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TOOL BASED SUPPORTING COLLABORATIVE DESIGN FROM SPECIFICATION DEVELOPMENT TO CAD MODELLING

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ABSTRACT

Management of dynamic information interdependencies and as well as management of multiple perspectives from specification development to conceptual design, as well as from conceptual design to detailed design are critical elements of collaborative and distributed design. Supporting collaborative design with computer technology is a strategy to enhance the ability of actors to interact with each other and with computational resources during different phases of product design and development. However, many observations from the industry and research support the evidence that both specification development phase and conceptual design are poorly supported by collaborative tools. Furthermore, though CAD tools support detail design, it is imperative to develop new collaborative design tools or renovate traditional standalone CAD systems by making it collaborative-native. Consequently, the first goal of this paper is to propose the development of collaborative tools related to the conceptual design. The second goal is the development of a mechanism for communication between the developed collaborative conceptual design tools and actually CAD tools. The mechanism and architecture of the developed tool for collaborative conceptual design is presented. A design problem illustrates the concepts discussed in the paper.

KEYWORDS

Product development, collaborative design tools, functional analysis, product data management, communication tools.

1. INTRODUCTION

Design is a problem-solving process that transforms an ill-defined problem into a final product (Ullman, 1992). Indeed, engineering design problems are fuzzy and complex. Requirements or the specifications are incomplete, ambiguous and instable. During the design problem evolution, new specifications and constraints yield from the initial requirements and this process is a recursive one. Instability comes from incompleteness, variability and sensitivity of design specifications and data produced during design process (Antonsson and Otto, 1995; Deciu et al. 2005).

Specification development and conceptual design are crucial phases in design. Identifying the customer, determining their requirements and specification, translating customer requirements into measurable engineering requirements is a highly interdisciplinary task. It is concerns more with understanding the problem and making general rather specific, decisions about the solution (French, 1992). Conceptual design succeeds the high-level description of requirements and proceeds to a high level description of a solution (McNeil et al., 1998). The objective of the

conceptual design is to find an optimal and feasible concept meeting functional specifications. It starts with clarified engineering specifications followed by the definition of functions and the establishment of function structure of the product (Pahl and Beitz, 1996). Developing concepts for each function and their combining permit to generate a set of potential concepts. Management of combinatorial explosion (Al-Salka et al., 1998) and functional design verification (Deng et al., 2000) are challenges of the designers and engineers during conceptual design. The generated concepts give no details about the product's final form, but they affect the basic physical embodiment in detailed design phase (Ullman, 1992).

Solving fuzzy and complex problems requires collaboration of actors from multiple distributed disciplines. Collaborative and distributed design is a complex, decision-making engineering process. This complexity results from the conjugation of an important number of heterogeneous data (domain, actors, perspectives, organization, and methods) interacting between them (Movahed-Khah et al., 2007). Self-organization, dynamics and self-similarity are some properties of the collaborative and distributed design organisation (Movahed-Khah et al., 2009). Collaborative and distributed design then could face the most difficult situation in which the information and task interdependencies, related to design phases of product design and development, are not fully defined à priori (Lu et al., 2000; Lu et al. 2007).

However, management of information interdependencies (Frey et al. 2009) and as well as management of multiple perspectives are critical elements of collaborative and distributed design (Détienne, 2006). Indeed, each actor has its design model and limited understanding of models of other actors (Kusiak et al., 1996; Frey et al. 2009). Different actors, pursuing goals that are specific to them, will often have different notions concerning what kind of design is best (Klein 1991). Furthermore, due to the multi-actors interaction, disagreement emerges between designers about incompatible and interdependent propositions (Ouertani and Gzara, 2008; Ouertani 2008). Unexpected interdependencies can be found when solutions generated by different designers are recombined (Case and Lu, 1996) because latent requirements or specification emerge. All these lead to complex and dynamic iteration from

requirements to the physical embodiment of the design product.

