☒	✓	☒	Literature suggests clearly the storage, or capitalisation, of the knowledge. But, once again, this stage is not completed today

5	Exploitation/Application/Value enhancement/Feedback: Knowledge must be used, shared, exploited, accessed, disseminated and its reuse must be facilitated. Knowledge must be used more effectively and improved and be put at the service of the company. New knowledge must be created. [1], [2], [3]	☒	☒	✓	☒	As mentioned before, modelling process is the most mature activity. However, only the current exploitation is highly developed. The future exploitation and enhancement is not possible due to the lack of capitalised information. The literature only differentiates between the current and future exploitation. For the other authors, "exploitation/application" contains both. We decided to differentiate between both activities (that in our case are well distinguished).
6	Maintain: evaluated, made updateable, and improved. [1]	☒	☒	☒	☒	The upgrade and maintenance of the information does not exist today

Table Literature:[1] (Grundstein 2000), [2] (Renaud et al. 2004), [3] (Oladejo et al. 2010)

Table 27: Capitalisation steps suggested in the literature for TDR knowledge creation activities

- The first step suggested in the literature is the extraction of the knowledge. This is the knowledge externalisation or the transition from tacit to explicit knowledge.
- The second step is the knowledge location, this is the selection of the knowledge, but also its characterisation and classification.
- Third, fourth and fifth steps (respectively: representation, storing and exploitation) are presented in the literature in different order. Some works merge third and fifth steps (representation and exploitation), while others split them, distinguishing between the current (representation) and the future (exploitation) knowledge usage. Likewise, some works do not explicit the fourth step (storing), but they include it tacitly. To be as specific as possible we include the three steps separately in Table 27.
- The last step is the maintenance and update of the knowledge.

The lack of standardised documentation often hinder the problem analysis process and the possible reuse and enhancement of the proposed solutions. In addition, we confirm that not enough time is dedicated to problem analysis (steps 1 and 2) in spite of the importance of those steps to succeed on the rest of the activities. Indeed, the literature highlights the importance of the elements related to the problem statement and documentation in the review (NASA 2007). A clear definition and documentation of the purpose/scope, the timing, the objectives, the all no-compliances and the

selected solutions are crucial to improve a review. In addition, these elements will be time reducing in future analysis.

In the second part of the analysis 1, we compare the current knowledge creation activities to the review success criteria (NASA 2007). Seven review success criteria have been extracted from the proposed criteria by the NASA and have been adapted to our case (changing the word *program* by the word *project*). These criteria are: the alignment of the requirements at different levels, the definition of the interfaces with other projects, the proposition of cost-effective solutions, the reuse of the proposed solutions through different projects, the change propagation plan, the validation and verification approaches and the strategies for risk mitigation. We present the criteria and their analysis regarding the current TDR situation in Table 28. Among the seven success criteria concerning TDR, only three of them are present through the current knowledge activities (the proposition of cost-effective solutions, the reuse of the proposed solutions through different projects and the validation and verification approaches). However these criteria are not systematically applied, and their quality depends significantly on the people carrying them out. The remaining four criteria have not been found among our observations at Renault in their current TDR.

	Literature	Existence	Analysis
Success criteria	The TDR stakes and requirements are in face with the high-level project requirements	☒	The high level stakes are not identified
	Defined interfaces with other projects are identified and approved	☒	The possible interfaces with past and future projects are not formalised and only few experts have this knowledge
	The TDR propositions provide a cost-effective program solutions	☒/✓	The problem solution proposition, sometimes does not provide a cost-effectiveness evaluation
	The propositions support one or several project requirements	☒/✓	Since the interfaces with other projects are not formalised, the proposed solutions are not able to support other projects .Except when the same stakeholders are involved
	The plans for controlling project requirement changes have been approved	☒	No change propagation plan are identified today
	The approach of verifying compliance with project requirements has been approved	☒/✓	No specific approach has been established. However, the proposed solutions are always verified regarding the requirements
	The mitigation strategies for handling identified major risks have been approved	☒	No mitigation strategy has been identified

Table 28: TDR success criteria analysis

In the analysis 2 (table of the middle in Figure 58), we study the existence of the collaborative mechanisms and enablers (Kleinsmann et al. 2007), in the current knowledge creation activities. Eleven elements enabling or hindering the collaboration have been analysed. Those elements could

improve (or decrease) the shared knowledge creation. The literature proposes grouping the elements according to three levels: actor level, project level and company level. We consider a fulfilled or halfway fulfilled element as an enabler (if it is always or often present in the current TDR situation), and the not fulfilled elements as barriers (if the element does not exist in the current TDR situation –it never appears during the observations-). Concerning the actor level, we consider the following elements: the ability of the actors to make the transition between tacit and explicit knowledge, the similarity in the language used between the actors, the applicability of the actors experience and the empathy regarding the assigned tasks. The last element is completely fulfilled today, and the actors show a high empathy on their work. The other three elements are halfway fulfilled. Concerning the project level, five elements have been analysed. Among these five, two of them are completely fulfilled (labour division and controllability of product quality), two of them are halfway fulfilled (quality of the project documentation and rigor of the project planning) and one of them is not fulfilled at all (efficiency of the information processing). Finally, concerning the company level we consider two elements. The first one is the organisation of the resource. This item is identified as a barrier since it is not fulfilled at all. The second one is the responsibilities allocation and is only halfway fulfilled.

Five collaborative mechanisms have also been analysed. Two of them are not fulfilled at all (the integration of the knowledge at different levels, and the reduction of the lack of information), while the remaining three are only a halfway fulfilled (detailed knowledge of each other, communication structure and interdependencies definition). Both, TDR success criteria and collaborative mechanism and enablers coincide on the importance of stablishing clear interdependences and proposing reusable solutions.

In the analysis 3 (right table in Figure 58) we identify the capitalisation steps and the success criteria linked to a collaborative mechanisms and enablers. All the steps and criteria are related to at least three enablers or mechanisms. Similarly, the mechanisms and the enablers are related to at least one step or criteria. Among the enablers, two element at the project level are related to all the steps and criteria: *the quality of the project documentation* and *the efficiency of information processing*. Likewise, the collaborative mechanism: *Detailed knowledge from the content* is also linked to all the steps and criteria. At the actor level, *the ability to transform the knowledge* and *the similarity*

in the language are also related to several steps and criteria. The results of this analysis demonstrate the importance of the capitalisation support during the TDR to improve collaboration.

