L'interface multi-utilisateur pour le travail collaboratif avec les multiples représentations de la maquette numérique

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Multi-user interface and its use for collaborative work with multiple representations of Digital Mock-Up

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Abstract

The current industrial management tools generally rely on Concurrent Engineering, which involves conducting Product Lifecycle Management stages in parallel and integrating technical data for sharing across different experts. Various experts use domain-specific software to produce various data into Digital mock-up. These multidisciplinary experts have trends to work collaboratively during product development. During co-located synchronous collaborative design activities, such as project review and decision-making, experts from different domains must discuss, negotiate, and compromise to solve multidisciplinary differences. Many areas, such as early collaborative design and multi-expert product evaluation, have a great demand for new collaborative support tools. With the development of Human Computer Interaction, it is possible to devise more intuitive tools and methods to enhance co-located collaboration across experts.

In this thesis, to enhance the collaboration with experts on different domains to communicate with DMU, a multi-user interface across users with different representations during a collaborative work has been taken into consideration and its influence on co-located multidisciplinary collaboration is investigated. A schema of the methodology for evaluating the contribution to a multi-user system and the multiple users' experiences is proposed. Results of experiments show the significances of the efficiency of task, the usability of interface, and the performance of collaboration during the use of multi-user CHI in multidisciplinary collaborative scenarios. The contributions of what multi-user interface brings to the design criteria of multi-user interface and multi-user co-located collaboration are discussed.

Résumé

Les outils actuels de gestion industrielle s'appuient généralement sur l'ingénierie concourante, qui implique la réalisation des étapes de gestion du cycle de vie des produits en parallèle et l'intégration des données techniques pour le partage entre les différents experts. Divers experts utilisent des logiciels spécifiques à leur domaine pour produire diverses données compilées via une maquette numérique. Ces experts multidisciplinaires ont tendance à travailler en collaboration pendant le développement de produits. Au cours d'activités de conception collaborative synchrones, telles que les revues de projet et la prise de décisions, les experts de différents domaines doivent dialoguer, négocier et choisir pour résoudre les différences multidisciplinaires. De nombreux domaines tels que la conception collaborative et de l'évaluation des produits avec multiples experts, ont une grande demande de nouveaux outils d'aide à la collaboration. Avec le développement des technologies de l'Interaction Homme-Machine (IHM), il est possible de concevoir des outils et des méthodes plus intuitifs pour améliorer la collaboration co-localisée entre les experts.

Dans cette thèse, afin d'améliorer la collaboration avec des experts de différents domaines et communiquer via la maquette numérique, une IHM multi-utilisateurs avec des représentations différentes lors d'un travail collaboratif a été pris en considération et son influence sur la collaboration multidisciplinaire co-localisée est étudiée. Un schéma de la méthodologie d'évaluation de la contribution à un système multi-utilisateurs et des expérimentations sont proposées. Les résultats des expériences des résultats significatifs concernant l'efficacité de la réalisation de la tâche, l'utilisabilité de l'Interaction Homme-Machine et la performance de la collaboration lors de l'utilisation de l'interface multi-utilisateurs dans les scénarios de collaboration multidisciplinaires. Les contributions et apports de cette interface sont discutés.

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List of Acronyms

BIM	Building Information Modelling
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAVE	Cave Automatic Virtual Environment
CE	Concurrent Engineering
CFD	Computational Fluid Dynamics
CHI	Computer-Human Interface
CSCW	Computer-Supported Cooperative Work
CVE	Collaborative Virtual Environment
DMU	Digital Mock-Up
FEA	Finite Element Method
FMI	Functional Mock-Up Interface
FOV	Field of View
HCI	Human Computer Interaction
HMD	Head Mounted Display
HVS	Human Visual System
IIVR	Institut Image Virtual Reality
MVM	Multi-View Mechanisms
PDM	Product Data Management
PLM	Product Lifecycle Management
POV	Point of View
SE	Sequential Engineering
VR	Virtual Reality
VRPN	Virtual Reality Peripheral Network
WYSNWIS	What You See Is Not What I See

Chapter I Introduction

I.1 Research context

Current industrial product lifecycle management (PLM) tools generally rely on the strategy of Concurrent Engineering (CE). Some of the product lifecycle stages are conducted in parallel and simultaneously and technical data on each stage are shared. Digital Mock-Up (DMU), the data set of all the technical data, has been used by various experts on different domains. Since the saved data has a variety of formats, e.g. the special format generated by domain-specific software, DMU stores multiple formats of data. Each expert work with one of the data representations of DMU. For communicating DMU data among its multiple representations, many works have been done to improve the interoperability among the engineering softwares and among the models in design activities.

Meanwhile, many creative tools have been developed to support these design activities. Though experts need to work together on the unique DMU, each expert has his/her own perspective of a specific representation of DMU's technical data according to his/her expertise domain. An appropriate Computer-Human Interface (CHI) allows each expert to have a customized preference on the CHI: a proper visualization of representation of DMU and a proper manner to interact with DMU. Therefore, when multiple experts work collaboratively, the number of CHI increases as the number of experts.

With the development of groupware and CHI technology, it is possible to devise more intuitive tools and methods to enhance the interoperability of collaboration among experts. CHI, which uses both multi-view and multi-interaction technologies, is applied by multiple experts when they work in co-located synchronous collaborative design activities. Our work is done in the context of research works belonged to the usability of CHI system for collaboration:

> ***"How people work together in groups and how groupware CHI can support collaboration?"***(Ishii et al., 1994)

Particularly, the question

> ***"How experts work together through multi-user interface in complex multi-disciplinary product development?"*** (Kraemer and King, 1988; Tomiyama et al., 2009)

Research context of this thesis is described in I.1, followed by the statement of the scientific problem in I.2. A further exploration of the research questions is conducted in I.3. Lists of main contributions in general of this thesis are shown in I.4. A manuscript of the structure of the thesis is given in I.5.

I.2 Problems

Multi-disciplinary experts have trends to work collaboratively during product development. Sometimes they require a co-located real time working situation, such as project review and decision making. However, current technical support cannot provide efficient solutions to co-located real-time collaboration. The present problems of CHI systems are shown in following aspects:

- Multiple mono-user CHI systems are used. Each expert must work with his/her own CHI because of his/her specialty.
- The communication styles during collaborative work using current multiple mono-user CHI systems have negative impact on working efficiency.
- Using current multiple mono-user CHI systems causes a lower mutual awareness of collaboration between collaborators.

These problems are across several domains.

- A. Domain of collaborative engineering. It concerns the new strategies that are taken into consideration in Industrial Engineering. During a product lifecycle, how experts work collaboratively and what collaboration can bring to the product development needs to be discussed.
- B. Domain of Digital Mock-up. Multiple representations of data are contained in DMU. The interoperability of data exchanging with several industrial phases in multi-disciplinary product development needs to be discussed.
- C. Domain of Computer-Human Interface (CHI). Many CHI technologies can support multiple users. Their advantages and disadvantages need to be discussed. New technologies to support multi-representation collaborative work has been developed. The usability and efficiency need to be evaluated.

To sum up, our research approach is in the fields of collaboration, DMU and CHI. A collaborative working framework of multiple users considering all the domains above will be proposed later to this thesis. A new scene of collaborative working style considering industrial needs in product design will be created and verified. Thus, our approach from collaborative working condition is going to be evaluated both in academy and in industry.

I.3 Research question

There are technologies aiming at the creation of multiple user CHI system. According to different mechanisms, a taxonomy of multiple user CHI system will be summarized in our studies. Mainly, a multiple user CHI system is developed in both multi-view system and multi-interaction system. The issues we are facing for the multiple user CHI systems are as follows:

- How to design a multi-view system?
- How to design a multi-interaction system?

Experts work with only one DMU during product development through a multiple user CHI system. Each expert can work with one representation of this DMU. Collaborating with each other, different experts can work together. Thus, the research issues for the behaviors of collaborators are:

- How's experts' working style when they are co-located?
- How multi-user system can help collaboration?

To know if our approach really satisfies industrial case, the research issue for the evaluation is:

- How to evaluate such collaborative work with multi-user CHI?

Considering all the research issues mentioned above, our research question to explore and to study in this thesis is as following:

"What is the influence of multi-user interface among users that work with different representations of a Digital Mock-Up during a collaborative work?"

I.4 Contributions

This thesis is in the context of industrial collaborative design. We describe the scientific context of several fields including CE, DMU, CHI. We then discuss the different approaches for displaying multiple representations of DMU and multiple interactions with DMU in the technical perspective. Aiming at exploring the influence of multi-user CHI on the collaborative work with several representations of DMU, we then carry out a series of work including technical developments, usage experiments and user experience evaluations.

This thesis was realized in collaboration with:

- Institute Image, one of research teams in the Laboratory of Electronics, Information, and Image (Le2i) which is a joined unit of University of Burgundy, Arts et Métiers and CNRS. Institute Image has also signed a framework agreement with the Renault's Technical Centre for Simulation to form a joint public-private laboratory (lab LiV). The objective of Institute Image is the development of methods and tools for virtual immersion for engineer. Its missions are those of education, research, and development.
- The laboratory of product design and innovation (LCPI, EA 3927) is a research laboratory of Arts and Métiers ParisTech in Paris, whose work is part of the field of industrial engineering. The research theme of LCPI is optimizing the process of design and innovation. LCPI's research activities benefit from both academic anchoring and a strong industrial partnership, which is an important vector for modernity and competitiveness. Based on the sciences of industrial engineering and Social & Human Sciences, LCPI has competences in: prototyping by virtual reality and rapid fabrication, innovation/foresight/creativity, analysis of the use, Kansei Engineering as well as eco-design and product lifecycle.
- Renault Technical Centre for Simulation, a competence center dedicated to the digital vehicle, based on virtual mock-up, and driving simulation tools. Its purpose is to benchmark advanced digital technologies and deploy relevant technologies inside Engineering departments. It has created a shared laboratory of LiV (Laboratoire d'immersion Virtuelle) with Institute Image, Arts et Métiers.

This thesis results in an important work with both scientific contributions and technical developments, including:

- A state of the art of collaborative computer human interface and multi-user technologies.
- The development of a double user's collaborative virtual reality working environment.
- Two academic experiments of collaboration between two users with different roles with different representations of a task using multi-view system
- Two industrial cases of collaborative work between different roles in design development, e.g. a product user and a product designer.

- The evaluation method of collaboration task with different representations.
- Scientific publications

I.5 Manuscript structure

In this thesis, a general introduction of the PhD thesis is given in Chapter 1.

In Chapter 2, a state of the art is developed on the topic of collaboration, DMU and CHI, particularly the intersection of these research fields. The concept of multi-user CHI with multi-view and multi-interaction is described in detail.

In Chapter 3, several approaches to establish a multi-user collaborative CHI system are proposed, followed by the method for evaluating the multi-user collaboration system through academic experiment and industrial cases.

In Chapter 4, the two academic experiments and an industrial case are evaluated. Experimental data are analyzed and discussed.

In Chapter 5, we draw a conclusion of the thesis. A perspective of multi-user collaborative CHI across multi-representation of DMU in the future is discussed.

Chapter II State of the art

II.1 Introduction

In this chapter, a state of the art across several domains is presented: Collaboration, Digital Mock-Up (DMU), and Computer Human Interface (CHI), as shown in Figure 1. These three areas and the intersections of them are discussed respectively in the state of the art. Collaboration is discussed in section II.2. We will describe the definition of collaboration in II.2.1, then the context of concurrent engineering in II.2.2. In II.2.3, collaboration working environments is explained, followed by the introduction of collaborative coupling styles.

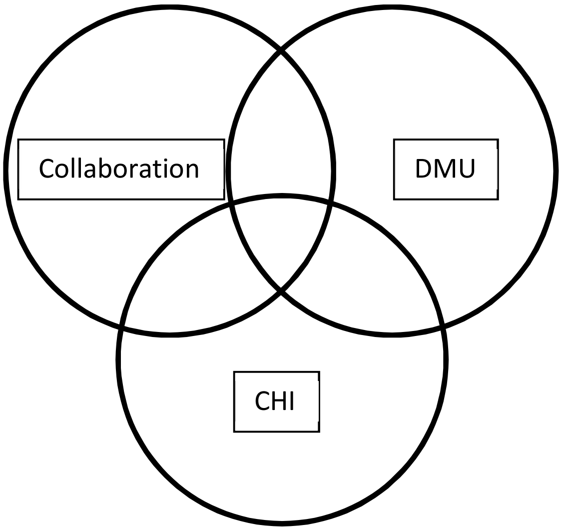


Figure 1 : Three research areas: collaboration, DMU and CHI.

In II.3, a definition of Digital-Mock Up is firstly explored. The multi-representation of DMU is emphatically discussed. Multi-representation is a characteristic of DMU with which multiple users must break the barrier due to domain-specific expertise, as well as real time human communications. The interoperability of models and softwares are also discussed in II.3.3.

The state of the art of CHI starts with the definition and CHI modalities in II.4.1 and II.4.2. Then the difference between mono-user interface and multi-user interface is analyzed and discussed in II.4.3. Then the state of the art for multi-view visualization technology and multi-interaction technology is presented in II.4.4 and II.4.5. All the applications related to three research areas: collaboration, DMU, and CHI are categorized by the criterions which are proposed in II.5.

A synthesis of the state of the art and a positioning of the research question are given in II.6.

II.2 Collaboration

II.2.1 Definition

In this section, we focus on one of the three research areas: collaboration. The positioning of collaboration in the state of the art is highlighted in Figure 2.

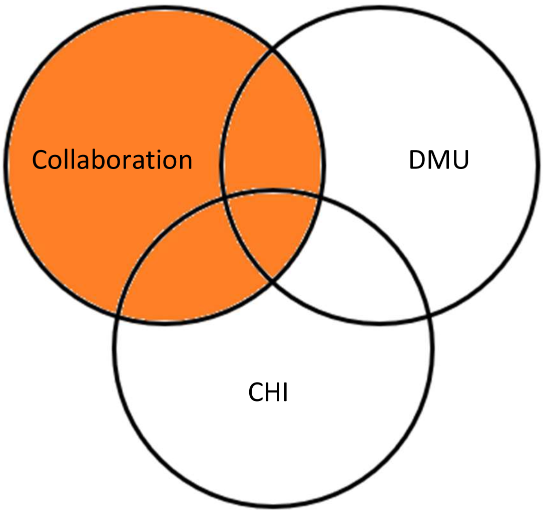


Figure 2 : The state of the art of collaboration which is one of the three research areas.

In general, collaboration is a process whereby two or more people or organizations join to do an intellectual work in accordance with common objectives. The early theory of collaboration can be traced back to a Game theory in applied mathematics and economics. When multiple players make decisions to maximize their returns, they should collaborate to find a solution with unanimous agreement. The early implementation of collaboration was primarily used in military industry. It is a private industry whose organization and cooperation were established among a nation's armed forces.

With the development in the theories of scientific management, in current industry, project management has been applied to different fields, including construction, engineering, and defense. The concept of collaborative work in project management refers to work that is no longer based on the traditional hierarchical organization, and more specifically a working mode where many people collaborate through information and communication technologies.

Over the years, in product management, the working mode has been evolving and changing. The theory of collaborative product management is updated towards economy and efficiency. We will discuss the recent collaborative working mode in product management in the next section.

II.2.2 Concurrent engineering

In industry, the product lifecycle management (PLM) is the process of managing backbone information of a product during different stages of the entire lifecycle, from product concept to exiting the market. In terms of methodology, PLM is also a supporting strategy for an enterprise that allows all the departments of this enterprise to share information and to control the business processes.

These departments usually include the activities of preliminary design, detailed design, physical simulation, ergonomic simulation, manufacturing, assembling, marketing, maintenance, design updating and optimization, destruction, and recycling. All these activities should be arranged in a proper way to ensure the lifecycle of a product.

The traditional Sequential Engineering (SE) is a product development method, which is known as "throwing it over the wall". It focuses on developing a structured process with clearly defined and sequential phases of product plan, design, manufacturing and entering the market. Each one of these activities only starts when the one before has finished. This results in a lack of communication and understanding between the needs of different activities (Sage and Rouse, 2009), for example, a part is not well designed because it cannot be manufactured by current machine. This approach may increase the development time, increase the development cost, and lower the overall product quality (Smith and Eppinger, 1998).

Since several years, PLM has adopted the Concurrent Engineering (CE) process, which allows all the experts from different production activities to work collaboratively in parallel.

One of the widest known definitions of CE is the one given by the United States National Institute for Defense Analysis, which considers it to be "**a systematic approach to the integrated, concurrent design of products and related processes, including manufacturing and support. This approach is intended to cause the developers to consider all elements of the product lifecycle from conception through disposal, including quality, cost, schedule, and user requirements.**" (Valle and Vázquez-Bustelo, 2009).

Instead of the traditional sequential process of a product, CE is integrated product development method with which everyone involved works in parallel. CE allows some proper overlaps in the scale of time among several activities, as shown in Figure 3, if they are possible to be arranged in the same time. Even some of the activities will be better operated if they are conducted in the same time. Compared to sequential engineering, concurrent engineering allows overlaps of several activities in the scale of time. This saves time for the whole product lifecycle.

The goal of CE is to minimize single person work and to gain team collaboration. This may improve quality, reduce costs, and save time.

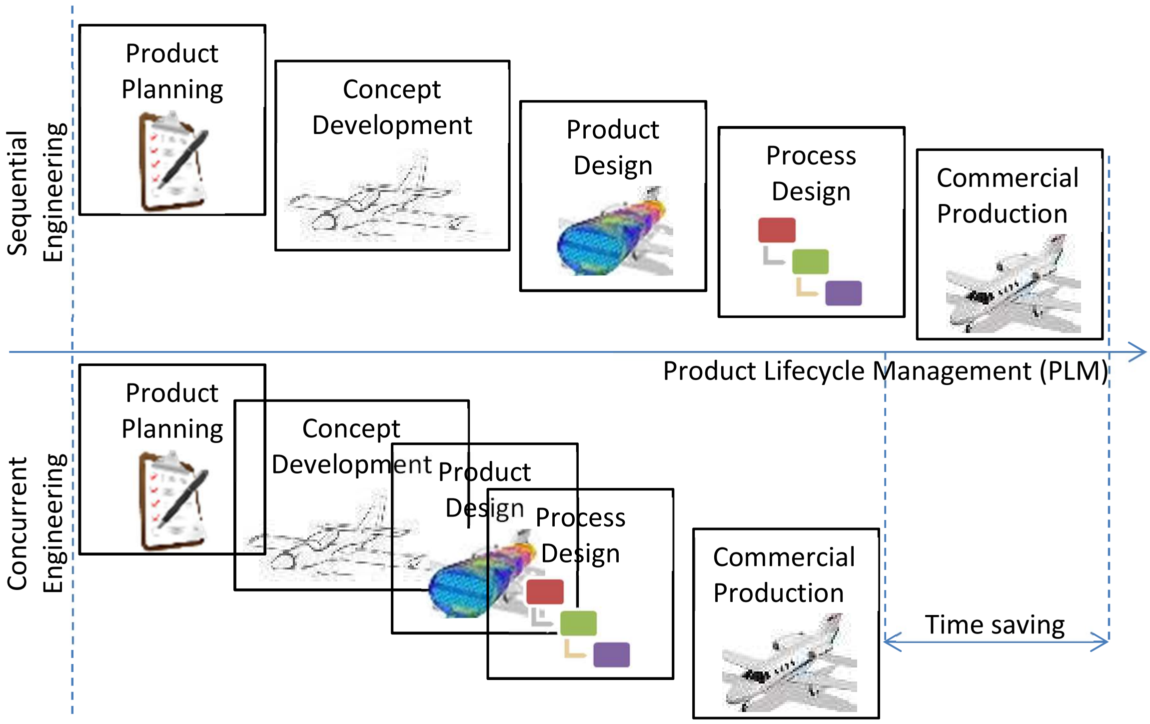


Figure 3 : Sequential engineering and concurrent engineering in product lifecycle.

Experts from different overlapped activities are now scheduled to work together. They can communicate, to have a result more than to repeat these activities. To improve the efficiency of their communication, they are now working collaboratively in parallel. From surveys of the companies who have implemented CE, we find that beyond a barrier of implementation of the management reluctance and resistance to change, CE brings companies obvious positive effects (Abdalla, 1999).

The benefits gained by companies implementing CE are illustrated in Figure 4. Shorter time to market (70%), better communication (59%), and better quality (56%) are direct reward of practicing CE. Reduction in repeatedly design changes are highlighted by almost 48% of companies surveyed. Reductions in testing, quality failures, and life-cycle cost are also achieved through the consideration of CE.

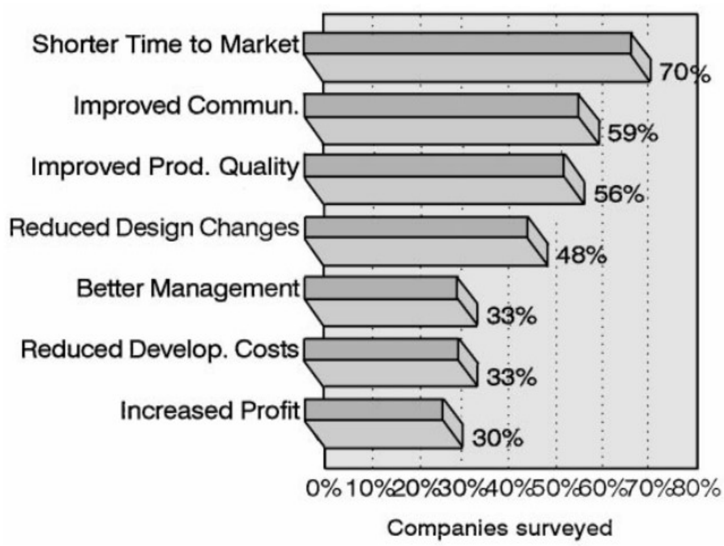


Figure 4 : Benefits gained during implementing CE (Abdalla, 1999).

For the companies which have different enterprise objectives and different characteristics of innovation process, they should prioritize their requests before selecting the most appropriate working style. CE leads to reductions in development time when it is used by companies who innovate in the product design or the production process. CE allows them to better meet the needs of specific market segments (Valle and Vázquez-Bustelo, 2009).

From the above, CE helps companies to quickly bring products to market at higher quality and less cost. Through integrated information technology tools, CE can support experts in product lifecycle, e.g. designers, to conduct development activities with latest changes, to share data with other parties involved in the product development process.

II.2.3 Collaboration working environment

In the theory of CE, product development activities may be arranged sometimes in a parallel way. Experts can work in a same time interval. Thus, collaboration is in need when they work together at the same time. The collaboration among experts would be realized only if they know the status of the product that every one of them is working on. They could catch up with others if they know and can keep change in real time (Mas et al., 2013).

To realize a collaborative working condition, special tools are in need to support experts from different activities. A concept of computer-supported cooperative work (Johansen, 1988) is proposed to research in supporting collaborative activities and their coordination by means of computer systems. Besides developing tools and techniques for group working, the psychological, social, and organizational effects of humans in collaborative activities are also being explored (Wobbrock et al., 2009).

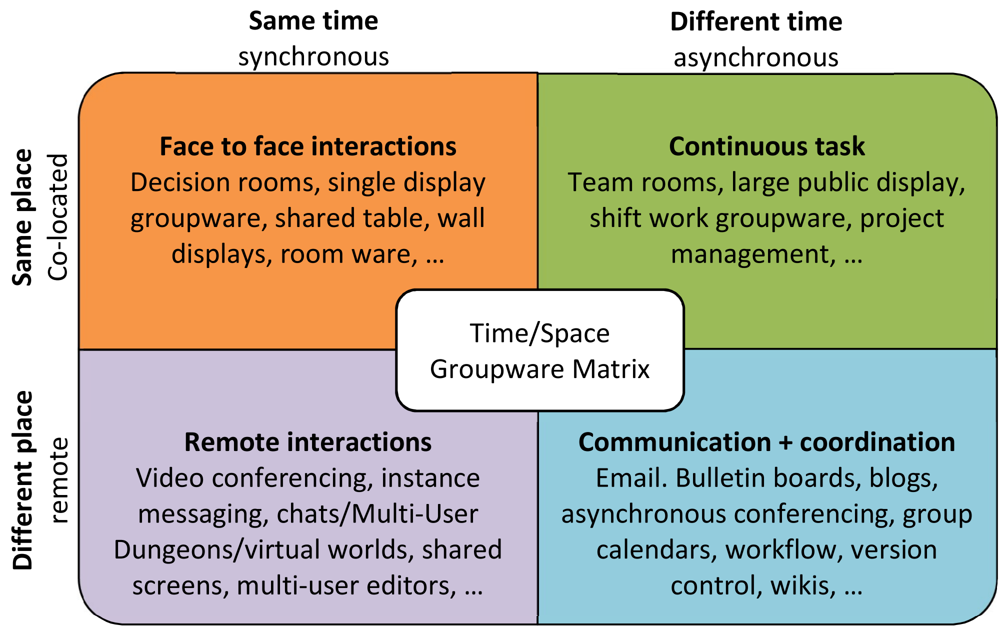


Figure 5 : Collaborative work is separated into 4 conditions. (Agrawala et al., 1997).

From the technical perspective, this supporting system is considered as a groupware which has the mechanism of working collaboratively. According to space scale on the vertical axis of and time scale on horizontal axis (Figure 5), some typical groupware for collaborative activities are categorized. The collaboration can be co-located or geographically distributed in space. The single work of each person can be collaborative with others' synchronously (same time) or asynchronously (different time).

In the matrix of time scale and space scale, collaborative work is categorized into four main conditions:

- Face to face interaction (Same time/same place),
- Continuous task (Different time/same place),
- Remote interaction (Same time/different place),
- Communication plus Coordination (Different time/different place).

For each collaborative working condition, some typical supporting systems are shown on Figure 5. At same time, in some place, the main collaborative tools are decision room, wall display, and shared table. It concerns a physical face to face meeting among users. At same time, in different places, we often use the collaborative tools, such as video conference or telephone meeting. If people are collaborating at different time, in a same place, the tools used for collaboration are often paper tools for restoring files in a same information system, e.g. a file library, as well as product data management (PDM) which arranges the shifting of users on a same project. If people are working at different time, in different places, the tools using Internet, Intranet are used, e.g. web storage, cloud computing, Google Sheet, especially the email, the most common tools used in collaborative work.

In this thesis, we focus on the same time/same place collaboration working environment as shown on Figure 5 during product development process. In a face-to-face interaction situation, people work collaboratively at a shared place. Firstly, they can use verbal communication, which is the most common type of interaction. Second, this group of people can use facial expressions to communicate and collaborate when they need discuss. This is more efficient than using remote communication voice method like a telephone (Agrawala et al., 1997). Besides, in face-to-face situation, the gestures of interaction are widely used because they bring an intuitive feeling of interaction. Face-to-face interaction collaborative working situation is very in common when people discuss. Nearly all the activities co-located and in real time are involved, including industrial applications, for example the collaborative work in product lifecycle.

During the product lifecycle, regular project reviews can strongly summarize the current work and assign the work of next stage by making modifications and proposing solutions to both strategies and technical details (Smith and Eppinger, 1998). Known as a part of collaborative design (Johansen, 1988), project review is often conducted by gathering experts in a same room, sharing information and making decisions. This working process needs collaboration among both the domain-specific software and the experts themselves. Thus, It is important to develop tools to support the project review process.

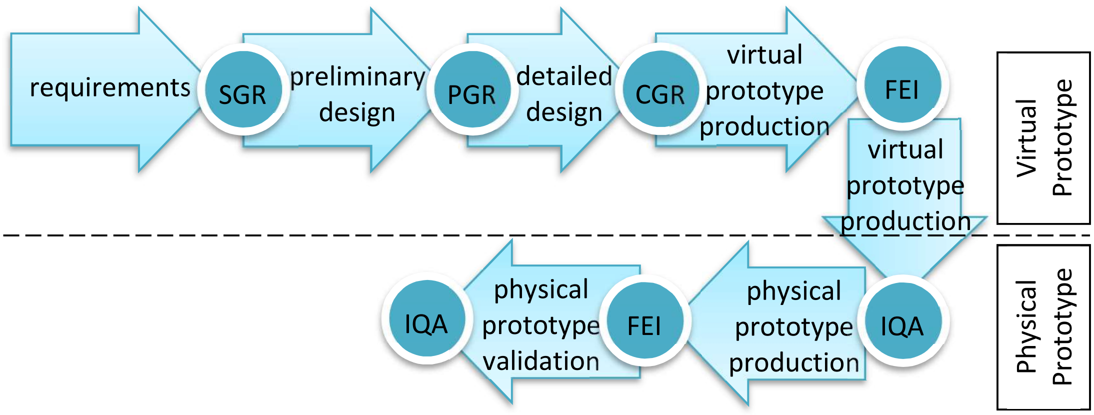


Figure 6 : Example of project reviews during product lifecycle (Fillatreau et al., 2013)

For example, Figure 6 shows how industrial companies intend to run project review checklists as many as possible during product lifecycle. The main development steps, and the associated project reviews(Fillatreau et al., 2013):

- the SGR (Specification Gate Review) is the requirements review;
- the PGR (Preliminary Gate Review), is the preliminary design review;
- the CGR (Critical Gate Review) is the detailed design review;
- the FEI (First Equipment Inspection) is the prototype review;
- the IQA (Initial Quality Approval) is the industrialization review.