Supporting collaborative design with computer technology is a strategy to enhance the ability of actors to interact with each other and with computational resources. Research in design technology systems aims at the integration of various design tools into a single holistic system, local or distributed, that is able to support all actions of designers (Horváth, 2004). Many observations from the industry and research support the evidence that conceptual design is poorly supported by collaborative tools (Wang et al., 2002). Fuzziness, incompleteness, and instability of information during the conceptual design are principal causes of difficulties of representation of the designed product during this phase. Though CAD tools support detailed design, it is imperative to develop new collaborative design tools or renovate traditional standalone CAD systems by making it collaborative-native (Roucoules and Tichkiewitch, 2000; Li et al., 2005; Fuh and Li, 2005). Because the conceptual phase is poorly supported by collaborative tools, and the detailed phase is supported by traditional CAD systems, the communication between these tools is quasi-inexistent. Highly distributed nature of the design, diversity of the engineering tools, complexity and dynamic environment are some real difficulties to develop tools for collaborative conceptual design as well as well collaborative CAD.

Consequently, the first goal of this paper is to propose the development of collaborative tools related to the conceptual design. The second goal is the development of a mechanism for communication between the developed collaborative conceptual design tools and actually CAD tools. The framework of the proposed research is based on a real model extracted from real industrial experiences. The second section of the paper analyse the extracted model. A new model is proposed to overcome the shortcomings of the real model. The developed tools, called TDC system are presented in the third section. The fourth section describes an application. Finally, the fifth section concludes the paper.

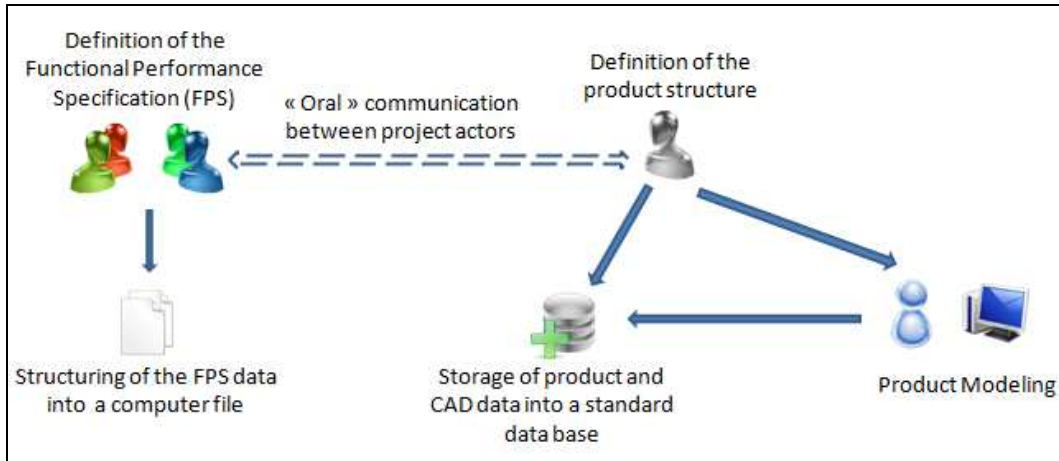


Figure 1 Current communication model

2. COMMUNICATION MODEL IN COLLABORATIVE PRODUCT DESIGN

2.1. Current communication model

According to our experience in many enterprises, we should note that the product design is often realised by two teams working together. On the one hand, it is the team that develop specifications and defines requirements that product should meet. On the other hand, it is the architect who defines the detailed structure of the product and gives the modelling instructions to the designer. The list of specifications usually regroups the set of requirements and constraints the final product should respect. Modelling will permit the elaboration of detailed drawings, assembly drawings and parts lists. This allows using of drawings for product production. Both documents specification list as well as drawings, must be therefore coherent in order to assure the quality of the final product.

However, the information communication from specification development to product modelling is only oral (Figure 1). Indeed, today, from thirteen consulted enterprises, 77% confirm having only an oral communication between actors corresponding to these two tasks. On the same survey, 77% of interrogated enterprises affirm to develop the specifications and requirements in group of different experts representing different product views, but this development is done without a formal approach. They use the basic soft office tools to put in form and stock the information on the specifications and requirements. A printed list

of the specifications and requirements is given then to the architect who defines the product structure meeting these specifications and requirements.

Once the architectural structure has been determined, the architect stocks and put it in the disposal of the CAD designer. Still, on the same survey, 85% of interrogated enterprises affirm that they stock the architectural structure product in a PDM. In the most cases, this storage is done in the form of an e-BOM (engineering Bill Of Material). Then, modelling instructions are given to the CAD designer. CAD designer models the product with the help of CAD tools and stock the organization of the CAD modelling files in a PDM in the form of a cad-BOM (computing aided design Bill Of Material).

