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Modelling collaborative knowledge to support engineering design project manager

Vincent Robin [a,*], Bertrand Rose [b], Philippe Girard [a]

[a] *LAPS, University Bordeaux 1, 351 Cours de la Libération, Talence 33405, France*
[b] *LGECO, INSA de Strasbourg, 24 Boulevard de la Victoire, Strasbourg 67084, France*

Product development cycles are nowadays tightened to the minimum and submitted to a growing competitive pressure. However, product and process complexities are constantly increasing. This paradox requires new organisational concepts to satisfy customers' requirements. Design actors are therefore invited to collaborate more and more closely in order to enhance design efficiency. Collaborative design process gathers actors which have to achieve a common objective linked to a new product, information and knowledge sharing, with a high level of activities co-ordination. In this paper, we are particularly interested in the knowledge exchanged and shared during these collaborations. We first identify the types of knowledge characterising a collaborative design process and the need for a framework to manage collaborative design. A model of design context is provided to support design process and knowledge exchanges. The particular case of conflict resolution during collaborative design is studied through the use of a software formalising the designers' exchanges during a real industrial conflict.

Keywords: Engineering design model; Collaborative knowledge; Collaborative design

1. Introduction

As complexity of engineering design processes continuously increases, designing has to integrate a great number of expertises based on collaboration between the different actors involved. In such a context, one purpose of design control is to define and to organise the system where the design transformation will take place, according to the needs for collaboration and design objectives. Hence, design control requires to understand design process context in order to adapt actors' work when necessary. The design context is defined considering at the same time product and process aspects, but also the human, social and organisational aspects [1]. This paper focuses on collaboration between actors and more specifically on knowledge shared during the engineering design process. In order to manage successfully this collaborative process, such knowledge has to be taken into account in a model describing the design context. In Section 2, a formalisation of useful knowledge for collaborative design projects is proposed. It is essential to capitalise the knowledge produced during a given project in order to make it understandable and reusable. Section 3, suggests to integrate this knowledge in a model describing the design context. Such a representation of the design context will help project managers in identifying the added-value pieces of knowledge for the collaborative design and in assisting collaboration between actors. Section 4 presents a description of collaborative design process and how it could be managed based on the design environment concept. Finally an industrial case study is presented to illustrate the management of collaborative design process based on collaborative knowledge management.

2. Define collaborative knowledge

To increase design performances and consequently to satisfy customers' requirements and expectations, the decision-makers (generally the project managers) have to adapt the designers' work-context to the environment of the design process. The work-context of the actors will be improved and, when the project manager will be able to create effective working group

* Corresponding author at: LAPS/GRAI, UMR 5131, Université Bordeaux 1, 351 Cours de la Libération, Talence 33405, France. Tel.: +33 5 40 00 24 07; fax: +33 5 40 00 66 44.

E-mail address: vincent.robin@laps.u-bordeaux1.fr (V. Robin).

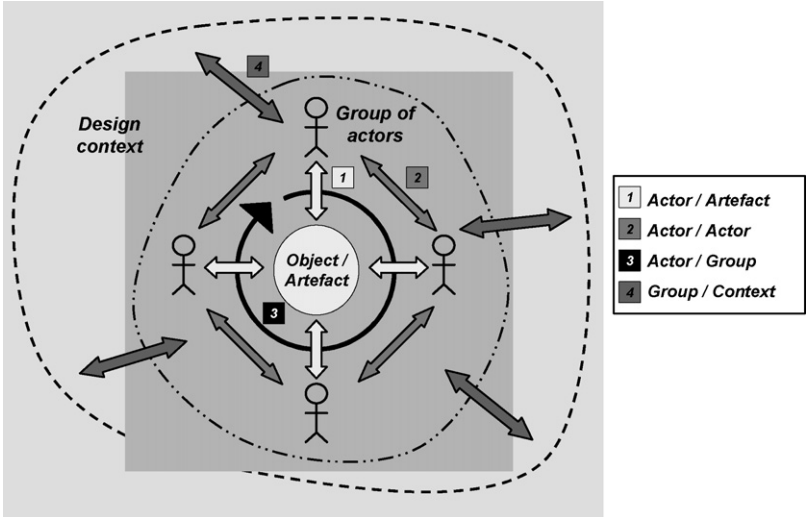

Fig. 1. Design actor's interactions with elements of his context of work [2].

according to the design objectives, human resources allocation will be more efficient. Girard et al. [2] have identified interactions between actors and the contextual elements of their evolution during the design process progress (Fig. 1). Four types of interactions have been identified depending on the point of view: actor/object of design, actor/actor, actor/group and interaction between the group of actors and the context. The first type concerns interactions between actor and the object of design (the design artefact). In this case, it's necessary to analyse actor's impacts on the evolution of the design artefact definition. Other point of view considers actor's interactions with the group, from which we can derive two types of interactions. For one type, the interaction focuses on the individual actor and it is based on his individual relationships with others members of the group. It will be relevant here to identify collaboration drivers and how collaboration between actors appears. The goal is to define collaboration form according to design needs and to favour the actor's awareness to his environment. For the other type, we describe the general group dynamics. It's important here to identify factors that create good state of mind and motivation in the group. The last type identifies interactions between the group and its environment, the design context. Internal and external factors having an influence on the group and on each actor and each step of the evolution of the group have to be defined.

