Collaborative Reverse Engineering Design Experiment Using PLM Solutions*

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The current climate of economic competition forces businesses to adapt to the expectations of their customers. To achieve this, in spite of the increasing complexity of mechanical systems, it becomes necessary, amongst other things, to reduce design time. Faced with new challenges, practices in design training must evolve to allow students to be mindful of these evolutions as well as to be able to manage projects in these new work environments. After presenting a state of the art of collaborative tools used in product design, our paper presents an experiment focusing on the reverse engineering of a complex mechanical product. This experiment was carried out between two centers of the Arts et Métiers ParisTech School of Engineering, located in Paris and Angers. We analyze the results obtained in this experiment and propose a collaborative environment that is well suited to our needs for design education, based on "Product Lifecycle Managament" (PLM) concepts. Finally, we present some modifications in collaborative design courses for our students, and we implement network modifications in order to significantly improve the ease of use of the design environment.

Keywords: reverse engineering; education, PLM; collaborative design

1. Recent changes in industrial businesses

In an environment marked by increasing competition, businesses must suit their organization to the demands of their customers. In this context, the reduced length of development cycles and the increasing complexity of mechanical systems force businesses to involve actors from various professional and cultural backgrounds in collaborative projects. The organization of design teams has also had to adapt to these changes in the industrial context.

Figure 1 illustrates the changing patterns in the structure of new product development teams as they have moved to greater collaboration and virtuality.

Obviously, this industrial evolution has been supported by the evolution in work methods and in the associated digital tools, such as PLM solutions.

2. Business process outsourcing and product lifecycle management

One of the most important changes in design habits in the first decade of the 21st century was the phenomenon of Business Process Outsourcing, also known as BPO, experienced by various professions [2]. In order to give mechanical engineering students an initial view of the extent of globalization, many Schools of Engineering have integrated design projects involving students as participants [3–6] within their training programs.

The main question from here is: "How can we, as engineering educators, respond to global demands to make our students more productive, effective learners?" and how can PLM help us to achieve this goal?

The Product Lifecycle Management approach to the manufacturing of complex goods is now considered to be one of the major technological and organizational challenges of this decade, to cope with the shortening of product lifecycles [7]. Thus, design education has changed in order to provide students with some experience in collaborative design during their studies. Moreover, PLM can also be a solution to looking at one of the main problems in our educational system: the fragmentation of knowledge and its lack of depth.

In the following, we propose a chronological review of the methods businesses use to improve their competitiveness, and describe the challenges these raise for education of engineering design. We then present an experiment carried out in the Arts et Métiers ParisTech School of Engineering. The goal of the experiment was to define an optimized environment for collaborative work in design projects. The next section gives the state of the art of these methods and tools.

3. State of the art

In this section, we give a chronological state of the art of the methods applied in the business world in order to improve their competitiveness.

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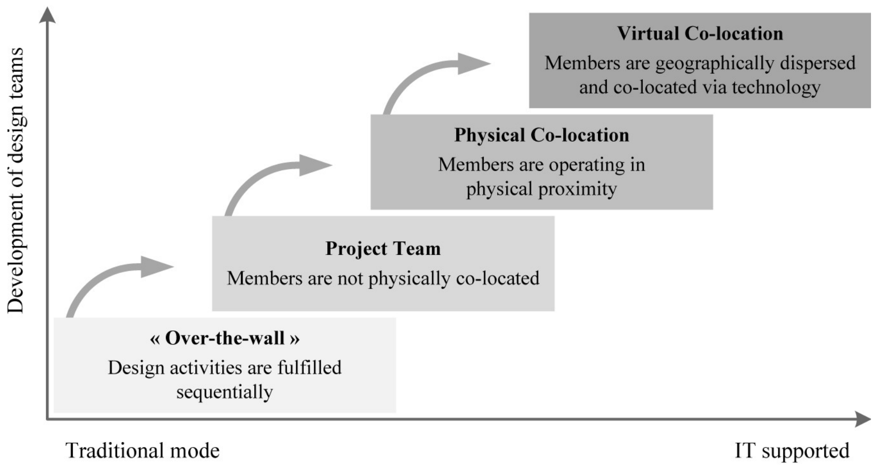

Fig. 1. Changes in design teams adapted from [1].