In this situation, it can be mentioned that only architect's rigor can insure that the final product will meet the list of specifications and requirements. Effectively, the communication between specifications and requirements on the one hand, and the product modelling on the other, is only realised via the oral exchanges between actors.

2.2. Discussion

The first problem in current model comes out from an overall oral communication between actors of product specification and requirements development on the one hand and the architects on the other.

Indeed, during data exchange via oral communications, there are a lot of problems related to the human issues such as different vocabulary utilization by different actors, uncommon ontology, disagreement and conflicts, difficulties

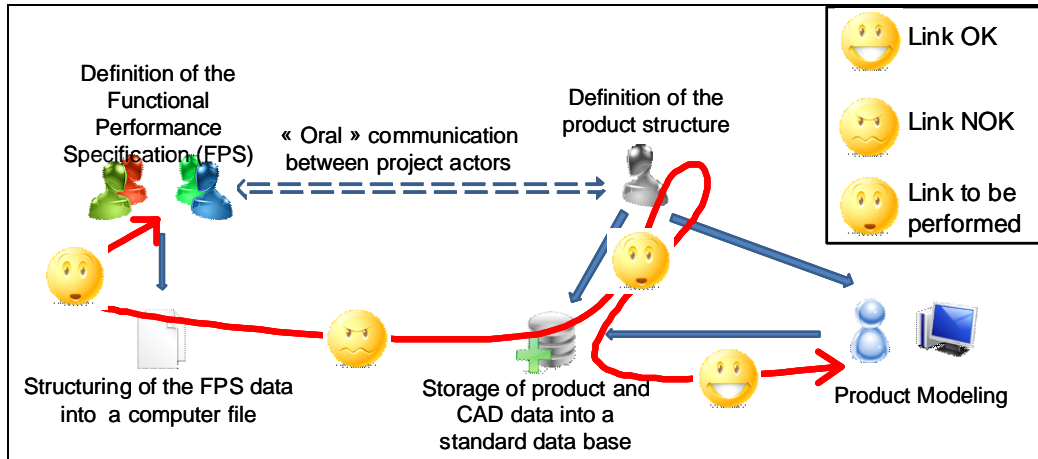


Figure 2 Shortcomings of the current communication model

of understanding each other, and so on. Therefore, the communication between the specification and requirements on the one hand, and the definition of the product structure on the other can not be only oral.

The second problem resides in the representation form of specifications and requirements. Today, most enterprises are in difficulties on this early phase of the product design. They often have interrogations as how to define and develop adequately the list of specifications and requirements. They frequently develop the list of specifications and requirement with the help of soft office tools but they have not any methodological approach to formalise it properly.

The third problem is related to the parallel definition of the product architecture as well as the development and the evolution of the list of specifications and requirements. This necessarily has a negative impact on the searching and the choices of solutions which therefore can not fully meet the specifications and requirements because of an absent dynamic communication. Consequently, there is not a certainty that e-BOM ensues of logical manner the specification and requirements.

Therefore, three problems to be improved can be identified (Figure 2):

1. The consistency of data related to the specifications and product modelling must be improved because the only oral communication is not sufficient;
2. The development of the specifications and requirements must be improved because it lacks

methodological support and is not sufficiently formalized;

3. The adequacy between the structure of the product on the one hand and specification on the other must be improved because the product structure does not reflect always the later.

2.3. Proposed Model

For solving these problems, we propose a communication model (Figure 3). The proposed model allows carrying out the product design through communication according to the following phases:

Phase 1: Specifications and requirements definition and its formalisation with the help of methodological tools;

Phase 2: Structuring of data related to specifications and requirements into requirement, functional and conceptual BOMs (respectively r-BOM, f-BOM and c-BOM) ;

Phase 3: Definition of the product structure (e-BOM) from c-BOM, generation of cad-BOM from e-BOM as well as the definition of CAD modelling instructions;

Phase 4: CAD product modelling.