We summarise analyses two and three in the Annex 1. Those analysis, allow us first, to identify the missing steps on the current TDR process; second, to assess the importance of each step; and third to evaluate the use of the means assuring an efficient TDR, such as, success criteria and collaborative mechanisms. Indeed, the tacit to explicit knowledge transition integrates the subjectivity of actors. However, this subjectivity can be reduced by formalising some data and by proposing appropriate guidelines facilitating the information sharing and capitalisation. The guidelines proposed in sub-section 3.3 are based on the main steps suggested in the literature, but in addition they integrates several means to ensure the success of the TDR by enhancing collaboration at the same time.

3.3. Proposed Guidelines

Each TDR is unique, and several factors, such as design complexity or people involved may turn a strict guidelines into an inappropriate support. Being able to create a support as specific and as general as possible has been one of the most important challenges during its development. . The proposed guidelines are the result of the juxtaposition of the elements studied in sub-section 3.1 and 3.2. We define the capitalisation guidelines *as a set of activities assisting the development of a capitalisation support through specific data elements*. The guidelines and the data elements are helpful especially in the TDR context, but adaptable to other design situations. The eight proposed guidelines are:

1. Detail the problem context and specifications
2. Describe the problem in detail and gather the historical information related to the problem
3. Set the target to reach
4. Analyse deeply the possible problem causes
5. Identify possible solutions
6. Detail the specific features of the selected solutions to be developed
7. Present the results (for each solution)
8. Standardise (if new standard is emerging)

Likewise, we detail the data needed for each guideline. In total, we identify 37 data elements satisfying, capitalisation steps and success criteria and supporting the collaborative enablers and mechanisms (c.f. Annex 2). The proposed data elements are distributed over the eight guidelines helping engineers to make the tacit to explicit knowledge transition in a standardised way, providing at the same time, a mean supporting TDR capitalisation.

We summarise the capitalisation guidelines for the development of collaborative supports, and their corresponding data elements in Figure 59. The eight guidelines are represented by the numbered rectangles whereas the data elements are represented by the fulfilled grey boxes in the figure. To explain each guideline and data element we use an industrial use case introduced in section 4.

It results important to clarify that we do not present any element in the guidelines related to the user's need because this element is studied in the first group of guidelines presented in Part I of this paper. Indeed, the establishment of a collaborative environment is necessary to develop collaborative supports.

PROBLEM DESCRIPTION		
1. Detail the problem context and specifications <div> <div>ID</div> <div>Project Name</div> <div>Milestone</div> <div>Department</div> <div>Team</div> <div>Person in charge</div> <div>ID Model</div> <div>Zone</div> <div>Additional Information</div> <div>Start date</div> <div>Planned end date</div> </div>		2. Describe the problem in detail and gather the historical information related to the problem <div> <div>Importance</div> <div>Abstract</div> <div>Symptoms</div> <div>Stakes</div> <div>No respected requirements</div> <div>Linked problems and requirements</div> <div>Released design rules</div> <div>Imposed design rules</div> <div>Last standardisation</div> </div>
3. Set the target to reach: <div>Target(s) or objective(s) to attempt</div>		
PROBLEM ANALYSIS		
4. Analyse deeply the possible problem causes <div> <div>Observable (s) : Detailed symptoms description</div> <div>Analysis</div> <div>Influencing factors</div> <div>Probable causes</div> <div>Major Cause(s): Hypothesis + test(s)</div> </div>		
PROBLEM SOLUTIONS		
5. Identify possible solutions <div> <div>Proposition 1 to n (possible solutions)</div> <div>Target impact</div> <div>Feasibility</div> <div>Impact on other performances</div> </div>	6. Detail the specific features of the selected solutions to be developed <div> <div>Proposition 1 to n (possible solutions)</div> <div>Test(s)</div> <div>Validation</div> </div>	7. Present the results (for each solution) <div> <div>Current results</div> <div>Past projects results</div> </div>
STANDARDISATION		
8. Standardise (if new standard is emerging) <div>New standard or rules for problem solution</div>		

Figure 59: capitalisation guidelines and data elements for the development of collaborative supports

4. Industrial Use Case

We carry out a use case at the French vehicle manufacturer Renault in order to implement and illustrate the capitalisation guidelines presented in section 3.3. The use case aims at providing a capitalisation support to the design teams during the technical design review (TDR). A total of five implementations have been done through different projects.

We present the summarised version of the support in Figure 60. The support presented in Figure 60 encloses eight black border rectangles (sections), each one of which represents the 8 guidelines proposed. For each section, the grey (fill coloured) rectangles contain the corresponding data elements. Figure 60 is a summarised A3 view of the support. However, by clicking on each section, it is possible to see a more detailed descriptions and images. This is especially important for the guidelines 6 (*Detail the specific features of the selected solutions to be developed*), where the detailed information contains all the iterations executed to reach the solution.

The support needs to be filled by the different members participating in the TDR. We identified the members in Part I of this work (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.): the performance department, the design department and the simulation department. At the end of each section we also indicate the participant filling the related data fields. We explain and exemplify the eight guidelines and their data element from sub-sections 4.1 to 4.8.

4.1.Guideline 1: Detail the problem context and specifications

This sub-section aims at specifying the highest level information concerning the problem. First, aiming at the future use of the information, the designation of a unique ID for the problem to study is needed. Then, engineers should indicate the project name, the milestone of the project, the department in charge of the problem, the team solving the problem and the person in charge. This information is important for the project documentation but also to structure the communication and interfaces between actors (identify the right interlocutors). Once this information is completed, the highest technical information level should be indicated. This is, the ID of the model having the problem, the zone affected and some additional high technical information level if needed, such as, a test number or a number of incident. Finally, the current day (start date) and the planned end date should be determined and noted down. This section is filled by the performance manager. The performance manager is the person in charge of the problem prioritisation at Renault.