3.1 Concurrent engineering

Towards the end of the 1980s and the beginning of the 1990s, two forms of design organization emerged as distinct alternatives: sequential design, which involves carrying out design tasks one after the other, and concurrent engineering, or integrated design [8–10]. Two aspects of Concurrent Engineering (CE) that distinguish it from conventional approaches to product development are cross-functional integration and concurrency. In sequential engineering, exchanges between actors are based on direct relationships. In CE, one must define common interfaces between the various tasks. Indeed, CE is an approach to product development in which considerations about product lifecycle processes, from product planning, design, production to delivery, service, and even end-of-life, are all integrated. By carrying out these tasks in parallel, it becomes possible to reduce the time and costs of design, and also to improve the quality of products.

With the development of Information Technology (IT), CE methods have gradually evolved toward collaborative engineering.

3.2 Collaborative engineering

In the case of collaborative engineering, which emerged in the 1990s, as in the case of CE, overlapping tasks are still present, but project stakeholders are requested to work together and interact in order to reach an agreement and make shared decisions. The degree of collaboration is assessed here by the level of decision coupling. Designers from the whole group work together to design the product, following the customers' requirements. The project leader, as well as the project group (a group of designers from various companies who have competences and skills in various fields) thus attempt to build and maintain a common view of the problem and solve it together [11]. Collaborative activity is synchronized and coordinated throughout the collaborative process.

Thus, as synergy is created between the project actors in collaborative engineering; PLM ensures that synergy is created throughout the whole of the product's lifecycle.

3.3 PLM

In the early 2000s, PLM emerged as a solution to adapting industrial design to the demands of globalization. Indeed, as PLM addresses the entire lifecycle of the product, it has a cross-functional nature and deals closely with the way that a company runs [7]. Collaborative design has been the subject of numerous studies. With the development of PDM (Product Data Management), PLM (Product Lifecycle Management) and associated workflows, software firms have proposed solutions to the everyday problems of engineering design departments (versioning of documents, naming, etc.). Product Lifecycle Management aims to cover all the development stages of a product, by integrating processes and the people taking part in the project [12]. This concept is generally used for industrial products. For Amann [13], over the past several years, PLM has emerged as a term to describe a business approach for the creation, management, and use of product-associated intellectual capital and information throughout the product lifecycle. Thus, PLM is an approach in which processes are just as important as data, or even more so. The PLM approach can be viewed as a trend toward a full integration of all software tools taking part in design and operational activities during a product life cycle [7, 14]. Therefore, PLM software packages need product data management system; synchronous and asynchronous, local and remote collaboration tools; and, if necessary, a digital infrastructure allowing exchanges between software programs.

Several important challenges, however, must be met if one is to integrate PLM tools within design education.

3.4 Challenges for design education

Design education focuses on teaching students how to do design. The key factor in design education is to learn how to design.

In engineering education, PLM is a means for students to structure their design methodology. Indeed, before entering an efficient collaboration, students must be mindful of how it works, and how the work can be divided between stakeholders. Thus, from an education point of view, PLM method can be viewed as a sophisticated analysis and visualization tool that enables students to improve their problem-solving and design skills, but, importantly, to improve their understanding of the behavior of engineering systems.

In a globalized world, products are nowadays typically designed and manufactured in several locations worldwide. Thus, it is essential to train students for Computer Supported Collaborative Work (CSCW) [15]. Moreover, they will increasingly need to use tools, skills, and experiential knowledge suited to 'extreme' collaborative environments. Even for the collaborative design of innovative products, there is an urgent need for specific educational pedagogical strategies and techniques [16]. In the field of engineering, companies and professional organizations expect students to be equipped with a basic understanding of engineering practices, and be able to perform effectively, autonomously, and in a team environment [17]. Up to a few decades ago, traditional design projects (i.e. those with co-located teams and synchronous work) could reach this aim, but nowadays they are insufficient.

The experiment presented in the following section aimed to apply the collaborative tools available at the Arts et Métiers ParisTech School of Engineering to a redesign project, in order to derive some pathways for the improvement of an existing collaborative work environment.