The first phase, definition and development of list of specifications and requirements referred to Figure 3 as Functional Performance Specifications (FPS), is proposed to be carried out with the help of External Functional Analysis (EFA) and Internal Functional Analysis (IFA) methodologies. The External Functional Analysis allows identifying the global service functions that designed product

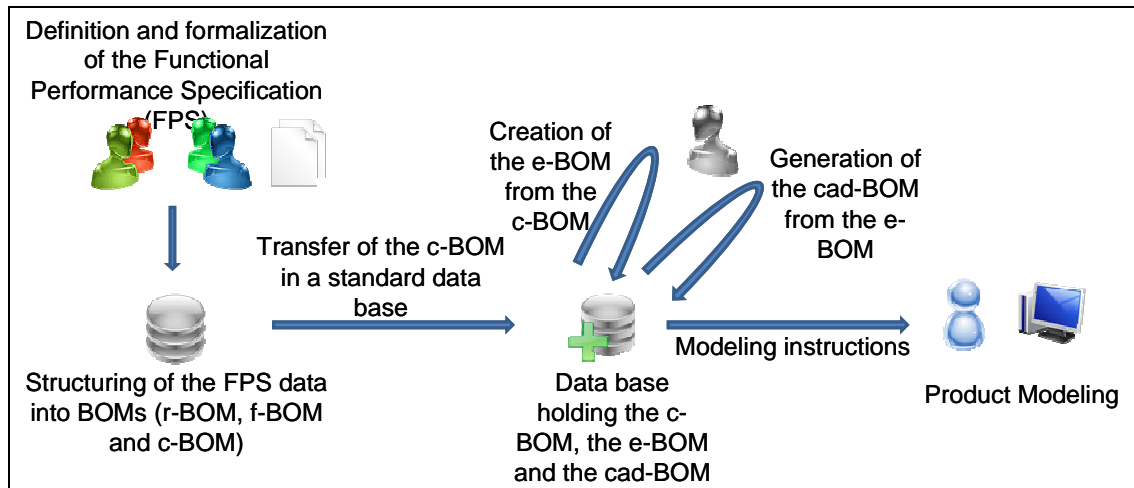


Figure 3 Proposed communication model

should meet, according to the identified customer needs. From the characterization of these functions, one can determine the functional criteria as well as their level of flexibility to be taken into consideration during product design. The External Functional Analysis (EFA) is followed by concepts searching. The Internal Functional Analysis (IFA) is applied on the retained concept. The Internal Functional Analysis (IFA) allows schematizing the early phase of structured solution which is organised as a graph of related no detailed components. It allows verifying if the concept answers fully to the global service functions identified by EFA. The verification is done through a Functional Block Diagram (FBF). The Functional Block Diagram can define what component of the solution participates to the realization of what global service function. The Internal Functional Analysis IFA also allows characterizing components through characteristics and levels. From both analyses, the External Functional Analysis (EFA) and the Internal Functional Analysis (IFA), a functional and technical list of specifications and requirements can be obtained.

The second phase consists in translating functional and technical specifications and requirements into BOM representations. Three BOMs are proposed:

- The requirement-BOM (r-BOM)
- The functional-BOM (f-BOM)
- The conceptual-BOM (c-BOM)

The r-BOM is constituted from the set of specifications and requirements defined in the previous phase. It defines the set of criteria and their levels of flexibility from the characterization

of global service functions. The f-BOM is composed of global service functions and their sub-functions classified previously in the EFA. The c-BOM is built based on the components of the concept. The components have been listed and organized in the Functional Block Diagram during IFA. These components are not necessarily final components of the product, but rather components or groups of components responding to a function. At the end of this phase, the c-BOM is transferred and stocked in data base.

The first goal of the third phase is to construct the product structure from the BDF schematized structure. Thus, the engineering-BOM (e-BOM) is deduced from conceptual BOM (c-BOM). Three actions are proposed for architect: (a) duplication of a c-BOM component; (b) creation of a sub-set of components from a component of the c-BOM; (c) creation a new component (no existing in the c-BOM). It is the architect which controls the consistency between the product structure, represented by e-BOM, and the developed functional and technical specifications, represented by r-BOM, f-BOM and c-BOM. Furthermore, during engineering BOM (e-BOM) building, the rationale of the choice and transformation is capitalised. The second goal of this third phase is to transcribe this e-BOM in cad-BOM (computing aided design-BOM). During this action, the data base creates the parts and assembly files according to the structure of the e-BOM. An organized cad-BOM modelling files is obtained automatically. These files must be completed during the fourth phase.