4.2.Guideline 2: Describe the problem in detail and gather the historical information related to the problem

A proper identification, description and characterisation of the problem will facilitate the target setting and the analysis steps. In addition, it will assist the development of the right solutions. We propose nine data elements to describe and characterise the problem. The first element to identify

is the importance of the problem. The company has established a scale from 1 to 3, where 1 means a problem blocking the project and 3 means a minor problem under control. Second, a concrete abstract of the problem should be formalised, for instance the problem abstract of the use case is the *over-speeding point in frontal crash*. The need of a brief description leads the people to work on their capacity to transform the knowledge and to use a generic vocabulary. The third data element to describe is the problem symptoms. Those are the observation (the reasons why we can see that there is a problem), which can be seen as a medical check. The problem symptoms of the use case are: a distortion of 5mm of the tunnel and a fracture on one specific welding point in the roof. The fourth data element to describe is the stakes. Expliciting the higher level stakes allows the participants to give sense to their work. In the use case, not finding a solution to the *over-speeding point in frontal crash* problem could lead to a loss of one start on the vehicle classification.

The fifth data element corresponds to a list of the non-respected requirements using the appropriate company designation. In Figure 60, we can see two requirements listed: N20 and N21 (N20: requirement regarding the manufacture of the buffer. N21: requirement related to the tunnel channel of the vehicle). The specification in the support of the non-respected requirement is important to establish the link between the project and a potential change propagation analysis. Then, in the sixth data element the linked problem and/or requirements should be specified. In the use case, two linked requirements have been identified (N22 and N22a). The identification of these requirements and problems is important to establish the change propagation plan and to keep clarifying the problem interfaces. Likewise, the identification of released and imposed design rules (data elements number seven and eight) can give some insights to the problem analysis. This information is difficult to find and is often based on the actor's experience. Finally, the exploration of the solutions given to similar problem in previous projects could prevent the development of a solution that already exists (last standardisation in Figure 60). Indeed, after development, and thanks to the experience, TDR participants have confirmed that sometimes the "re-development" situations are common. A proper capitalisation, should allow (in the future) the research of the past projects information through the problem symptoms.

This section is filled by the performance manager in cooperation with the rest of the participants, especially for the elements calling on the experience.

4.3.Guideline 3: Set the target to reach

After a detailed problem description, the participants should agree on the target to reach. This is the expected results when a solution is found. Section 3 of Figure 60 presents the two targets to reach concerning the use case. The first one applies when no vehicle roof fracture occurs using a 3,5% Al alloy in a crash at 50km/h, and the second applies when the distortion of the tunnel channel is at maximum. Target setting is important to ensure a cost-effective solution and to focus everyone effort in the same direction. Like for section 2, section 3 is filled by the performance manager in cooperation with the rest of the participants, especially for the elements calling on the experience.

4.4.Guideline 4: Analyse deeply the possible problem causes

As mentioned in section 3.1, the current knowledge creation activities lead to several loops during the development and execution of the solutions. This situation is due to the lack of problem description and cause analysis. Finding a suitable solution during the first attempt will avoid design loops and decrease the global design development time. Section 4 of the support, is inspired on the Radical Innovation Design (RID) methodology (Yannou et al. 2011). RID methodology pays attention especially to the causes analysis and factors involved. We also include the Root cause analysis concept (Vorley 2008). In this concept the selection of the major causes is necessary before solving the problem. The identification of the probable causes and the selection of the most important ones, should drive a pertinent solution proposal (20/80 Pareto's law).

The first data elements to be highlighted are the problem symptoms. A detailed list of observables is suitable. In the use case, engineers have taken back the problem symptoms and have detailed them through models. The detail in the images, shows for example the temperature of the zones around the tunnel channel, or the distances between the welding points in the roof. The use of illustrations facilitates the knowledge transfer and gives a better detail level of the content.

The second data element is the analysis. The analysis, aims at capitalising the factors that engineers used for their analysis. This summarised version only contains a list of the factors studied. The detailed analysis remains "support free" today. It is up to each participant to capitalise it or not. Two main questions drive the analysis of the use case. The first one analyses the environment around the problem observables (*Does the parts next to the tunnel heat the atmosphere?*) and the second one is more related to the symptom itself (*Is the number of roof points enough?*). The formalisation of the key elements used for the analysis is important to improve the ability of the

actor to transform the knowledge, and to build data bases containing helpful elements for future analysis.

The third data elements of the section are the determination of the influencing factors. The definition of the influencing factors is important to enhance the identification of the interfaces, and the eventual change propagation paths. As for other elements related to historical information of the product, the ability to identify those factors is directly linked to the know-how and the experience. Capitalising those information will increase the knowledge-assets (Nonaka et al. 2001) in the company. The influencing factors in the use case include the detailed information about the heating parts next to the tunnel channel, and the total number of welding points, sizes and distances between them.

The fourth and the fifth data elements of the section are the causes. The fourth data element aims at obtaining a list of all the probable causes of the problem (Vorley 2008). In our case, four probable causes have been identified: the size of the welding points, the distances between them, the material of the tunnel channel and the temperature of the elements next to the channel. Among the four causes, two of them have been identified as the major causes of the problem: the size of the points and the material. The identification of the tests validating the causes at the end of the process is also requested. As mentioned before, the identification of the right causes is crucial to save time during the development process. The proposed data field stimulate and encourage participant to analyse and externalise their knowledge. The ROI (Retour of Investment) of the time dedicated to this face will be noticed later in the design process. In addition, the anticipation of the validation tests has already been pointed out in the literature as success criteria for the process (NASA 2007).

This section is mainly filled by the simulation manager and his team. However, they can always call on the experience of the others participants.

4.5.Guideline 5: Identify possible solutions

Once the main causes are determined, the participants think about the possible solutions for each cause. During this step, participants re-design the product in order to reach the requirements. For each possible solution four data elements need to be specified: a short description of the solution, the impact on the target, the feasibility and the impact on the other performances of the vehicle. The first solution proposed in the use case is the modification of the welding points size. Several

diameters should be tested (between 30mm and 40mm). This solution will probably help to reach the target, by avoiding fracture on the roof, however, it may have a negative impact on the durability performance. This solution is feasible with the given budget and time, and its development time is estimated to two days. The second solution concerns the evaluation of the material. The solution consists in evaluating different alloy percentages (between 2% and 3,5%). This solution will probably reduce the distortion and its impact on the durability performance will probably be insignificant. This solution is also feasible with the given budget and time, and its development time is estimated between three and four days.