4. Experimentation

4.1 Pedagogical approach and experiment objectives

We propose a pedagogical approach based on two kinds of tools: the "engineering toolbox" with CAD and PDM tools to store and share data and the "communication toolbox" with communication tools such as Sametime, Skype, MSN. In the proposed design project, two distantly located teams collaborate and must face some problems that are partly related to some general aspects of distributed work, such as effective communication, building and maintenance of a shared understanding and conflict management. They are also partly inherent in the design process [18].

An efficient collaboration requires, according to Yesilbas [19], three different types of knowledge: pre-collaborative knowledge, in-collaboration knowledge, and post-collaborative knowledge. Pre-collaborative knowledge is the pre-requisite information, necessary to enter the project. In our case, pre-collaborative knowledge might include prior knowledge of CAD and PDM tools. A lexicon was also created at the beginning of the project in order to give the same names to the same mechanical parts in the two teams, which constitutes pre-collaborative knowledge. This lexicon was enriched with photos of real mechanical parts, to avoid any ambiguity. The in-collaboration knowledge then deals with the knowledge that must be shared and exchanged to achieve the action, specifically expressed through Intermediary Representations (IRs) [20]. In these stages, representations adapted to business constraints must be found to enable effective collaboration. As part of our project, the main IRs generated were CAD parts and "Microsoft Office" documents. Finally, post-collaboration knowledge, i.e. knowledge produced after collaborative actions. These were archived as best-practice documents in the database, to capitalize on the solutions found to the main technological challenges raised during the project. Once pre-collaborative knowledge was established, the first goal of our experiment was to evaluate remote codesign activities, specifically to study design activities involving several participants working from several distant sites, using the tools at their disposal to communicate and share data. Next, we analyzed the relevance of these tools, their impact on designer activity and, more broadly, on the design process. This was done using questionnaires handed out to the students working in the project. Based on this study, we propose some perspectives for optimizing this remote codesign activity, which have since been implemented.

In the next section, we present the project that served as a basis for this experiment.

4.2 Presentation of the project

In this section, we first present the context of our study, and then the product whose design served as teaching material in our project.

4.2.1 Context and methodology

Arts et Métiers ParisTech is a School of Engineering composed of eight centers located in France in Aix-en-Provence, Angers, Bordeaux, Châlons en Champagne, Cluny, Lille, Metz, and Paris. The School has developed a collaborative engineering platform aimed at managing innovation projects between its centers. Each center has computer workstations equipped with CatiaV5 (Computer Aided Design software) and Smarteam (Product Data Management software). Students assigned to the project (seven students in our case) have access to the platform and the data it contains. Students also have access to Sametime, which allows the sharing and exchanging of presentations or work on a whiteboard.

The project, lasting about eighty hours over six months, involved two teams of students in their second year in the School of Engineering. Team A, located in Paris comprised three students. Team B, located in Angers (about three hundred kilometers west of Paris) comprised four students. Sessions allocated to the project (twenty working sessions of four hours) did not necessarily take place simultaneously between the two teams. Thus, asynchronous modes of collaboration were implemented. None of the participants had ever completed a design project in remote collaboration. Students were able to communicate using the tools of their choosing. However, they had to design the Digital Mock-Up (DMU) of the object using Catia and Smarteam software. Following the first "physical" meeting to launch the project, the students could communicate by telephone and videoconference (via Skype), e-mail, chat (via MSN). At the kick-off meeting in Angers, which last about four hours, a project methodology was defined. The overall architecture of the database was validated by the two teams and formatted thereafter. This architecture allowed students to find and classify their data easily. The preferred design methodology was as follows. First, a functional skeleton was created to allow each team to position its components in the overall design environment. Then, sub-assemblies were assembled and the overall digital model was created in Catia. The overall schedule was also frozen during this first meeting. The overall project methodology implemented in the course of this project is illustrated in Fig. 2.