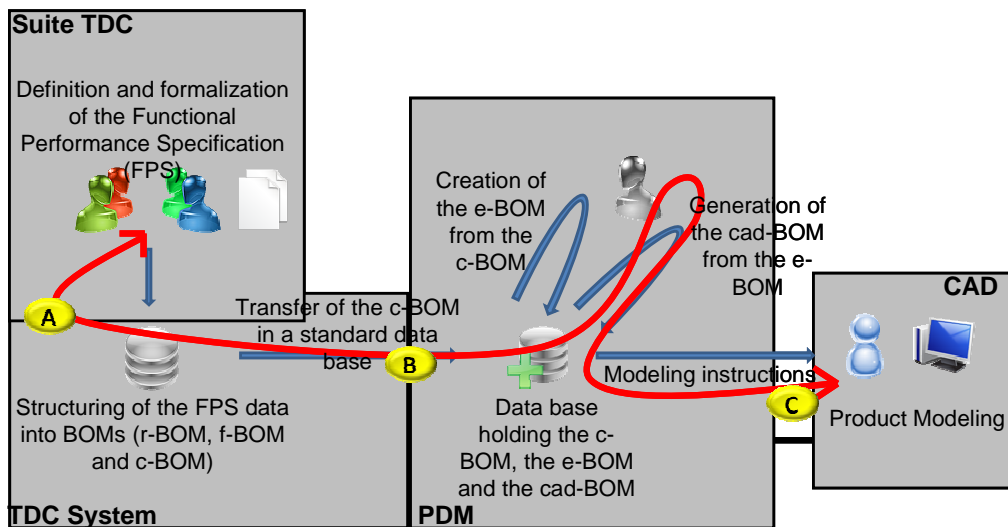


Figure 4 Architecture of inter-communicated tools

The fourth phase enables us to have essentially the product modelling based on predefined the cad-BOM. Modelling files have been created previously in the third phase. Thus, modelling designer can open these files and follow the part or sub-assembly modelling according to the files' modelling instructions. The communication between different BOMs permit to have the necessary information on the part or assembly modelling such as the global service functions realised by the part or sub-assembly, criteria and levels of flexibility related to the functions that the part or sub-assembly model realise, and so on. All these information allow the CAD designer to carry out the product modelling in consistency with the developed specifications and requirements.

3. TOOLS AND THEIR ARCHITECTURE FOR COLLABORATIVE PRODUCT DESIGN

In order to implement the proposed model, it is necessary to develop software tools allowing supporting each phase of the model. For that reason, the following tools are proposed for each of described phases (Figure 4):

Phase 1: The software tool called, Suite TDC, is proposed to carry out the first phase. TDC Suite is methodological tool permitting to lead the actors to carry out the Functional Analysis. The Suite TDC is composed of two modules: TDC Need that permits to implement the Exterior Functional

Analysis and TDC Structure that allows applying the Interior Functional Analysis.

Phase 2: The platform TDC System supports the second phase. TDC System restructures the functional and technical specifications into a linked structure of BOMs: requirement BOM, (r-BOM); functional BOM (f-BOM) and conceptual BOM (c-BOM).

Phase 3: Product Data Management (Smarteam) tool supports the third phase. It allows the architect to be able to create the e-BOM and the cad-BOM from the c-BOM transferred from TDC System.

Phase 4: CAD modeller (CATIA V5.R16) is used in the fourth phase. It gives the possibility to the designer to carry out product modelling using the data and the instructions from cad-BOM.

Between these four tools, three interfacing mechanisms can be distinguished (Figure 4):

Interfacing mechanism A: It allows the integration of data in TDC System from specification and requirement defined in the Suite TDC. Here, the term integration is used because the Suite TDC and TDC System tools have a common core.

Interface mechanism B: It carries out the transfer of the c-BOM from TDC System to the PDM tool.

Interface mechanism C: It carries out the transformation of PDM data (essentially of the cad-BOM, but also of r-BOMs, f-BOMs and c-BOMs) to CAD data, supported by CAD modeller.