The data elements identified improves the understanding of the interfaces between the other departments (performances) and they bring a helpful information when trade-off are needed (e.g: choosing between a solution having a longer development time and less impact or the opposite). Capitalising this information is valuable for future projects but also for the definition of the change-propagation policy, the risk management strategy and the integration of the knowledge at different levels of the project also.

Even if this section is mainly filled by the simulation manager and his team, the feasibility data element is provided by the participant from the design department.

4.6.Guideline 6: Detail the specific features of the selected solutions to be developed

The first data element to be identified in this section is the solution itself. The short description of the solution represents the design change. For instance, solution one involves a change on the distance between the welding points. Each solution needs to be tested under different situations. The features describing both, test to do and validation methods for each solution should be specified. For the first solution (modification of the distance between the welding points), eleven sizes (30mm to 40mm included) are tested. For each size, three different speed tests are applied (30 km/h, 45km/ and 50km/h). Each couple {size-speed} represents one iteration. Then to evaluate the first solution, 33 iterations are needed (11 sizes x 3 speeds). At the end of each iteration, the validation is done by evaluating the speed of the fracture, the time that it takes to happen and its angle. The same reasoning is done for the second solution. The second solution needs 48 iterations (16 alloy X 3 speeds), and its evaluation is done through a curve distortion Vs time.

The data elements detailed in this guideline contribute to the definition of the validation and verification approach. In addition, these elements are helpful to structure and prepare the development process. This section is filled by the participant from the design department.

4.7.Guideline 7: Presenting the results (for each solution)

In this section, the data elements of the most important results are presented. Indeed, each iteration represents a given result. As mentioned in guideline six, several iterations are executed under different conditions. Only the iterations which reach the target or which are very close to reach the target are presented. However, an exhaustive support containing all the iterations details can be accessed. For each presented solution on this section, three data elements are required: an illustration, the current results regarding the validation elements defined during the precedent guideline, and the results of the same elements in past projects (if those exist). The two solutions presented during the use case display the value of the three validation elements (the speed of the fracture, the time that it took to happen and its angle). In solution 1, only one of the three elements reach the target whereas solution 2 reaches the three validation targets. If at this point no solution is found, a new analysis should start.

Even if the data elements contained in this section are not detailed, they are enough to complete the global picture of the approach used by the participants to solve the problem and to confirm the hypotheses and analysis presented in the earlier guidelines. These elements, plus the detailed support of the iterations, enable to significantly externalise the knowledge used during the re-design process. In addition, this information also enhances the quality of the project documentation and offers a detailed understanding of the design content.

Since the execution of the iterations are executed by the simulation team, they are invited to fill the data elements of the section.



4.8.Guideline 8: Standardise (if new standard is emerging)

If the modified design is a standardised solution, then it becomes a reference (standard) for the next project. In the use case, no standardisation is established. An example of standardisation could have been changing the distance between the welding points. Then, the new distance will be set at 32mm (solution) instead of the current distance for the future projects. This section is filled by the

simulation team –as they work on the technical aspects- with the agreement of the rest of the participants.

The capitalisation of standardisation is very important to avoid time losses during future projects. It is also important to boost the innovation and to improve the efficiency of the information processing.

1. Problem context specifications					
ID	K12378	Department	Crash	ID Model	mc_1457
Projet Na	Logan	Team	2	Zone	Front top: Z 2b
Milestone	CCM	Person in ch	XXXX	Additional Information	N/A
				Start date	03/08/2016
				Panned	
				end date	10/08/2016

2. Problem description	4. The Root/ Major cause	6. Results																								
Importance K4	Observable (s) : Detailed symptoms description Tunnel distorsion 5mm Fracture on the roof point P56 <div>   </div>	<div> Solution 1 (32mm - 3%AI) <table border="1"> <thead> <tr> <th>Current Results</th> <th>Last Project Results</th> </tr> </thead> <tbody> <tr> <td>OK: 0,02m/ms</td> <td>None</td> </tr> <tr> <td>NOK: 0,03 ms</td> <td>None</td> </tr> <tr> <td>NOK: 13°</td> <td>None</td> </tr> </tbody> </table> </div> <div> Solution 2 (32mm - 3,3%AI) <table border="1"> <thead> <tr> <th>Current Results</th> <th>Last Project Results</th> </tr> </thead> <tbody> <tr> <td>OK: 0,015m/ms</td> <td>None</td> </tr> <tr> <td>OK: 0,028 ms</td> <td>None</td> </tr> <tr> <td>OK: 5°</td> <td>None</td> </tr> </tbody> </table> </div> <div> Solution 3 <table border="1"> <thead> <tr> <th>Current Results</th> <th>Last Project Results</th> </tr> </thead> <tbody> <tr><td></td><td></td></tr> <tr><td></td><td></td></tr> <tr><td></td><td></td></tr> </tbody> </table> </div>	Current Results	Last Project Results	OK: 0,02m/ms	None	NOK: 0,03 ms	None	NOK: 13°	None	Current Results	Last Project Results	OK: 0,015m/ms	None	OK: 0,028 ms	None	OK: 5°	None	Current Results	Last Project Results						
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Abstract Overspeeding point in frontal crash	Analysis Does the parts next to the tunnel heat the atmosphere? Is the number of roof points enough?																									
Symptoms description Tunnel distorsion 5mm Fracture on roof point P56	Influencing factors Detailed list of parts next to the tunnel heating the atmosphere Number of roof points, sizes and distances																									
Stakes Loss 1 start on classification	Probables causes The size of the points seems too small Some distance between points exceeds the optimal distance																									
No respected requirements N20: Buffer / process N21: N20+tunnel channel	The temperature of the athmosphere is not very high. The distorsion comes probably from the material The temperature of the next to tunnel elements																									
Linked problems and requirements N22: N20 + cradle fracture N22a: idem (cradle fracture)	Major Cause(s) <table border="1"> <thead> <tr> <th>Hypothesis</th> <th>Test (s)</th> </tr> </thead> <tbody> <tr> <td>1. Roof points too small</td> <td>Crash</td> </tr> <tr> <td>2. Material heat to much</td> <td>Trear AI 2% and AI3, 5%</td> </tr> <tr> <td>n.</td> <td></td> </tr> </tbody> </table>	Hypothesis	Test (s)	1. Roof points too small	Crash	2. Material heat to much	Trear AI 2% and AI3, 5%	n.																		
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1. Roof points too small	Crash																									
2. Material heat to much	Trear AI 2% and AI3, 5%																									
n.																										
Released design rules None																										
Imposed design rules R567_3: Max number of roof points = 145																										
Last Standardization None																										