4.2.2 Product to design

The project is a Reverse Engineering (RE) project. RE is a vast domain in which products are digitized in order to create a DMU on a CAD tool. RE approaches are widely used in competition analysis or when integrating hand-made prototypes into a global DMU [21]. The study of RE methodology is therefore important for future engineers. The product to design is a directional headlight that equips top of the range Renault vehicles (see Fig. 3). The headlamp is made of a block that performs the logical functions, and includes the low beam headlight and directional headlight located at the bottom. From a real directional headlight, the objective was to achieve the design of this mechanism through a collaboration between the two teams, using the "collaborative" and "engineering tool-

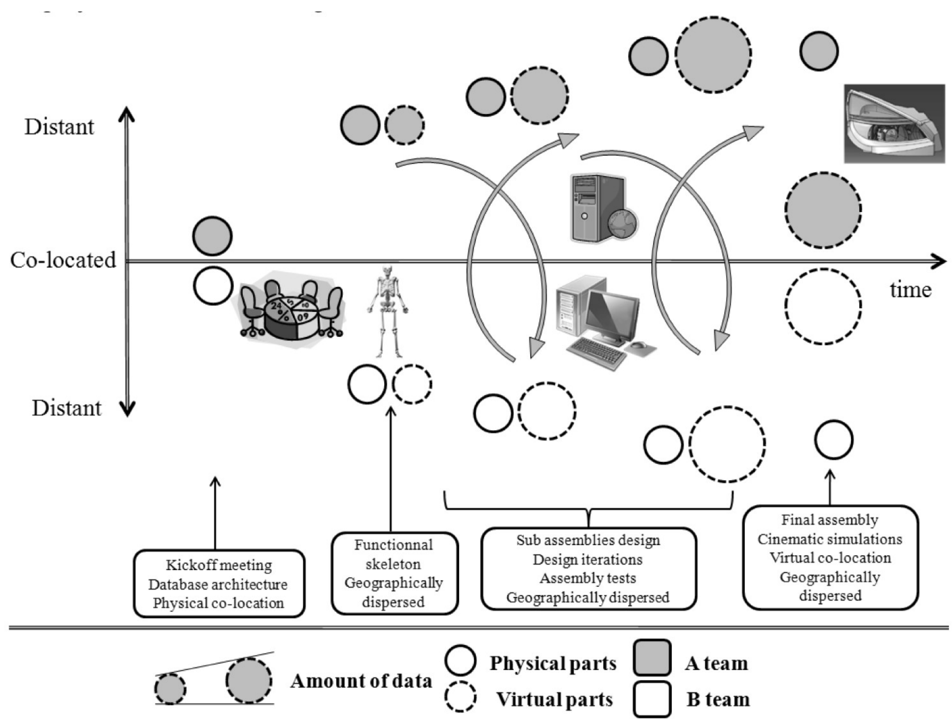

Fig. 2. Synopsis of the project methodology.

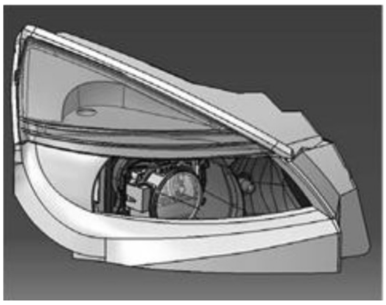

Fig. 3. Final assembly DMU of the directional headlight.

boxes". The DMU was then animated to visualize the trajectory of the light beam on CAD software, according to the input references, i.e. mainly the angle of the steering wheel. The project began with a stage that aimed to structure the team [22]. The distribution of the parts to redesign between the two teams could be considered according to two modes: either a functional division, leading to design modules associated with functions that are then assembled together, or a division based on the local expertise of stakeholders, which suited the needs of such a short project well. For example, surface reconstruction from a 3D data cloud, which is necessary to design the frontal pane of glass, requires expertise that was only present in Paris. For this reason, the second alternative was chosen.

Collaboration in this project was analyzed in order to identify the limitations and the difficulties encountered by our students. In the next section, we present the results of these analyses as well as the pathways for improvement that we chose in order to optimize the collaborative work environment provided to our students.

5. Results

Data relating to collaboration were identified by a method of semi-structured interviews. The interviews for Team B took place in conference calls, those for Team A were held face to face. Two series of interviews were carried out. All participants were interviewed in French, recorded and subsequently analyzed. General impressions about the project, shared at the final defense, were gathered and video recorded.

Questions posed in the first interview concerned three topics: first, the ease with which participants "got to grips" with the tools at hand; then, the types of IRs and collaborative tools used throughout the project; and finally, a question at the end of the interview allowed students to express an open opinion regarding which criteria should be used to improve the working environment and collaboration.