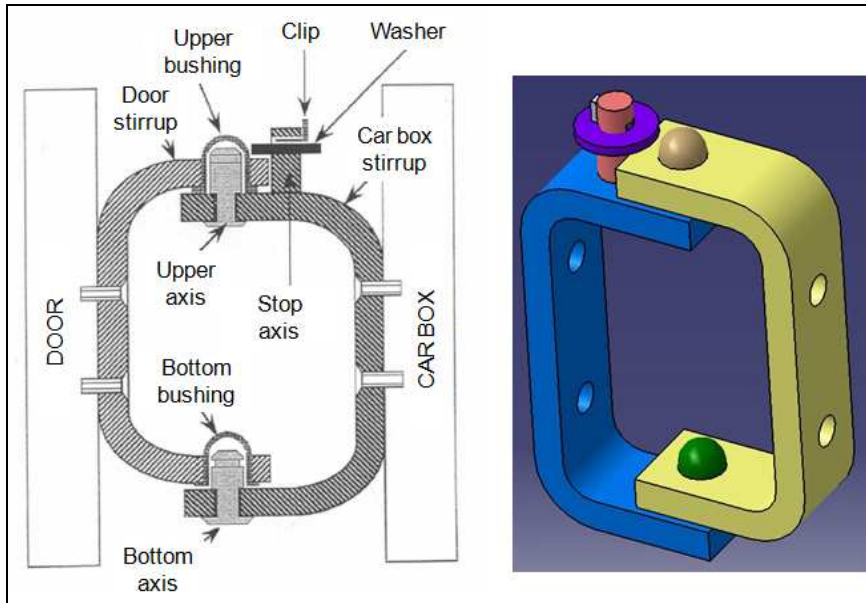


Figure 5 Hinge of car door

4. APPLICATION

The application is a hinge of car door. It is a mechanical system decomposed in two main subsets: the hinge side door and the hinge side case. These subsets are composed of several components as shown in Figure 5.

Phase 1: Specification and Requirements Definition. For specification and requirement

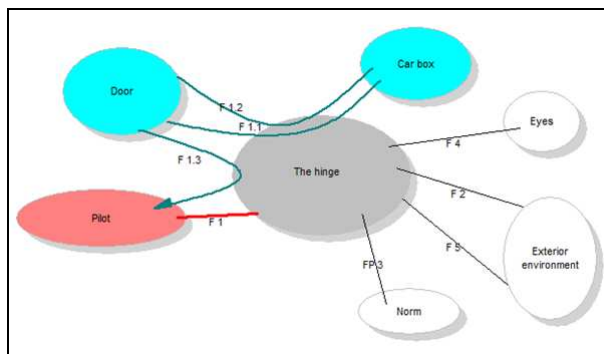


Figure 6 Interaction diagram

development, the Exterior Functional Analysis and the Interior Functional Analysis are carried out with the Suite TDC. First, Exterior Functional Analysis is realised for hinge of car door through the following steps:

- Service functions searching and definition using interactions diagram (Figure 6);

- Hierarchical diagram based service functions ordering;
- Service functions characterization through criteria, values and flexibility (Figure 7);

	Criteria	Level	Flexibility
(F 1) To simplify the access in the car			
(F 1.1) To make the car hinging on the car box	Opening angle	Mini: 47° Maxi: 70	F1 F2
(F 1.2) To assure the connection between the door and the car box	Precision of the outcrop door / car box	0,05°	F0
(F 1.3) To simplify the opening and the closing of the door for the pilot	Opening strain	Maxi 50N	F2
	Closing strain	Maxi de 40N	F2
	Reverse moment	10 N.m	F0

Figure 7 Functions characterization

Second, Interior Functional Analysis is applied for hinge of car door. The following models are generated:

- List of components and hierarchical diagram based component ordering ;
- Components characterization through criteria, values and flexibility;
- Initial product structure representation through Functional Block Diagram and the definition which component realises which function (Figure 8).

Phase 2: Structuring of data into BOMs. It consists in translating functional and technical specifications and requirements into BOM representations. Figure 9 shows the generation of

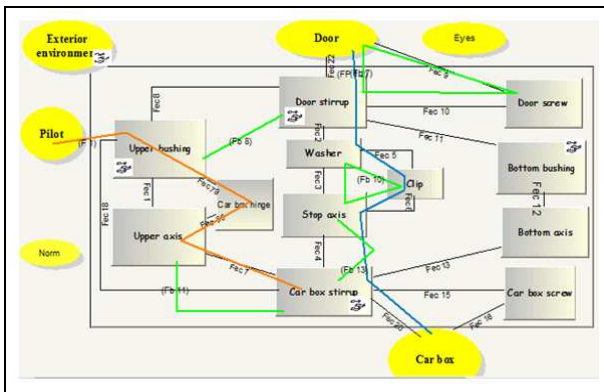


Figure 8 Functional Block Diagram

BOMs from the data represented in Figure 6, Figure 7 and Figure 8.