5. Possible solution proposition			
Solution	Impact on target	Feasibility	Impact on other performances
1. Roof points btw 30-40mm	Avoid the tear, less p	OK. Less than 2 days	Durability
2. Material test AI btw 2-3,5%	Less distorsio, but	OK. Between 3-4 day:	durability
n.	less impact on the		

6. Specific features of selected solutions		
Solution	Test(s)	Validation method
1. Roof points 30mm to 40mm	Crash 30 km/h / 45 km/h/ 50 km/h	Speed point, breaking time, breaking ang.
2. Material test AI btw 2-3,5%	Crash 30 km/h / 45 km/h/ 50 km/h	Idem + Curve distorsion Vs Time

3. Set the Target
Targets 1. Roof fracture < 3,5%AI/ 50km/ 2. distorsion <3,8mm n.

Figure 60: Guidelines and data elements illustration (the models illustrations are not readable for confidentiality issues)

5. Results

The importance of the capitalisation supports for the industry has been largely discussed in KM literature. However, besides the TDR success criteria, no research studying capitalisation during the design review have been found. Even if the research suggesting the TDR success criteria agrees on the importance of these practices, no method supporting them has been suggested. The proposed guidelines fulfil the gap in the literature, given that no capitalisation support guiding the TDR exists today.

The proposition of the *guidelines for the development of TDR capitalisation supports*, enhances collaboration by guaranteeing capitalisation at the same time. The eight guidelines ensure through its 37 data elements:

- Six collaborative mechanisms and 36, among the 37, enablers improving shared understanding proposed by Kleinsmann et al.(Kleinsmann et al. 2007)
- The six capitalisation steps proposed in different literatures (Grundstein 2000), (Oladejo et al. 2010), (Renaud et al. 2004).
- The TDR success criteria (NASA 2007).

The only collaborative enabler -situated at the company level- is not ensured through the guidelines is the *organisation of the resources*. However, this element can be ensured through the collaborative environment presented in previous work (Roa-Castro, Stal-Le Cardinal, Landel, et al. n.d.). We assume that an enabler is more likely to occur if several data elements are related to it (e.g: in ANNEX 3, the column corresponding to the actor level enabler “the ability of an actor to make a transformation of knowledge”, will probably take place since more than half of the data elements address this element somehow). The two collaborative enablers the most likely to occur are situated at the project level, while the third one is situated at the actor level. The two enablers situated at the project level are: the efficiency of the information processing and the quality of the project documentation. It is not surprising that most of the enablers are situated at the project level since during the TDR the work is done at this level. Likewise, it is not surprising either that the enablers concerning documentation and information are highly likely to occur if we consider that the objective of the research is to propose capitalisation means.

At the actor level, the enabler the most likely to occur is the similarity in the language used. This result is also coherent because of the standardisation proposed by the guidelines elements (Figure

60). The second enabler the most likely to occur at the actor level is the ability of the actor to transform its knowledge (from tacit to explicit). This is also one of the objective of the support. However, it does not appear as the enabler the most likely to occur since several data elements included in the support refers to projects information (Name, participants, deadline...). The last two enablers at the actor level concern the applicable experience of the actors and their empathy for their tasks. Since it is difficult to evaluate if a data element responds to those enablers, we base this evaluation on the industrial observations, where participants affirmed that they are mostly motivated for the development tasks.

Regarding the company level, as mention before, only one of enabler is not ensured by the data elements (the organisation resources). The second enabler at this level (the application of the tasks and responsibilities) is mostly defined by the elements concerning the interfaces, but also by the identification of the participants filling each section.

On the other hand, the collaborative mechanisms the most likely to occur through the proposed data elements are: the improvement of the *knowledge content*, the setup of the communication structure, the clarification of the interdependencies and the reduction of technical uncertainty. Those mechanisms are conformed to the enablers the most likely to occur. Indeed, the externalisation and formalisation of the knowledge give a clearer *knowledge content* of each participant (what he knows about his task) and reduce the technical uncertainty since the information is transparent and available for all the participants. Likewise - as for the organisational level enablers - the interdependencies and communication structures are set up through the data elements concerning the interfaces and the participants contributing to the support.

The results allow us to validate the two hypothesis of this research. First, the reduction of misunderstanding problems is possible through an appropriate knowledge transfer. Second, reducing those problems improves collaboration in the TDR whereby we conclude that the implementation of an appropriate capitalisation support improves collaboration through TDR participants.

6. Conclusion and Perspectives

The research presented in this work aims at proposing guidelines to develop capitalisation supports for technical design reviews (TDR). We have based our research on two main hypotheses:

- *The minimisation of the misunderstanding problems improves the collaboration in the TDR context.*
- *We can reduce the misunderstanding problems through an appropriate capitalisation and knowledge transfer support.*

To succeed in the proposition of the guidelines, we have first explored the literature in the KM field. Although the large discussions regarding the importance of the capitalisation approaches, no method supporting TDR exists today. Thus, we have identified the current knowledge creation activities of TDR through industrial observation at the French vehicle manufacturer Renault, and we have analysed them regarding: first, capitalisation steps, second, TDR success criteria and third, collaborative mechanisms and enablers proposed in the literature. After the analysis we have concluded that the current knowledge creation activities do not completely fulfil the literature principles.