From these project review checklists, we find that industrial companies aim to use virtual numerical models of a product more often than a real prototype. Only the steps that cannot be performed without a physical prototype will involve a real prototype. The virtual numerical model, digital mock-up, will be discussed later in section II.3.

II.2.4 Collaboration coupling styles

As we discussed in last section, co-located synchronous collaboration is often applied in face to face working conditions. Many group activities, such as project review, which contains brainstorming, designing, discussing, and planning, involve co-located synchronous collaboration. Another characteristic of co-located synchronous collaboration is user's transition between individual and shared tasks within a group. To describe a group activity, we introduce collaborative coupling.

Collaborative coupling is defined as "***the manner in which collaborators are involved and occupied with each other's work***" (Tang et al., 2006). This "coupling" implicates that collaborators' activities are linked to one another. According to the different requirement of switching between independent and shared activity, collaborative coupling varies dynamically through the course of work from being very tight to very loose. When participants cannot do much work before having to simultaneously interact, the work is tightly coupled. Conversely, when participants can work independently for long periods of time, the work is loosely coupled.

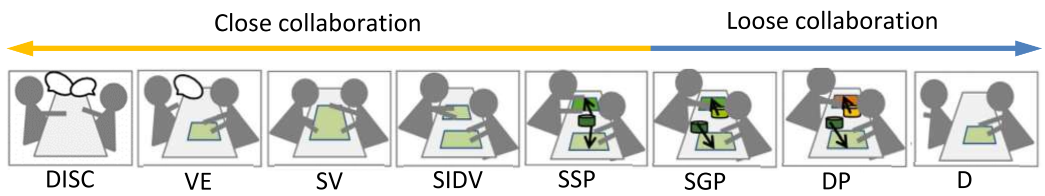


Figure 7 : Collaboration styles which influenced how much information was shared among collaborators.

Collaborators' interactions are identified based on their data views and personal interactions. Eight different collaboration styles are shown on Figure 7: DISC: Active **discussion** about the data or task; VE: **View engaged**; SV: Sharing of the **same view** of a document or search result; SIDV: Sharing of the **same information** but using **different views** of the data; SSP: Work is shared to solve the **same specific problem**; SGP: Work on the **same general problem** but from different starting points; DP: Work on **different problems**, and hence different aspects of the task; D: **Disengaged**. As collaborators working on a data set, they adopt different collaboration styles. During a workflow, the collaborators present a fluid transition among coupling styles (Tuddenham and Robinson, 2009). E.g. at times, they discuss on the same problem (DISC), e.g. pointing to items, or scrolling in documents, even sharing a single document together (SV), e.g. look at the same document reader or the same search result list together at the same time; at other times, they would separate to work on different problems (DP), e.g. participants issued a search for "injure driver", one person is interested in the injured driver, the other searches for ambiguous event around a missile launch facility.

During the transition of collaboration styles, the percentage of common data and individual data in the amount of used data changes. In the coupling styles above SSP in Figure 7 (DICS, VE, SV, SIDV), sharing information is on the same problem, e.g. both read different documents from a shared set. Participants issued a search for "injure driver", and then divided the results so each person read one half of the documents. Collaborators get common data from sharing information so that they can very well understand each other. In the coupling styles below SGP (DP, D), each collaborator gets his/her individual data because they work on different problems, e.g. participants issued a search for "injure driver", both participants search for docs to find information on a collision but start from different searches "accident" & "obituaries" and consider different sets of documents. In SSP and SGP working styles, people receive both common data and individual data. A transition of common and individual data means people must not only be focus on his/her own data but also try to understand his/her collaborator to complete a collaborative task.

In industry, the collaboration degree is also defined by the coupling style among decisions. These decision need a smart collaboration structure or a collaborative working environment to allow the distributed collaborative development activities (Segonds, 2011). The project manager, as well as the experts from different domains, their common data from sharing information to quickly reach an agreement. For the individual data, they must discuss, negotiate, and compromise to solve the problem.

Each expert adopts a special tool for his/her working domain. To support the collaboration across different product lifecycle stages, system tools are created to integrate all the individual tools. The conversion and recognition of common features across individual tools can simplify the design of the tools (Ma et al., 2008). We will discuss more about how to share information and how to construct system tools in the section II.3.

People have transitions among coupling styles. Common data and individual data alternate. However, in collaborative case, at the same time, more than one coupling styles can be used. Individual data from different problem, individual data from different starting of the same problem can be mixed with common data during the collaborative work. In this thesis, to simplify the category, we distinguish between three different coupling styles (Lissermann et al., 2014; Tuddenham and Robinson, 2009):

- Tight Coupling (Tight), sharing the same information;
- Loose Coupling (Loose), working on completely different problems;
- Mixed Coupling (Mixed), working on the other styles that has transition between common and individual data.

Coupling is primarily a reflection of collaborators' need or desire to work closely or independently of one another. A collaborative sense making is then established among collaborators. Since the effect of collaboration is very subjective, the evaluation of collaboration is complex as well. In chapter III, we will discuss the evaluation method.

In this section, the definition of collaboration has been discussed and the collaborative working situations have been investigated in the process of product development. Co-located collaboration is widely used in the project review and decision-making phases during the product lifecycle. The coupling styles of collaboration have been discussed and categorized. A mixed coupling collaboration will be discussed in the next chapter considering the characteristic of Digital Mock-up.

II.3 Digital Mock-Up (DMU)

II.3.1 Definition

The positioning of the research area of this section in the state of the art is highlighted in Figure 8 . In this section, we focus on Digital Mock-up and its multiple representations. The need of multi-representation of DMU in early collaborative design and in the process of ergonomics evaluation is described in II.3.2.1 and II.3.2.2. The interoperability across multiple representation is discussed in II.3.3, followed by the introduction of the intersection of collaboration and DMU in II.3.4.

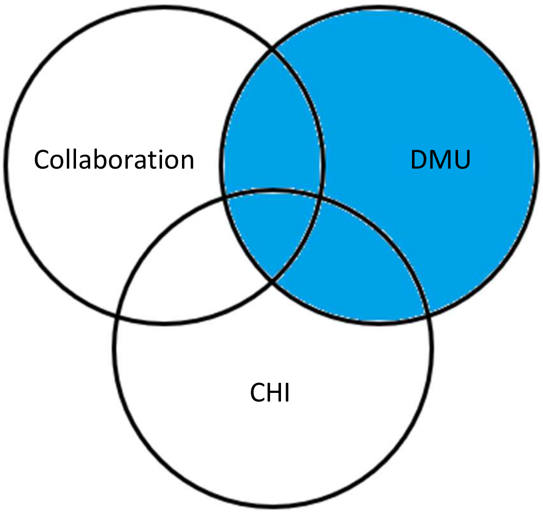


Figure 8 : The state of the art of DMU which is one of the three research areas.

A Mock-up is traditionally a hardware or physical model of a component, an assembly, or an entire product. It can be full-size or a scaled model made of paper, wood, metal, or actual production hardware (Leitner et al., 1994). The development of computer aided design (CAD) has essentially changed the way of developing a product in virtual model. And then more efficient development methodologies of CAD have been realized from the 2D to 3D. Meanwhile, the development of Product data management (PDM) has made an optimization of the product development processes to reduce time and cost during product lifecycle.

The establishment and development of virtual working environment and its data management benefit from the Digital Mock-up. The Digital Mock-up is defined as ***"a complete virtual product environment for the whole process of 3-dimensional development and maintenance of a complex product including configuration and change management"*** (Kaun, 2003).

Ideally, all participants in a PLM, such as a manager of the whole project, a department of one procedure, even an individual who oversees a specific task shall have the right to use the same PLM database and shall make contributions to this database.

Every product lifecycle activity of CE needs expert and domain-specific computer tools. These tools mainly contain the planning and management tools (PPS/ERP), the computer aided design (CAD) of the product, computer aided engineering (CAE) for physical analysis, computer aided manufacturing (CAM) for all operations of manufacturing and other software from different domains. Various experts use domain-specific software to produce various data (Pardessus, 2004). Each expert considers his/her own contribution to the product from one point-of-view (POV) of the whole product development according to his/her expertise. Then he/she shares his/her information with other experts by sending the data produced by the domain-specific software into a global database (Garbade and Dolezal, 2007) The large package of data itself, together with the product structure and attributes of this package of data builds up a Digital mock-up (DMU) in industrial engineering, as well as Building Information Modelling (BIM) model in architectural engineering (Segonds et al., 2012). BIM model is also a set of interacting policies, processes and technologies containing building design and project data in digital format throughout the building's lifecycle.

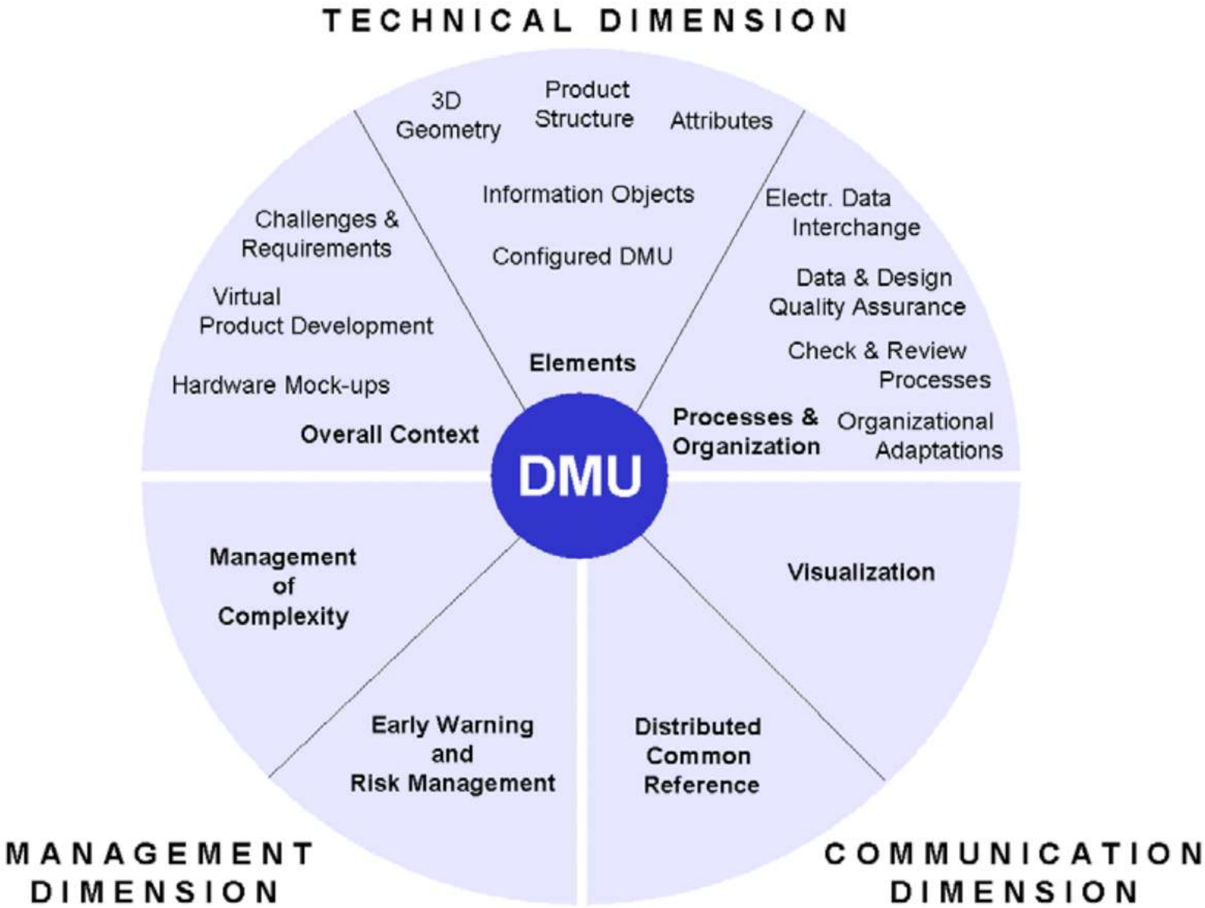


Figure 9 : DMU is a virtual prototype which consists all the technical data of product characteristics (Dolezal, 2008)

From the definition of Digital mock-up, DMU is a virtual prototype of a product constructed before the physical prototype using manufacturing. In current industry, DMU is package of a product with digital technique data.

In addition to accurate geometrical database, a complete DMU also reflects the characteristics of the actual product, including appearance, complex structure analysis, kinematics and dynamics, the relationships between the assembly, tolerance, simulation information, human resources, materials, manufacturing resources, costs, and other information, shown in Figure 9. Through all aspects of DMU characteristics: analyzing, simulating and optimizing, we could repeatedly modify the design, transfer information, make decisions and ultimately get the optimal design solution (Kaun, 2003). These characteristics form additional metadata. Metadata of DMU consists in the Product Structure together with all attributes (Figure 10). Beginning from a preliminary Work Breakdown Structure (WBS) of a project, many PDM tools have been created to deal with the complex branch structures of a project tree. The Product Structure is a DMU metadata that defines the hierarchical dependencies of DMU models. It is a process of work breakdown and re-organization. The metadata of attributes identify 3D models and Product Structure elements in the DMU. The identification of models and the status of updating the models are recorded in these attributes in PDM tools (Dolezal, 2008).

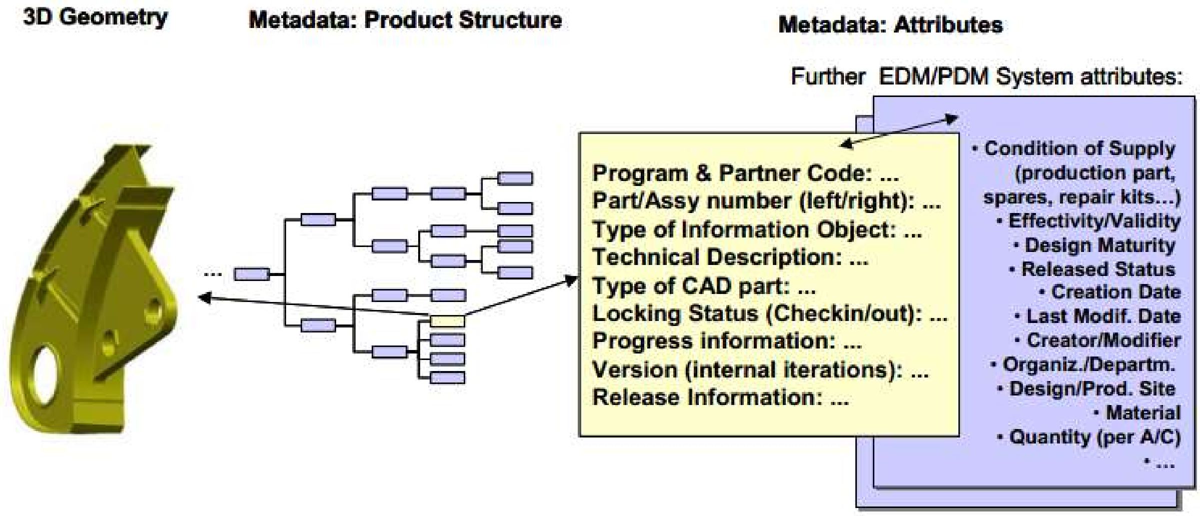


Figure 10 : Relation between DMU's geometry and metadata on a simplified example (Kaun, 2003).

II.3.2 Multi-representation

DMU offers data to every product lifecycle activity of CE according to the special needs of the expert and tools. DMU can represent data with different meaning and form a series of data in different data mode. E.g. an automobile sketch, an assembly of an automobile DMU, a point cloud format of an automobile in reverse engineering and a mesh model of this automobile DMU are all representations of DMU.

In Figure 11, DMU provides multiple representations to experts in a certain domain, such as a sketch, a single part, an assembly of a component or the whole car, CAE model for simulations, exterior design and a point cloud or mesh model for reverse engineering. On the contrary, from the experts point, how to get specific data depends on their special point-of-view of DMU. Every expert has his own point-of-view of the DMU.

Here the notion of “Representation” indicates that a given concept can be translated, in an equivalent manner, through different "models". Each of the "models" used matches a specific criterion in DMU. Considering only geometrical database in DMU, the geometry data of a model can be obtained through different "models”. According to user requirements in different development activities, such as project review and simulation, multiple representations of this model can be formed. E.g. mesh modelling, triangle modelling for graphic card, point cloud modelling, boundary representation (B-Rep) modelling, Constructive solid geometry (CSG) modelling, or simply the images of the model, if objective is to get an identical object geometry as the user sees it. The same DMU can be also represented with different "models" (strength of material model, finite element model) to get an equivalent "representation" in the sense of mechanical strength. To extend, a "representation" could also coincide with an instantiation of a "model" participating to the definition of a product regarding special dataset and criterion (MG-IT, 1999).

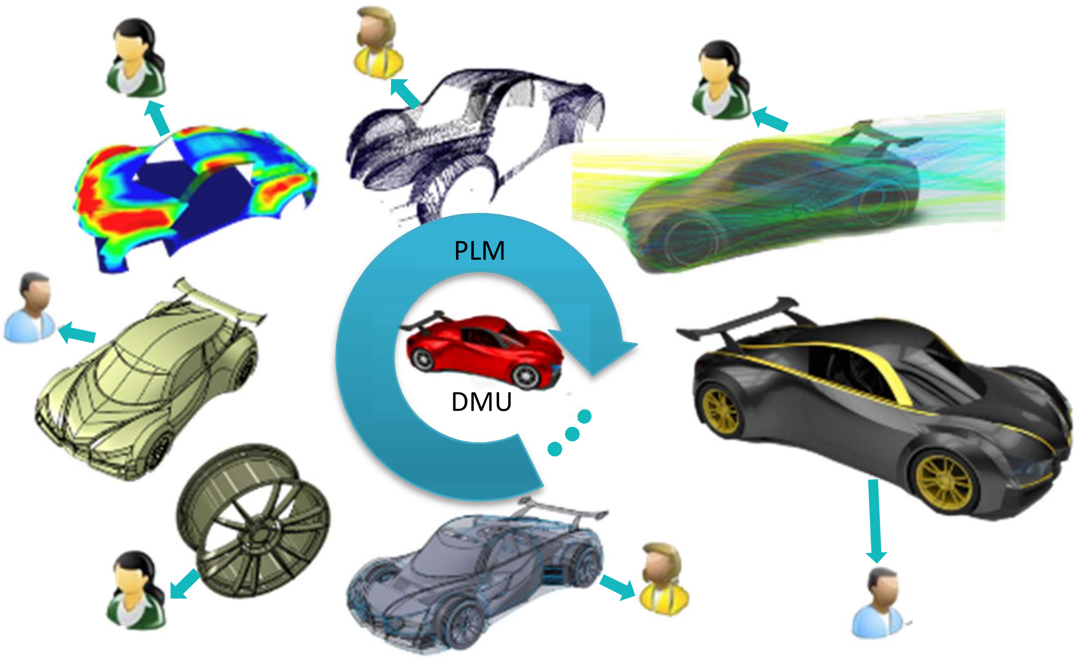


Figure 11 : During entire PLM, multiple experts work with one unique DMU.

E.g. DMU can usually provide CAD tools geometry data for component interference examination, assembly process design, maintenance design, kinematics simulation; provide CAE tools mesh and constrain data for Finite element method (FEA) calculations preparation for the structural simulation or for Computational fluid dynamics (CFD) calculations in the aerodynamics and thermal simulations; provide CAM tools geometry and martial data for numerical manufacturing process management (Boussuge et al., 2012; Foucault et al., 2011).

In industry, expert not only just cares about his own representation of DMU, he/she even has their preferred manner to interact with the DMU. Data goes both-way by inputting and outputting from DMU as shown in Figure 12. Both inputting and outputting have different manners according to the different domains of experts.

More precisely, experts from different domains use different tools e.g. software to deal with the data coming from DMU. Normally these tools cannot share data; experts will have difficulty in understanding the others' data in the form of result. One expert is only expert in his field while not has the knowledge of all the corresponding fields. He/she is not interested in other expert's field even cannot understand other expert's concept and tolerance. This may cause his work less efficient with less communication and less cooperation and finally a possibility to rework.

In this thesis, the requirement of multi-representation of DMU is investigated in detail in two applied domains: Early collaborative design and Automotive ergonomic design, respectively corresponding to the two applications that we have developed in Chapter IV.

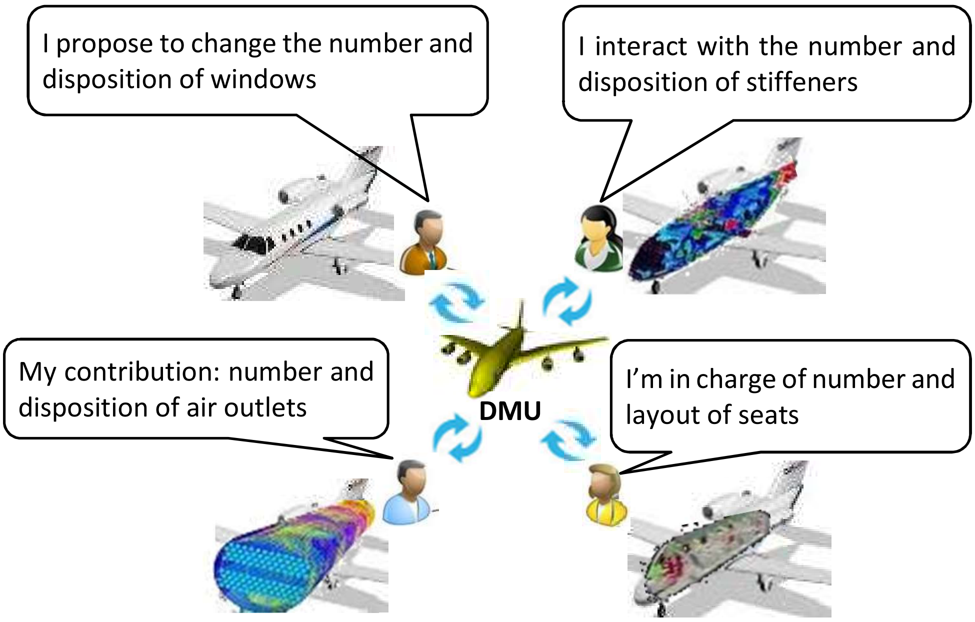


Figure 12 : Multiple experts work with multiple representations and interact with DMU using certain manners.

II.3.2.1 Multi-representation in Early collaborative design

Early stages of design, also called preliminary design, starts from the research of feasible concepts to first overall preliminary layout (Segonds et al., 2016).

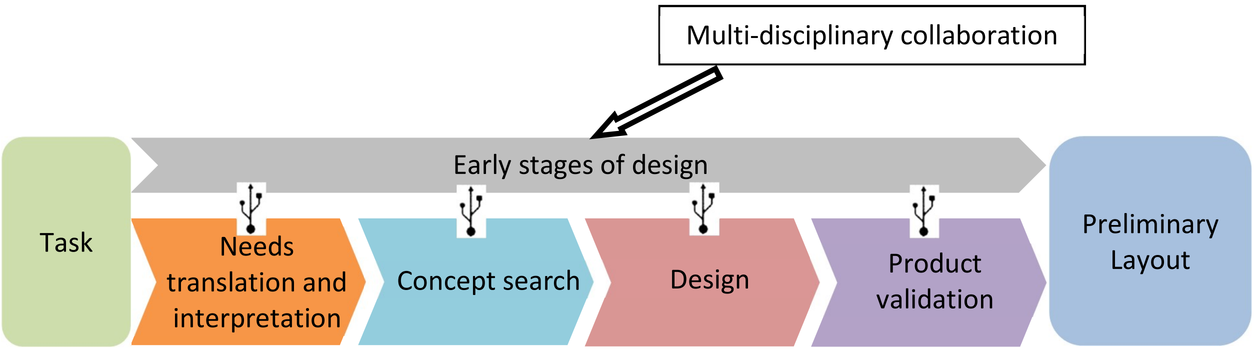


Figure 13 : Framework describing the early stages of design process (Segonds, 2011).

According to two main product design methodologies, Pahl & Beitz (Beitz and Pahl, 1996) and Ullman (Ullman, 2002) , the first overall preliminary layouts describes the complete construction structure of the system or product being designed. First preliminary layout provides information about the advantages and disadvantages. The decision of the preliminary concept often leads the development of the future products. As shown in Figure 13, early stages of design are defined as all the activities from the "task" to achieve to the first preliminary layout.

During the early stages of design, every decision on the product engages most of the future development of design, production, assembly, maintenance, and disassembly. Thus, a collaborative design across the involved experts is in need. To share information among experts, the DMU of the preliminary product can be adopted by multiple users. Because of the characteristic of multi-representation, various models of the product are created. E.g. in Figure 14, various models used during the design of an electric motor are illustrated in multiple representations. Since experts are just starting the preliminary design activities, basic mechanisms of every engineering domain (e.g. electromagnetic model, mechanical model) are presented by DMU. Only some models are considered: dynamic analysis model, electromagnetic model, machined shaft model, clamping shaft model, to illustrate the diversity of the models set up during the design phase of a product (MG-IT, 1999).

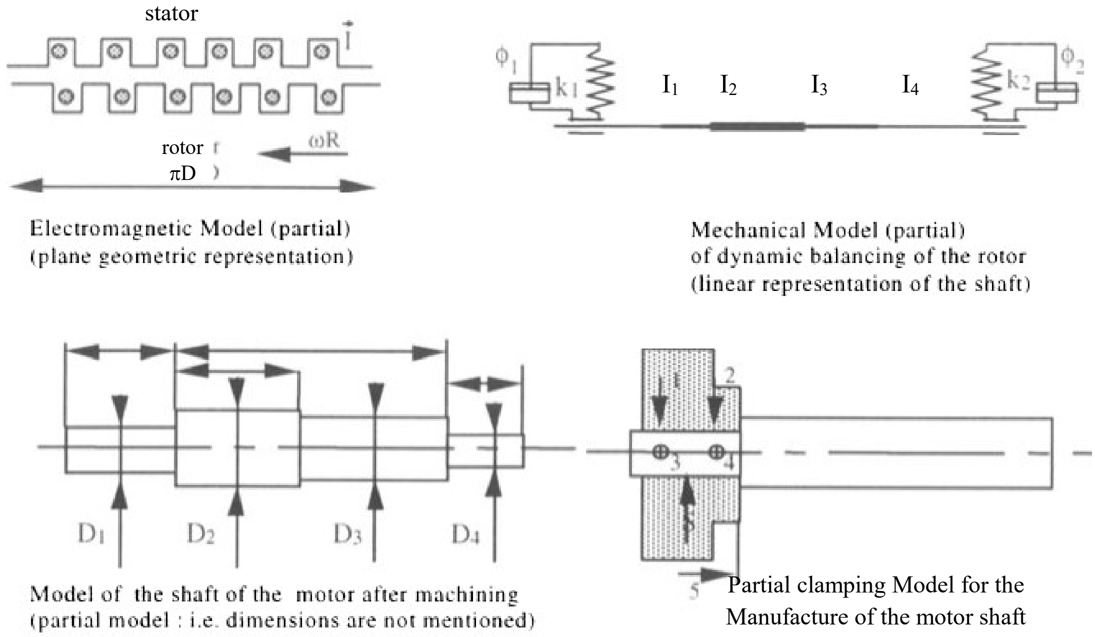


Figure 14 : Various models used during the design of an electric motor (MG-IT, 1999).

Besides the collaboration across the experts, as mentioned in the theories of design methodologies (Bennes et al., 2012; Segonds et al., 2012), in interactive design, three factors constrain the creation of a product: the expert's knowledge, the end-user satisfaction and the realization of functions (Nadeau and Fischer, 2011). A human centered collaborative design methodology must take the usability of the tools into account (Nielsen, 1994). User behavior and satisfaction, usability of interface of the preliminary layout must be evaluated by experts leading to a modification and improvement of the design. A DMU representation for user and a DMU representation for designer need to be presented separately to users and to experts. These human factors are also a key aspect for the success of industrial products.

To study user behavior and to evaluate user interface, there are many design methods. E.g. Persona method could be used in a virtual environment. Buisine (Buisine et al., 2016), has experimented the use of persona through avatar in virtual environment. The goal was to make engineers embody persona to make them think as users. The experiments were made using "Second Life" as a virtual world of collaborative design. Results show that ideal production was closer to the user needs. Engineers produced more ideas to anticipate user experience. The embodiment of an avatar in a virtual world was appreciated, and helped them to feel closer of the users.

In this thesis, an application of user/designer collaborative design is developed. A usage evaluation and product design optimization is conducted in Chapter IV.

II.3.2.2 Multi-representation in Automotive ergonomic design

Considering human factors in a product, ergonomics has been introduced in the product design to better study user interface. defined by The International Ergonomics Association, Ergonomics (or human factors) is "***the scientific discipline concerned with the understanding of interactions among humans and other elements of a system.***" (Dul et al., 2012).