r-BOM Opening angle mini 47°, Flex1 Opening angle maxi 70°, Flex2 Precision of the outcrop door / car box 0,05°, Flex0 Opening strain maxi 50N, Flex2 Closing strain maxi 40N, Flex0 Reverse moment 10Nm, Flex0	c-BOM C1 : Hinge C1.1 : Door hinge C1.1.1 : Door stirrup C1.1.2 : Upper bushing C1.1.3 : Door screw C1.1.4 : Bottom bushing C1.2 : Car box hinge C1.2.1 : Car box stirrup C1.2.2 : Upper axis C1.2.3 : Bottom axis C1.2.4 : Stop axis C1.2.5 : Washer C1.2.6 : Clip C1.2.7 : Car box screw
f-BOM F1 To simplify the access in the car for the pilot F1.1 To make the car hinging on the car box F1.2 To assure the connection between the door and the car box F1.3 To simplify the opening and the closing of the door for the pilot	

Figure 9 BOMs of hinge of car door in TDC System

Phase 3: Definition of the product structure (e-BOM). Thus, the engineering-BOM (e-BOM) for hinge of car door is deduced from conceptual BOM (c-BOM). Here, for instance, based on the c-BOM, the architect duplicates door screw in e-BOM of hinge of car door. The e-BOM as well as cad-BOM are shown in the Figure 10.

e-BOM Hinge Door hinge Door stirrup Upper bushing Door screw (x2) Bottom bushing Car box hinge Car box stirrup Upper axis Bottom axis Stop axis Washer Clip Car box screw (x2)	cad-BOM Hinge Door hinge Door stirrup Upper bushing Door screw (1) Door screw (2) Bottom bushing Car box hinge Car box stirrup Upper axis Bottom axis Stop axis Washer Clip Car box screw (1) Car box screw (2)
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Figure 10 BOMs hinge of car door in PDM

Phase 4: Hinge of car door CAD modelling. CAD modeller (CATIA V5.R16) is used in the forth phase. It gives the possibility to the designer to carry out Hinge of car door modelling using the data and the instructions from cad-BOM. The files for the parts and assemblies modelling are generated automatically. The set of information in CAD files allows the designer to carry out the hinge of car door modelling in consistency with the developed specifications and requirements.

CONCLUSION AND FUTURE PROSPECTS

Management of dynamic information interdependencies and as well as management of multiple perspectives from specification development to conceptual design, as well as from conceptual design to detailed design are critical elements of collaborative and distributed design. Supporting collaborative design with computer technology is a strategy to enhance the ability of actors to interact with each other and with computational resources during different phases of product design and development. The observations from the industry and research support the evidence specification development phase as well as conceptual design are poorly supported by collaborative tools. The proposed research proposes the development of collaborative tools related to the conceptual design. The development of a mechanism for communication between the developed collaborative conceptual design tools and actual CAD tools is proposed. In the proposed model, specification development can be assisted by collaborative tools. The mapping from specification to the CAD model is realised through different BOMs. Requirements and specifications are then structured in requirement BOM (r-BOM), functional BOM (f-BOM) and conceptual BOM (c-BOM). The structure of the product, represented by engineering BOM (e-BOM) is inferred based on the conceptual BOM (c-BOM). The proposed mechanism translates the conceptual BOM (c-BOM) in computer-aided-design (cad-BOM). Among the advantages of the proposed model, the following ones are noteworthy. The proposed model permits to assist the collaborative product design according to specifications handled by collaborative tools. Furthermore, the tools allows the capitalization and sharing of the know-how of the various actors.

Nevertheless, further points remain to be considered on the issue of collaborative tool development for conceptual as well as collaborative CAD. As we continue our research, our aim is to search for the granularity of the requirements, their propagation and feedback mechanisms in different stages of collaborative design. View management and augmented annotation in CAD system (Shen et al. 2008) related to the developed x-BOMs is another direction of our work.