With the actor placed in a central position, we have to integrate many human aspects to describe properly the design situation. The objective is to provide project managers with a tool for an efficient capitalisation and re-use of pertinent information from previous projects. Our goal is to support the prescription of collaboration for a new project, but also to support the reactivity of project managers when a new need for collaboration appears in the course of a running project. The traceability of design activities has to be ensured, especially when the design process has been efficient. Many elements could be considered to ensure such traceability, but we propose to focus on knowledge and collaborative experience of each actor. We make this choice because the actor is a key factor for the design process performance.

Knowledge of the actors refers to all their expertises in one or several given domains [3] and could be defined as being at the crossroads of in-depth knowledge and collaborative knowledge. Rose et al. [4] proposed to structure this knowledge in four different types (Fig. 2):

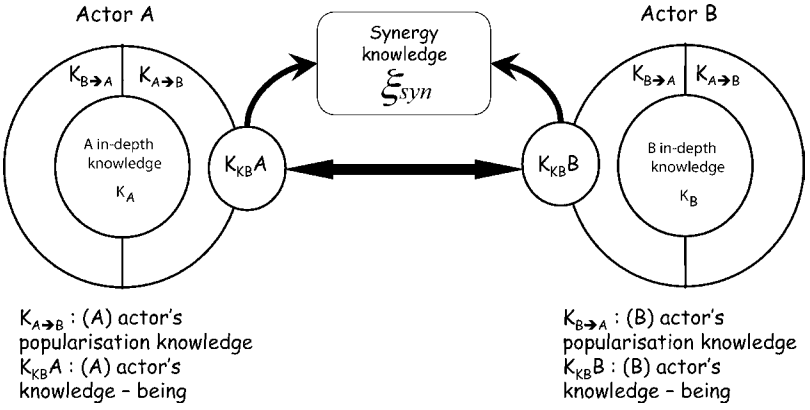

Fig. 2. Knowledge shared during collaborative design process.

- Popularisation knowledge acquired by the actor, coming from the other members of the group.
- Popularisation knowledge distributed to the other actors of the design project. It is a support of problem solving.
- Knowledge-being used by each actor when he has to initiate communication with the other actors. It can be seen as interface ports to reach other actors of the surrounding context.
- Synergy knowledge, implemented to carry out and maintain the intra-group knowledge exchanges. It's a support of communication.

So, we are able to define actor's general knowledge as a set of all this knowledge [5]:

$$K_{\mathrm{g}}(A) = K_A + \sum_{i=B}^{N} K_{i\to A} + \sum_{i=B}^{N} K_{A\to i} + K_{\mathrm{KB}} + \xi_{\mathrm{syn}}$$

In this equation:

- K_A is the actor's own expertise;
- $\sum_{i=B}^{N} K_{i\to A}$ is the addition of the popularisation knowledge acquired by the actor, coming from the other members of the group;
- $\sum_{i=B}^{N} K_{A\to i}$ is the addition of the popularisation knowledge distributed to the other actors of the design project;
- K_{KB} represents knowledge-being of the group, depending on the culture of each actor;
- ξ_{syn} represents synergy knowledge which is necessary to develop the process of popularisation of knowledge between all the actors.

Rose et al.'s proposition [4] focuses on the fact that during a collaborative activity, even if actors' knowledge and know-how have to be taken into account, it is also necessary to consider on the knowledge-being in order to encourage and favour collaboration. Depending on the situation, it is necessary to use this kind of knowledge to perform efficient design collaboration [6]. For instance, during a design activity, one actor uses his in-depth knowledge to solve a given problem. He also uses some pre-requisite information on which he bases his assumptions. The actor who is affected to the design task could solve the problem alone or with an other one. In this case, the initial actor must communicate the problem data to the second one by using synergy knowledge that enables the communication and popularisation knowledge which explains it. Problem solving goes through a succession of popularisation and mediation actions. Each actor uses respectively his popularisation knowledge to communicate with the other and his in-depth knowledge to find a solution to the problem [4]. Moreover, each actor uses different synergy knowledge and pre-requisite information according to the situation. At the end of the collaborative solving process, a set of knowledge is generated, related to the retained solution and the solving historic. This generated knowledge contains product information (structural definition, calculation results, machining process, etc.) but also information about the process and the organisation adopted to solve the problem.

Among the various kinds of knowledge identified above, it is essential to capitalise the generated knowledge regarding a given design project, by structuring the exchanges of popularisation knowledge. This knowledge has to be taken into account in a model describing the design context to manage properly the collaborative design process. The more facilitated and pertinent the exchanges of knowledge are, the more efficient the collaborative design process is. To formalise these exchanges and this knowledge, we suggest integrating them in the Robin et al.'s design system modelling [7]. Following section shows how knowledge could be integrated in this general design system modelling in order to influence management of the design process.