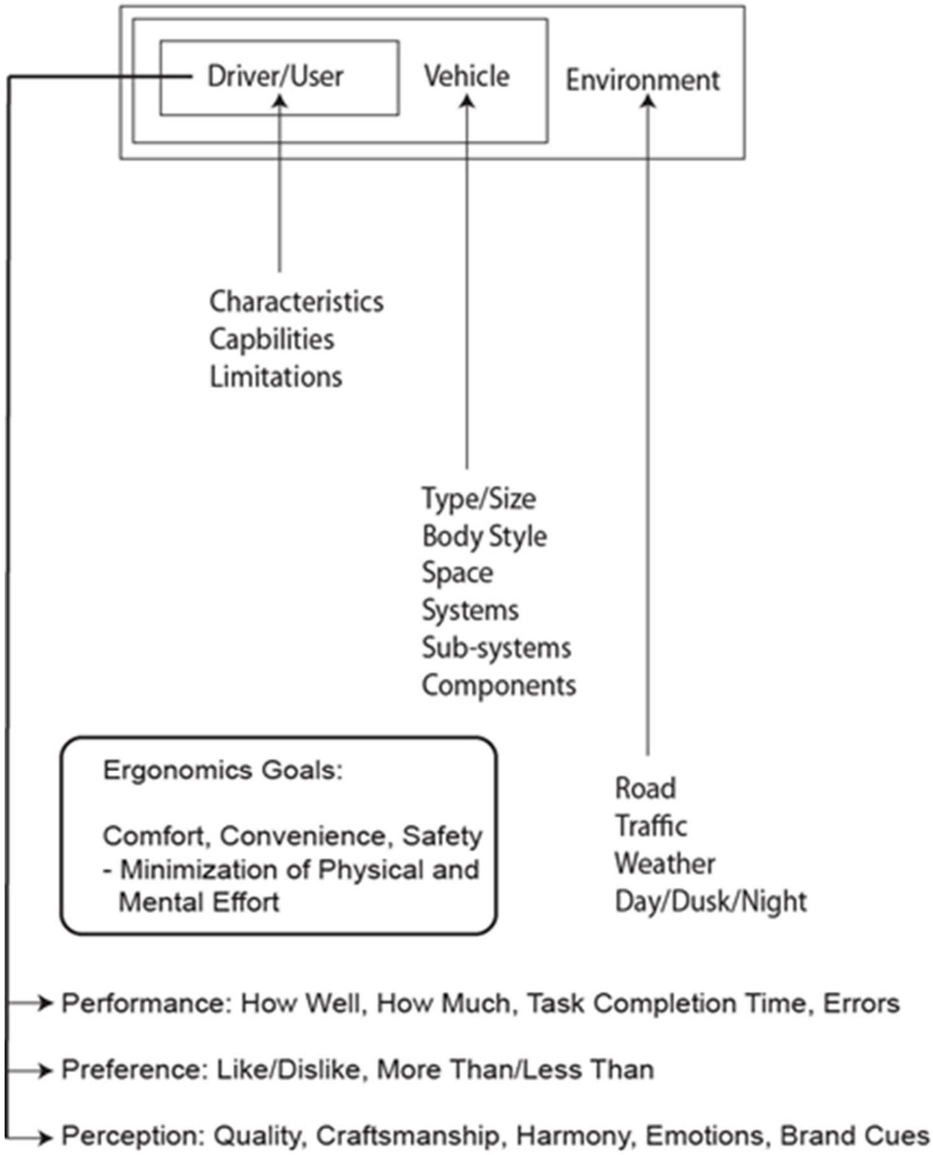


Figure 15 : Ergonomic evaluation of Driver, Vehicle, and Environment (Bhise, 2011)

Ergonomics is a multidisciplinary science that focus on all the information about people, such as Psychology, Anthropometry, Visual Sciences. Ergonomics studies human characteristics, capabilities, and limitations. The goal of ergonomics is to design and evaluate equipment and systems, in turn, to design for human comfort, convenience, efficiency, and safety products and systems (Bhise, 2011).

During the product lifecycle, the act of Ergonomics deals with the product quality improvement, safety improvement and product liability reduction. Ergonomics helps reducing product development time so that a product can be released right in the first time. These increase the product's competitiveness and customer satisfaction (Bhise, 2011).

In worldwide automobile manufactures, ergonomists' work is to apply ergonomic theory, principles, data, and methods to design better vehicles and optimize overall vehicle performance.

To achieve the best fit between drivers and vehicles, ergonomics evaluation must be made in the aspects shown in Figure 15: performance, preference, and perception (Bhise, 2011). The process of ergonomics evaluation is a multi-user working situation. With the development of virtual design environment, most of the design aspect evaluation activities can be firstly done on virtual car model, including ergonomics.

E.g. the ergonomic analysis of the driver's posture and visual field in the car cockpit is one important stage along its design optimization. Ergonomist often needs to work besides the driver, to deal with some anthropometric measuring. During a simultaneous measuring activity, the driver and the ergonomist are provided with views in different orientations. They also focus on completely different professional information. In virtual design environment, this ergonomics evaluation activity can be realized by using the DMU of the car. The different professional information of both driver and ergonomist come from the multiple representations of the DMU. Unlike traditional evaluation process, now the ergonomics evaluation can be proceeded in a collaborative working condition across different product development aspects.

In this thesis, an application for car seat ergonomics evaluation between driver and ergonomist is developed in Chapter IV.

II.3.3 Interoperability in DMU software

As we discussed in the last section, DMU data are composed of data from multiple representations. Normally, an expert on a domain produces technical data with a domain-specific software. The models used by domain-specific software are usually different in data format and structure. Similarly, the technical files produced by software have different data files that cannot be exchanged. E.g. there are a lot of commercial CAD software that have different data formats, such as U3D, X3D, 3D XML, JT Format, PLM XML, etc. (Li, 2012). To understand each other's files, a translation of the technical data or an interpretation of the result of the software is in need. This makes an obstacle among experts and the knowledge that they have mastered.

In order to reduce misunderstanding among experts and to save the collaborative working time, many works have been done to improve the interoperability among engineering software and among the data (Bettaieb and Noël, 2008).

Interoperability, as defined by (Wegner, 1996), is "***the ability of two systems (or more) to communicate, cooperate, and exchange data and services, despite the differences in languages, implementation, and operating environments or abstraction models***" (Segonds et al., 2010). An interoperability supporting tool allows people to work together for a common task and/or information exchange. The interface of the supporting tool is completely understood for working with other products or systems.

There are many solutions to improve interoperability among multi-representation of DMU. Mainly, a media system for creating a common format and a master model for managing all corresponding software are usually adopted.

(Chung and Lee, 2002) proposed a framework for engineering software using XML format as the media among designers, software programmers and clients. The design information can be interpreted by multiple users. (Brissaud and Tichkiewitch, 2003) proposed a similar UML based software framework for multiple users to share data with only one format.

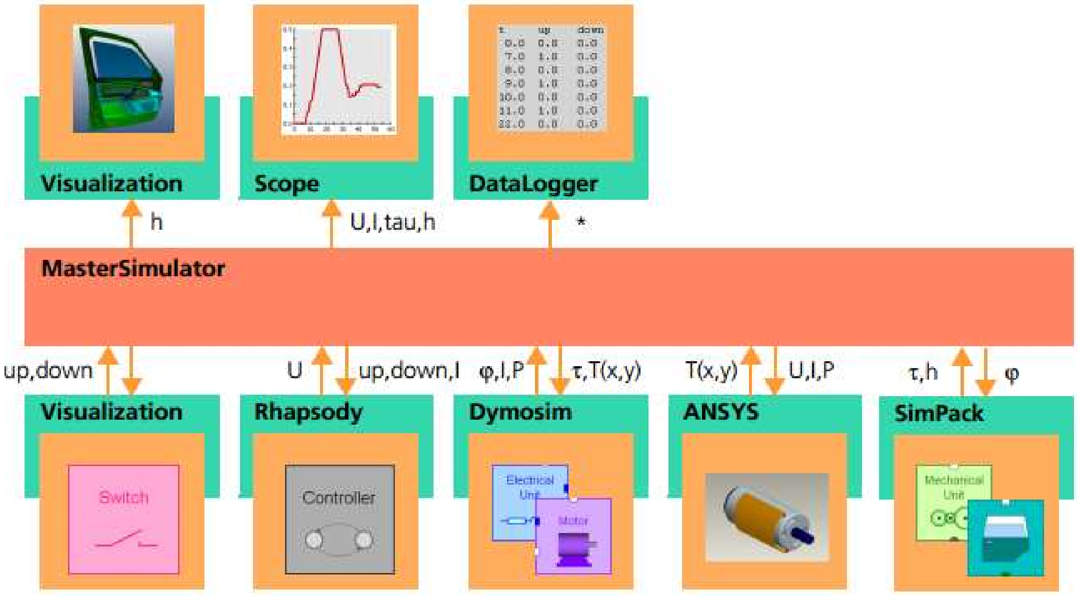


Figure 16 : Interface among simulation softwares increases interoperability (Schneider et al., 2009).

Functional Mock-up Interface (FMI) is a media interface proposed by (Enge-Rosenblatt et al., 2011)and (Schneider et al., 2009) which can be added into different simulation tools (Figure 16). This improves the interoperability among simulation software so that they can be able to co-simulate using a master simulator.

Figure 17 : Master model based approach which contains FEA, CAD and kinetics representations (Bettaieb and Noël, 2008).

In the research of (Brissaud and Tichkiewitch, 2003) and (Song and Chung, 2009), they describe other intermedia systems for improving interoperability. Both design activity and assembly activity are organized around multiple resources. The intermedia system must connect the various representations performed from these resources. It is assumed that other resources handle their own representation of structures, functions, and behaviors, while the intermedia connects these representations together. E.g. different formats of visualization data of an assembly are constructed for parts and subassemblies because of the use of various CAD software. Through an XML-based intermedia system, however, multi-level assembly and visualization of the feature data are performed by including the positional data of each part.

(France and Rumpe, 2007; Rio et al., 2013) proposed a master-model-based approach for the design of mechanical products. The model exported by several expert tools can be shared as collaboration knowledge in the domains of mechanical design and eco-design. The similar approach (Bettaieb and Noël, 2008) is creating a master model for CAD, FEM and kinetics model as shown in Figure 17.

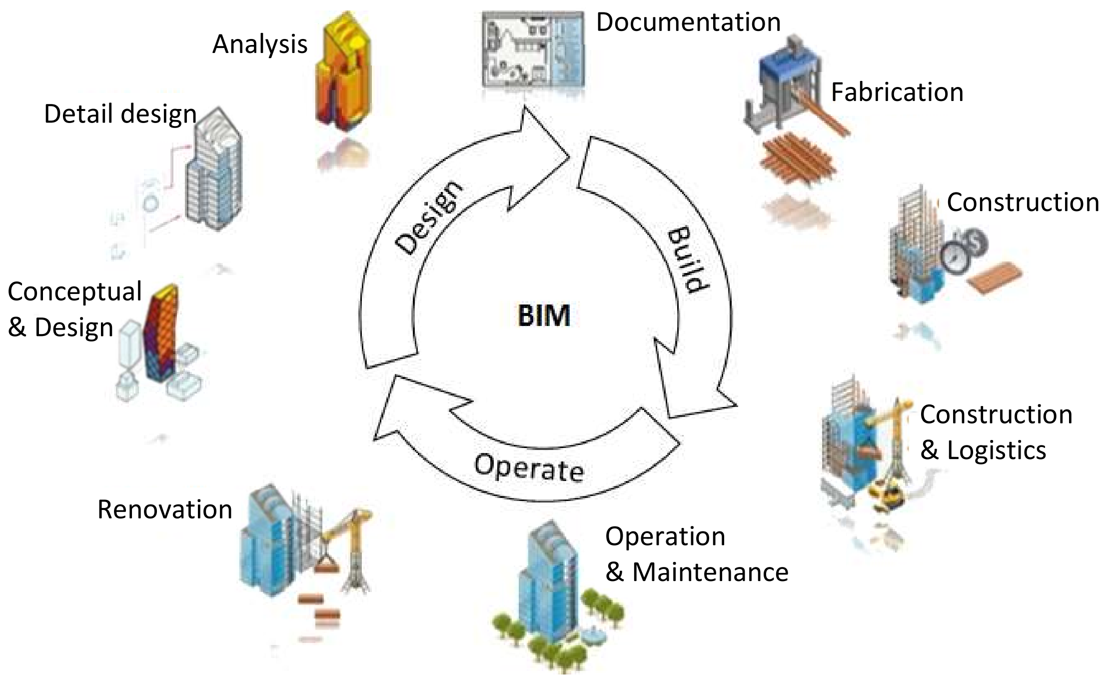


Figure 18 : BIM model contains different building information.

BIM software are widely used in architecture design, e.g. the commercial tools: Revit, Civil 3D, MACAO (Microstation), Vianova Virtual Map, etc. BIM tools are acting as master model which could integrate all the domain specific softwares along its lifecycle in one platform and save them in a unique file format. BIM software overcomes the problem in terms of interoperability among them (Smith and Eppinger, 1998). BIM is also an intelligent 3D model-based process, known as the DMU of building.

The geometric structure and semantic data of BIM model are defined by Industry Foundation Classes (IFC), an industrial standard data model of building and construction (Cruz and Nicolle, 2006). As shown in Figure 18, BIM model also contains representations of all the physical and functional characteristics of the building process and could make digital representations of plan, design, construct, and manage buildings and infrastructure. BIM gives all the experts a possibility to store different building information in a same format so that they can share their work and communicate with each other.

Thanks to these approaches in improving the interoperability of softwares and models, when experts are working in the overlaps of activities, they can now communicate with one certain software system.

Because this software system has integrated all the information and has no problem in different software formats.

II.3.4 Collaborative DMU

The intersection of DMU and collaboration represents a multi-disciplinary collaboration, in Figure 19. Multi-disciplinary collaboration is composed of experts with varied but complimentary experiences, qualifications, and skills of a representation of the product DMU that contribute to the achievement of the collaborative product development activities.

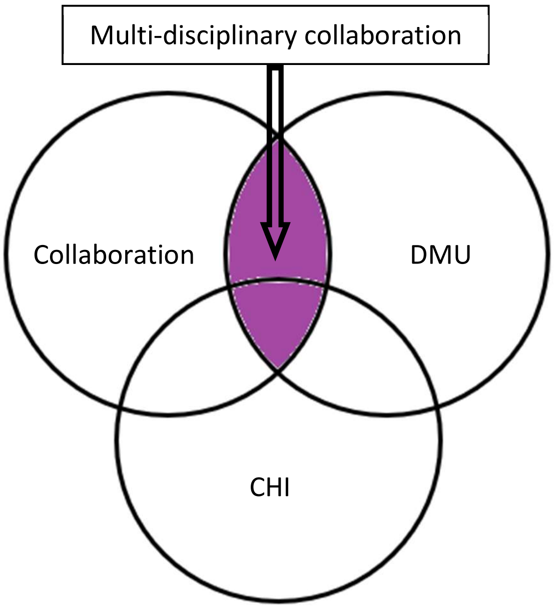


Figure 19 : Intersection of DMU and collaboration: multi-disciplinary collaboration

As we discussed above, DMU has a characteristic of multi-representation. An expert works with the DMU of the product under a certain representation.

Some softwares or models have been developed to improve the interoperability of different data formats. As described in Figure 20, the problem of software and model which involves the interfaces among machines and tools has been solved.

Considering the collaboration coupling style in II.2, we will discuss the collaboration work with multiple representations of DMU in this section. During a product lifecycle, an expert works with one representation of a product DMU. When CE working strategy is adopted in the process of product development, multiple experts will work with the same product DMU. Some experts may have the same representation of DMU, but others not. There are experts who need to work collaboratively while work with different representations of product DMU, e.g. during a project review, experts are from various domains of the product and each of them has its own professional requests. The differences of limitation, criterion, and requirement of the product result in the special disciplines.

To better support the multi-disciplinary collaboration, human factors for the user experience of the tools is considered. The interface between human and tools is going to be discussed in the next section.

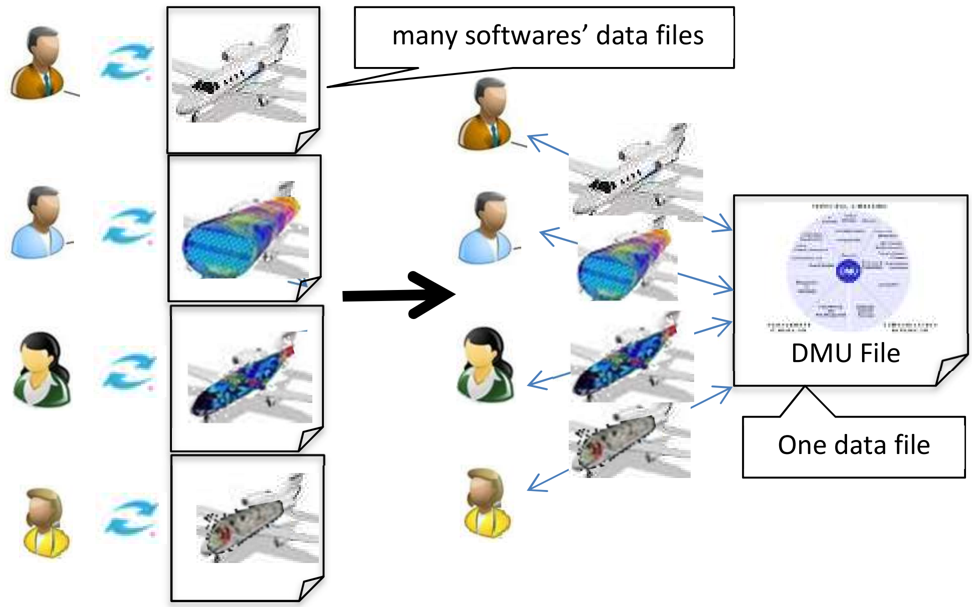


Figure 20 : Software-based and model-based approaches allow users to interact with one master model with one file format.

II.4 Computer-human interface (CHI)

II.4.1 Definition

Computer-human interface (CHI) is described as medium for communication between the computer and the human user. The positioning of CHI in the state of the art is highlighted in Figure 21. As shown in Figure 22, CHI means the communication between a human user and a computer system, referring to the metaphors of interaction.

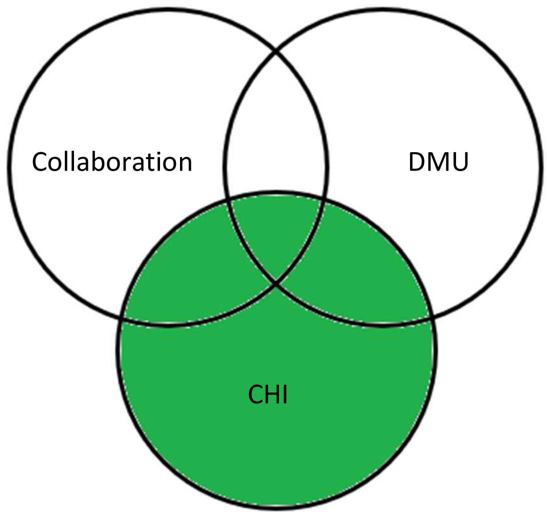


Figure 21 : The state of the art of CHI which is one of the three research areas.

II.4.2 CHI modalities

The reception of computer information includes visual, audio, and haptic metaphors. While by voice, gesture, and haptics, human gives orders to computer. These orders consist of selection, manipulation, and navigation.

- Selection: The metaphor of pointing an object and validating it.
- Manipulation: The metaphor of modifying the transformation (translation, rotation, scaling) of an object.
- Navigation: The metaphor of modifying the user's point of view in a virtual world with limited physical movement in real world.

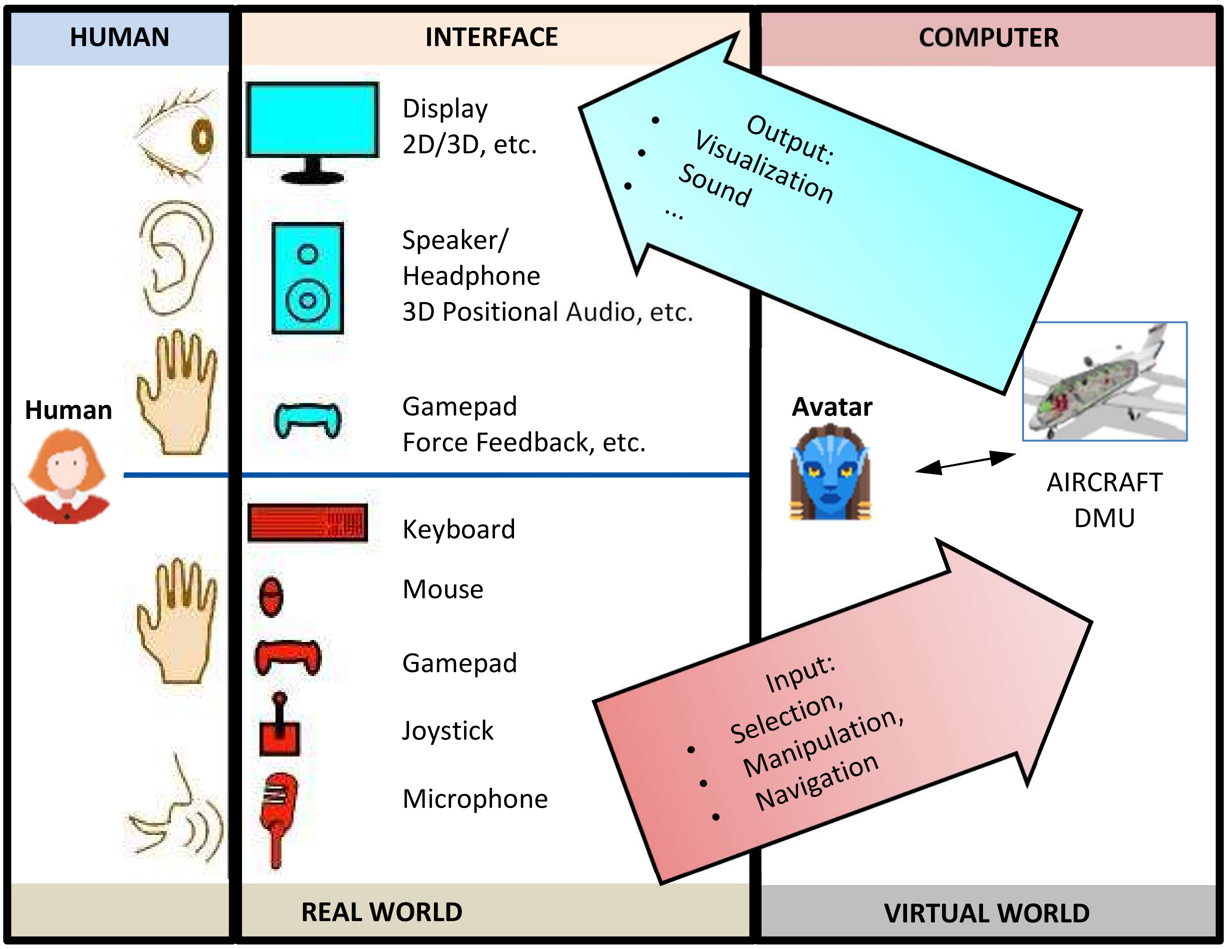


Figure 22 : Components of a CHI.

CHI can be categorized into output devices and input devices with supporting software according to the connections of computer and human sense organs. Devices of increasing sophistication are becoming available to mediate the human-computer interaction. These include graphics devices, touch-sensitive devices, and voice-input devices. They must be configured in a way that will facilitate an efficient and desirable interaction between a person and the computer.

- The output CHI consists of the devices that output information to human form computers. The main output devices are listed below.

- Visual output: computer screen, screen walls, projectors, Head Mounted Display (HMD), Cave automatic virtual environment (CAVE), etc.
- Audio output: speaker/headphone, etc.
- Haptic output: gamepad vibration, force feedback joystick, etc.

- The input CHI consists of the devices that input information to computer form human. The main input devices are listed: keyboard, mouse, haptic joystick, data gloves, microphone, etc.

II.4.3 Mono-user CHI vs. Multi-user CHI

II.4.3.1. Mono-user CHI

Because of the development of computer science, the usability of a CHI is becoming more important (Abe et al., 2010) when comparing to another CHI. Besides having the basic feature of the CHI, what human factor reflects to this CHI is very important for evaluating it. For example, laptop is the most common CHI, most laptops have similar functions. Users have various interaction metaphors with laptops because of the different needs they requested.

CHI is usually a bridge between user and machine. Each user can customize a certain CHI according to his preference. A user is supported by a certain tool for working; the user chooses a certain manner, which is a CHI with a certain interaction metaphor. During the use of CHI, the intentions of users are translated to computers. How to design a CHI to communicate in a new way and to improve the interaction experience of user is wide research field in computer technology.

In the context of the collaborative working conditions of advanced product lifecycle, CHI plays a great role on how experts from various specialties work together for a certain task. Current CHI may have problem with multiple users rather than single user and needs to improve to satisfy collaborative interface for multi-user interaction with computer. When being in a collaborative task, users may have some different kinds of CHIs. These CHIs are still barriers between different users because if they want to discuss something they should first work with their tools through their special CHIs. The interoperability of CHIs from different representations is becoming more important.

II.4.3.2. Multi-user CHI

When the working situation is with multiple users instead of a single user, the working task is a collection of all the users and each user can affect the result of the task. As we discussed above, there are approaches that turned multiple mono-user tools' data format into unique multi-user tool's data format. This interoperability among tools allows one tool to interpret "correctly" the files generated from other tools.

While for CHIs, each user has a certain manner to express his/her commands and to understand the information given by tools. This CHI is the way how user works which remains the independence of mono-user.

Many collaborative platforms (Bennes et al., 2012; Hrimech, 2009; Martin et al., 2011) have been proposed in creating collaborative virtual environment (CVE) through multiple mono-user CHIs. If experts collaborate with multiple mono-user CHIs, the CVE on which they are working is regarded as a remote mode, as shown in Figure 23. Plus, many web-based multiple mono-user CHIs solutions, in which CHIs are far away from each other, have been developed. These remote-adjacent (RA) solutions allow the users to operate the application concurrently without the need to replicate an application on the each other's side for exchanging information (Abe et al., 2010). For example in a 3D application, two users can see common environment information in each CHI and an avatar of each other (Kan et al., 2001). Experts may send each other notes or messages or speak through microphones to communicate in remote-adjacent collaborations (dos Santos et al., 2012).

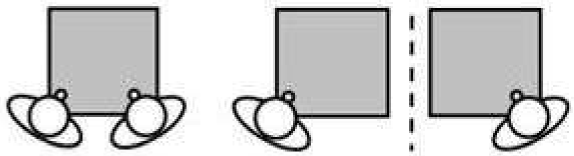


Figure 23 : Different styles of collaborative virtual environment (Tuddenham and Robinson, 2009)

II.4.4 Multi-view

II.4.4.1 Definition

The synchronization of representations become a key point to organize collaborative activities (Bettaieb and Noël, 2008). Multi-view system overcomes the drawbacks of separated displays which cause mental transformation in cognitive psychology and reduce an individual's performance when one's eyes switch between mono-view displays to collaborate corresponding information (G. Zhai and Wu, 2014).

Multi-view system is a visual-perception interface which allows humans to see simultaneously multiple images through a unique shared medium (Matusik et al., 2008). Several images are emitted simultaneously from the display medium and then received respectively by human vision. In (Wu and Zhai, 2013), multiple views are described as frames with view-dependent pixels. These multiple views can be displayed as an output package at the same time. Compared to mono-view system that has only one view at one time, the multi-view system can have separated views at one time. Using certain techniques, this package of multiple views can be captured separately by receiving devices.

Snowdon proposed the frame of individual perspective in virtual environment: What You See is Not What I See (WYSNWIS) (Snowdon et al., n.d.). In this fundamental issue for collaborative virtual environments, each user has view-dependent representations of the virtual environment. The subjectivity of a user's vision is assumed to have different multiple views. The reasons why users don't want to see other user' views are: User 2 has a very complex model that User 1 wants to replace it with a simpler one because it takes up too much of machine's resources; User 1 may not care about User 2's database and does not want to see any users with radically different views of the model.

II.4.4.2 Multi-view visualization system mechanism

To create a system of multiple views, various technologies exist in the literature and they can be classified into three categories: filter-based, time-based, and space-based (Figure 24).

For filter-based mode, the emitted images are projected in the different subspaces of colorimetry or light shape (Figure 25). Anaglyph images are created by putting images in different anaglyphic color channels, then these images can be seen separately with Red/Cyan filters (Thompson et al., 2011).

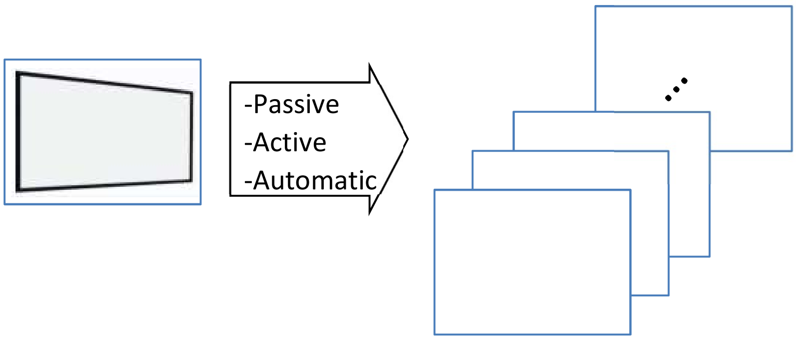


Figure 24 : Three mechanisms of multi-view system

As an analogue definition of multi-view images in (Matusik et al., 2008), if one thinks of a pixel's color of an image from a multi-view system as a function of not only its x and y coordinates, but also the filter used in multi-view system, filter becomes a means of changing the appearance of the multi-view system. The color of a multi-view images' pixel is typically a function of its filter and can be defined as:

$$pixelcolor_{x,y} = f(x, y, Filter).$$

The similar mechanism is using the polarized filter and there are different types such as linear and circular. For linear polarization, two images are projected with orthogonally oriented projecting polarizing filters on a same screen. For circular polarization, two images use polarizations of opposite direction. Using suitable receiving polarized filters for each corresponding projecting filter, images can be encoded with a separation. The circular polarization produces better separation than linear polarization because the filtering quality is not affected by the orientation or tilting of filters (Thompson et al., 2011). Because what people see is decided by the which filter he/she choose, so this mechanism is often called "passive glasses".