We propose eight guidelines to develop capitalisation supports for TDR coming from the literature review analysis and industrial needs. We define the capitalisation guidelines as *a set of activities assisting the development of a capitalisation support through specific data elements*. The guidelines and the data elements are helpful especially in the TDR context but also adaptable to other design situations. We illustrate the use of the guidelines through an industrial vehicle use case.

The results show how the proposed data elements support the literature principles and allow us to validate the two hypothesis driving this research whereby we could conclude that the implementation of an appropriate capitalisation support improves collaboration through TDR participants. We have been able to implement the support five times in the company having a good feedback from the participants. Each implementation have allowed us to validate and modify the proposed data elements. However, it is still too soon to obtain a quantitative measure of the improvement provided by the guidelines in the company. Participants estimate that they can avoid development loops if the past project information is exploitable, and they consider that the proposed guidelines will favour this exploitation.

Future research should include the exploration of the methods allowing a quantitative evaluation of the collaborative improvement in the TDR when participant capitalise and when they do not. Likewise, more implementations of the support in the company will be helpful for the evaluation,

just as its implementation in other design phases. Finally, the study of the ontologies and data mining approaches to define fixed values for each data element could also be an interesting hint to explore.

Acknowledgments

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ANNEXES

ANNEXES SHORT SUMMARY

Annexe 1: Interview Guidelines and Partial results obtained in Study 4 (P. 283)

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Annexe 1: Interview Guidelines and Partial results obtained in Study 4

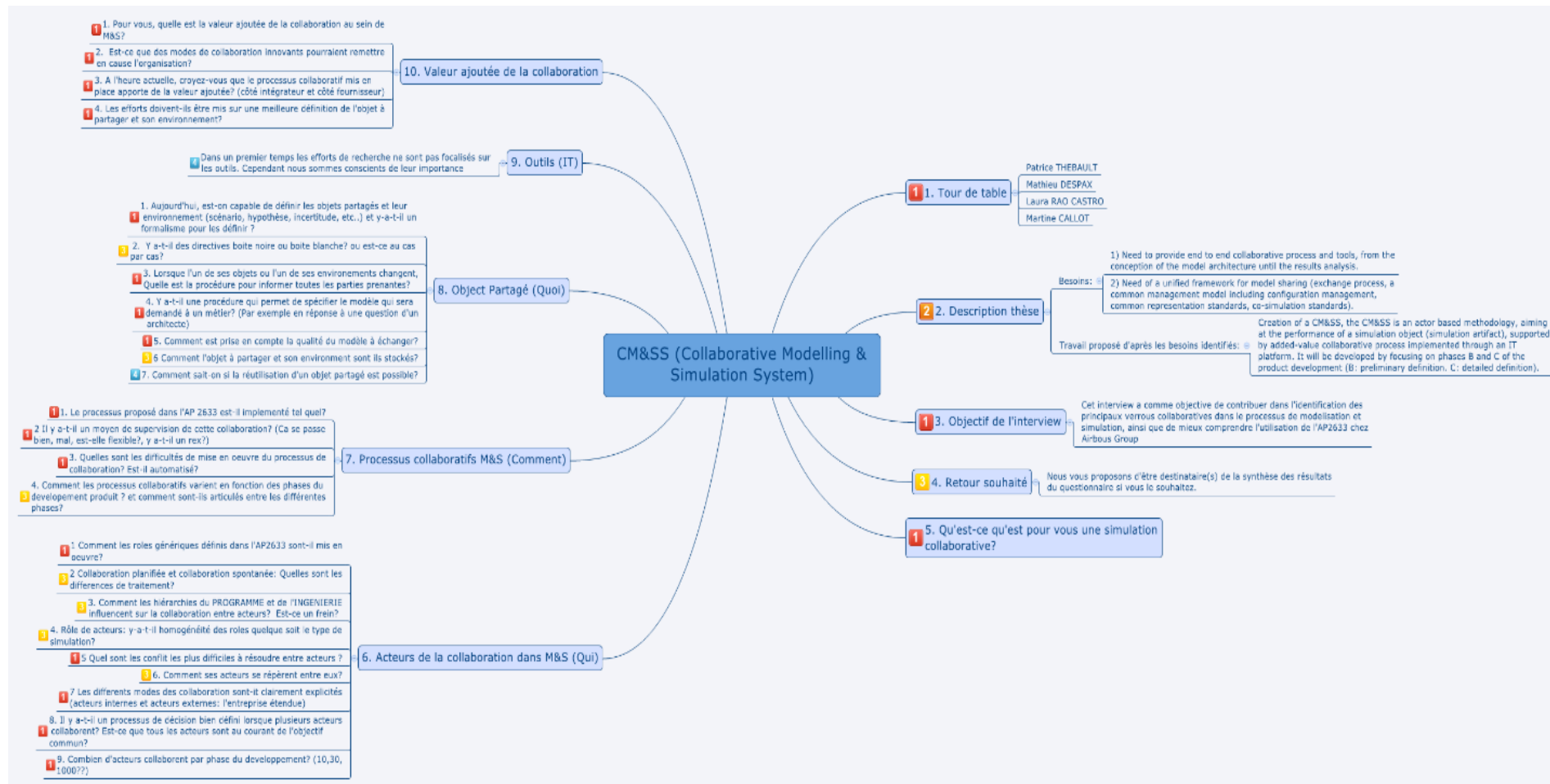


Table 29: Clues for an adaptive model for collaborative simulation

Axe/phase	Initialize Collaboration	Collaboration and Monitoring	Retour of Experience and capitalisation
Process			Create a faculty to adapt and to learn from the collaborative process
		<p>→ <i>Plan to do an upgradeable platform based on the proposed process, where the user's actions could be summarised as he goes along.</i></p> <p>→ Consider an take into account the monitoring and REX</p>	
		<p>Take into account the global constraints (at system architect level) and the local constraints (at trade level).</p> <p>→ <i>Include an actor based model aiming at finding the best trade-off, making the constraints as compatible as possible.</i></p>	
Actors		Have a better vision of the trade-off key points, between the actors (system architect and model architect)	
	<p>↑ Improve simulation objectives comprehension at model provider level</p> <p>→ Better define the objects and information to share during the collaboration phase.</p>		
	<p><i>Improve the model description and its environment through a data-configuration model where all the objects to exchange are identified and described as well as its links with the actors</i></p>		
Objects			Capitalise the simulation and its related objects
			<i>Capitalise all the objects related to a simulation study together based on a data-configuration model</i>