3. Modelling the design system

A great number of models describing the design system have been proposed [8,9]. Generally speaking, these models integrate elements linked with the product, process and organisation but they do not take into account clearly human aspects. Rosenman and Gero [10] emphasise on the fact that design is above all a human activity and that is very difficult to understand all the designers' actions very well. They show that the evolution of the product is the result of interactions between techno-physical, natural and socio-cultural environments. They concede a central place to human in the design process, since it is thank to human that interactions between all the elements are concretised in term of evolution of the product. So, a description of the design system has to focus on human aspects, to fear all the factors that could influence the design process. Eder [11] reinforces this idea by placing the design activity at the intersection of three axes: a socio-cultural axis, a techno-scientific axis and an econo-organisational one. He defines the context of the design system with a view to the product, the process but also to human, social and organisational aspects. A synthesis of theses different approaches permits to conclude that if we have to describe the context of the design, we have to consider human aspects, scientific and technological knowledge and the socio-economic and organisational environments. Robin et al. [7] have proposed a model describing this context and which integrates all these elements (Fig. 3). Interest of this model is to make appear and define all elements which influence design system and interactions between them to support engineering management according to structuring of decisions making.

In the provided model, we take account of each factor influencing the design system (external and internal environments, scientific and technological knowledge, human aspects), at each decision level (strategic, tactical and operational). They allow obtaining a static global description of the context of the design system. Dynamic of the system appears by the mean of the interactions between each element which give a vision of the possible evolution of this context (links 1–3). Collaborative knowledge appears during the

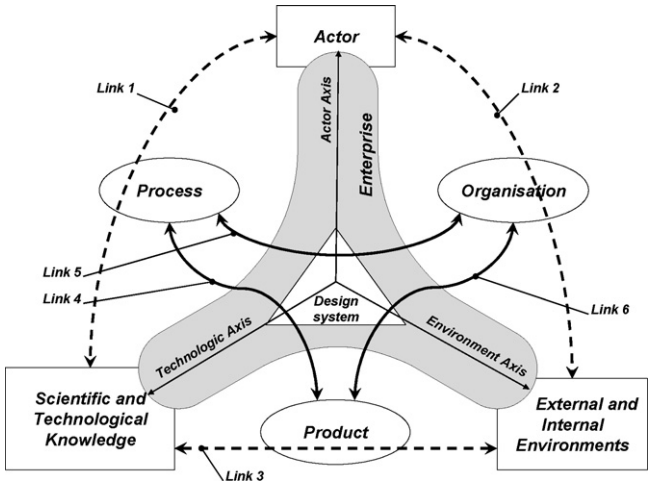

Fig. 3. Interactions modelling between factors influencing the design system [7].

progress of the project and mutual evolution of the product, process and organisation models (links 4–6). That refers to a detailed level of modelling, more operational. Thanks to this degree of detail each type of collaborative knowledge is described in the model.

Hence, thanks to such a representation of the design system context, the manager can easily analyse the design situation, identify particularities of each project and knowledge that will be useful to the collaborative design process. Consequently he is able to adapt his project management method by taking the right decision of control to satisfy objectives and to assist collaboration between actors. Following section presents how shared knowledge is taken into account during the management of design process.

4. Management of design process

At the beginning of the collaborative activity popularisation knowledge does not exist in the model (Fig. 3). The model could only integrate the in-depth knowledge of each actor. In this representation, the scientific and technological knowledge is linked to each actor thanks to the process model. Each actor will developed his own cognitive process to transform his scientific and technologic knowledge in tangible results on the product [11]. So, in-depth knowledge appears and could be capitalised only by the mean of the management of cognitive processes. It will be also the case for the popularisation knowledge and synergy knowledge. These types of knowledge will be the result of a collaboration process [12], so they do not exist without collaboration. This process obliges to take into account of being-knowledge in order to allocate adapted human resources to the collaborative activity. Well-adapted resources permit to favour initialisation, popularisation and mediation phases of the collaboration process (Fig. 4) [5].

We could make a parallel between this model and the O'Neil et al.'s taxonomy of teamwork process [13]. This taxonomy has six teamwork processes:

(1) adaptability: recognising problems and responding appropriately;
(2) communication: the exchange of clear and accurate information;
(3) co-ordination: organising team activities to complete a task on time;
(4) decision making: using available information to make decisions;
(5) interpersonal: interacting co-operatively with other team members;
(6) leadership: providing structure and direction for the team.

This taxonomy gives a global framework to describe teamwork processes whereas Rose's proposition [5] permits to obtain an interesting degree of precision in the description of the collaboration process. These two approaches show that it is necessary to integrate classical criterion of human description and evaluation, as hierarchical function or availability but also psychological criterion in the description of the design context. These criterions allow us to describe the knowledge-being of each actor. For instance, the four fields of competencies of Flück [14], the social competencies by Levenson and Gottman [15] or the Myers–Briggs indicator [16] are taken into account. They permit to obtain a description of an actor's ability to collaborate which partially corresponds to his knowledge-being. The actors' description offers a framework to manage collaborative design process since it defines the collaboration process and how knowledge is shared. Based on this description and on the GRAI model for the design process management [17], Girard and Robin [18] have developed the concept of design environment, to integrate these aspects. They have defined them as the actors' context of work developed in order to optimise performances relative to customers' or enterprises' expectations. It permits the project manager to promote collaboration between actors during the progress of the project. Creation and deployment of a design environment obliges to analyse the design situation that it has to be optimise. A design situation is defined as the state of the technologic system at a specific point of time [18] and takes into account elements previously described. A design environment will be defined as a combination of many parameters, which will evolve during the project progress according to the design system situation. Management of design environments will consist in a continuous phase of adjustment and evolution of design environment according to the design situation. The dynamic of design environments management is based on four main phases [18]:

(1) Identification of a need for collaboration.
(2) Description of the as-is design situation.
(3) Analysis of the as-is situation and comparison with the objectives of the design system in order to decide whether or not a parameter needs to be introduced or changed.
(4) Implementation of a design environment adapted to the design situation in order to efficiently change the design context.