The second interview allowed us to use the criteria thus identified by the students to establish a list of high-priority actions to improve the collaborative work environment. A choice was made to focus on the three sources of dissatisfaction most mentioned by students.

After analyzing the data collected in these interviews, we present the results of the collaborative activities carried out in our project. We also propose some paths for improvement, in defining an optimized software platform to support collaboration in design education.

5.1 The collaborative project

During the collaboration in the project, the collaborative tools that were used by the students were: e-mail (86%), chat (71%), videoconference (100%), DMU or paper documents (86%) and PDM (Smarteam, 71%). A recent study by Brown [23], on a panel of one hundred companies shows that the main technology enabler for design collaboration is e-mail, still used in 95% of cases of collaboration, far ahead of PDM or DMU tools. It also shows that 87% of the best performing companies in terms of time and development costs have used collaboration tools in design for over a year. Figure 4 presents a comparison between this industrial study and our project.

The industrial practices in design collaboration observed by Brown and by ourselves are broadly similar. First, e-mail remains a widely used tool. Given the nature of our design project, which focuses on mechanical engineering, we noticed that DMU tools were more often used in our study than in Brown's.

Secondly, in the student project presented in this paper, a large part of collaboration relies on chatting software, partially explaining the less frequent use of e-mail.

We also noticed that not all students used the collaborative platform, possibly suggesting that the platform is not easy to use. To the first question "What is the first thing you need to start making the most out of Smarteam?", 71.5% of the students answered that they needed a tutorial to start. A tutorial was provided, consisting in a training exercise where the various stages in the design of an example product were described one after the other. This tutorial allowed students to get to grips with the software on their own. In case of set-backs, a video of the design sequence was available on each computer connected to the platform.

During this experiment, students only had access to the database when they were physically present in project meetings. In other words, they were unable to access project data freely outside of the hours allocated to this work. This also was perceived as a

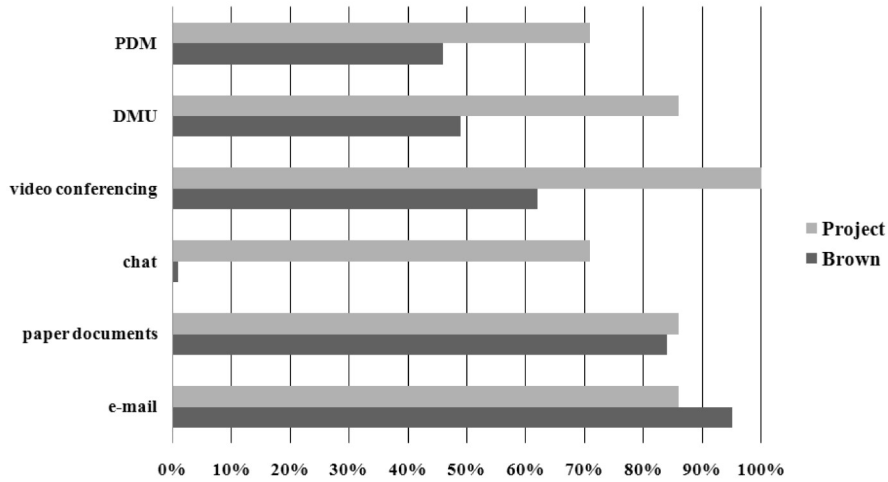

Fig. 4. Use percentages for various collaboration tools, comparing Brown's results [23] with those from our project.

strong obstacle to collaboration. Of the five participants who used PDM, all expressed the wish to access the software from home, mainly to be able to exert some control over the progress of the project, since working hours differed between the two centers.

One final obstacle to a more widespread use of Smarteam was the time needed to work on data stored in a vault server based in the center of Châlons-en-Champagne. Connecting times to the environment and file loading times were assessed as either long or very long, by 28.6 and 42.9% of participants, respectively.

Finally, we listed the main criteria identified regarding the resources available to students for collaboration. In the next section, we present the results of the second interview, which allow us to prioritize the implementation of the proposed improvements.

5.2 Towards optimizing our platform for collaboration

Following the early results presented above, the results of the second interview suggest two main pathways to improve the current PLM environment. Indeed, three main criteria for dissatisfaction have been identified:

1. the inability to remotely access project data, outside of the dedicated locations (71.5% of subjects were dissatisfied);
2. the ergonomics of the user interface (57.1% of subjects were dissatisfied);
3. overly lengthy transfer times: file transfer times (71.5% of dissatisfied users) and connection times to reach the work environment (42.9% of dissatisfied users).