Annexe 2: Detailed analysis of the generic activities proposition (Paper # 4)

Table 30: Social framework and knowledge creation activities compared to Industrial TDR observations at Renault

source				Literature\observations	Identified activities during TDR																					
					Prepare the required documentation	Prepare the communication system and laptops	Verify the system	Call long-distance participants	Introduce the agenda	Concerns discussions (if disagreement)	Present the problem(s)	Old documents/files researches	Mailing researches	Questioning the experts	Ideas discussions	Reformulate (understanding)	Write the minutes	Display and modify others files	Switch the display	Design the results	Design over results (point)	Interact with designs	Discuss the conclusion	Short informal talks		
[Vosinakis et al. 2008]	social framework and design	Instrumental action	Constructing a landscape or (context) background	x																				Activities to prapere the TDR (communication system and document readiness)		
			Filling the design brief documents	x									x													
			Orientate tangible ressources into the design work space															x	x							
			Drawing sketches												x			x	x							Same. Engineers use the sketches and designs to communicate
			Prototyping												x			x	x							
			Creating mock-ups and models												x			x	x							
		Communicative action	Meetings, presentations and short verbal communications				x	x	x					x										x	All the observed actions are communication actions (oral or written/visual). Except for the rediness activities (prepare the system and the documents)	
			Mail exchanges									x														
			Interviews of key people										x													
		Discursive action	Expressing high-level descriptions of requirements							x	x	x				x										Express an idea is also a way of communication
			Introducing ideas					x	x	x				x	x		x			x	x	x	x	x		
			Expressing concerns about the progress and direction						x					x	x	x							x			
			applying methods for design																							
			applying methods for evaluating and validating solutions																				x			
		Strategic action	negotiating																				x			
considering particular design constraints as unavoidable							x	x																		
imposing access restrictions to tangible objects and resources																										
expressing expert opinions													x													
[Paul 2006]	Knowledge in coll. Activities	knowledge tranfert					x	x	x			x	x		x	x	x	x	x	x	x	x	x			
		knwoldege discovery						x				x	x					x		x		x				
		Knowledge creation											x	x							x		x			

Table 31: Analysis aiming at the general classification of the TDR activities

	Identified activities during TDR																				
	Prepare the required documentation	Prepare the communication system and laptops	Verify the system	Call long-distance participants	Introduce the agenda	Concerns discussions (if disagreement)	Present the problem(s)	Old documents/files researches	Mailing researches	Questioning the experts	Ideas discussions	Reformulate (understanding effort)	Write the minutes	Display and modify others files	Switch the display	Display the results	Design over results (paint)	Design on boards	Interact with designs	discuss the conclusion	Short informal talks
Readiness activities	x	x	x	x				x	x				x								
Visual communication activities					x		x					x	x	x	x	x	x	x			
Oral communication activities					x	x				x	x	x						x	x	x	
knowledge tranfert					x	x	x			x	x	x	x	x	x	x	x	x	x	x	
knwoldege discovery						x				x	x					x		x		x	
Knowledge creation										x	x							x		x	

Table 32: Analysis aiming at the general classification of the TDR activities (Identified activities have been reorganised regarding their belonging general

activities group		Readiness activities	Visual communication activities	Oral communication activities	Analysis
Identified activities during TDR					
1 Prepare the required documentation	x				Files set up
8 Old documents/files researches	x				
9 Mailing researches	x				
2 Prepare the communication system and laptops	x				System setup
3 Verify the system	x				
4 Call long-distance participants	x				
15 Switch the display			x		These activities are based on screen sharing. Sometimes, this sharing needs video sharing capacities allowing the remoted connected participants to understand when people point out key design points. . Likewise, these accould also need some simulation ressources to run especific models
7 Present the problem(s)			x		
16 Display the results			x		
14 Display and modify others files			x		In addition to sharing capacities mentioned before the documents modification can be also idenfity as a main activity during the review as those modifications are the aim of the review. The observations allow us to classify the modifications into documents modification and design modifications. The disign modifications could be done from an existing design (image) or from scratch (board)
13 Write the minutes	x		x		
17 Design over results (paint)			x		
18 Design on boards			x		
5 Introduce the agenda			x	x	Those activities concern discussions but also other kind of communications like a formal presentations and sometimes video interactions
19 Interact with designs			x	x	
6 Concerns discussions (if disagreement)				x	In general those activities are discussions in an especific subject
10 Questioning the experts				x	
11 Ideas discussions				x	
12 Reformulate (understanding effort)				x	
20 discuss the conclusion				x	
21 Short informal talks				x	

Annexe 3: Detailed analysis of the capitalisation support development (Paper # 5)