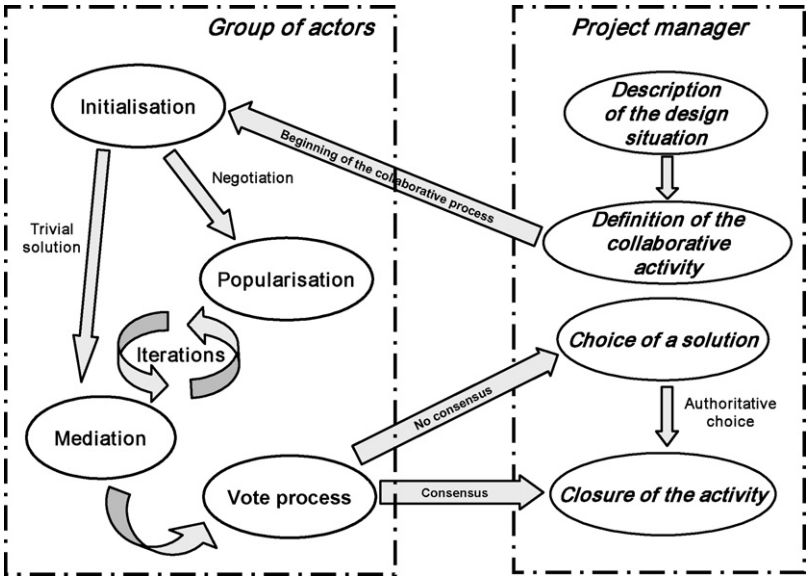

Fig. 4. Description of a collaboration process [5].

Even if product and process models are integrated in the model of a design environment, it is the quality of the knowledge shared between design actors which will have especially an influence on the evolution of the design environment. Indeed, results of the collaborative design activity directly depend on relationships between design actors. Integration of shared knowledge in the design environment model could be done into the description of the design situation and during the control of the evolution of the design environment [19]. After many projects capitalisation it will subsequently be possible to suggest pertinent information in the design environment to favour creation of a common culture and of a common language for each expertise represented in the project. This information will enable to create collaboration between actors. Following section describes the use of the design environment and of the shared knowledge to manage an industrial design process by the mean of IPPOP software.

5. Application

As more and more stakeholders are involved in the integrated design process, more and more knowledge is used and shared and to develop products. Improvement of design process of enterprises supposes to control knowledge flow between actors during the collaboration phases. The information system is supposed to ensure the traceability of this knowledge by collecting the various data more or less structured and organised. One of the rare consensuses in the knowledge management domain is that knowledge is now perceived as an organisational and production asset. It is a valuable patrimony to be managed. Thus there is a need for tools and methods assisting this management [20], especially in a collaborative context. As shared knowledge has to be managed to control design process, it's necessary to take into account formalisation and capitalisation of them.

Many research works focused on development of strong collaborative tools and especially collaborative design tools. As tackled by Klein [21], workflow systems currently provide support for adaptive processes and some of them do not allow one to modify a process model once it has started executing. Besides most of computer supported collaborative work (CSCW) tools focus on communication features (messaging) and co-ordination (approval forms, workflow tools, video-conference tools) but few of them are interested in collaboration among actors. There are relatively few studies, however of the role of CSCW in product development and design and its effect on problem-solving activities [22]. A great number of software proposes forums to facilitate exchanges among actors and helps actors during their design activities but they are not often well adapted to actors' work. They do not formalise inter-skills relationships and do not guide the actors towards the setting up of a common knowledge project. Moreover, they can only support simple, predicable processes, but not the dynamically changing and complex processes that are present in many organisations they are too predictive. The CAD tools are principally focused on the generation of the objects and not on their functional and behavioural aspects [23]. Moreover, in the case of a collaborative work, the multiple point of view (technological, human, expertises, etc.) are rarely supported [24,25]. A great number of projects have tried to answer to the problem of the multiple points of view as DICE [26], IBDE [27], ACL [28] but results were often limited and disappointing, and now many projects are developing a new approach as DCS [29] for instance. As a consequence, we conclude that any operational application which permits to support the actors' needs during collaborative design activities exists. In particular, no one considers mutual influences between product knowledge, evolution of this knowledge and the context of this evolution.