In order to propose a collaborative environment that is well suited to our needs for design education, we strove to address these various sources of user dissatisfaction, which might hinder the use of this platform. This improvement task involved an inter-centers task force. The results of its work are presented below.

First, due to confidentiality issues regarding the industrial projects, coupled with issues surrounding network security, we were unable to implement network access from outside the designated sites.

Second, to address the issues surrounding user interface design, we added a compulsory four-hour training session for all students, added to the tutorials that were already available online. This prior training allows students to become somewhat familiar with the tools proposed in the engineering and communication toolboxes.

Finally, we modified the architecture of the national data network, in order to significantly reduce transfer times. To achieve this, we replicated some data, which up until now was centralized on a single nationwide server, to all other servers. As a result, file transfer times fell by approximately 50%. Finally, the network architecture requires that software licenses be stored on a nationwide server, which lengthens connection times. One should note, however, that students only connect to the server once per session, at the beginning. One might therefore consider that these delays are less of a hindrance than file transfer delays in the design process.

In short, several actions were undertaken in order to allow optimization of the collaborative work environment provided collaborative design. Much effort remains to be put in, however, in favoring work sessions carried out synchronously in several

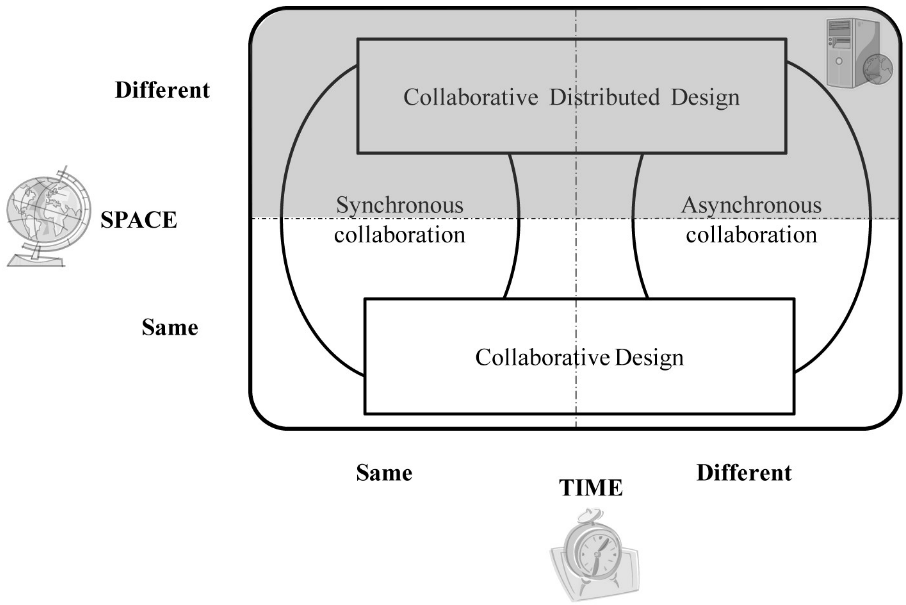

Fig. 5. Collaboration matrix and position of a collaborative distributed design platform, adapted from [25].

locations. In the next section, we present a proposal of design project organization to optimize collaboration between the stakeholders.

5.3 Towards defining an optimized design project

In the open question at the end of the first interview, five of the seven students remarked that just one face to face meeting at the beginning of the project did not allow them to create relationships and work methods that were robust enough. There is a need for students to spend more time in co-localization (i.e. in the same location) at the beginning of the project.