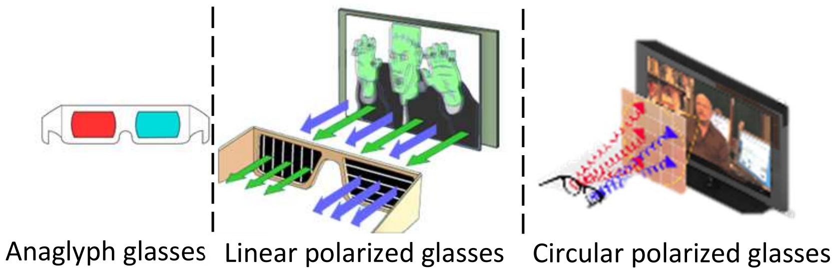


Figure 25 : Filter-based multi-view system mechanism

For time-based mode, the images to display can be simultaneously separated in temporal dimension. Within a very short period, images are displayed one after the other in sequence (Figure 26). This mechanism is used to synchronize the emitter and the receiver. E.g. shutter glasses, which is a receiver, can switch the transparency of the two glasses alternately, synchronizing with the refresh rate of the emitter, which is usually a projector or a screen. As an analogue definition of multi-view images in

(Matusik et al., 2008), if one thinks of a pixel's color of an image from a multi-view system as a function of not only its x and y coordinates, but also the time that the image lasts in a time interval according to the synchronizing frequency of multi-view system, time becomes a means of changing the appearance of the multi-view system. The color of a multi-view images' pixel is typically a function of the highest synchronizing frequency of the screen f_{syn}, and can be defined as (Wu and Zhai, 2013):

$$pixelcolor_{x,y} = f(x, y, (1,2 \dots n) \ * \ 1/60/n).$$

with $n = f_{syn}/60$.

As a well-known condition of Human Visual System (HVS), 60Hz is the lowest frequency for human to have a reflection of continuous images without flick fusion (Wu and Zhai, 2013). Human being cannot perceive what happens in this short period of 1/60s, so that we consider the durations within this 1/60s as "at the same time". A 120Hz projector and the supporting shutter glasses can create two views in sequence that each has a 1/120s period. Image A and image B are displayed by a projector in an alternate way. Each image is displayed for 1/120 second before switching to the other one. Then the 120 Hz shutter glasses alternate between opaque and transparent. If the user wearing the glasses want to see the image A, the glasses should be transparent only when the image A is displayed. Thus, the displayed phase for the projector should be synchronized with the shutter phase. Usually an signal emitter can give a unique rhythm to be followed by the projector and shutter at the same time.

Modern optoelectronic displays with their supporting receiving devices can operate much higher refresh rates, thus multiple views more than two can be created (Wu and Zhai, 2013). Unlike filter-based mechanism, time-based mechanism is often called "active glasses".s

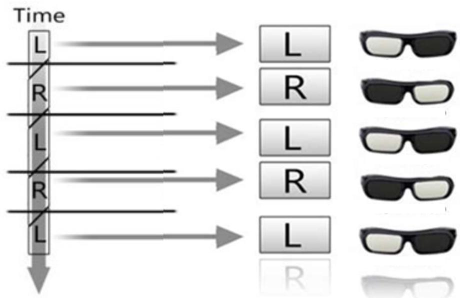
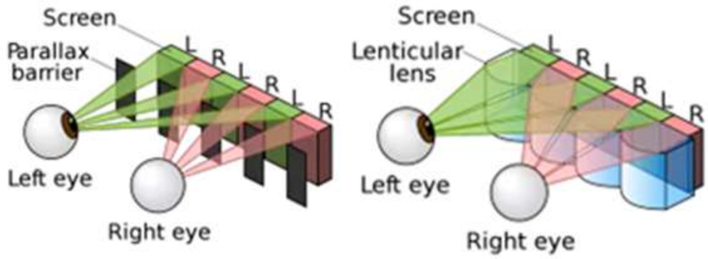


Figure 26 : Time-based multi-view system mechanism

In contrast with the filter-based and time-based modes the space-based mode does not need any wearable equipment (e.g. Glasses) on the image reception side (Figure 27). Because of the naked eyes and the automatic adjustment of point-of-view according to space, this mechanism is often described as "Automatic".

If one thinks of a pixel's color as a function of not only its x and y coordinates, but also the user's point-of-view (POV) in space, POV becomes a means of changing the appearance of the application. Where the color of a pixel is typically a function of its position on the screen, the color of a multi-view pixel can be defined as (Matusik et al., 2008):

$$pixelcolor_{x,y} = f(x, y, POV).$$



Parallax barrier screen Lenticular lens screen

Figure 27 : Space-based multi-view system mechanism

Spatial dimension is applied to the separation of views. Using screen technology, images can be seen separately from different position in space beyond the same screen. E.g. A display is placed behind a parallax-barriers that has an opaque sheet with patterned holes stamped out of it or a lenticular sheet who has an array of magnifying lenses. Light from an individual pixel in the display is visible only from a narrow range of viewing angles. Thus, the images seen through each hole or lenses will change with the change of one's position in space (Matusik et al., 2008). With advanced screen technologies, multiple spatial views (more than two) can be realized and the combination of the mechanisms above can produce the system with even higher number of views (Balogh et al., 2005).

II.4.4.3 Multi-view and Virtual Reality (VR)

A Point-of-view (POV) of an object is generated from a certain spatial position. E.g. in a sketch of a product, designer may need three POVs including front view, up view, and left view to define the geometry structure of the product. Multi-view system can be applied to display the multiple POVs of an object, especially in the field of Virtual Reality (VR) where these multiple POVs are used to create the visual feeling of stereoscopy VR enables users to enter a virtual world which is created with multi-sensory devices and 3D software. One of the important characteristic of VR is immersion. In this virtual world, users will have an experience of vision, sound, haptics and even smell and taste. The multi-sensory immersion of virtual reality can create the feeling of being present in the virtual world to users (Slater and Usoh, 1993). All their perceptions of the realism of the virtual world affects how they act in physics.

The main characteristics of VR is that it can cut the real senses between user and real world, and it creates virtual senses to users. If VR cuts more senses and re-build more senses, it will become more "real". Another VR characteristic is that it brings the visual feeling of depth to users. Stereoscopic vision gains user's perception of depth of virtual environment, which is the key for user to feel "3D".

To transform a 3D virtual world to computer graphics, 2D images are computed from a 3D world. Each 2D image corresponds to a snapshot (or other word) of the 3D world taken from a position with an orientation. Therefore, when we see the 3D world from different positions with different orientations we will have different POVs. Since two eyes from human being have a distance between them, they have different views of a same object in horizontal direction.

Thus, any VR device for creating 3D images is equivalent to a multi-view system. E.g. 3D glasses, including anaglyph, polarized (Bell et al., 2008; Fujimura et al., 2012; Lissermann et al., 2014; Nagano et al., 2011), and shutter glasses (Mistry, 2009; Sibecas and Eaton, 2012) are creating two POVs. In a two-user VR application (Martin et al., 2011) or a multi-view table (Lissermann et al., 2014), the multi-view system, a combination of polarized filters and shutter glasses, should create 4 POVs for four eyes. Autostereoscopic displays (Kim et al., 2012; Matusik et al., 2008; Peterka et al., 2007) are also working as a multi-view system to create two POVs for each eye following different spatial positions of the eyes.

With stereoscopy, users can have visual perception of depth through the display system. From Head-Mounted Display (HMD) system and Cave Automatic Virtual Environment (CAVE), users will even get the feeling of immersion in virtual 3D world. To adapt the POV in virtual world to users' physical movement, tracking system usually traces user's head position and orientation.

In the virtual world, user's POV can be manipulated by user's motion and other virtual elements. Users also can interact with the virtual elements through 3D user interfaces, e.g. 3D mouse, fly stick, haptic devices etc. These devices allow users to introduce their movement to the virtual environment for touching the object, manipulating the object, and navigating in 3D.

With advances in various technology fields, such as computer graphics, man-machine interaction technology, sensor technology, high performance computing and artificial intelligence, the simulation of virtual world now becomes increasingly realistic.

Becoming a new way for visualization and interaction, VR has found an increasingly wide utilization in all fields. An survey made by Helsel & Dohertyin (Schroeder, 1996) indicated that VR applications were involved mainly in the fields of entertainment, education and art. The fields followed are military, aircraft design and healthcare. VR has created a virtual way of conducting physical actions. The virtual activity can be a situation that can never happen in real life, such as video game, or can be a simulation of the real activity that is very hard to be done in real life. The simulation of reality has anyhow replaced the real activities because of certain advantages, e.g. economic, fast, and repeatable. The literature on the use of VR is vast in many fields. E.g. in the survey (Moline, 1997), VR is widely used for healthcare in simulation of surgical procedures and medical education and training to improve the remote surgery or telepresence and to save cost. VR is widely used in product design and manufacturing, especially in automotive industry (Martin et al., 2011; Zimmermann, 2008). VR has been used in the simulation of physical product lifecycle with car prototype. This virtual solution can help evaluate the design, simulate the real driving, and train the participants in some activities, e.g. assembly and maintenance. In compare with the activities in real industry, VR may help in saving time and cost.

II.4.5 Multi-interaction

II.4.5.1 Definition

An intelligent CHI will allow users to interact with it using multiple metaphors and interpret one metaphor to more than one single command (Morris et al., 2006). Multi-interaction of a CHI can be defined as a multi-input system which allows both multiple devices and multiple interactive metaphors.

Figure 28 : Intelligent CHI will allow users to interact with optional devices: vision, sound, haptic devices, etc.

II.4.5.2 Multiple interaction device & metaphor

Multi-Interaction has two levels of meaning. From the technical level, multi-interaction means multiple interaction devices (Herrmann, 2008; Sangiorgi et al., 2014). As far as we could imagine, 3D visualization and vision techniques, 3D sound technologies and haptic devices like force feedback and tactile feedback, these devices could give the user one or more interaction methods with the DMU. They bring the user not only the visual perception, but also the perception of immersive sound and touching effect on virtual object (Merienne, 2010). Multi-interaction can support a variety of creative work for group experts' alternating activities like collaborative discussions and presentations (Geyer et al., 2010).

Table 1 : Experts can choose metaphors on objects to realize same/different significances.

Same Metaphor	Same Object	Same Result	Multiple Meanings
×	×	×	N
×	×		Y
×		×	N
×			N
	×	×	Y
	×		N
		×	N
			N

From an interaction metaphor level, multi-interaction means that different user-defined metaphors can be conducted in real time (Wobbrock et al., 2009). As listed in Table 1, the same result or not indicates whether a collaborative multi-interaction has an alternative meaning.

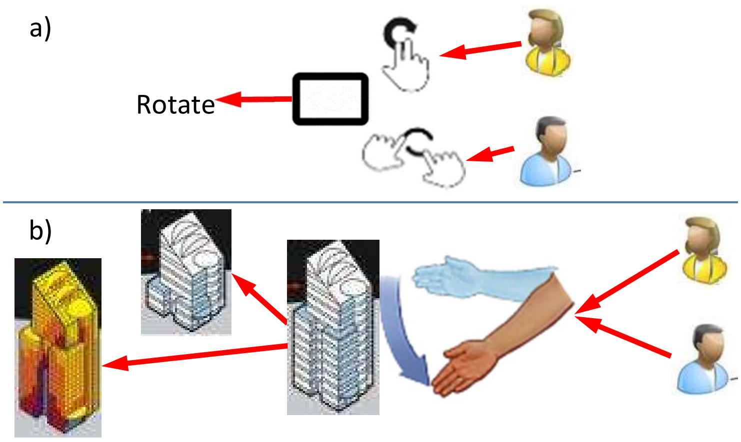


Figure 29 : Different interaction metaphors.

When interacting, two experts may choose metaphors to use on objects and obtain some results. We put a "Y" in the table for the situation that various metaphors result in alternative meaning. So multi-interaction can be summarized as: one interact metaphor can be used by different experts and generate different meaning according to the experts' domains (Pistorius and Utterback, 1997). Similarly, two experts interact with the same object but their interaction metaphor (gesture) may be different, e.g. in Figure 29.a, two experts' interaction metaphors (gesture) are different, but with a same action of "rotate"; in Figure 29.b, one waving metaphor can be used as changing the size or changing the color of a building model.

Each expert could choose interaction metaphors different from the ones chosen by the others in virtual navigation and manipulation of the models (Bell et al., 2008). As discussed in II.4.2, interaction metaphors consist of selection, manipulation, and navigation. The definition of user's motion for these metaphors can be flexible based on user needs.

For example in manipulation, experts manipulate the model by modifying (addition, deletion, rearrangement etc.) its parts or the elementary sub models, e.g. modifying airplane rivets, building, or deleting pipes (Baxter III et al., 2002; Ma et al., 2004; Wang and Li, 2006). One-time interworking can replace multiple interactions with similar objects. Grouping a specific category of objects according to a specific rule will reduce the number and time of operations.

II.5 Collaborative CHI through DMU

II.5.1. Introduction

We have discussed the collaboration in current industry and collaborative coupling style; the use of DMU in design activities during product lifecycle and its multi-representation; the CHI that supports multiple users and its realization in a multiple input and multiple output, respectively. We will talk about the intersection of DMU, collaboration and CHI in Figure 30.

According to II.3.4, the intersection of DMU and collaboration results in a multi-disciplinary collaboration working condition. Considering human factors, the multi-user CHI that support multi-disciplinary collaboration is positioned in the intersection of DMU, collaboration, and CHI. In this thesis, we will develop such CHI tools that allow multiple users to interact with. The multi-disciplinary collaborative scenarios will be created. Both CHI and scenario will be evaluated in this thesis. The motivation of the thesis work is due to the disadvantage of CHIs used in current collaborative work.

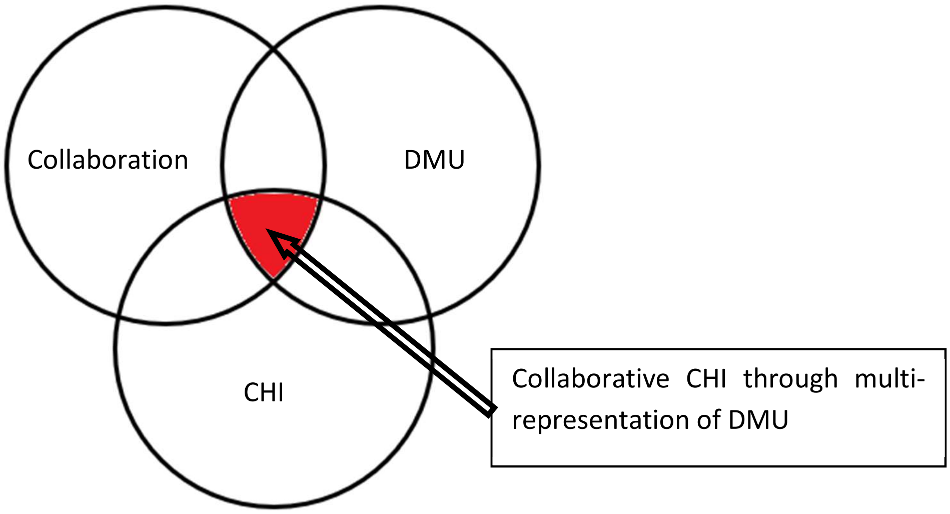


Figure 30 : Intersection of DMU, collaboration and CHI: collaborative CHI through multi-representation of DMU

Many commercial DMUs and BIM platforms can integrate design, analysis, and manufacture. However, an expert only uses a part of the platform to finish his/her work. Separate displays, like using single laptop or screen wall that put several separate screens together, display different domains of information separately. Expert must exchange eyes and body to deal with the information fragments. This may reduce the expert's concentration psychologically and increase the possibility of misunderstanding and complexity about communication (Guangtao Zhai and Wu, 2014).

When attending a project review, in which facial expressions and hand gestures is important to express ideas of each other, experts requires more face-to-face communication. To avoid the switch between the perspective of other experts and the perspective of his/her own perspective, it is better that an expert in a visual space shared with other experts only have their own perspective. This will help the expert to communicate and collaborate (Agrawala et al., 1997) with others and also to overcome the sense of isolation that happens when experts use their own mono-CHIs, e.g. their laptops, to attend project review.

If experts are co-located and working in real time, each expert has one proper CHI when he/she is communicating with DMU. They cannot overcome the barriers of CHIs. At this point, although the experts have a face-to-face discussion, the collaboration among them cannot be fully concurrent due to the restrictions of multiple mono-CHIs. For example, when experts discuss a modification of a product during a project review, each expert uses his/her own laptop as a CHI to interact with each other through a specialized tool. A modification caused by expert needs to be verified by other experts from different CHIs. The results of the interactive specialized tool can suggest if the modification of this expert can be accepted or not in other specialized fields.

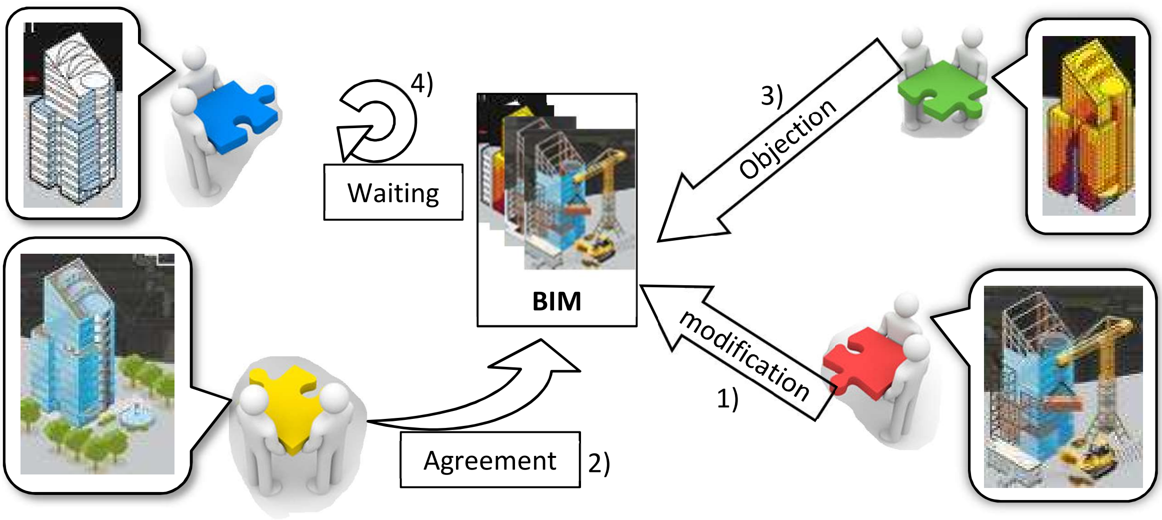


Figure 31 : Normal collaborative work condition.

In Figure 31,

- Expert 1, field of expertise: construction, proposes a modification of the BIM model;
- Expert 2, field of expertise: urban engineering, obtains the modification effected in urban view of DMU in real time, expresses approval of Expert 1;
- Expert 3, field of expertise: structure analysis, finds a conflict in the building structure view of DMU, expresses an opposition and conducted a further discussion with Expert 1;

- Expert 4, field of expertise: building design, has not much change in his view, chose to stay and wait for the discussion result.

When user 1 proposes a modification, other users must judge this modification with their tools through their CHIs. This takes time and reduces the collaboration effect. As we can imagine, everyone wants to show others the opinion on his/her domain. But the fact is when one sees others' view on the information that he/she is not familiar with, he/she always cannot understand other's domains. This is because the experts on all other domains with all different technical, different educational and cultural level, even simply different language backgrounds (Chevaldonné et al., 2005). They don't have the same knowledge in their mind and cannot exchange information immediately in real time. This reduces the effect of communication and increases the difficulty of discussing and negotiating with others.

The disadvantages of current collaborative work using multiple mono-user CHI systems are going to be overcome by new CHI and new strategies of collaboration, multi-user CHI. To search for similar scientific conception, we explored a lot of literatures on the multi-user CHI. A categorized list of both multi-user mechanism and multi-user applications are presented in the following sections.

II.5.2. Taxonomy

We are going to examine the applications that we found in the field of collaboration, DMU, and CHI, using the criterions we have presented before. A taxonomy of applications is described as below.

Because of the implementation of CE in industrial activities and CE's collaborative nature, much more collaboration with various domains of expertise in the whole product lifecycle is in need. As we discussed in II.2.4, when individual experts must work together in an interactive way of the different phase of product lifecycle, the coupling styles are categorized into:

- Tight Coupling;
- Loose Coupling;
- Mixed Coupling.

DMUs should be shared among the different sorts of domain-specific software and among experts. It is perfectly reasonable to relate DMU with activities of its multiple applications for the multiple softwares. To realize this, the applications should be created by following the characteristics of DMU:

- Multi-representation

From a DMU, it is also possible to generate 3D models with VR software. They are normally built of triangles (polygons) and can be converted into DMU tool proprietary formats. Normal visualization device provides one 2D view to the user, like television, computer, and smartphone. Compared to single view display, multi-view visualization offers more than one view for users. Two slightly different 2D images present respectively into human eyes can be fused in the human brain for having stereoscopic view (Dodgson, 2005). Since the geometry model of a DMU is usually in 3D format, it will be at least four 2D views for two users to have stereoscopic view of a DMU. Because of a special usage of multi-view system in multiple POVs, multi-view can be used to generate stereoscopy:

- Multi-POV (VR)

As we categorized in II.4.4II.4.4.2, multi-view system has three mechanisms:

- Filter-based,
- Time-based,
- Space-based

Multi-interaction system has two phases:

- Multi-modal devices,
- Multiple metaphors

II.5.3. Study of applications

We are going to categorize the applications that we found in intersection of three aspects: collaboration, DMU and CHI. Using the taxonomy that we proposed in II.5.2, we are looking for information system solutions to support co-located synchronous collaboration. These systems should be a multi-user CHI that allows user to complete multi-disciplinary tasks. With this unique CHI, all the experts can get information corresponding precisely to the expertise from DMU to discuss synchronously, to modify collaboratively and to make decision together in the same place and at the same time.

- *Applications found in multi-disciplinary collaboration:*

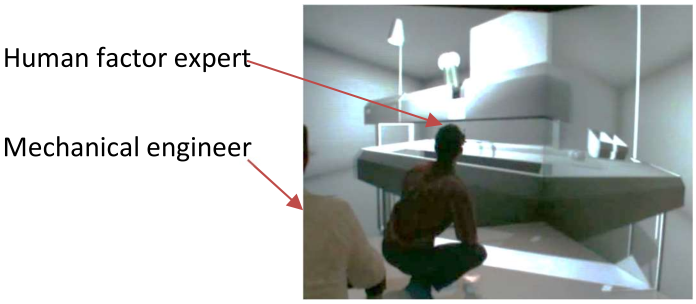


Figure 32 : Two cross-disciplinary design experts work in a collaborative product design environment (Bennes et al., 2012).

(a) A concurrent and collaborative product design methodology is described in (Bennes et al., 2012). It is synchronous and cross-disciplinary among different design experts, including industrial stylists, human factor experts and mechanical engineers. A VR solution, as shown in Figure 32, is proposed as an intermedium among multiple representations. The application helps to elaborate an early design proposition considering two experts' requirements: industrial designer (stylist) and human factor expert. Some general collaborative functionalities of these two experts are realized in detail. However, this system cannot give multiple images to the users at the same time. Experts should work on it one by one.

Figure 33 : Two experts collaborate to place a car seat (Martin et al., 2011).

(b) An immersion CAVE-like display approach for co-localized multi-user collaboration is proposed in (Martin et al., 2011). This approach combines technologies of active 3D glass (shutter glass) and passive 3D glass (anaglyph or polarized glass). Gesture manipulation device, speech recognition device and haptic input device are applied in this system for a multimodal interaction. A car body model with seats are displayed to two users separately in two alternating time intervals. Because user's space position is tracked, the displayed images are recalculated from the virtual model according to the last position of the user. In a virtual assembly chain application shown in Figure 33, two users collaborate to define the position of a seat by speech command and movement with haptics. They work with the same representation of a car DMU. However, to realize multi-interaction, tracking system tracks user A's hand position, whereas user B's hand position is directly known with the haptic device.

- *Applications found in multi-view CHI:*

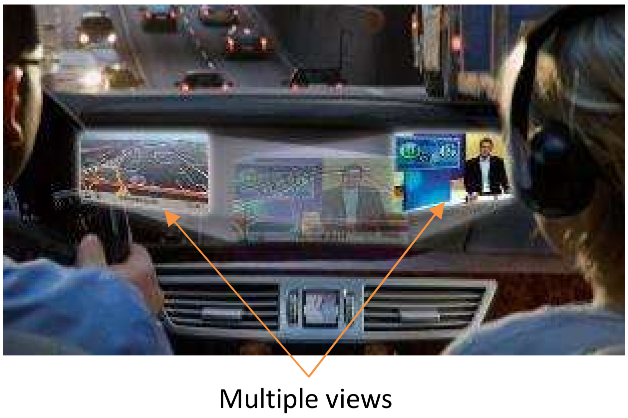


Figure 34 : Multi-view screen on the dashboard of a car (Brown, 2013).

(c) SPLITVIEW (Brown, 2013) enables the front passenger to watch a film while the driver keeps an eye on the navigation information on the same screen (Figure 34). Two different images are displayed simultaneously on this screen. A mask in front of the display splits the source of double image such that only the pixels for one or the other image are discernible, according to the respective seat positions. When there is not any relationship between two displayed contents, SPLITVIEW has no differences with watching movies on two personal devices like tablets / smartphones.

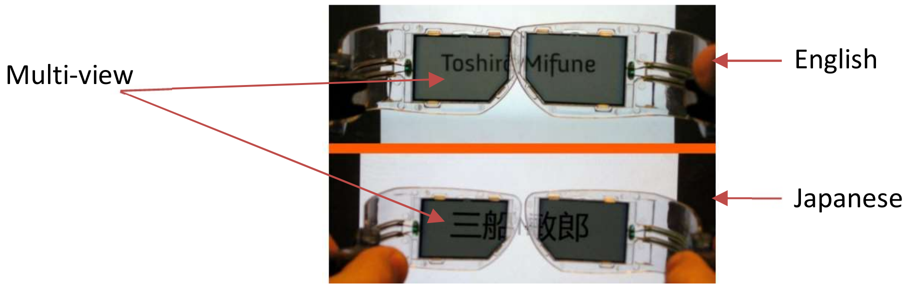


Figure 35 : two users to read a same paper in different languages (Nagano et al., 2010)

(d) (Mistry, 2009; Nagano et al., 2010) proposed the glasses with which two people are looking at a sentence which has been translated into two languages, each user only understand what he does see and can communicate with the other viewers because the unchangeable sentence meaning. These glasses were made of two original shutter glasses or polarized glasses, which were restructured by putting two left eye lenses together and two right eye lenses together (Figure 35).

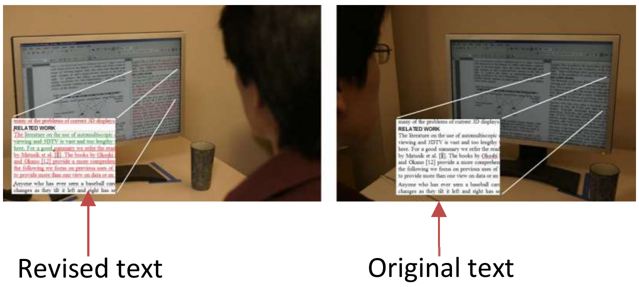


Figure 36 : Multi-view screen with different contents looked from left side and right side (Matusik et al., 2008).

(e) (Matusik et al., 2008) describes how to make screen-based autostereoscopic systems display two 2D views for two views. The naked 3D parallax-barrier or lenticular sheet screen let the user see one image with two eyes but with slight difference in vertical direction. Adding more images and resetting the parallax in vertical direction, each user works as one eye in 3D display. He/she can have a view of 2D image in a stable position and from a fixed angle. As shown in Figure 36, users can see different views standing different angles with the autostereoscopic display.

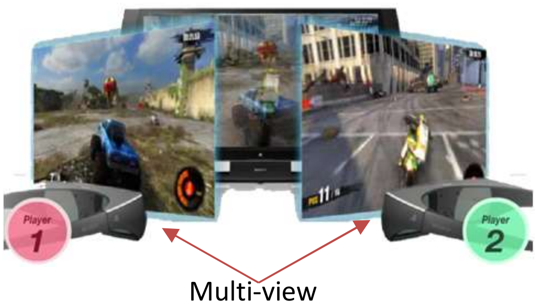


Figure 37 : multi-view screen can give two 3D views because of the High frequency (240Hz) (Sibecas and Eaton, 2012)

(f) High frequency display like (Sibecas and Eaton, 2012), in Figure 37, improved the shutter glasses technology accompanied with a screen with high refresh ratio of 240Hz. Each of the four eyes from two users is displayed in the ratio of 60Hz, which is the lowest ratio for human being to see clearly. And four eyes could be displayed in sequential separately. In total four 2D views are as two 3D views for two users to play two different games separately and simultaneously.