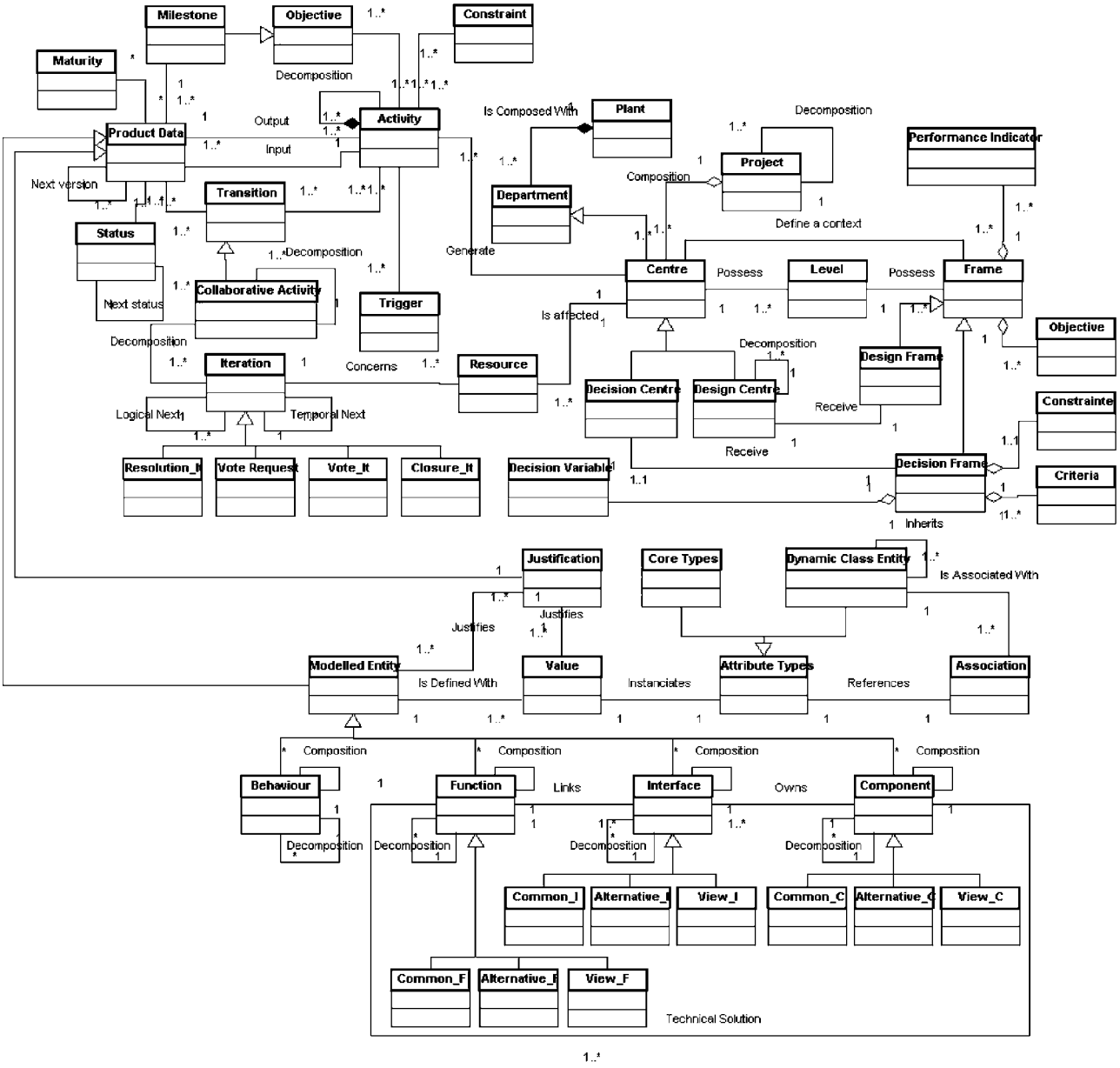

Fig. 5. UML class diagram of the IPPOP project.

5.1. The IPPOP demonstrator

IPPOP[1] is a software developed to help designers and more specifically the decision-makers to manage design process at each three decisional level defined in the GRAI model [17]. Strategic level defines the global organisation of the enterprise. Tactical level provides a vision of the functional structure of the enterprise. And operational one represents the project organisation. The aim of this project is to develop an IT-tool integrating the product, process and organisation dimensions to support design activities and engineering design management. Many concepts and all the elements which have been described in this paper have been integrated in the software as classes or as attributes of a class in the class diagram of IPPOP (Fig. 5). For instance, human class regroups elements of knowledge, competencies and availability.

The organisational view described the structure of the enterprise and specifically the structuring of decisional aspects according to the GRAI model. If we focus on the operational level, collaborative activities regroup actors distributed in each partners' location. Each actor's task is defined and each one knows his context of work (human and material resources, distribution of these resources, objectives, constraints, influence of the others actors, etc.). This decisional level provides to upper decisional levels tangible results on the product and

[1] Integration of Product, Process and Organisation for engineering Performance Improvement (IPPOP) is a French RNTL network project labelled by the French Ministry of Economy, Finances and Industry gathering industrials and academic partners to develop a software demonstrator based on the integration of product, process and organisation view points during design process.

information about collaboration (shared knowledge, number of exchanges between actors, actors' capacity to collaborate, etc.). It will be easier to collaborate if we favour collaboration by the mean of design environments (Section 4).

Creation and implementation of design environments will be done at a tactical level. To create design environment, project manager has to identify human and material resources that have to collaborate in order to achieve design objectives. He has to know information about design process, design system and functional structure of the enterprise and of the others partners. He manages one department of the enterprise and has to initialise internal or external collaboration identified by the upper decisional level. He has especially to create and control work groups according to knowledge, distribution, culture, collaborative capacities and interoperability of each human and material resources.