This phenomenon, studied by Davidson [24], occurs because a design team is more than just a group of individuals working in an isolated way on their project. The stakeholders require factual work, relationships and the coordination of a central workflow. Social aspects such as a shared social context and a feeling of trust need to be balanced

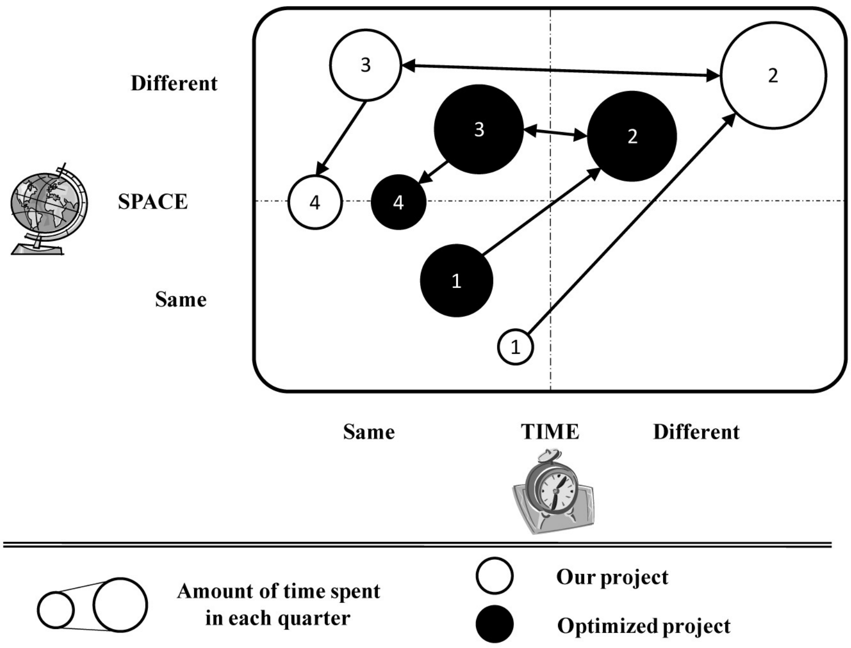

Fig. 6. Collaboration process in our project and in an optimized one.

against the more "process-oriented" aspects such as planning of work and scheduling of activities to maximize the performance of the team.

To achieve this, we drew inspiration from the physical environments used in large-scale industrial projects. A famous example is the development of the Dassault Aviation F7X aircraft, which was designed in four years using PLM solutions, and physical and virtual platforms. First, the physical platform consists in co-localization of the major stakeholders of the project coordinated by the lead firm. In this aircraft project, actors spend several months together to get to know one other, to establish the methods and work rules and to define the sharing policy of the DMU. Then the virtual platform stage can start, where engineers go back to their society. A collaborative and distributed design platform is then established and stakeholders work in synchronous and asynchronous modes, in a distant way, i.e. at the top of Fig. 5, adapted from Johansen [25].

In the case of our project, students only spent about four hours together in Angers, with their teachers, to create relationships and work methods that were robust. That is obviously not enough to perform well. At our specific request, the project's schedule was adapted to give students two successive days. Thus, for the next pedagogical project, we will plan project work sessions over a period of two full days, which will be dedicated to setting up collaboration methods and tools, as well as fostering a team spirit in the students. The change in terms of time spent in each quarter of the collaboration matrix is presented on the Fig. 6.

The stages are numbered chronologically, from the kick-off period "one" to the final videoconference "four". Our proposal for an optimized educational design project is to promote the team spirit and work organization in the first part of the project. Then, due to the scheduling of the project sessions, which are different in each center, the work will necessarily be synchronously and asynchronously distributed collaboration during the project (stages "two" and "three").

Thus, changing the design project process and optimizing our platform will allow students to be more efficient in their use of PLM solutions.

6. Conclusions

Owing to competition between companies worldwide, design training practices must evolve to allow students to gain be aware of evolution in design practices as well as to manage projects in these new work environments. The Arts et Métiers ParisTech School of Engineering has adapted its courses and design project methodology in order to fulfill these needs. After having presented a state of the art of collaborative tools used in product design, we presented an experiment focusing on the codesign of a complex mechanical product. We proposed some modifications, such as a compulsory four-hour training session for all students, and we implemented network modifications in order to significantly reduce transfer times. We created synergies between several training centers and provided a detailed analysis of collaborative design activity. Keeping in mind the need for data security, we nevertheless were able to respond to many sources of stakeholder dissatisfaction in this pilot project. Finally, we proposed an optimized educational design project to promote the team spirit and work organization in the first part of the project. As a prospect for future research, we note that this optimized environment will be tested using a new experiment that allows students to understand the concept of workflow using real life industrial examples.

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