Figure 38 : Three players of a card game: two opponents can't see the other's cards. One judger can see every cards (Kim et al., 2012).

(g) (Kim et al., 2012)is based on a Liquid Crystal Display (LCD) screen which can display images only when line of sight is perpendicular to the screen or in a range of field of angle. Three views can be realized by displaying three different images in the same time. There are two views from each side of the screen and one view from the perpendicular direction in front of the screen. Users can play cards face-to-face with a judge in the middle. The judge can see not only the common parts of the other two, but also the private parts of them, in Figure 38.

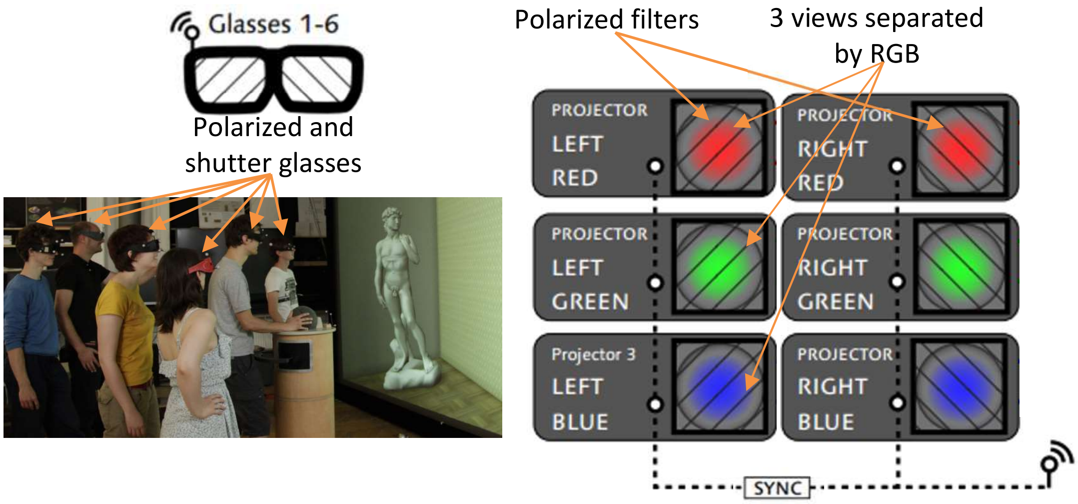


Figure 39 : High frequency project's RGB is divided into 3 views, plus polarized filters, a multi-view system of 12 views is realized (Kulik et al., 2011).

(h) A co-located multi-view system which provides six users different views of a virtual environment is proposed in (Kulik et al., 2011), in Figure 39. Three high frequency (360Hz) Digital Light Processing (DLP) projectors are for six users' left eyes. Each projector displays only one of the basic colors (red, green, and blue) to one left eye with frequency of 60Hz. These three projectors can have 6 views. Adding another 3 projectors for six right eyes plus polarized glasses, totally 12 views, or we could say 6 3D VIEWs is realized. This multi-view system has been applied to see and to manipulate a 3D model.

(i) One application of (Lissermann et al., 2014) in Figure 40 is to manipulate pictures separately and to share pictures in a specific zone on the screen. Each user chooses some pictures of a certain theme together to create an album of two themes. They need to communicate to decide which pictures to pick. Another application is to annotate roads on a map to generate a path. Two users can see two maps of the same region in different size and with different information. One with city roads details while the other with altitude level map. In this application, multi-view of different maps is really helping the collaboration between two kinds of users.

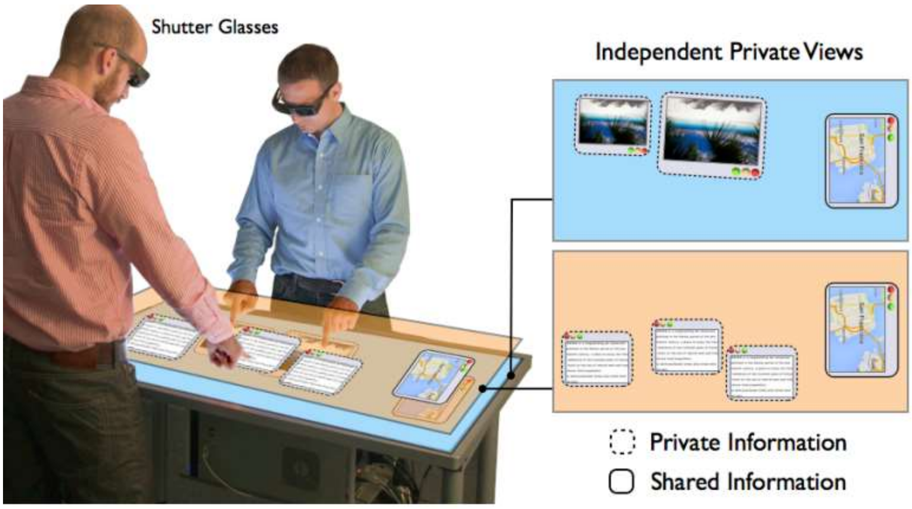


Figure 40 : Two users can have private views on the same screen. They collaborate with private and shared views (Lissermann et al., 2014).

(j) An application of multi-user karaoke on a same screen is described in (Fujimura et al., 2012) and (Littfass et al., 2014). Users can watch different contents on the screen: lyrics for singing or postures for dancing at the same time.

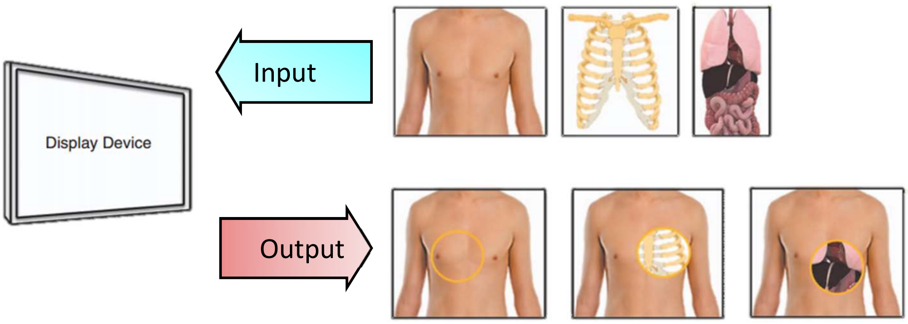


Figure 41 : Multiple users can view different 3D regions of interest independently.

(k) The application of (Kakehi et al., 2004) and (Matsushita et al., 2004) is to play a 4-person card game. Each one can only see the card in his own direction. Stereoscopic Touch Table (de la Rivière et al., 2010), with polarized projection technique, allows each user to have its own point of view along different table sides.

(l) A space-based visualization solution is proposed in (Wu and Zhai, 2013). From two sides of the screen, a body's different representations (skeleton, organs) can be displayed respectively, as shown in Figure 41.

(m) Holografika (Balogh et al., 2005) is a screen with advanced space-based technology that provide naked eyes 3D images as shown in Figure 42. Using multiple projectors and special membrane technology, this device can display a 3D object seen by anyone standing in front of the screen. Standing at different angles and directions in front of the screens, users can get different views of seeing the 3D object, e.g. a user on the left-side position in front of the screen can see the left sides of the cards, while a user on the right-side position in front of the screen can see the right sides of the cards.

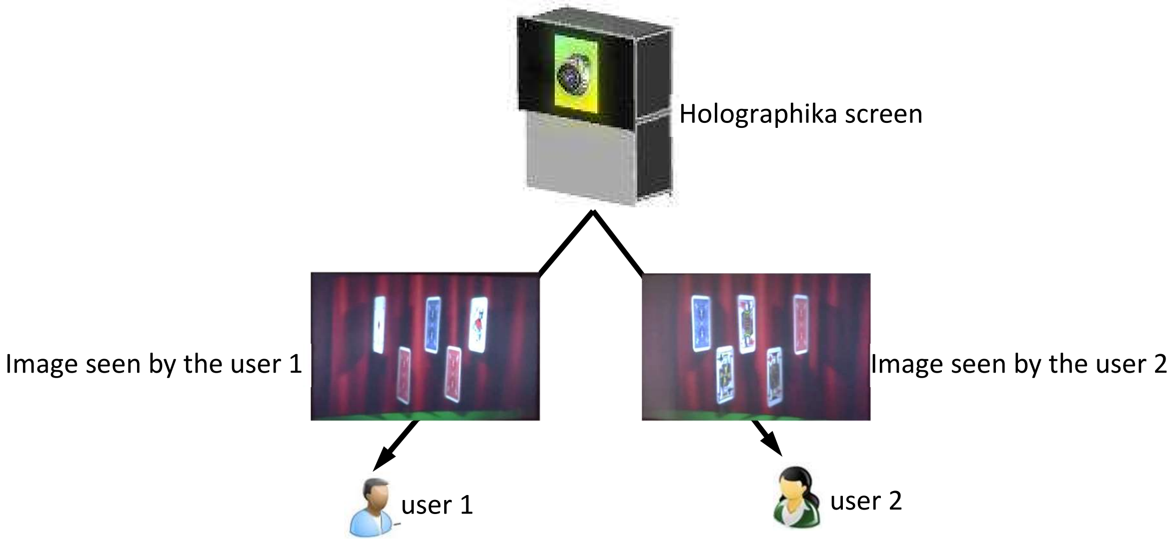


Figure 42 : 3D object can be seen from different positions in front of a screen.

As we discussed in II.4.4, the importance for a multi-view system is to choose appropriate mechanism and try to create as many views as we could. From anaglyph and polarization approach, we obtain two views. From shutter glasses, the screen refresh rate defines how many separate views can be offered (Matusik et al., 2008).

All of them must face their disadvantages: color distortion for anaglyph, less brightness for polarization, and flicker for shutter glasses. The disadvantage of space-based technology is the decreasing of viewing range with the increasing of number of views.

- *Applications found in multi-interaction CHI:*

To realize a multi-interaction CHI, many applications have been done by extending interaction to a multiple way.

(n) A multi-interaction screen that allows users to interact with it by standing at different distance away from the screen is present in (Vogel and Balakrishnan, 2004). Not disturbing other users, this CHI can help multiple users interact with the content at the same time with their own gestures.

(o) As shown in Figure 43, the multi-interaction methods of selecting an object by users are described in (Bell et al., 2008). For example, a user may select an object if he/she holds their hand for more than a specific period, or if they make a rapid poking motion at the object. This approach allows user to define the interaction metaphor according to the user's willing.

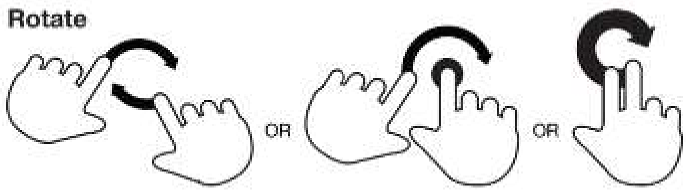


Figure 43 : three metaphors for rotating an object.

As we discussed, the multi-interaction of this CHI system should be multiple not only in using different devices, but give users the freedom of define the interaction metaphor.

II.6 Synthesis of the state of the art and positioning

II.6.1 Synthesis

In this chapter, a state of the art in three research areas: collaboration, DMU, and CHI is investigated. The definition of collaboration and the need of CE in current industrial product development process is discussed. According to different collaboration conditions, typical collaborative styles are decided.

Since experts need to work collaboratively with models and softwares, the unique database, DMU, is widely used across the activities during product lifecycle. The characteristics of multi-representation of DMU are discussed. The need of using multi-representation in industry is investigated in early design and automobile engineering.

The importance of CHI in supporting collaborative works is discussed, especially for supporting co-located simultaneously collaborative works. The mechanisms to create multi-user CHI are listed. The intersection of collaboration, DMU, and CHI is emphasized in this chapter. The applications for the intersection of these three areas are found and categorized under criterions.

II.6.2 Positioning

The aim of this chapter is to position the work. The study of applications is summarized in Table 2 around the three field of collaboration, DMU and CHI. Using the taxonomy of each research area in II.5.2, a synthesis of these applications will be given in this section.

In collaboration, the collaborative coupling style of most of the multi-user applications is loose, which means the multiple users work as individual users. The applications (b)(g)(i) have mixed coupling collaboration. Only (b) has a multi-view system in immersive 3D but the two users of this system watch a same representation of DMU. The scenarios in the other two applications are multidisciplinary in visualization but lack of multiple interactive input devices.

In DMU, the applications usually adopt multi-representation to loose-coupling collaborations. (b)(g)(i) are the applications which use multidisciplinary representations of DMU for mixed coupling collaborative scenarios.

In CHI, multi-view CHI systems studied are developed with mechanisms of filter, time, and space based technologies, even with the combinations of these techniques. (a) (b) (f) (h) have immersive 3D multi-view environments, which integrate VR in the collaborative scenarios. In (a) (b), multiple users have multiple devices to interact with the CHI system. However, the different metaphors of interaction are rarely mentioned and defined.

We propose in this thesis a multi-user CHI that can present different representations of DMU to multiple users simultaneously. A multidisciplinary collaboration scenario with these representations can be realized through this CHI system. Multi-view and multi-interaction technologies are applied in this CHI system to support multiple users.

Table 2 : Collaborative design through DMU

Applications	**Collaboration (Coupling)**			**DMU**	**CHI**					
					Multi-view				Multi-interaction	
					Multi-view mechanism (-based)			Multi-POV (VR)		
	Tight	Mixed	Loose	Multi-representation	Filter	Time	Space		Multi-device	Multi-interaction
(a)	×					×		×	×	
(c)			×				×			
(d)			×	×	×	×				
(e)			×	×			×			
(f)			×	×		×		×		
(g)		×		×			×			
(b)		×			×	×		×	×	
(h)	×					×		×		
(i)		×		×	×	×				
(j)			×		×					
(k)			×	×			×			
(n)			×				×			×
(m)	×						×			
(o)										×
(l)				×			×			

The positioning of our research is shown in Figure 44. A collaborative CHI through DMU supporting the multidisciplinary collaborative scenarios will be developed and evaluated in this thesis. The multi-user CHI in co-located simultaneously collaboration with using multi-representation of DMU which is the key contribution of this thesis, will be discussed in Chapter III in detail.

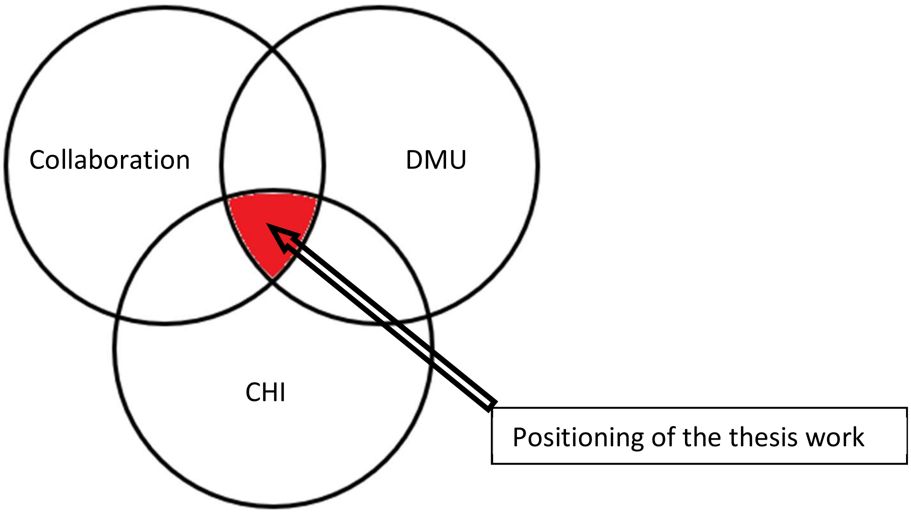


Figure 44 : Intersection of DMU, collaboration and CHI: Collaborative CHI through DMU

Chapter III Scientific approach

III.1 Introduction

The previous chapter proposed a state of the art on:

- the collaboration,
- the multi-disciplinary engineering activities using Digital Mock-ups (DMU) in industry,
- the computer-human interface (CHI) for supporting collaboration among multiple users.

The intersection of these contexts is discussed, and the taxonomy of the multi-user applications is listed. The purpose of this chapter is to clarify the scientific approach that we have adopted in this thesis.

In this chapter, our scientific problem is presented in section III.2, as well as the method adopted to study this issue. The method to design a multi-user system is proposed in III.2.1 The need of creating a multi-user collaborative scenario is discussed in III.2.2. The evaluation methodology used in our study is proposed in III.2.3, with the objective and subjective measurements and qualitative user analysis in III.2.3.1. The contribution to evaluation is discussed in III.2.4. A synthesis of scientific approach is given in III.3.

III.2 Scientific problem

According to the state of the art, the positioning of research question is at the intersection of collaboration, DMU and CHI. When several experts are working in a multi-disciplinary activity, existing CHI systems have troubles in visualization and interaction of the multiple representations in the activity.

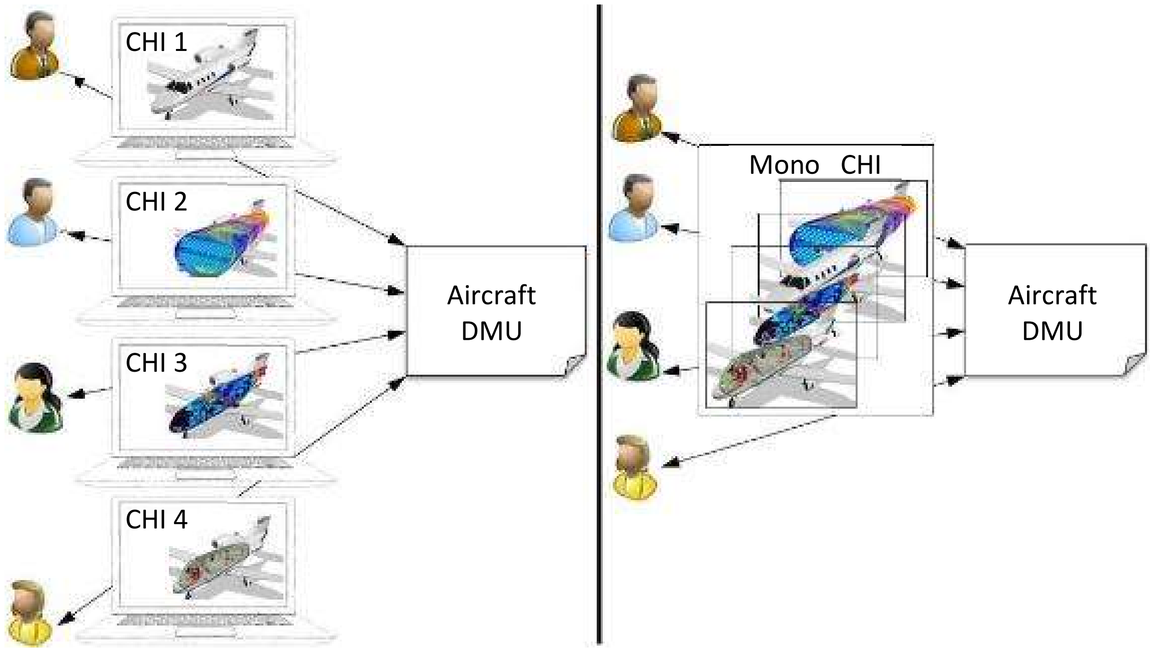


Figure 45 : One single CHI (right) replaces several CHIs (left).

To enhance the collaboration with experts on different domains to communicate with DMU, a novel support system of CHI has been taken into consideration, as shown in Figure 45. On the left, each user picks up his own CHI and has his proper input and output through that CHI and in total four CHIs are used. On the right, four users adopt one single CHI to work with DMU. This unique CHI allows multiple users to work with the tools that he/she prefers. They can get synchronized modifications in real time. They may feel free to discuss with other experts in a co-located working condition.

As mentioned in the last chapter, one single CHI mainly contains multiple visualization mechanisms and multi-user interactions. There are technologies aiming at the creation of multiple user CHI system. According to different technologies, the CHI system is mainly developed in both multi-view system and multi-interaction system. The question about these systems to be searched is:

- How to design a multi-view system?
- How to design a multi-interaction system?

Collaborating with each other, different experts work together, with one representation of DMU for each. The behaviors of the collaborators are the problems to be searched:

- How's experts' working style when they are co-located?
- How multi-user system can help collaboration?

To know whether users are satisfied with the approaches with new CHI both in academic research and in industrial cases, the problems about evaluation methodologies should be solved:

- How to evaluate multi-disciplinary collaboration?

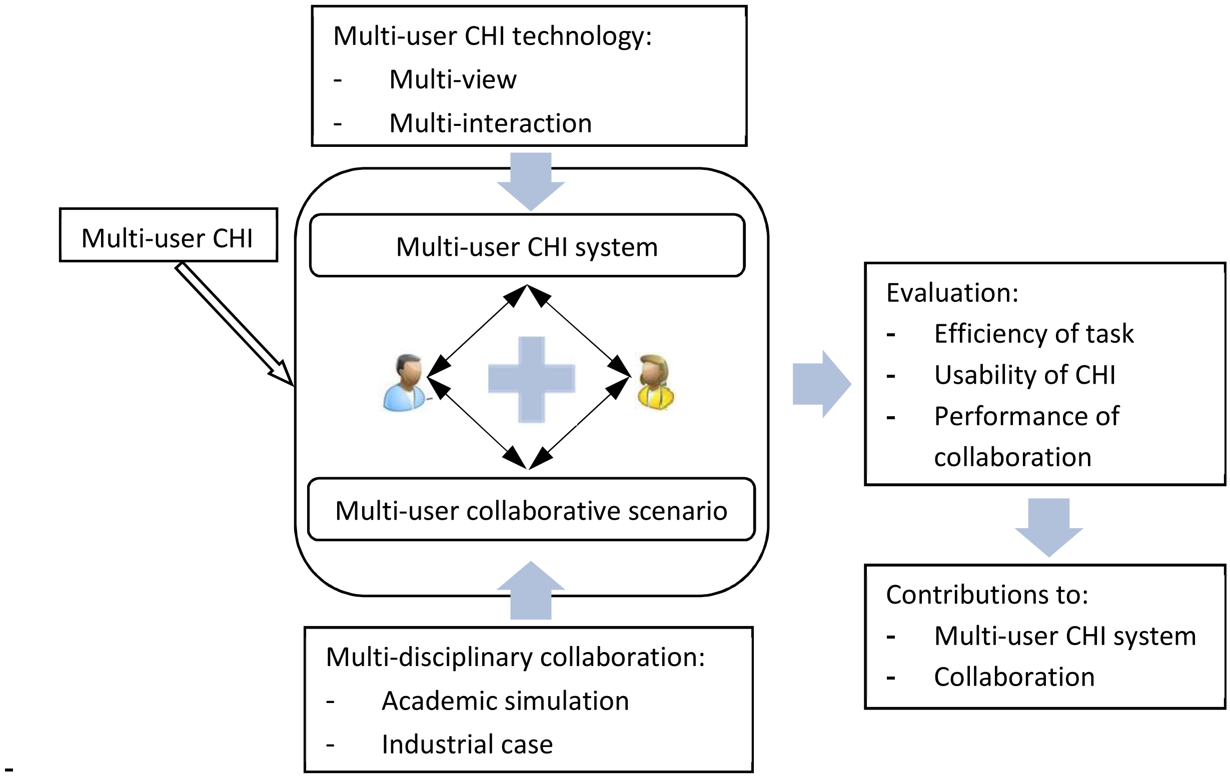
Considering all the problems, our research question to explore and to study in this thesis is as following:

"***What is the influence of multi-user interface among users with different representations of a Digital Mock-Up during a collaborative work***?"

To solve these scientific problems, the following scheme for the approach is proposed (Figure 46).

A multi-user CHI, which is composed of a multi-user system plus a multi-disciplinary collaborative scenario, is proposed. Multiple users can interact with the CHI system respectively. They can also work together in a collaborative scenario, having different representation of a same DMU. To investigate the research question, a methodology for evaluating the efficiency, the usability of this multi-user CHI and the performance of collaboration is then proposed. The results of the evaluation may have contributions to multi-user CHI design and the improvement of group collaboration. The proposed scientific approach consists of the following steps:

- Establish a multi-user system using existed technologies: multi-view and multi-interaction.
- Define multi-user collaborative scenario considering the special representation that is adopted by each user.
- Evaluate the efficiency of task, the usability of CHI and the performance of collaboration by evaluation methods.
- Analyze the evaluation results and discuss the contributions that the new CHI can provide for the design criteria of multi-user CHI and multi-user co-located collaboration.



- Figure 46: Proposed scientific approach.

III.2.1 Designing a multi-user system

III.2.1.1 Multi-view

We proposed several solutions to multi-view system based on the technologies in Institut Image of LE2I laboratory.

- Two pairs of filter-based approach of anaglyph glasses, as mentioned in Figure 25, can be used to separate mixed light of red and cyan. Similarly, two pairs of filter-based polarized glasses can be used to get two views from mixed light because of the difference in the direction of polarization.
- Using the device of Holografika (Balogh et al., 2005) with advanced autostereoscopic technology as mentioned in Figure 42, we can propose a space-based multi-view solution. This device has a screen that can display several images according to different spots before the screen.
- A system combining both filter-based and time-based technologies has been also proposed. Two active shutter projectors emit images through two polarized filters and both active shutter glasses receive images pre-selected by the corresponded polarized filters attached to the glasses. Therefore, this system can provide simultaneously four simple views or two stereo views for displaying two 3D scenes synchronously.

The selection of technologies and the detail of their configuration will be discussed in IV.2.

III.2.1.2 Multi-interaction

In our proposed CHI system, several modalities of interaction are available. Using keyboard to control the navigation of the object of the scenarios, the user has many choices of interaction manners, so he/she can get used to the system. Mouse buttons are used to determine a control mode of navigation in a 3D scene.

Tracking system can obtain the space position of point defined on the user (e.g. the head, hand), or on an equipment (e.g. a car seat). It can help updating the position of the virtual representation of the user or the car in a 3D scene. Multiple users' positions can also be captured with tracking systems. Combined the mouse buttons, multiple users can interact with the scenarios of selection, manipulation, and navigation by some pre-defined interactive motions.

More technical details of selected interaction technologies will be discussed in IV.2.

III.2.2Proposal of multi-user collaborative scenario

As can we see in Figure 46, a multi-user CHI for multiple user is realized by combining multi-user CHI system and multi-user collaborative scenarios. Multi-user CHI can solve the multiple user problem of using several interfaces technically with certain techniques that we have discussed before in II.4.3.

Especially in multi-view system, as mentioned in section II.4.4II.4.4.2, the different mechanisms of obtaining multi-view will have effect on the ultimate emitted images. If one thinks of a pixel's color as a function of not only its x and y coordinates, but also the different mechanisms of multi-view mechanisms (MVM). The color of a multi-view pixel can be defined as:

$$pixelcolor_{x,y} = f(x, y, MVM).$$

With MVM: multi-view mechanisms (Filter or Time or Space).

The representations of users determine the multi-user collaborative scenario. The ultimate emitted images from the multi-view system are related to the representations of the users' scenarios. Considering users' representations, we proposed that for a multi-view collaborative system, the color of each pixel can be defined with this formula:

$$pixelcolor_{x,y} = f(x, y, MVM, REP).$$

With MVM: multi-view mechanisms (Filter or Time or Space).

REP: Representations of DMU

In collaborative working context, it is important to integrate multiple representations of DMU to the scenario of multiple users in a multi-view system.

We will propose both academic experimental scenarios and industrial case scenarios. To study the multiple users' collaboration styles with quantitative experiment, simulations of multi-disciplinary collaboration are designed. Each user has its own representation of the working task. The two users also must collaborate to finish a simulated task. These simulations are corresponding to the industrial collaborative works. Since an academic simulation game can represent the process of collaboration among multiple users in industrial product design, in addition, it can be evaluated with quantitative criteria, we proposed two scenarios of simulation games to establish experiments. These scenarios are detailed in IV.3.2.

According to the industrial fields that has needs of multi-user collaboration, discovered in section II.3.2, scenarios of multi-user collaborative design have been designed. A scenario of an early collaborative design of a mug, involving the user experiences and design criterions has been proposed. This scenario involving the user experiences and design criterions. A scenario of the multi-disciplinary collaboration between ergonomist and driver in automobile industry has been designed.

The detail of the selection of scenario, the prototype of scenarios, and the implementation of the scenario of experiments is described in Chapter V

III.2.3Evaluation

Evaluation is an important concept and helps guide the design process. Since we are investigating the CHI system plus the multidisciplinary collaboration scenarios, most of the evaluation techniques are used in the domain of the user interface.