The strategic level has a global vision of the design system. It defines departments that have to work together but could not manage all interactions between them. Strategic level gives a functional vision of the design system and tactic level completes this vision with a procedural one by creating effective collaborations. This description of the design process is based on a global description of the design system at a strategic decisional level. Strategic project managers have to define the general functional structure of the product in order to identify which design departments have to work together. The decisional structure of the enterprise is described by the mean of GRAI grids [17] and modelling with the IPPOP software by its administrator. In this case we have a static vision of the design system which corresponds to the as-is situation of the design system. When design process begins its evolution could be taken into account dynamically by IPPOP software. It capitalises information about design process (objectives, performance indicators, decision frameworks, etc.) and allows designers to make evolve design process by creating activities if it is necessary. So, each decision-maker has a specific GUI that gives him information about his tasks and helps him to manage relationships with other partners by defining exchanges of information (Fig. 6).

That permits to identify relationships and influences between each partner and each department of enterprises. So, strategic decisional level has to define global objectives of the design but also interoperability and collaboration between departments. When all these elements are identified it is possible to focus on evolution perspectives of the design system to judge on the pertinence of the decisions. This step makes appear action levers that could influence the system. If it is conclusive, objectives and performance indicators, adapted to action levers could be deployed to the lower decisional levels.

It is the combination between the description of the design system, the adapted PMS definition and the management of the design process thanks to the design environment that provides to design managers opportunity to follow and evaluate the design system. IPPOP permits control of collaborative activities by the mean of an adapted product model based on FBS Framework [30] and a specific collaborative design process model. All these elements are integrated in an organisational model constructed on the design environment concept and implemented and managed in IPPOP. Implementation of IPPOP is based on an enterprise modelling by the mean of the GRAI grids that makes appear decisional and functional structures. Each actor is identified in the GRAI grid that implies IPPOP could provide to each user a specific graphical user interface (GUI) on which he finds all information

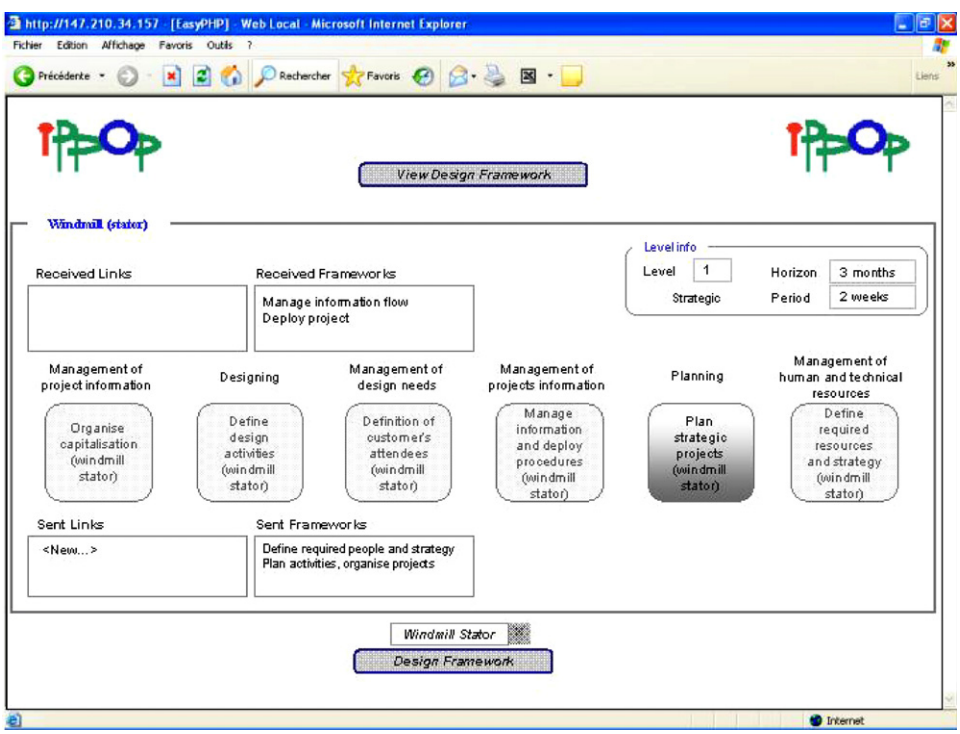

Fig. 6. Example of IPPOP GUI dedicated to a decision-maker at a strategic level.