REFERENCES

- [1] D. Ullman, *The mechanical design process*, McGraw-Hill, New York, 1992.
- [2] E. Frey, E. Ostrosi, S. Gomes, L. Roucoules, A model to develop multi-domain product taking into account the initial requirements until the modelling and simulation tools. *International Conference on engineering design, ICED'09, 24 - 27 August 2009, Stanford, CA, USA.*
- [3] E. R. Deciu, E. Ostrosi, M. Ferney, M. Gheorghe, Configurable product design using multiple fuzzy models, *Journal of Engineering Design*. 16(2) (2005) 209-233.
- [4] E.K. Antonsson, K.N. Otto, Imprecision in Engineering Design, *ASME Journal of Mechanical Design*. 117B (1995) 25-32.
- [5] F. Détienne, Collaborative design: Managing task interdependencies and multiple perspectives, *Interacting with Computers*. 18(1) (2006) 1-20.
- [6] French MJ. *Conceptual Design for Engineers*, The Design Council, London, 1992
- [7] G. Pahl and W. Beitz *Engineering design—a systematic approach*, Springer-Verlag, London (1996).
- [8] I. Horváth, A treatise on order in engineering design research, *Research in Engineering Design*. 15(3) (2004) 155-181.
- [9] J.Y.H. Fuh, W.D. Li, Advances in collaborative CAD: the-state-of-the art, *Computer-Aided Design*, Volume 37, Issue 5, 15 April 2005, Pages 571-581
- [10] Kusiak, J. Wang, D.W. He, Negotiation in Constraint-Based Design, *Journal of Mechanical Design*. 118(4) (1996) 470-477.
- [11] L. Wang, W. Shen, H. Xie, J. Neelamkavil, A. Pardasani, Collaborative conceptual design—state of the art and future trends, *Computer-Aided Design*. 34(13) (2002) 981-996.
- [12] M. Klein, Supporting conflict resolution in cooperative design systems, *IEEE Transactions on Systems, Man. And Cybernetics*. 21(6) (1991) 1379-1390.
- [13] M.A. Al-Salka, M.P. Cartmell and S.J. Hardy , A framework for a generalised computer-based support environment for conceptual engineering design. *Journal of Engineering Design* 9 1 (1998), pp. 57–88.
- [14] M.P. Case, S.C-Y Lu, Discourse model for collaborative design, *Computer-Aided Design*. 28(5) (1996) 333-345.
- [15] M.Z. Ouertani, L. Gzara, Tracking product specification dependencies in collaborative design for conflict management, *Computer-Aided Design*. 40(7) (2008) 828-837.
- [16] M.Z. Ouertani, Supporting conflict management in collaborative design: An approach to assess engineering change impacts, *Computers in Industry*. 59(9) (2008) 882-893.
- [17] McNeil T, Gero JS, Warren J. Understanding conceptual electronic design using protocol analysis. *Research in Engineering Design* 1998; 10: 129-40.
- [18] R. Movahed-Khah, E. Ostrosi, O. Garro, Analysis of interaction dynamics in collaborative and distributed design process, *Computers in Industry*. doi:10.1016/j.compind.2009.05.007.
- [19] R. Movahed-Khah, E. Ostrosi, O. Garro, Understanding the dynamics of state-problems in distributed and collaborative design process, *Int. J. of Concurrent Engineering: Research and Application*. 15(1) (2007) 33-41.
- [20] Roucoules L. and Tichkiewitch S. CODEMO: A cooperative design environment - a new generation of CAD systems, *Concurrent engineering: research and applications*, 2000, 8/4, 263-280.
- [21] S.C.-Y. Lu, J. Cai, W. Burkett, F. Udawadia, A Methodology for Collaborative Design Process and Conflict Analysis, *CIRP Annals* -

Manufacturing Technology. 49(1) (2000) 69-73.

- [22] S.C-Y. Lu, W. Elmaraghy, G. Schuh, R. Wilhelm, A scientific foundation of collaborative engineering, *CIRP Annals – Manufacturing Technology*. 56(2) (2007) 605-634.
- [23] Shen, S.K. Ong, A.Y.C. Nee, Product information visualization and augmentation in collaborative design, *Computer-Aided Design*. 40(9) (2008) 963-974.
- [24] W.D. Li, W.F. Lu, J.Y.H. Fuh, Y.S. Wong, Collaborative computer-aided design—research and development status, *Computer-Aided Design*, Volume 37, Issue 9, August 2005, Pages 931-940.
- [25] Y.M. Deng, G.A. Britton and S.B. Tor , Constraint-based functional design verification for conceptual design. *Computer-Aided Design* 32 (2000), pp. 889–899.