As shown in Figure 46, to evaluate how the proposed multi-user CHI system influence on the multi-user collaboration through representations of DMU, three aspects are related:

- Efficiency of task: the time used to finish a task. The communication during the task is considered if the task has collaboration among users. Errors made during the task are also considered.
- Usability of CHI: the evaluation of the interface adapted of the field of human computer interaction (HCI). Usability is the quality that a system offers at the level of ease of learning, ease of use and user satisfaction (Nielsen, 1994). There are three factors that contribute to the usability of a system: human performance, cognitive effort, and collaborative activity. These factors are complementary shown in (Hrimech, 2009; Rosson and Carroll, 2002).
- Performance of collaboration: the multiple users' performance when users are completing a task collaboratively. It is about the cognitive psychology factors, such as involvement in collaboration, awareness of collaborator.

According to these related aspects, in this thesis, we propose hypotheses to response to our research question as follow:

H1: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Efficiency of task**.

H2: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Usability of CHI system**.

H3: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Performance of collaboration**.

For each hypothesis, there are several criteria to be measured. As shown in Figure 47, for H1: Efficiency, criteria to be measured are **Finish time**, **Communication time**, **Error committed**, etc. **Learnability** and **Satisfaction** are criteria to be measured for usability of CHI. In the performance of collaboration, we usually consider **Involvement**, **Awareness**, and **Collaboration effort** as criteria. In the next section, the criteria are discussed in detail.

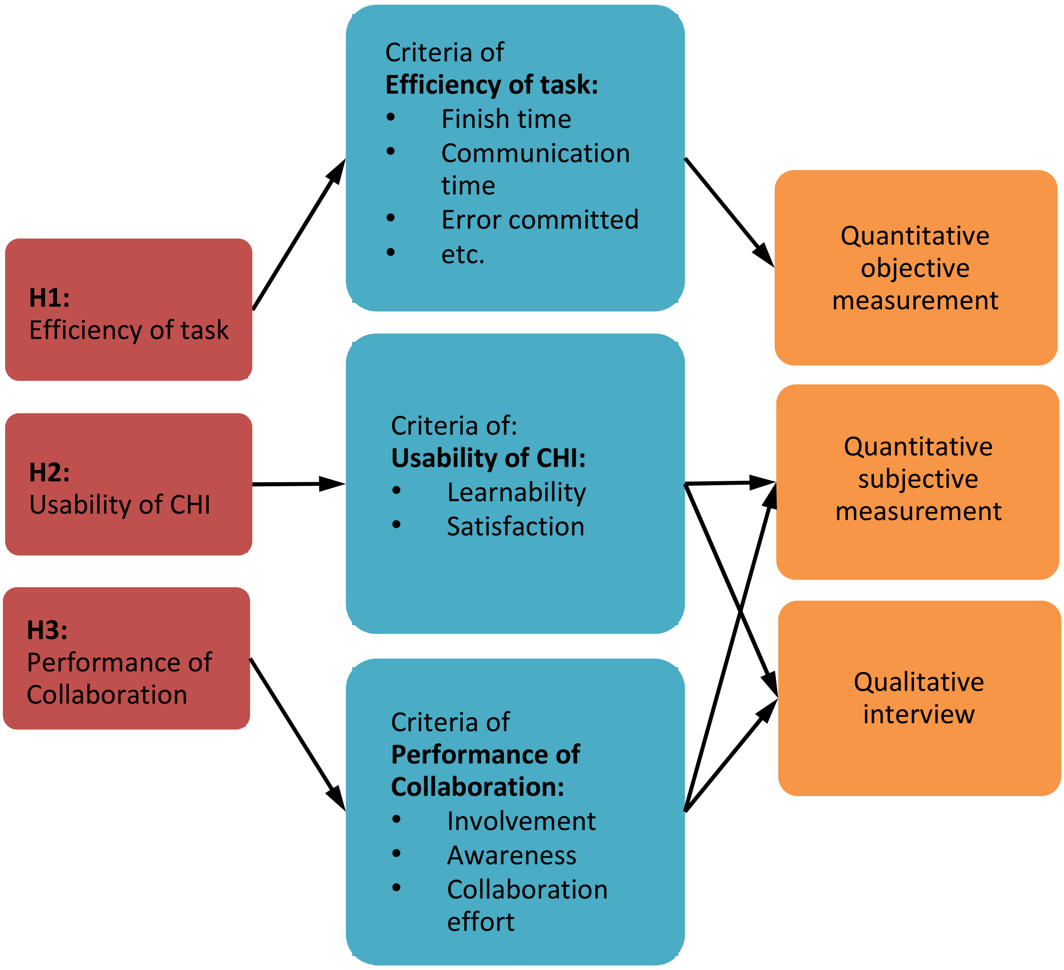


Figure 47: Criteria of hypotheses and methods of evaluation

III.2.3.1 Measurement

According to the categorization of (Hrimech, 2009), evaluation consists of formative evaluation and summative evaluation. Formative evaluation is used to refine the design of an interaction technique or an interaction metaphor. Generally, two formative evaluation methods are used: 1. Online evaluation. Observational studies will be performed on users (simultaneous presence of user and design expert is required). 2. Off-line evaluation. Questionnaires, interviews, audio and/or video recordings. Summative evaluation consists of comparing several techniques during a single evaluation session. One can give as an example the study of the most appropriate technique for the accomplishment of a specific task. In this case, the results of a summative evaluation, which consists of strict experimental protocol, user selection, etc., are usually quantitative and the evaluation of collaborative work is analyzed statistically (Hrimech, 2009).

In our thesis work, both formative and summative evaluation methods are used during our experiment. According to different criteria, our methods of evaluation are classified as: quantitative objective measurement, quantitative subjective measurement, and qualitative interview.

- Quantitative objective measurement

An objective measurement according to the performance of the task is conducted. The measured criteria of the efficiency of task, based on literatures (Lissermann et al., 2014), include:

- **Finish time**: The length of the completion times during a collaborative task;
- **Error committed**: the error committed during the task;
- **Communication time**: how much time participants spend on communicating with their partner;
- **Number of question/answer pairs**: the total number of communications with the task;
- **Sum of response time of all question/answer pairs**: an accumulation of response time of all the questions;
- **Ratio of communication time to finish time**: the percentage of communication time in finish time.

- Quantitative subjective measurement

Using a questionnaire, we can measure the variables adapted to our hypothesis 2 and hypothesis 3:

- **Learnability**:

How easy it is for users to accomplish basic tasks the first time they encounter the design (Nielsen, 1994).

- **Satisfaction:**

Satisfaction means user's acceptance of the tools or system performance (Hrimech, 2009);

- **Awareness:**

Awareness is a key concept emerged from the field of Computer-Supported Cooperative Work (CSCW). It proposes that, in addition to the ability to communicate directly, users of shared systems should be generally made aware of each other's presence and activity, (Gerhard et al., 2001).

Four types of awareness often maintain collaboration when working in groups (Greenberg et al., 1996):

- Informal awareness, which concerns the member present in the working group;
- Social awareness, which focus on the social aspects of collaboration, e.g. the attention or the motivation of the participants;
- Group-structural awareness, e.g. the role of each participant.
- Workspace awareness, which concerns a person's knowledge of the workspace, e.g. what other participants are doing.

In our research, we propose to consider awareness as the willingness and the degree of knowledge of collaborator's position and special need.

- **Collaborative effort:**

Collaborative effort is how much work that two collaborators provide to accomplish a specific task in a collaborative context (Harms and Biocca, 2004). It represents the quality and complexity of the collaborative task.

- **Involvement:**

Involvement indicates the participants' feeling of how well they participate in their activities (Gerhard et al., 2001).

- Qualitative user analysis

Qualitative user analysis is method of evaluation based on focus groups, interviews, user observations and other forms of qualitative research. The scientists, engineers and technical writers determine the characteristics of users will influence the development of the product being tested (Pruitt, J.S, & Grudin, 2003). It is usually used in ergonomic analysis of a product. In our thesis, we adopt a qualitative interview to analyze the performance of user and feedback from the point of view of user in the experiment.

As shown in Figure 47, criteria of efficiency of task are evaluated by objective measurement. Criteria of usability of CHI and performance of collaboration can be evaluated by both subjective measurement and qualitative user analysis.

III.2.3.2 Statistics analysis

An average and deviation of the data from different conditions are compared. Then an analysis of differences among experimental conditions is in need. In our experiments, since we let each group of participants conduct experiments in different conditions, the samples attending different conditions are related and dependent. When choosing analysis method, these dependent samples need paired analysis methods, or repeated sample analysis.

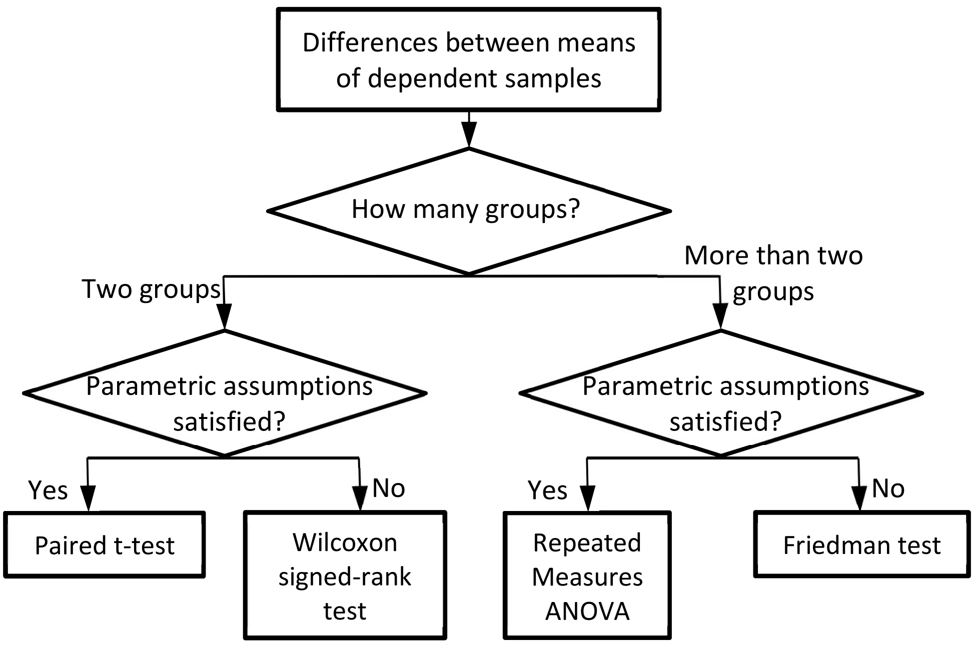


Figure 48 Statistics analysis of the differences between means of dependent samples

As shown in Figure 48, different statistics analysis methods are adopted to compare means of dependent samples (Freedman, 2009). Parametric assumptions must be checked before testing the data, including the assumption of normality (e.g. Kolmogorov-Smirnov test) and the assumption of homogeneity of variance (Levene's test). If data respect both normality and homogeneity, the parametric methods of Paired t-test and Repeated Measures ANOVA can be used. If data respect normality but not homogeneity, having unequal group sizes and/or variances, there are methods, such as Brown Forsythe test and Welch test. If data do not respect normality, non-parametric methods, such as Wilcoxon signed-rank test and Friedman test should be adopted. When there is significant difference among more than two groups, a Post-hoc test is used for the comparison between any two of the three conditions (Parametric: LSD, Scheffe, etc. Non- parametric: Games-Howell).

III.2.4Discussion on the contributions of evaluation

The discussion of the evaluation results will focus on: the technology, the usability, and the human factor of collaboration. From an objective measurement, the system can be basically evaluated the efficiency of the task to emphasize the benefits of the multi-user CHI technology.

The usability of the system and users' comments about are considered as important user feedbacks. The future improvements for the system in terms of human factors rely on these feedbacks such as drawbacks of current devices and possible feature requests.

The discussion of the performance of collaboration will give us a guidance to manage collaboration styles with multiple users. The evaluation results may influence the improvement on collaborative engineering method in future.

III.3 Synthesis of the scientific approach

Our scientific issue concerns the study of the influence of multi-user interface on the users who have different representations of collaborative work. The investigation into this study may be beneficial to the definition of new criteria and design rules for multi-user CHI. Also, the discussion of the influence may allow us to better understand the user's experience in the multi-user CHI from a point of view of collaboration.

This thesis introduces a process of designing a multi-user system with multi-disciplinary collaboration, and a method of evaluating the CHI system during a multi-disciplinary collaborative work.

In our research work, methods of designing a multi-user CHI can be chosen from different mechanisms mentioned in II.4. The development of the multi-disciplinary collaborative task depends on the users' needs both in academic simulation and industrial cases. The evaluation method consists of objective measurement, subjective measurement, and qualitative user analysis. The details of chosen method are discussed in Chapter V in the beginning of each experiment.

Chapter IV Technological background

IV.1 Introduction

A platform for co-located multi-user collaboration was developed. This platform consists of multi-user CHI system and collaborative scenario. The architecture of the developed collaborative platform is inherited from the scheme of scientific approach in Figure 49 below.

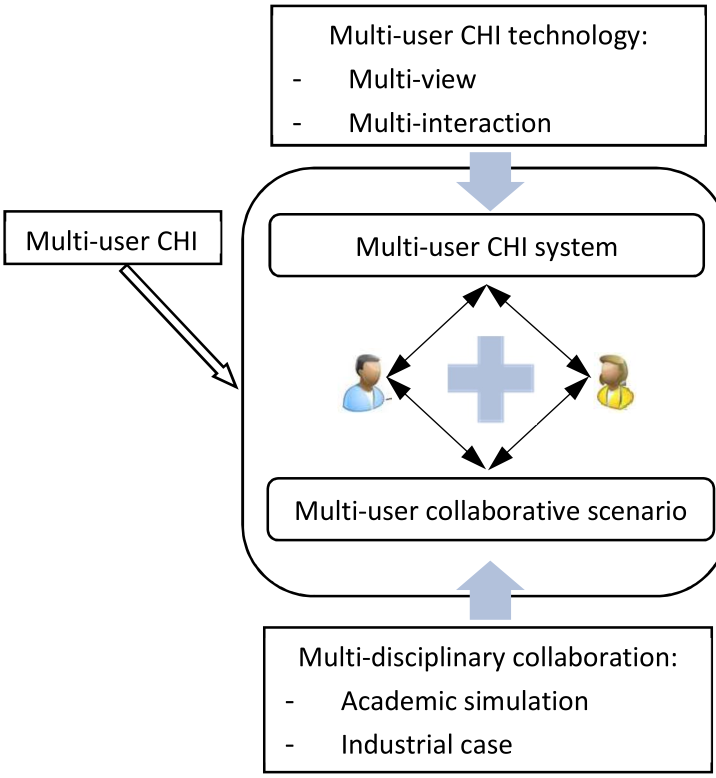


Figure 49 : Multi-user CHI platform consists multi-user CHI system and collaborative.

In this chapter, we will introduce the technologies that we have developed for the experiments. From a technical perspective, the platform is designed with hardware and software. The hardware includes:

- Output hardware: the different multi-view display devices that we used for multiple views. According to the different mechanisms, several kinds of display are shown below in details.
- Input hardware: the devices that are used to detect the position and movements of the users and the commands given by the users.

For the software:

- Exchanging network: both hardware peripheral network and user-to-user network.
- Applications: the collaborative applications that we developed.

IV.2 Hardware development

IV.2.1 Output hardware: Multi-view display

The main output hardware of a multi-user system is a screen that can emit several images differentiated according to users' preferences. As we have discussed in section II.4.4, there are many mechanisms for creating multi-view system, including filter-based, time-based, and space-based. We have developed four multi-view systems taking advantage of the devices available in Institute Image.

IV.2.1.1 Multi-view via lenticular system

As mentioned in II.5.3, Holografika is a space-based double-view lenticular system. From different angles in front of the screen, people can see different contents. We tried to develop this device and three images can be seen from three positions, shown as Figure 50. The limitation of Holografika are: 1. Holografika is composed of 36 projectors. Each of them emit one image of the object displayed from a certain POV. The images are stable, hard to be calculated to change and updated in real-time. 2. The field of view in front of the screen is not large. When the number of users increases, each image can only be seen from a very limited angle. E.g. in three users' situation, the angle of one user is limited within 5 degrees.

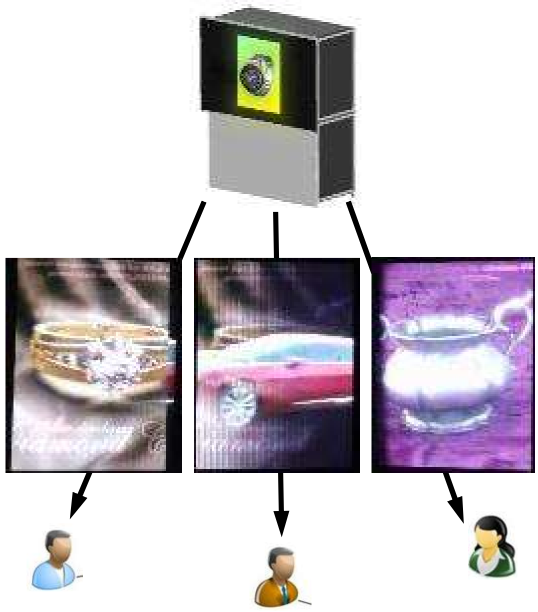


Figure 50 : 3 images can be seen from different positions before a screen.

IV.2.1.2 Multi-view via anaglyph filter

Anaglyph is a filter-based technique using different colors, mainly red and cyan, to provide user two different images. The eye viewing through the red filter can't see red object. The eye viewing through the cyan filter perceives the opposite effect.

Figure 51 : Color filter-based multi-view glasses.

Instead of two monocular views for two eyes of one user, two users now see two binocular views, respectively. As shown in Figure 51, we have developed two pairs of glasses, one pair with red color and the other with cyan color. Color-adjusted images can be seen through the pair of glasses in different colors and can represent different contents to multiple users.

IV.2.1.3 Multi-view via polarized filter

Polarized filter-based technology is often used in giving the user a stereoscopic visualization through polarized light. When equipped to one eye with a certain filter, each filter let pass through only the light which is similarly polarized and blocks the light polarized in the opposite direction. So, user’s eyes can see two different images.

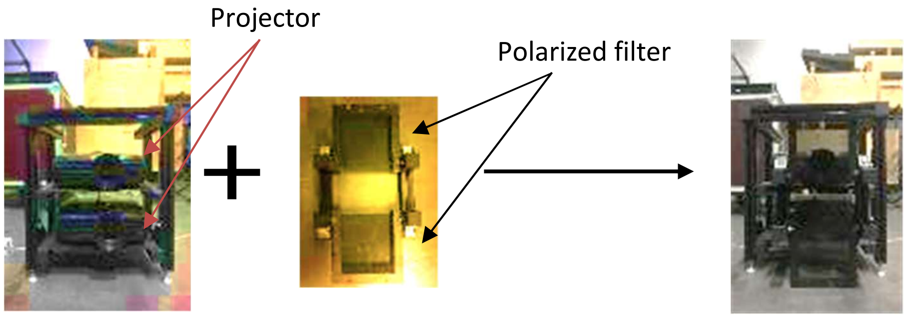


Figure 52 : Using polarized filters and two projectors, a multi-view system is realized.

As shown in Figure 52, each projector is equipped with a polarized filter in front of its lens. These filters are linearly polarized as mentioned in II.4.4II.4.4.2, which means that light can pass through these two filters with orthogonal directions. Before the light enters the user's eye, it will first pass a pair of linear polarized glasses associated with the orthogonal direction of the filter. Thus, this multi-view system can give two views to two users wearing orthogonal linear polarized glasses.

IV.2.1.4 Multi-view via shutter glass & polarized filter

To provide a dedicated stereoscopic view to two users, a system filtering based on the light shape and on the time phase. is proposed. The system utilizes High Brightness digital video projectors. Each projector is controlled by a computer and can provide an individual stereoscopic view because of its refresh rate of 120Hz. Each user wears a pair of shutter glasses with LCD eye lens. The emitter of the RF signal is connected to each projector and received by the shutter glasses. The opening of the LCD screen of the two glasses on the shutter will be synchronized with the signal sent to achieve the time-based multi-view of each eye. Meanwhile, to serve multiple users, the light emitted by the two projectors is projected on a same silver screen, but be separated by polarized filter for getting certain polarized light. With the matched polarized filters on shutter glasses, thus, users will only see the image issued by the projector that corresponds to the filters, in Figure 53.

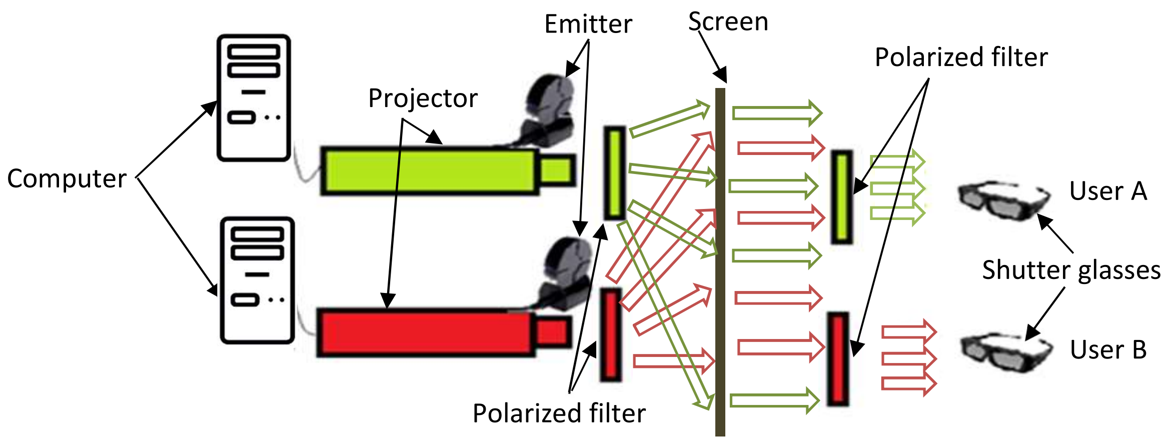


Figure 53 : Mechanism of a combination of a two-user 3D multi-view system.

The implementation of this multi-view system is shown in Figure 54, two projectors of DIGITAL PROJECTION TITAN 1080p 3D are used (Figure 54.a). Each projector has a frequency of 120Hz and a WUXGA (FHD) resolution. Each projector has been connected to a Volfoni ActivHub RF50 emitter. This emitter can give a synchronized signal to its corresponding shutter glasses Volfoni EDGE VR, which allows user to receive two different images in time scale. When two glasses are searching signals, the signals from emitters should be set to two signal channels so that signals do not interfere with each other. Volfoni provides a support software to initialize the channel of both emitters and shutter glasses.

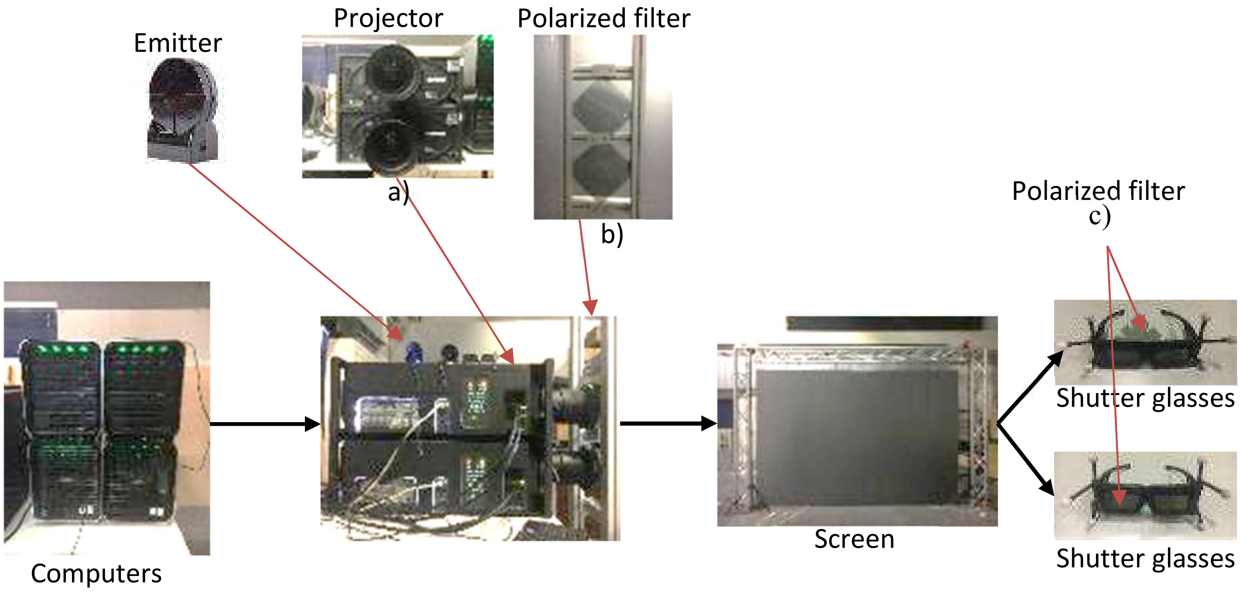


Figure 54 : Implementation of a combination of a two-user 3D multi-view system.

Two polarized filters (Figure 54.b) with orthogonal directions are positioned in front of the exit of the lenses of projectors. Filters (Figure 54.c) with same direction are also positioned in front of users' glasses so that two users can get light with orthogonal directions.

IV.2.2 Input hardware

IV.2.2.1 Keyboard & Mouse

To input orders, keys on keyboard can be defined as actions like manipulation and navigation. Users can be quickly familiarized with keyboard input because today most people use keyboard.

Mouse buttons can be defined as actions like selection and navigation. Combined with tracking system, a mouse can be upgraded to a "joystick" which allows users to select an object in 3D virtual environment and realize transformation (position, rotation, and scale) in space.

- multi-interaction metaphors

According to the control manners, the pressing and holding of the keys and mouse buttons have different significances. They can be pressed as a switch for inputting binary values (on/off), also they can be held down for continuous values. The control metaphors of keys and mouse buttons can be adjusted to user's need.

In addition, the mouse wheel metaphor can act as different actions for different users. For example, when two users are working collaboratively in a multi-disciplinary scenario, one can change the scale of an object with the control of mouse wheel, while another user can change the distance of two objects with the same technique. They achieve multiple interactions using one of interaction: rolling the mouse wheel.

IV.2.2.2 Tracking system

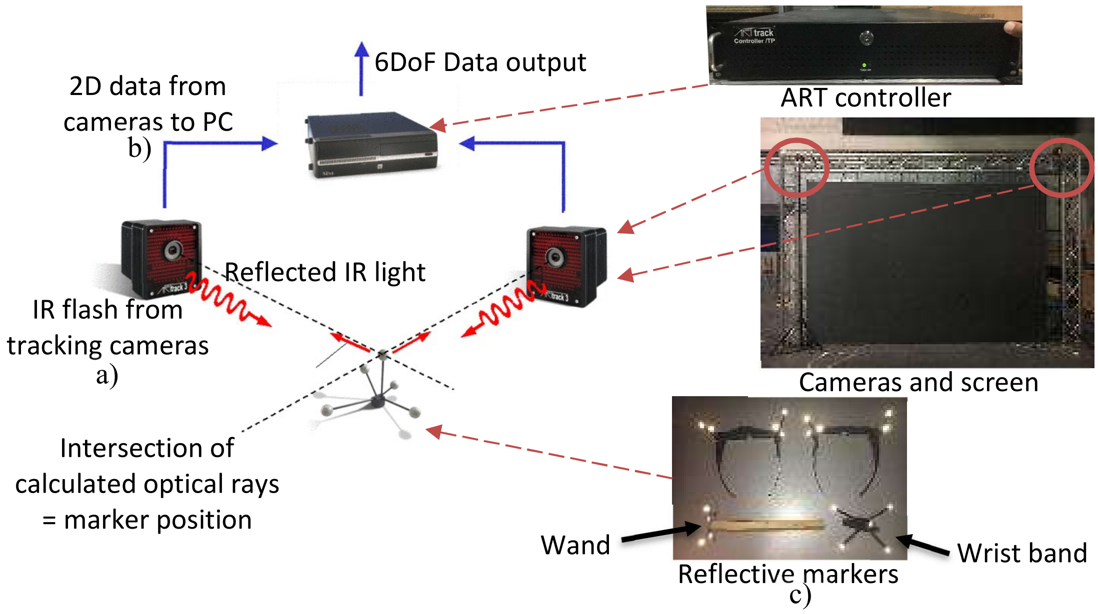


Figure 55 : Technical schematic of tracking system and tracking hardware used.

In 3D virtual environment, computer graphic card calculates images from user's point of view (POV). When user's position is changing in space, their POV changes as well, so the images must be re-calculated (II.4.4II.4.4.3). The change of user's position needs to be updated in real time so that a synchronized visualization can be given to the user. In our proposal of 3D multi-view solution, a tracking system with ART DTrack2 has been used.

As shown in Figure 55, the scheme of tracking system consists of the tracking of markers and the geometric transformations of Six degrees of freedom (6DoF). A reflecting ball is a marker that can be captured by a IR camera (Figure 55.a). Two cameras emitting infrared (IR) light are arranged in a crisscross pattern. The intersection of their reflected optical rays from markers will be calculated by the ART controller (Figure 55.b). The output of the controller, 6DoF data of a marker, can be integrated into other software and is updated in high frequency.

Two cameras have a limitation in the number of the markers captured at the same time. Four markers in our system can be tracked for two users, in which two markers should be used for tracking two pairs of glasses to track the that give the position of user heads. The other two other markers are tracked developed to help locate user hand interaction.

To realize a function of selecting 3D object, two metaphors of using these two markers have been developed. As shown in Figure 55.c, besides markers on two pairs of glasses, there are two markers for hands.