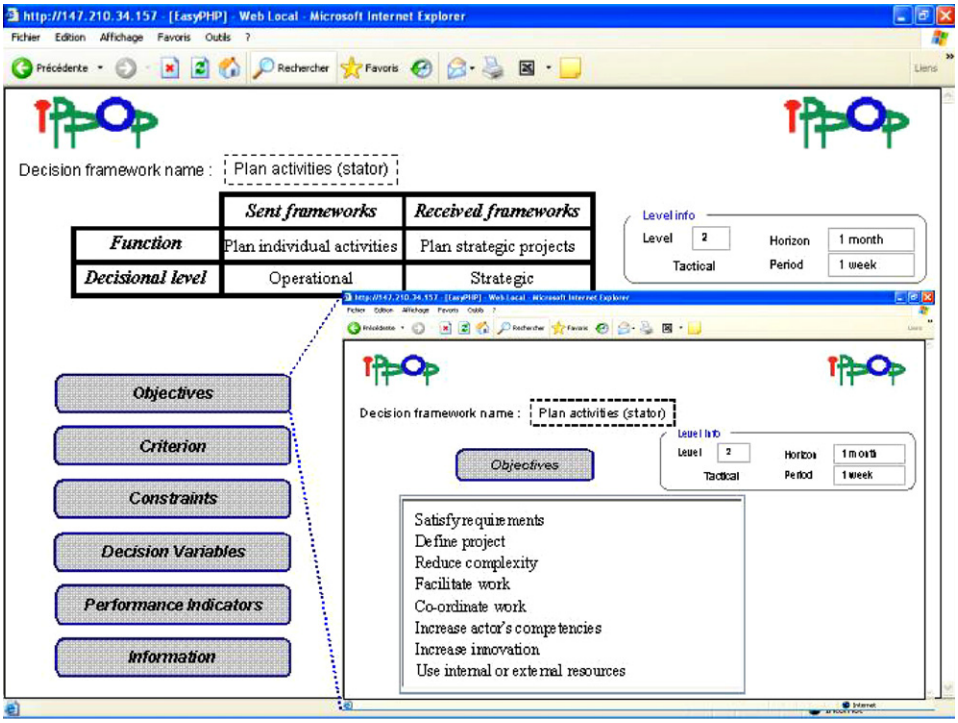

Fig. 7. Example of IPPOP GUI dedicated to a decision-maker at a tactical level.

necessary to achieve his task (Fig. 7). This description is completed with a PMS and an integrated model of product, process and organisational models to obtain a dynamic system to manage design process and to control design system evolution.

The next section presents an industrial case study illustrating the proposed concepts and modelling with the IPPOP project.

5.2. *Industrial case study*

The industrial case study concerns the design of a stator sheet dedicated to a windmill generator at Alstom Power Conversion facilities (Nancy, France). This design phase is representative of the needs for collaboration that could appear during a design project since it embeds some key characteristics of this activity:

- The various stakeholders are evolving in an extended enterprise context. The involved actors come from different departments distributed in different plants and countries, with different technical, managerial and social cultures.
- They perform concurrent activities in order to meet as soon as possible the various milestones.

Several design actors are involved to co-design the stator sheet and composed a design team gathering an electrical calculator, a designer from the Research Consultancy office, a mechanical calculations expert, a member of the machining department, a subcontractor and the customer.

During the design process, the mechanical expert identifies that a data regarding the stator diameter does not fit within the authorised range of values since it is supposed to bring about a resonance phenomena (as it is described in the UML sequence diagram in Fig. 8). As this data is critical to the global dimensioning of the stator, it is of primary importance to quickly solve this possible conflict that it could be a brake for the design process. The mechanical expert captures the detected conflict within the software application. He also should create and deploy an adapted design environment to solve the conflict and launch vulgarisation/mediation phases through the software application in order to solve the conflict. Then the IPPOP software notifies the conflict to the selected actors and enables the various stakeholders to discuss and argue during the vulgarisation/mediation phase. All the exchanges and proposed solutions are capitalised in order to be reused for further conflicts in the same field.

IPPOP collects and spreads information concerning product, process and organisation. Consequently, project manager could complete different matrix concerning actors and refine his knowledge on the actors. Thanks to the follow-up of the dynamic protocol of popularisation and mediation process, he could complete knowledge on the collaborative experiment of each actor and supply needs for information. The last iteration of the process summarises the various stages of the solving process while embedding the collaborative knowledge used to solve the problem and to agree on the alternative solution proposed. This information permits to the project manager to be reactive to the group's needs and to capitalise this experiment to reuse it in a future similar project. At this moment, if project manager has optimised the design process, the contents of the design frame and the team composition by considering capitalised information about actor, he will be able to propose a design environment more efficient. Before the creation of the new design environment,