N/A ✓: Exists ☒/✓: Partially exists ☒: Does not exist

N/A √ : Exists ☒/√ : Partially exists ☒: Does not exist			Capitalisation steps															Success criteria								
			Extraction/Elitization	Location	Preservation/Modelling/Representation	Storing	Exploitation/Application/Value enhancement/Feedback	Maintenance	Definition of high-level project requirements	Definition of interfaces with other projects	Propositions of cost-effective solutions	Development of solutions supporting one or several project requirements	Definition of a change propagation plan	Definition of verification approach	Definition of risk management strategies											
Literature			Existence Analysis regarding current knowledge creation activities																							
Barriers and enablers	Actor level	The ability of an actor to make a transformation of knowledge	☒/√	The actors have a high ability to formalize the knowledge for their own. However this transformations is not standardised at the organisational level										X		X				X		X	X			
		The similarity in language used between the actors	☒/√	High similarity between the languages of the actors coming from the same department. Nevertheless, some differences can be found between the language of the actors coming from different departments											X		X	X					X			
		The applicable experience of the actors	☒/√	The applicable experience is more related to the senior actors. However, both, junior and senior, profiles participate during the TDR													X									
		The empathy of actors about the interest of a task.	√	Problem solution task is an highly interesting task for the members because of the significant added value of the task												X		X			X	X		X		
	Project level	The efficiency of information processing	☒	Currently, TDR is a low efficiency information process. The right information is not identified in the cause analysis, and the proposed solutions are not capitalised										X	X	X	X	X	X	X	X	X	X	X	X	X
		The quality of project documentation	☒/√	Project documentation is more or less adequate for the current process. It depends on the actor documenting. Both, high and lesser quality documentation have been found. In any case, the quality is not high enough for a potential reuse										X	X	X	X	X	X	X	X	X	X	X	X	
		The division of labour	√	Labour division between two TRL is appropriate. This is mostly because of the presence and agreement of the involved actors.										X												
		The rigor of project planning	☒/√	Projects deadlines are not negotiable. However, sometimes the deadlines are not often reached because they were set without taking into account the real daily work constrains															X							
		The controllability of product quality.	√	The evaluation is done regarding the requirements. Nonetheless, product quality is difficult to evaluate when the deadlines are not reached																				X		
	Company level	The organization of resources	☒	Two kind of problems regarding the resources are identified. The first one, concerns human resources when the right stakeholders are not implied. The second one concerns the material resources. For instance, the calculation execution is often a bottleneck.												X										
		The allocation of tasks and responsibilities.	☒/√	As in the Project level, task allocation is appropriate when the right stakeholders are involved										X												
coll. Mechanisms	Detailed knowledge from the content of each other's design	☒/√	Today the content is not updated. Actors knows t-1 other's design										X	X	X	X	X	X	X	X	X	X	X	X	X	
	Communication structure to be set up	☒/√	The communication is not structured enough. This is also a consequence of the lack of standard documentation of the project																X							
	Interdependences between actors strong	☒/√	Interdependences are strong because of the complex of the system. Actors need to clarify design interfaces as much as possible in order to analyse interdependences											X					X							
	Make all the interfaces clear			X						X																
	Integrate knowledge on different levels of the projects	☒	Knowledge integration at different levels is still difficult because of the lack of capitalisation											X				X								
	Reduce technical uncertainty and lack of information	☒	The uncertainty and the lack of information can be reduced by the implementation of an appropriate capitalisation of the proposed solutions													X	X				X	X	X			

Titre : Management de la complexité organisationnelle des projets en ingénierie systèmes: Mise en place d'une approche socio-technique pour l'amélioration des aspects collaboratifs.

Mots clés : Conception collaborative, Collaboratif MBSE, Systèmes Socio-Techniques, Théorie des jeux, Approche Systemique

Résumé : Du fait du développement de nouveaux produits (NPD) dans l'industrie, l'organisation devient de plus en plus complexe, ceci est dû notamment à la complexité même des produits. Dans ce contexte, le MBSE (Model Based Systems Engineering) et les approches collaboratives, qui adressent ces complexités, ont été reconnus pour leurs facultés à améliorer le NPD. Une implémentation réussie d'une conception collaborative du type MBSE, doit permettre de gérer ces deux complexités. Cette thèse de doctorat a pour objet l'étude de projets de conception collaborative MBSE au sein des équipes françaises chez des équipementiers automobiles et aéronautiques, afin de mettre en avant l'amélioration du développement des produits. La conception collaborative du type MBSE est assimilable à un système organisationnel complexe, impliquant des vues ou dimensions différentes. Ainsi, l'identification de ces dimensions, leur définition et l'étude de leurs interactions constituent le premier objectif de cette recherche. La compréhension de chacune d'entre elles pour améliorer la collaboration entre les différents membres du projet, est le deuxième objectif.

Le troisième et dernier objectif de cette thèse est de proposer des systèmes socio-techniques (STS), assistant la collaboration. Les résultats de cette recherche, fournissent une méthodologie pour manager la complexité organisationnelle dans des projets collaboratifs du type MBSE. Elle est le produit d'une combinaison de quatre méthodes permettant la caractérisation de ses dimensions (processus, acteurs, objets et outils), tout en définissant leurs interactions. Ces méthodes assistent respectivement : 1) La description et l'évaluation de ces projets avec une perspective systémique 2) l'établissement d'une vision partagée du travail 3) l'analyse des coopérations entre les acteurs, et 4) le développement de STS tels que des environnements collaboratifs et des supports collaboratifs de capitalisation. L'implémentation en industrie des méthodes proposées, processus et recommandations, a montré comment la mise en avant de la collaboration dans les projets de design MBSE, permet d'améliorer l'ensemble du développement de produit.

Title : Managing Organisational Complexity in MBSE design projects: Use of a Sociotechnical Perspective to improve Collaboration

Key words : Collaborative design, Collaborative MBSE, SocioTechnical Systems (STS), Games Theory, Systemic approach

Abstract: The organisational complexity implied by New Product Development (NPD) within the industry, is often induced by the complex nature of the products themselves. In this context, MBSE (Model Based Systems Engineering) and collaborative approaches address those complexities and have been recognised by their contribution to improve the NPD processes. A successful implementation of a collaborative MBSE design would allow to manage both complexities. This PhD thesis describes an investigation on collaborative MBSE design projects within French teams in automotive and aeronautics companies, with the purpose of enhancing them to improve product development. We understand collaborative MBSE design as a complex organisational system which implies different views or dimensions. The identification of those dimensions, their definition and the study of their interactions constitute the first objective of this research. Understanding each dimension in order to improve collaboration between the project members is the second objective.

The third and last objective of this research is to propose Socio Technical Systems (STS) supporting this collaboration. The results of the thesis provide a methodology to manage organisational complexity in collaborative MBSE design projects. The methodology is a combination of four methods assisting the characterisation of the MBSE dimensions (people, process, information objects and tools), while defining their interactions. These methods support respectively: 1) The assessment and description of collaborative MBSE design projects from a systemic perspective 2) The establishment of a shared vision of the work 3) The analysis of the cooperation among the actors 4) The development of STS such as collaborative environment and a collaborative capitalisation support. The implementation of the proposed methods, process and guidelines in the industry has shown how the enhancement of collaboration in MBSE design projects can improve the overall product development.