- The wand with a marker on it allows user to point somewhere in the virtual 3D environment. A visible ray casting to help selecting visualize the direction of pointing and an object intersecting with the ray is selected. This selection metaphor is designed for the user who cannot move physically in the working space.
- The wrist band with a marker on it can be put on user's wrist. When selecting an object, user needs to reach the object in 3D environment. This selection metaphor is designed for the user who needs reaching the object and moving his/her body or hand during the experiment.

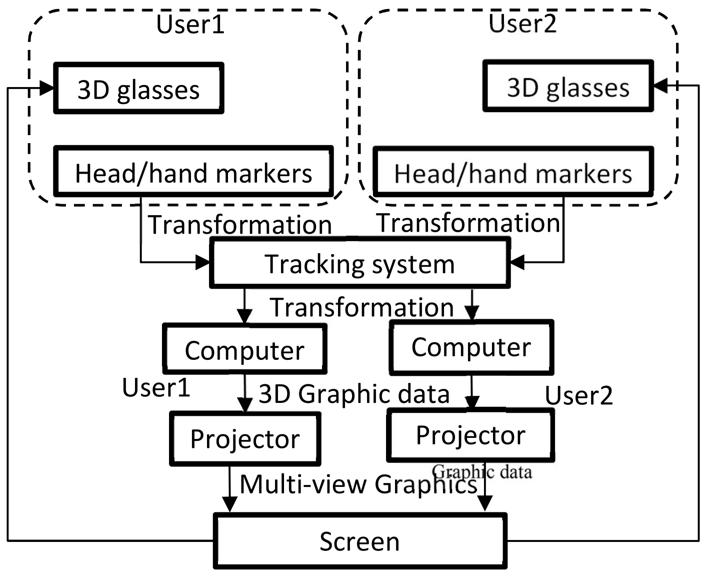


Figure 56 : Tracking system for two users

The general architecture of multi-user tracking system is shown in Figure 56. This two-camera tracking system can theoretically capture four markers at the same time. Each user's movements are represented by head marker (on the glasses) and hand marker (on one hand). The markers' movements are captured by the tracking system and sent to the computer. According to new coordinates, the two computers process the data and generate new 3D images.

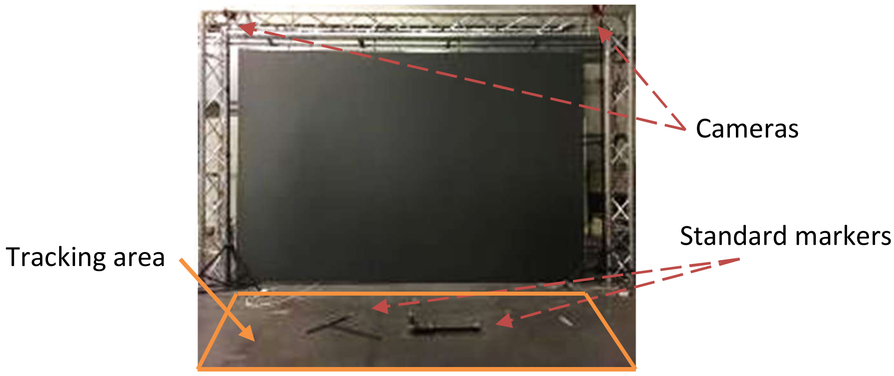


Figure 57 : Calibration of tracking system.

Before adopting the data output from tracking system, we should make sure that the 6DoF data obtained is accurate according to the space coordinates. A calibration process should be done using standard markers. After that, markers can be captured precisely in a limited spatial area, as shown in Figure 57.

IV.3 Software development

IV.3.1 Exchanging network

We adopt Virtual-Reality Peripheral Network (VRPN) and Institut Image VR (IIVR) to realize the network of data exchanging. In Figure 58, VRPN is a set of servers that are designed to implement a network-transparent interface between application programs and the set of physical devices (tracker, joystick, data gloves, etc.) used in a virtual-reality system. VRPN provides connections between the VR peripherals and the application (Taylor et al., 2001). When client of VRPN gets data from network, IIVR transmits the data into an 3D application, e.g. game engine Unity3D.

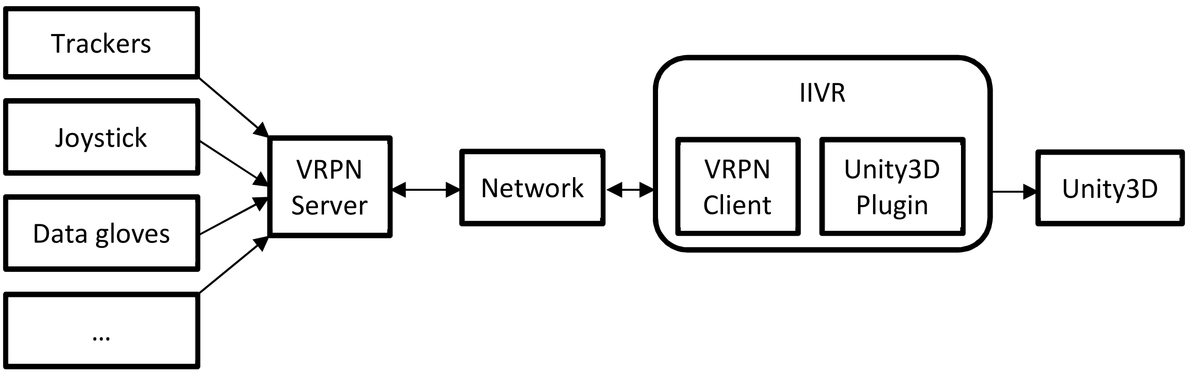


Figure 58 : Scheme of exchanging network

Multiple users need multiple applications. To communicate among several multidisciplinary applications, there is also network exchanging among Unity3D applications. A Unity3D function "Network Manager" lets applications communicate through network. Several variable types can be easily transmitted.

IV.3.2 Applications

IV.3.2.1 Identification of the needs for applications

In total 4 applications are developed: two academic applications and two industrial applications. The two academic applications are designed (IV.3.2.1 and IV.3.2.2) to simulate scenarios of a multi-disciplinary collaborative work with multi-representation of DMU.

To investigate the influence of multi-user interface among users with different representations of a DMU during a collaborative work, the needs of developing applications are analyzed and listed in Table 3. In the applications mentioned before in the state of the art, multiple users work with:

- Several mono CHIs
- Multi-user CHI with one representation
- Loose collaboration coupling through multi-user CHI with multi-representations

The scenarios in our application are all mixed coupling collaboration through multi-user CHI with representations of DMU. COLLAB_PACMAN and COLLAB_MAZE_3D are simulations of industrial case because we need applications which are easier to conduct quantitative evaluation.

Table 3: Identification of the needs for applications

Name	Identify needs	Applications
COLLAB_PACMAN simulation game	A control experiment to investigate the impact a multi-user CHI has on collaboration	2D multidisciplinary collaborative task
COLLAB_MAZE_3D simulation game	A control experiment in 3D immersive VR environment to compare: a. several mono CHIs and b. unique multi-user CHI	3D immersive multidisciplinary collaborative task
Collaborative product design: CASE_OF_MUG	Influence on an industrial case study in early product design through collaborative VR tools	3D immersive multidisciplinary collaborative scenario for mug design
Collaborative ergonomic evaluation: CASE_OF_CAR	Influence on an industrial case study in car ergonomic validation through collaborative VR tools	3D immersive multidisciplinary collaborative scenario for car validation

To evaluate the collaboration scenario, a quantitative measurement statistics analysis is necessary. The simulated collaboration can be repeated and certain evaluation criteria could be quantified. Regarding to the characteristics of the multi-representations of DMU, two users receive two representations of one game map. They can accomplish the task in this game only by communicating respective constraints with each other. In Figure 59.a, a multi-disciplinary collaboration has its characteristics. First, this collaboration has a goal to complete and the work of multiple users can be evaluated by the completion status of the goal. Second, this collaboration must be co-located and must be conducted in real time working condition. Third, each collaborator sees a special design constraints or rules from his expertise domain. When we design the game to simulate this collaborative work, we must consider these three points.

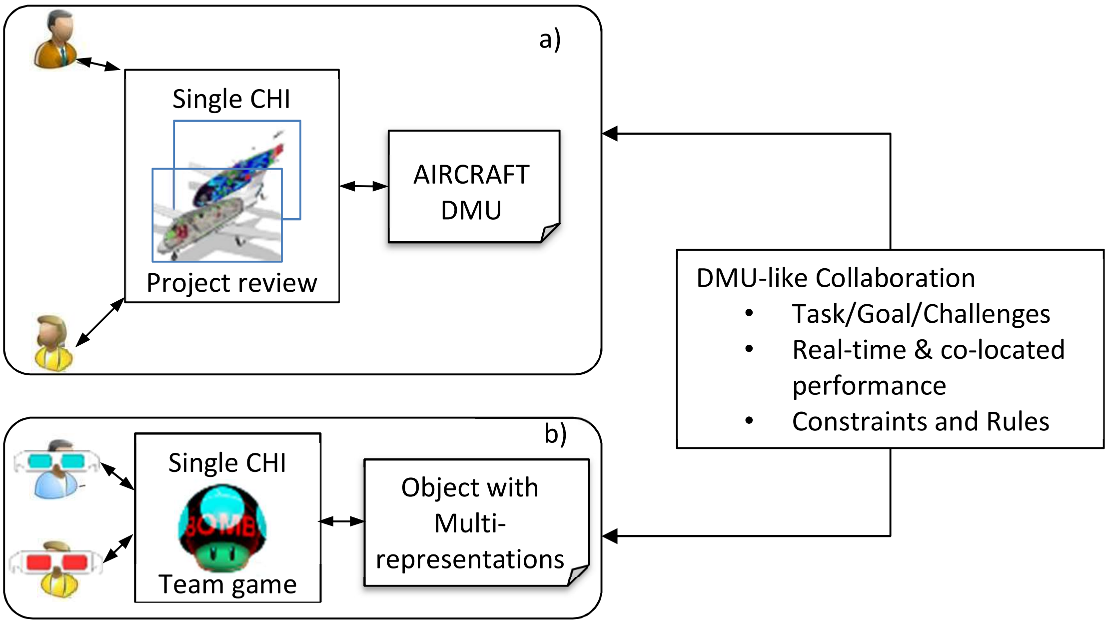


Figure 59 : A complementary team game simulates an industrial case.

The designed game (fig.52.b) will have following specifications. The 1st user is going to finish a certain task and he/she can modify what he/she sees. However, the 2nd user has a constraint to respect and he/she will tell 1st user where the constraints are. Both player have different jobs to do. The one will maximize the task achievement score and the other one will minimize the broken constraints.

In DMU scenario, 1st user is going to modify airplane interior, but this action reaches the limit of the constraint identified by the 2nd user, who is an expert in domain of structural analysis. This structure expert must help the 1st user to avoid the danger of structure crash.

Similarly, in the simulated game, 1st user acted as a player, as expert in domain of searching objects. 2nd user acted as a helper, who is expert of providing constraints. The helper will tell the player where the constraints are.

IV.3.2.2 COLLAB_PACMAN simulation game

To design a control experiment to compare: a. several mono CHIs and b. unique multi-user CHI, a 2D multidisciplinary collaborative task is proposed (in Figure 60). The simulation game is a.

The task of this simulation game is:

COLLAB_PACMAN: as shown in Figure 60, on the game map there are mushrooms and bombs. The purpose of this simulation is to let the Pacman hit as much as possible the mushrooms and avoid as much as possible the bombs. The 1st user, ‘player’ with blue glasses, needs to eat all the mushrooms.

But some mushrooms in his/her eyes are mixed bombs. The 2nd user, 'helper' with red glasses, needs to help player to avoid the bombs and the mixed bombs.

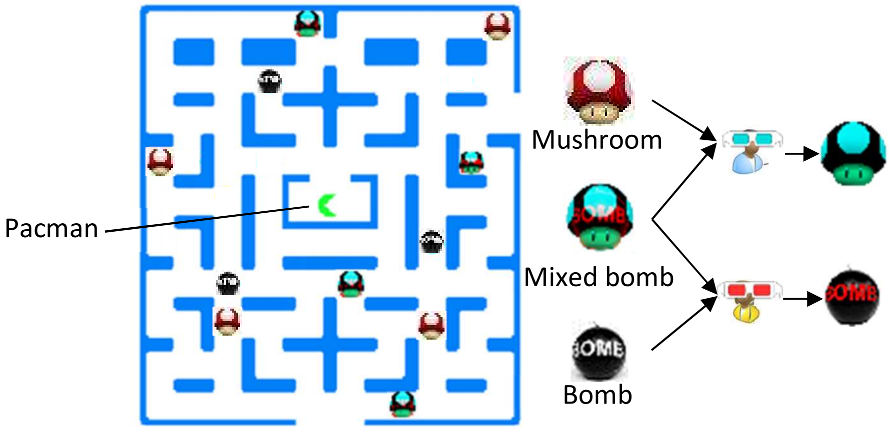


Figure 60 : Simulating game map and elements: 1st user, with blue glasses, can see only the mushrooms, and 2nd user, with red glasses, can see only the bombs.

The 'player' needs to control the Pacman with keyboard and keep asking his partner whether there is a bomb. The 'helper' needs to focus on the position of Pacman and answer the question asked by "player" and gives "player" tips to avoid bombs because with red glass on he can see only bombs. They could hardly move unless they communicate a lot. If bombs are hit, as a punishment the Pacman will be frozen for several seconds.

IV.3.2.3 COLLAB_MAZE_3D simulation game

In further design of industrial cases of collaborative product design optimization: car seat ergonomic evaluation and mug design are developed with 3D immersive system. So, a 3D immersive simulation game is also developed to evaluation collaboration. We proposed a 3D collaborative game for two participants with two different roles: "player" and "helper". They must work together for going through a maze.

The player's objective is to move in the maze and to find the exit. The player can see and collect golden coins (Figure 61.a and .b). At meanwhile the player should avoid the bombs that are not visible for him/her. The helper supervises and directs the player to avoid the bomb while finding the exit of the maze. At an intersection of the maze, the helper can tell to the player the correct way to take due to its highlighted appearance (Figure 61.c and .d).

In addition, the helper can also see the bombs that are not visible for the player and guide the player to pass by it without touch it. In summary, the helper should tell the player which way to take and where is the bomb, shown in Figure 61.

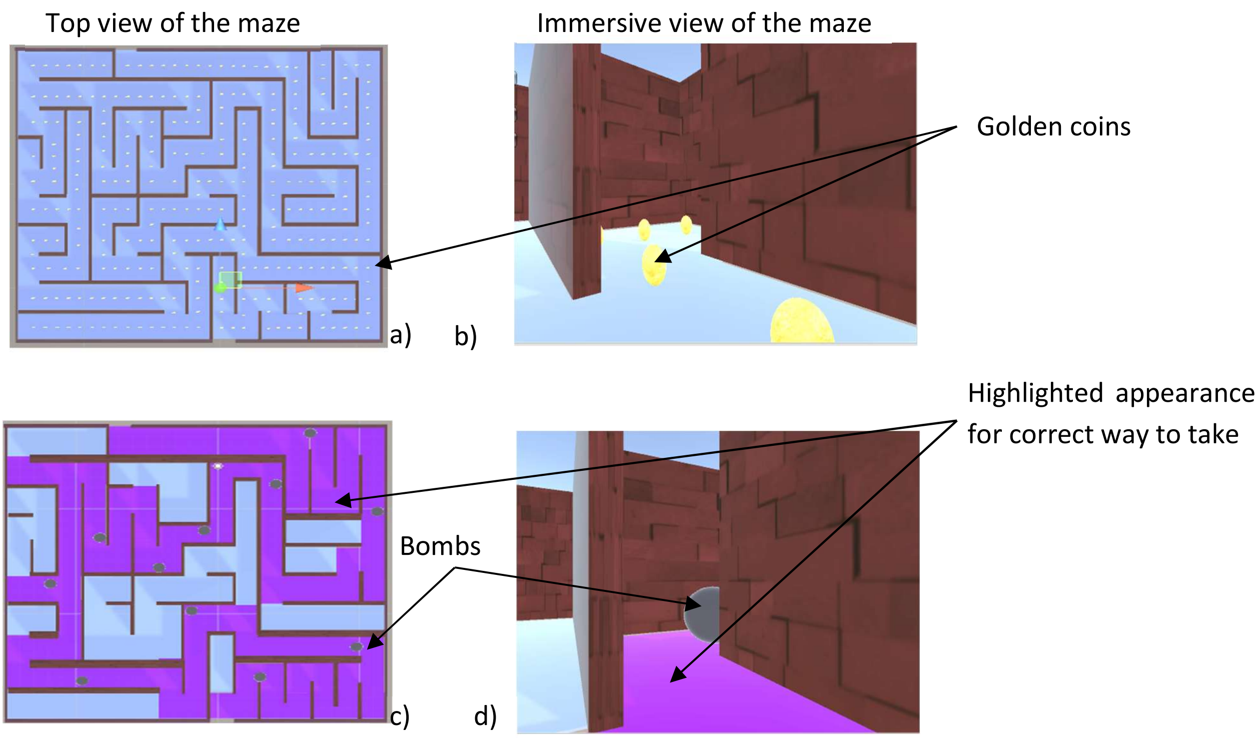


Figure 61 : The player's top view of maze is shown in (a). The player's perspective is shown in (b); the helper's top view of maze is shown in (c). The helper's perspective is shown in (d).

IV.3.2.4 Collaborative product design: CASE_OF_MUG

An application of early collaborative design is conducted between two collaborators. One of them is a specific user of the mug who has a typical character setting, such as age, profession. The other collaborator is a designer of the mug who can handle the various functional and design parameters. The developed multi-user system supporting the DMU's multi-representation allows two users to collaborate in real time.

The idea is to join two collaborators in one scene to optimize the design solution and experiment the usage of a mug.

The user of the mug experiments its usage under a specific context (inside a car) in virtual environment (Figure 62.a)

- manipulate the mug,
- put the mug into the car mug holder,
- put the tea-bag into the mug,
- take the document without overthrowing the mug.

Meanwhile the designer of the mug is more interested in design parameters and analysis data (Figure 62.b), e.g. size, thermal analysis etc. If the size of the mug is changed, both user and designer of the mug will see. Both have other individual elements that only each one himself can understand. The user has the accessories accompanying the use of the mug. The designer has the tool panel of design that only he/she can see. If user put a teabag in the mug, he/she can design a handle for the mug to tie the teabag. User can ask designer to show the transparent mug to verify the teabag (Figure 62.c). A real time displaying of the size of the mug is shown in (Figure 62.d). Designer can use a virtual wand in the scenario to select and control objects. The reflections of objects on the windshield can be so disturbing for users that he/she can ask the designer to follow his/her advices (Figure 62.a).

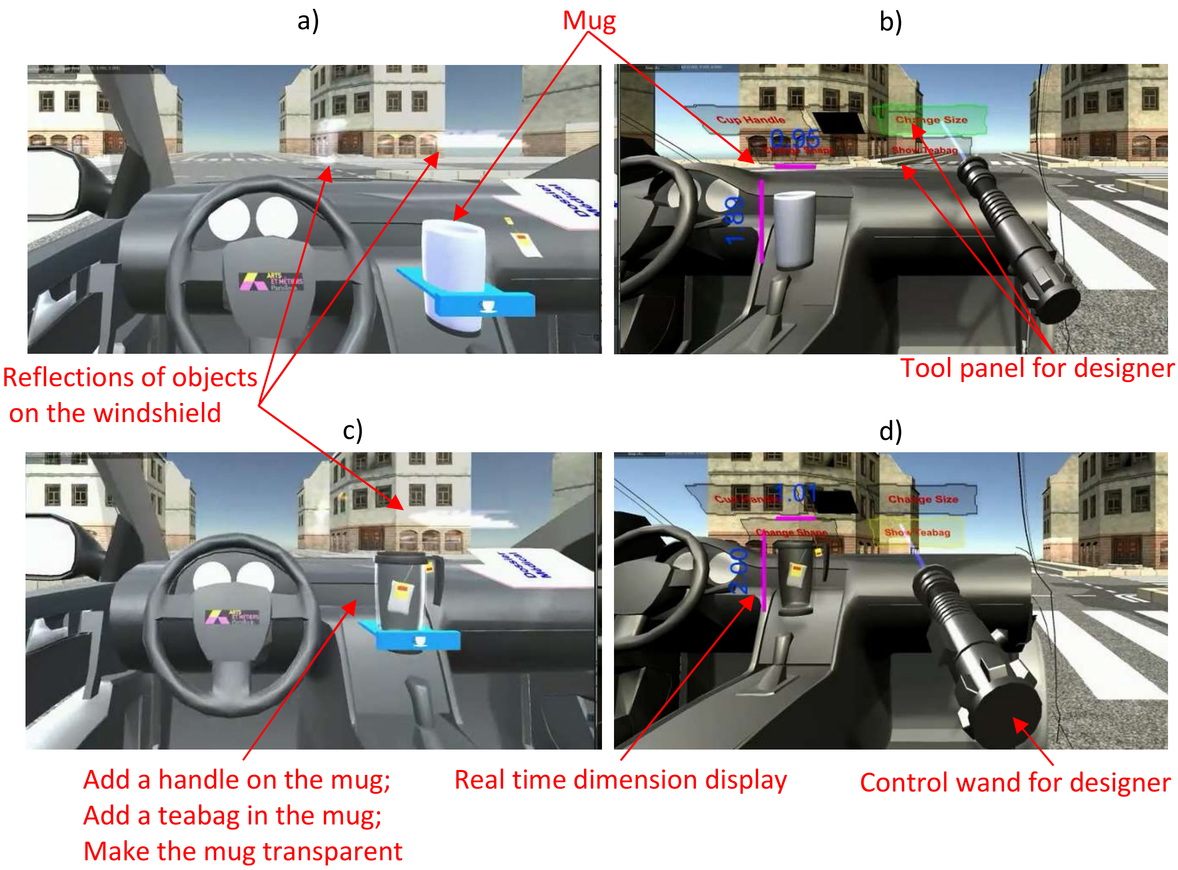


Figure 62 : a) and c): user's view of a cup in the car; b) and d): designer view of a cup in the car

This application involves two representations of a DMU of mug. As displayed with 3D VR system, each representation has two POVs to form stereoscopy, 4 views are in need for this multi-view system.

Table 4 : Definition of the functions of multiple Personas in the scenarios.

USER's actions:	**DESIGNER's actions:**
Reachable objects - Highlight objects which can be moved (mug, teabag, folder, cup holder) - Highlight effects (coffee, cup holder) Personas motion simulation - Move and rotate the mug - Pour water to coffee mug - Grab teabag and drop into mug - Grab folder and open it	Synchronous observation - Analysis result - Thermal analysis - Performance analysis (Teabag) Exterior design - Geometry dimension - Color - Part/assembly design (mug lid, handle) - Shape design (change mug form)

To realize an early collaborative design application, each collaborator has an experimental scene with special functions. As we described, one of the collaborators is a USER, the other is a DESIGNER. Their corresponding actions in this multi-view system are summarized on Table 4.

IV.3.2.5 Collaborative ergonomic evaluation: CASE_OF_CAR

In automobile industry, the analysis of driver's field of view (FOV), which involves designers and ergonomists, is often realized with a virtual mock up in CAVE [4]. Two steps are often followed: 1. Verbalization: The ergonomist questions the designer: what blocks the lower visual field? The designer responds: the dashboard. 2. Geometry analysis: The ergonomist notes the positions of the eyes when the designer answers verbal questions. A post-processing geometric calculation will then be launched to verify if the dashboard limits the lower visual field.

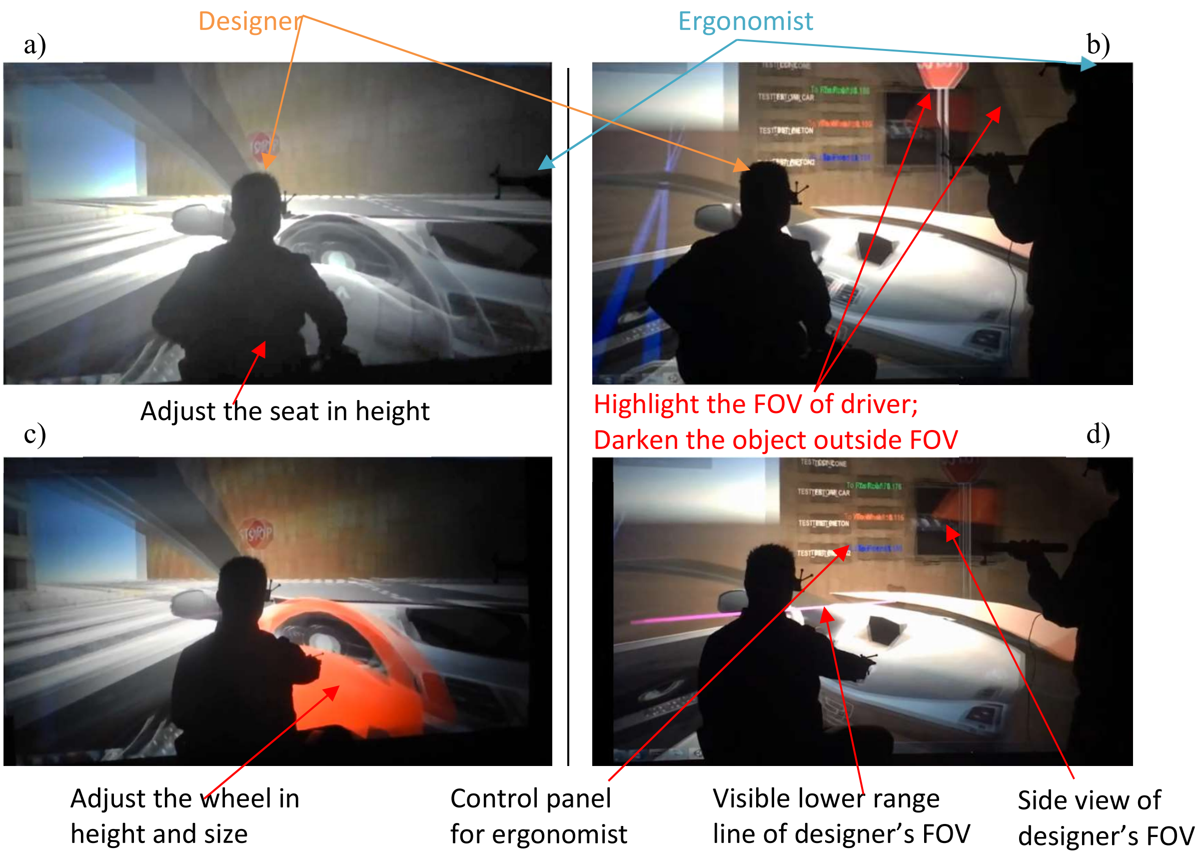


Figure 63 : Designer view (a): A-pillar blocks a part of red street sign; Ergonomist view (b): A shadow covers the part of red street sign which can't be seen by designer; Designer view (c): Designer adjusts the wheel; Ergonomist view (d): Visible lower range line can show the intersection between designer's FOV and the car.

We propose a scenario that combines Verbalization & Geometry analysis for a co-located synchronous ergonomic evaluation using multi-view system, as shown in Figure 63. Driver can adjust the seat's height and wheel's height and size (Figure 63.a and c). in real time, the FOV of the driver is shown in the perspective of ergonomist. FOV is highlighted. The objects outside FOV are covered with a shadow (Figure 63.b). A side view of driver's FOV is also displayed on a virtual 2D panel (Figure 63.d).

The ergonomist can realize at once that the object blocking the lower visual field is the car hood. So immediately the ergonomist can rephrase his question and ask the driver to explain more precisely why that part blocks him. This may help the driver to increase the reliability of answers from the driver and decrease the waste of time and data. Both functionalities for driver and ergonomist are listed in Table 5 below:

Table 5 : Definition of the functions of multiple users in ergonomics.

Driver's functions:	**Ergonomist's functions:**

Interaction for driving:
- moving the car
- Sitting position adjustment
- Steering wheel adjustment
- Confirmation of the object that blocks the lower visual field
	Interaction for ergo evaluation:
	- Geometry dimension
	- Environment adjustment
	  • number of walkers,
	  • position of the car in front
	- Analysis result
	Interaction for checking:
	- Driver's position in the car
	- Driver's field of view
	- Visible/invisible part of the environment for the driver
	- Driver's confirmation about the Lower visual field "limitation"

IV.4 Synthesis of technological background

In this chapter, we have introduced the technologies that we developed for the thesis, including the hardware and software. As shown in Figure 64, to create a multi-user CHI for multiple users, we focus on two main aspects, multi-user CHI system and multi-user collaborative scenarios. For the visual outputs of a multi-user system, we developed multi-view with the space-based system in IV.2.1.1, multi-view with anaglyph filter in IV.2.1.2, multi-view with polarized filter in IV.2.1.3, and multi-view with shutter glasses & polarized filter in IV.2.1.4. We developed a different device as the input of a multi-user system, including keyboard, mouse, and tracking system. Multi-interaction metaphors for different users have been defined with mouse and tracking system. The connection between hardware and software, as well as the connection among applications have been developed by using VRPN, IIVR, and Network Management of Unity3D. Four collaborative applications for multiple users have been created. COLLAB_PACMAN adopts the multi-view anaglyph filter technology and it is a 2D simulation game. The other three applications can be executed with immersive system. Two industrial cases have been created according to the industry needs of multi-disciplinary collaboration.