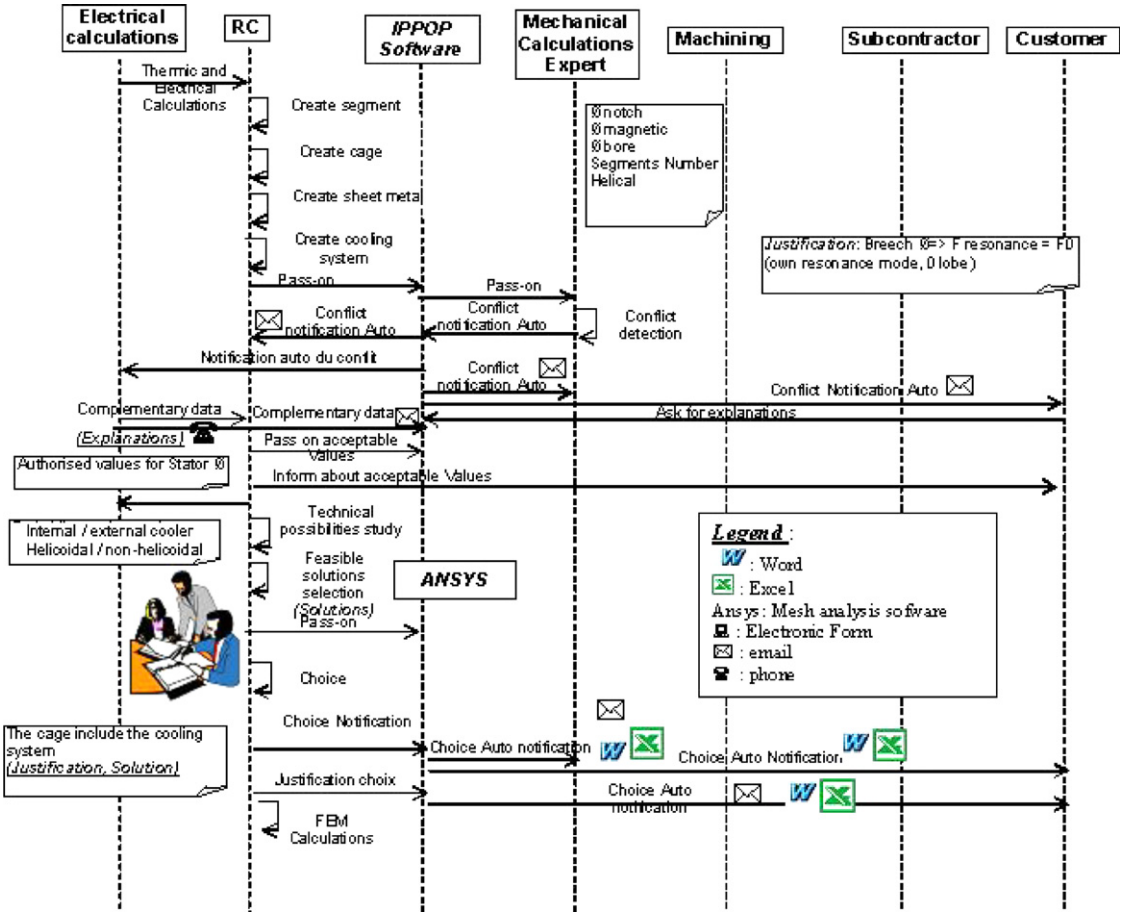

Fig. 8. Part of the design process of Alstom stator sheet.

design process was sequential and sequence of design activities was not precisely defined. Now, thanks to IPPOP, project manager is able to follow the evolution of the design process, in the frame of the design environment and he is able to capitalise this process.

5.3. Synthesis

Fig. 9 presents the various relations existing within the networks build to solve the resonance problem on the Alstom stator sheet design. This analysis was performed thanks to the traceability of the various exchanges occurred during the conflict and capitalised thanks to IPPOP. We can notice that the research consultancy appears as the nerve centre of the network of actors because it centralises most of the relationships. Even if the network of actors seems to be well established, we can observe that the resources ties are less numerous and it is even truer regarding the activities links. It is a characteristic of an evolving consortium where the partnerships are not well established. Such an analysis gives some feedback to the project manager on the ability of the various stakeholders to work together and to quickly create synergies within the subscribers' group. We also analysed the knowledge exchanges between the different actors involved in this solving process. This enables to highlight crucial exchanges that allowed sharing crucial knowledge in order to lead to an acceptable solution.

This example suggests interests of IPPOP to follow evolution of a project and to put in evidence the need for collaboration and to supply a detailed description of the design situation. IPPOP permits to be more reactive and more adaptable in the phase of creation of the design process in order to satisfy the needs for collaboration between actors. It also increases the reactivity of the project manager towards a potential conflict or when a conflict appears during the design process.

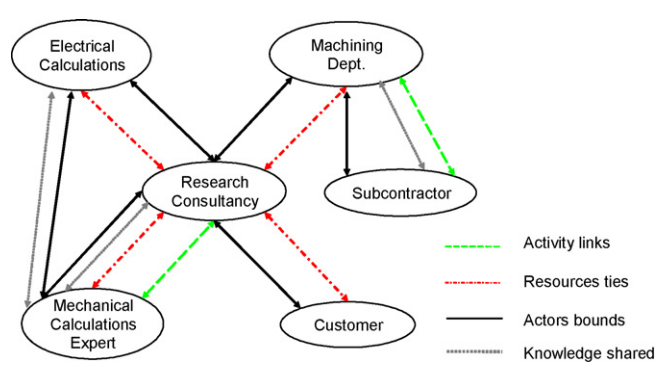

Fig. 9. Networks created regarding stator sheet design conflict.

6. Conclusion

Product design today requires new interaction forms between the various stakeholders involved in this specific process. Nevertheless, the sharing of expertises, knowledge and know-how jointly linked with the development of communication means generate a great number of pieces of information and knowledge. It becomes necessary to ensure the traceability of such knowledge in a way that it can be re-used [31]. It is therefore necessary to manage and to capitalise relationships as well as knowledge exchanged between actors and more generally the design process as a whole, with a particular attention on the organisation that was set up to satisfy design objectives. The organisation has to integrate aspects centred on the actors in order to be reactive and efficient considering the design process evolution. Software solutions are still needed in order to fill the lacks existing today. This paper presents a way to take into consideration the design actors and underlines a typology of knowledge manipulated by these actors during the design activities. The objective is to demonstrate the need for a framework to formalise and capitalise this knowledge. A formalisation of design environment is proposed as an answer to such requirements. To validate this framework, we implemented it within a real industrial case study: the design of a stator metal sheet. This implementation within the IPPOP software demonstrator is correlated with performance indicators which provide some insights on the project roll out and which are also useful to take new decisions in future similar situations.

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