Under the scheme of building a multi-user CHI system for multiple users, many technologies and various scenarios can be adopted with technology and scenario to choose depends on user needs. With the development of technologies of multi-view system and the wide application of multi-disciplinary scenarios, multi-user collaborative CHI will have a diverse combination from multi-view system and collaborative scenarios.

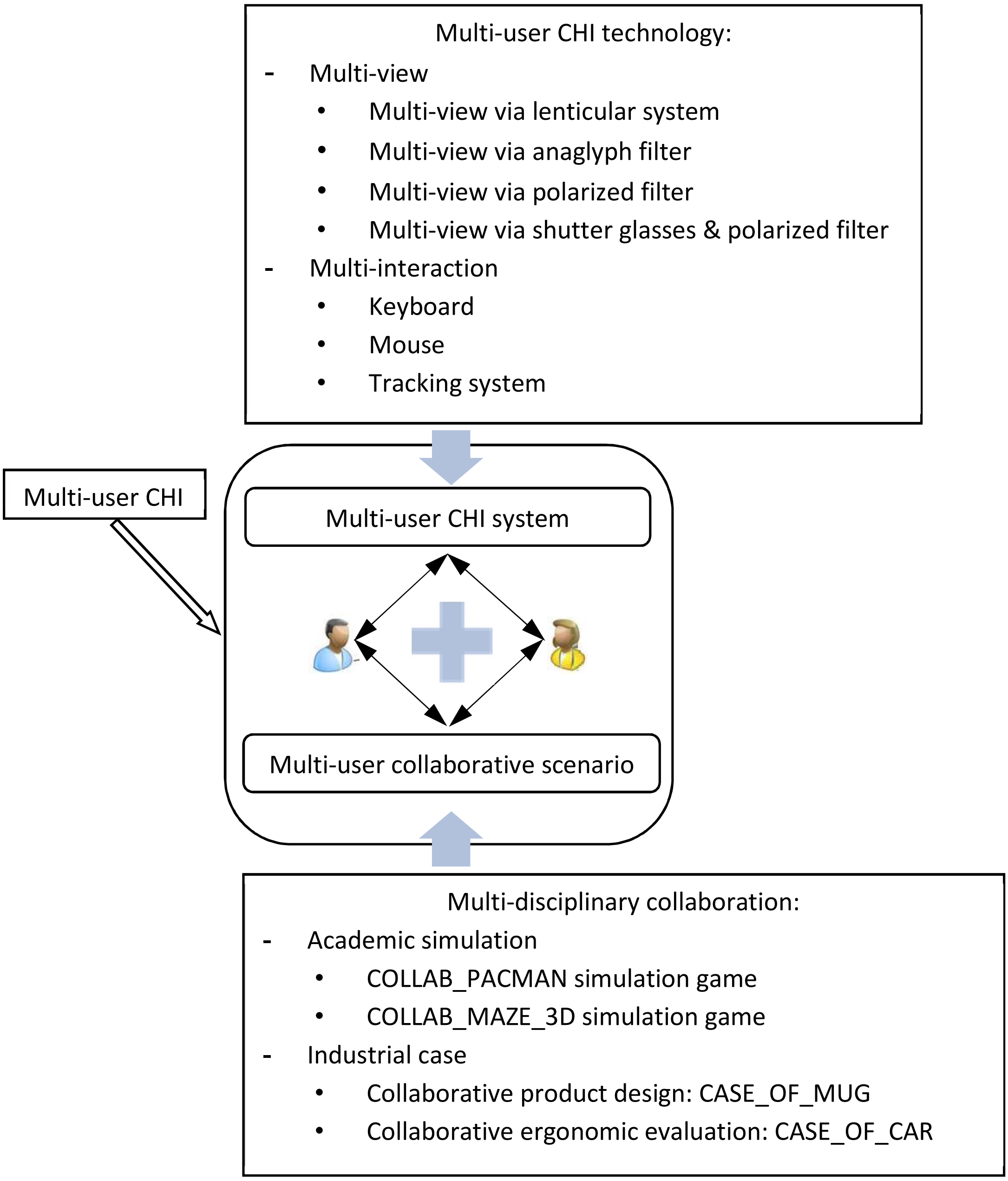


Figure 64 : Multi-user CHI platform has various combinations of multi-user CHI systems and collaborative scenarios.

Chapter V Experiments

In Chapter III, the solutions of collaboration using multi-representation of DMU through a multi-user CHI were proposed. The evaluation method and measurements during the collaborative tasks were discussed. In this chapter, experiments are designed to evaluate the proposed method of multi-user CHI and to answer the research question.

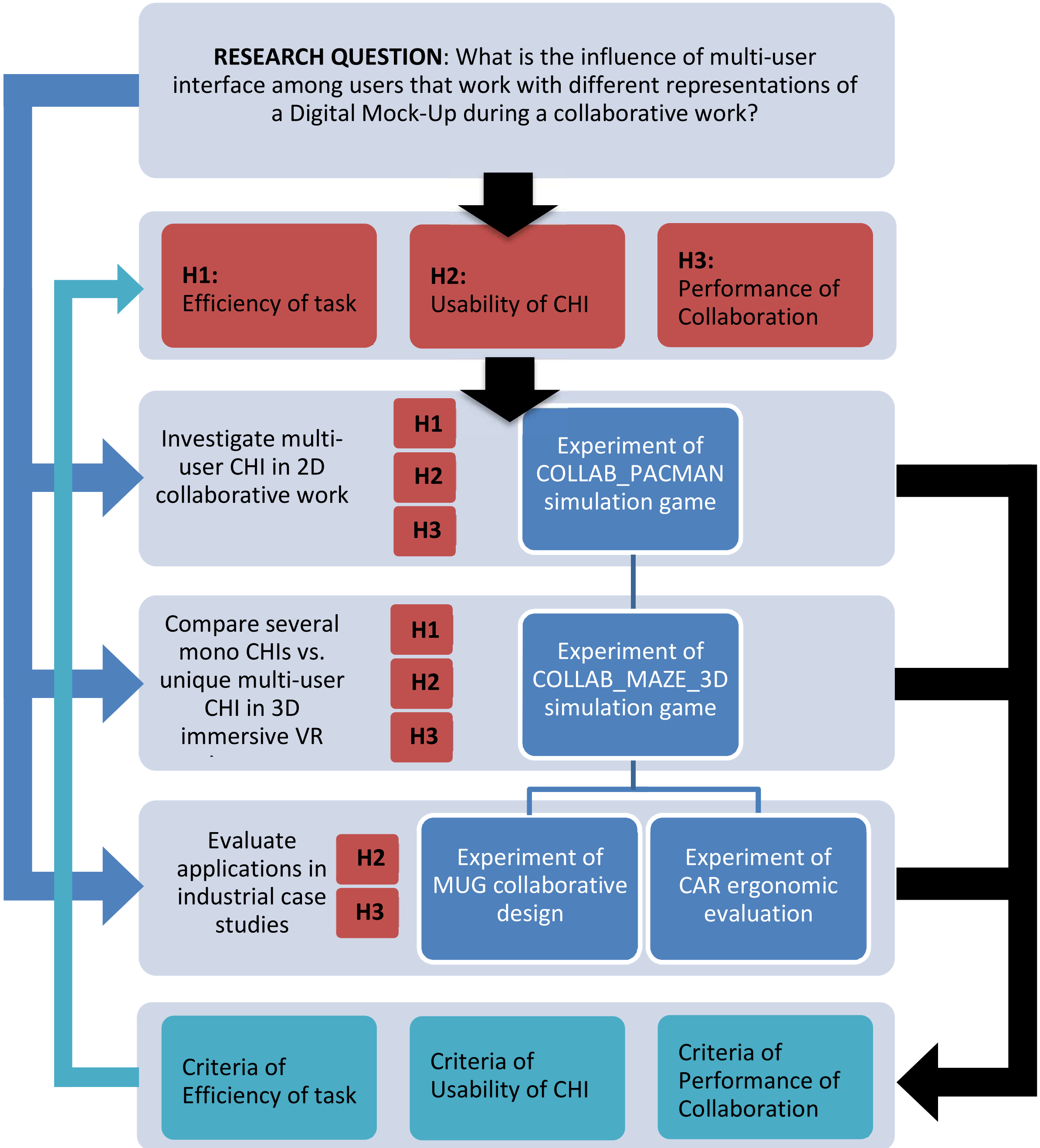


Figure 65 Experimental plan to validate the method.

As we discussed in III.2.3, we proposed hypotheses to the research question: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on **H1**: Efficiency of task, **H2**: Usability of CHI system, **H3**: Performance of collaboration.

During the experiments, as shown in Figure 65, our research question is firstly investigated in an experiment of COLLAB_PACMAN simulation game, using the application developed in IV.3.2.2 which simulates the multi-representation of DMU and its multidisciplinary task. An exploration of differences among multiple mono CHIs, multi-user CHI with split views, and multi-users CHI with merged views is conducted. The criteria of **H1**, **H2**, and **H3** are evaluated during this experiment.

Then a 3D collaborative multi-user CHI system and a multidisciplinary task simulating multi-representation of DMU with quantitative measurements are tested in the experiment of COLLAB_MAZE_3D simulation game, using the application developed in IV.3.2.3. This experiment has a comparison between different CHI experimental conditions of multiple users' collaboration in 3D design activities. The criteria of **H1**, **H2**, and **H3** are evaluated with this 3D multi-user CHI system.

As we discussed in IV.3.2.1, industry case of design takes time to evaluate. Since the efficiency of task needs the factor of time to calculate, in this experiment, we do not need to compare the different experimental conditions using the criteria of efficiency. That is also why we simulated the collaborative product design activity as a game. An experiment of design application of collaboration with multi-user CHI is then conducted. This mug design application, developed in IV.3.2.4, has a DMU of a mug and a collaborative multidisciplinary scenario. Another experiment of collaboration with multiple experts for ergonomic evaluation of a car is also proposed, using the application developed in IV.3.2.5. These experiments are to study the usability of CHI and user performance under the specific examples of the implementation of multi-user CHI in industry.

The criteria both on the usability of CHI (**H2**) and performance of collaboration (**H3**) have feedbacks to the hypotheses. To response to our hypotheses, these criteria are analyzed with statistics methods and are discussed after each experiment.

V.1 Experiment of COLLAB_PACMAN simulation game

This experiment is conducted to investigate the criteria of the hypotheses **H1**, **H2**, and **H3**. A 2D multi-user CHI and a collaborative scenario are designed to test these criteria of efficiency, usability of CHI and performance of collaboration.

V.1.1 Description of experiment

To prove our hypothesis (in section III.2.3) that multi-view and multi-interaction CHI supporting system can help multiple users in a collaborative co-located and real time working condition in **H1**: Efficiency of task, **H2**: Usability of CHI system, **H3**: Performance of collaboration, we proposed a collaborative game to simulate an industrial collaborative design case. As shown in Figure 66, multi-view anaglyph filter for visualization and keyboard controlling technologies are applied. COLLAB_PACMAN game, described in IV.3.2.2 is chosen simulation game is used in this experiment. We will evaluate efficiency, usability of CHI system, and performance of collaboration during the experiment.

As we described in IV.3.2.2, COLLAB_PACMAN lets two users collaborate to finish a task on a 2D map with a maze. Two different elements of "Mushroom" and "Bombs" are displayed respectively to two users. One of them must control the Pacman to move and collect “Mushroom”. The other user must remind the first user the position of the “Bombs” that needs to be avoided. They should communicate with complementary information of each other on constraints to proceed the task.

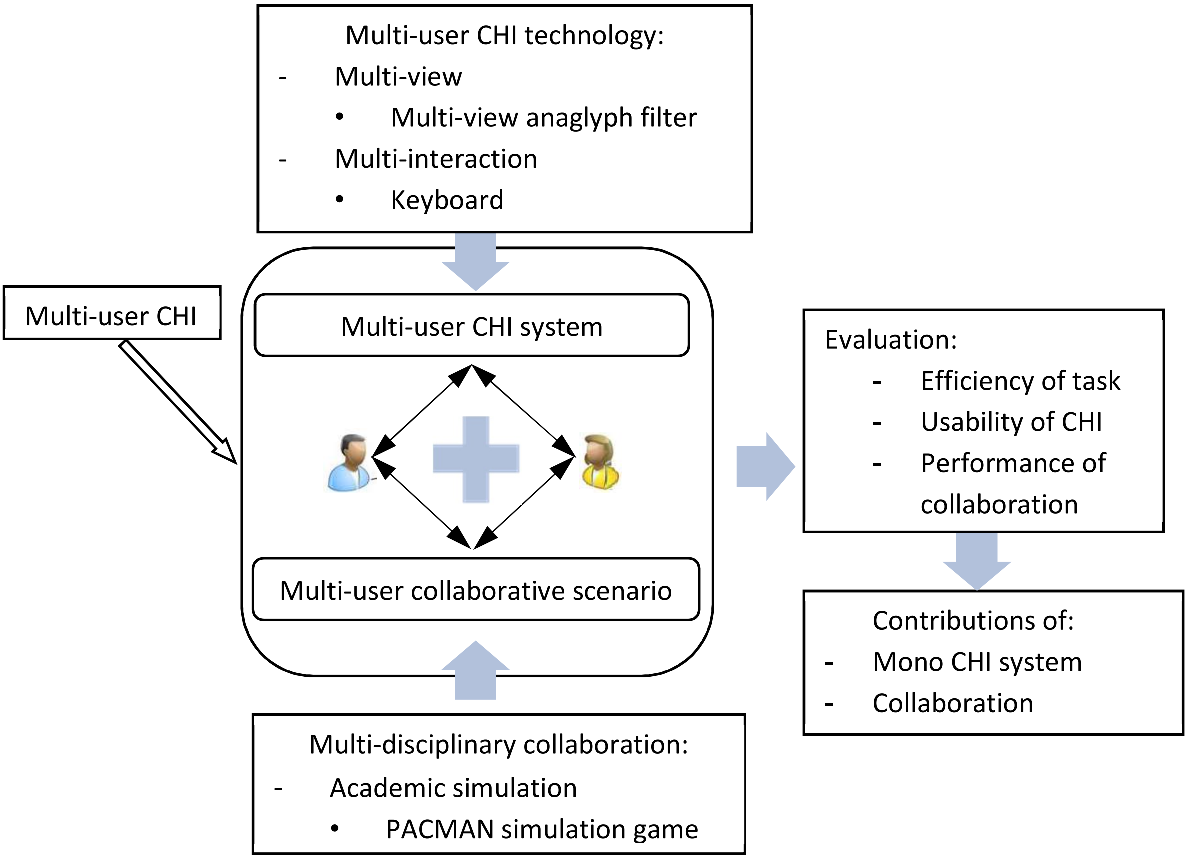


Figure 66 : Experiment scheme of COLLAB_PACMAN simulation game

V.1.2 Experimental conditions

This experiment is conducted by a group of two users under three experimental conditions, as shown in Figure 67.

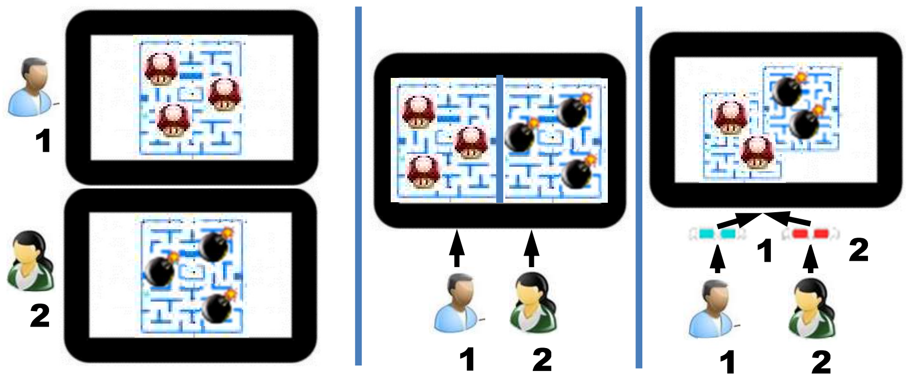


Figure 67 : Three experimental conditions, from left: multiple mono-user CHI systems (2Cs), multi-user CHI with subdivided views (1CSV), multi-user CHI with multi-view (1CMV).

(a) One screen for each user; multiple screens for multiple users (multiple mono-user CHI systems, shorted as 2Cs)
(b) One screen with subdivided views and one view for each user (multi-user CHI with Subdivided Views, shorted as 1CSV)
(c) One screen with multiple overlapped views for each user (multi-user CHI with Multi-View, shorted as 1CMV)

V.1.3 Hypotheses

We investigate the following hypotheses:

H1: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Efficiency of task**.

H2: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Usability of CHI system**.

H3: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Performance of collaboration**.

V.1.4 Experimental protocol

20 participants consist in 10 groups have attended the experiment. All the experiments are video-recorded to count the communication time during gaming. Each experiment lasted on average 1.5 h.

1). Introduction (5-10 min):

Before experiment, users have been trained to play the game with a trial map under the three experimental conditions to be familiar with the game as well as their partner. They could repeat the trial until they feel ready enough because for each experimental condition.

2). Test phase (50 min)

Two users get different information from the map. They should collaborate by sharing the information from their own representation to accomplish the task.

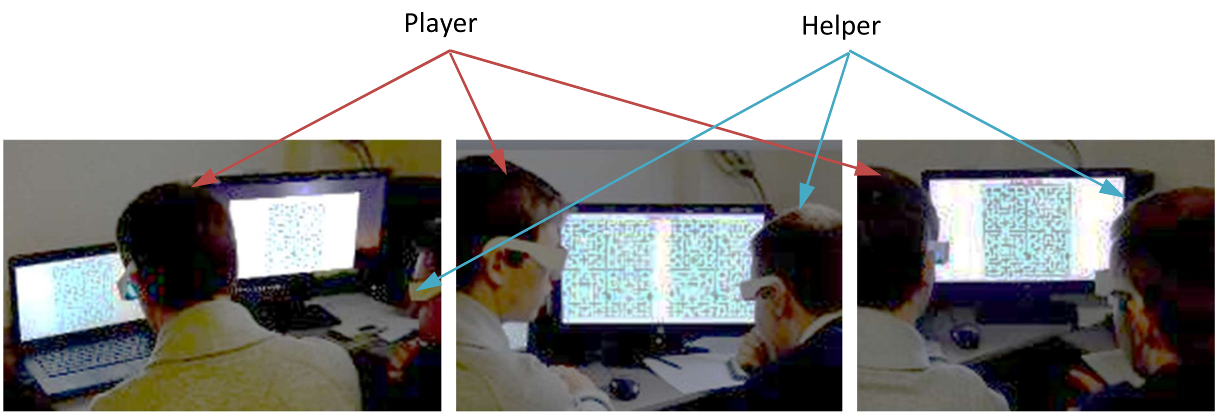


Figure 68 : Three experimental conditions. From left: multiple mono-user CHI systems (2Cs), multi-user CHI with subdivided views (1CSV), multi-user CHI with multi-view (1CMV).

According to the experimental condition, three sections are setup during the experiment. For each section, 8 maps are conducted in collaboration. Each group of participants was arranged to test with three experimental conditions in a random order. These slightly different maps are re-used for other groups by randomly changing the corresponding experimental conditions.

3). Feedback of experiment (20 min)

After each section, each participant is invited to fill a questionnaire separately. Each group of participants will contribute 24 games data and 6 questionnaires. We totally obtained 240 data and 60 questionnaires.

V.1.5 Measurement

In our experiment, both objective measurement is used for the criteria of **H1**: Efficiency of task. Subjective measurement is used for the criteria of **H2**: Usability of CHI system, **H3**: Performance of collaboration.

Objective measurement, including time (complete time, time for vocal communication) and number (number of error, number of speaking, number of question and answer and number of active cue). All these variables are listed:

- **Time**: Finish time
- **Time_QnA**: Sum of response time that helper answers player's questions (all the question/answer pairs).
- **Num_QnA**: Number of question/answer pairs
- **Time_QnA_devidedby_Time**: Ratio of communication time to finish time

A questionnaire is used to measure the subjective variable which is described below:

- **Involvement**: participation level of the participants in their activity;
- **Learnability**: ease of learning;
- **Satisfaction**: user's acceptance of the performance of tool or system;
- **Awareness**: The willingness and the degree of knowledge of collaborator's position and special need;
- **Collaborative effort**: how much work that two collaborators provide.

V.1.6 Results

1) The main result of representative themes of the quantitative objective measurements are shown below:

According to three experimental condition, 2Cs, 1CSV and 1CMV, the mean and standard deviation of the variables are calculated: **Time**, **Time_QnA** are shown in Figure 69; **Num_QnA** is shown in Figure 70; **Time_QnA_dividedby_Time** is shown in Figure 71.

We can see that the Finish time (**Time**), Number of question/answer pairs (**Num_QnA**) and Sum of response time of all question/answer pairs (**Time_QnA**) to complete the task decrease from 2Cs, 1CSV to 1CMV. The Ratio of communication time to finish time (**Time_QnA_devidedby_Time**) shows that multi-view (1CMV) is better than the other two conditions.

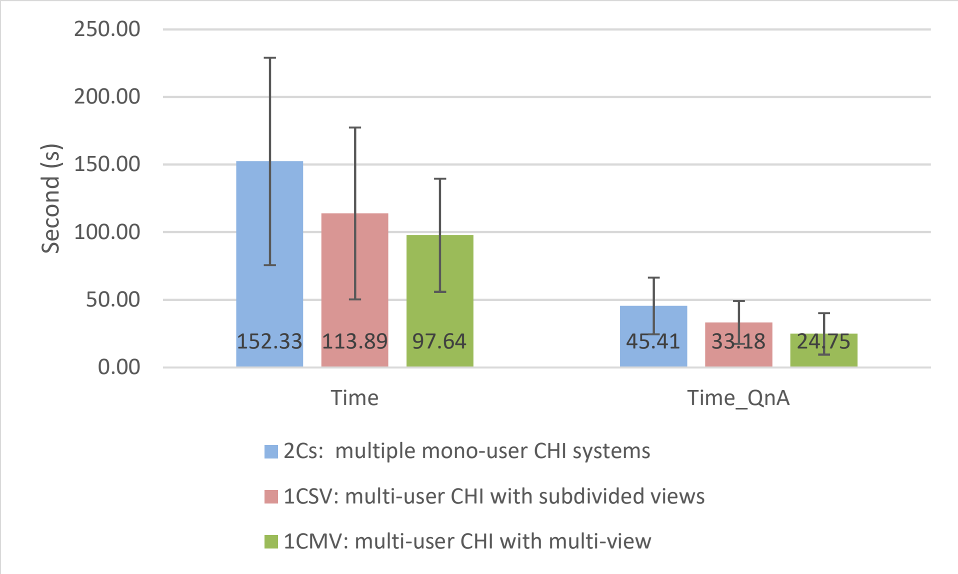


Figure 69 : Average and standard deviation of the measured variables: **Time**, **Time_QnA**.

Following the typical means of statistical principles, a test of Homogeneity of Variances is conducted (Winer et al., 1971). We could obtain that using Levene statistic test, the distributions of data from Num_QnA and Time_QnA respect normal distribution. We could use ANOVA for these two variables in the next step.

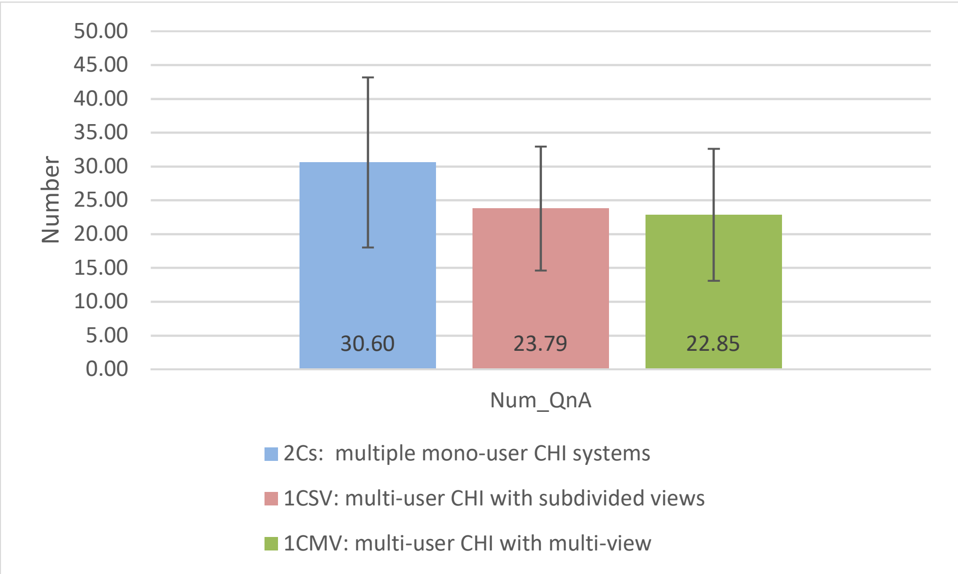


Figure 70 : Average and standard deviation of the measured variables: **Num_QnA**.

The result of ANOVA for **Time_QnA** shows differences in three conditions ($F (2,237) = 27.973$, $p<0.001$). A LSD post-hoc test shows that a difference between 2Cs and any of two other conditions is obvious ($p<0.001$). The difference between 1CSV and 1CMV is obvious ($p<0.05$).

However, **Time** and **Time_QnA_dividedby_Time** don't respect normal distribution. We should use Robust Tests of Equality of Means (Welch or Brown-Forsythe method) for further analyzing.

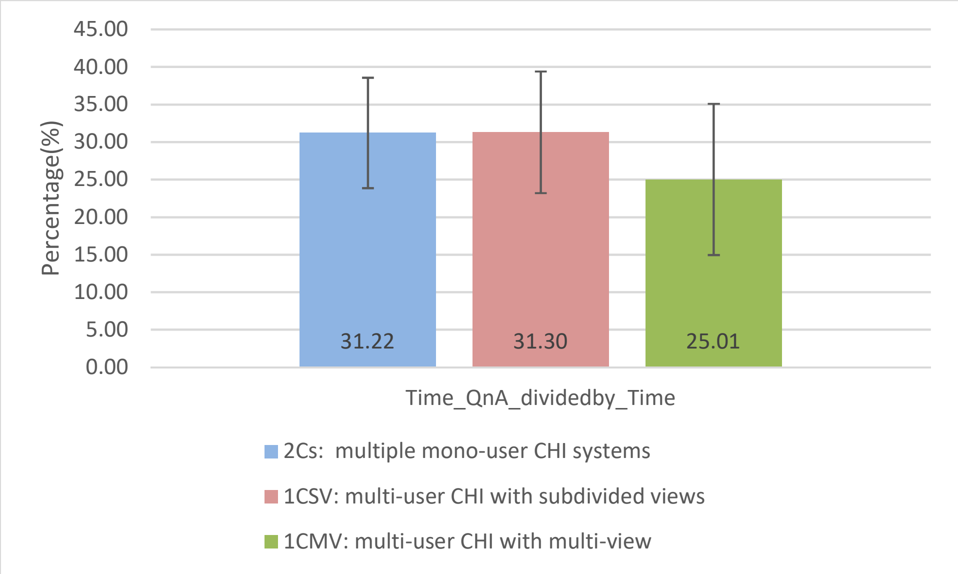


Figure 71 : Average and standard deviation of the measured variables: **Time_QnA_dividedby_Time**.

Brown–Forsythe tests for both **Time** and **Num_QnA** have results that there existed differences among three conditions (p <0.001). With correction of Games Howell method, 1CMV and 1CSV show the difference with 2Cs (p<0.001). But between these two conditions, the difference is not significant. Brown-Forsythe test for **Time_QnA_devidedby_Time** shows differences among three conditions (p<0.001). With correction of Games Howell, 1CMV shows the difference with other two conditions (p<0.001).

Table 6: Objective measurements of COLLAB_PACMAN simulation game. (*: p<0.05 significant; **: p<0.01 highly significant)

	Time (s)	**Num_QnA**	**Time_QnA (s)**	**Ratio of communication time to finish time (%)**
2Cs	152.33	30.60	45.41	31.22
1CSV	113.89	23.79	33.18	31.30
1CMV	97.64	22.85	24.75	25.01
Significant (p)	2Cs -1CSV: ** 2Cs -1CMV: **	2Cs -1CSV: ** 2Cs -1CMV: **	2Cs -1CSV: ** 2Cs -1CMV: ** 1CSV -1CMV: *	2Cs -1CMV: ** 1CSV -1CMV: **

To summarize the comparisons under different subjective criteria. From the Table 6 we can oversee the results. In the condition with 1CMV, participants have less finish time and less communication time, less number of question and answers, and less ratio of communication time during the whole time. These differences are significant through statistics analysis.

2) The main result of representative themes of the quantitative subjective measurements are shown below:

Involvement, learnability, satisfaction, awareness, and collaboration effort are investigated by questionnaire with a Likert scale from 1 to 5 points. Since the data do not respect normal distribution, a non-parametric statistical hypothesis test, Friedman test as mentioned in III.2.3.2 is used to analyze the differences is significant or not among three groups of data. Wilcoxon signed-rank test is used for the comparison between any two means of the three conditions.

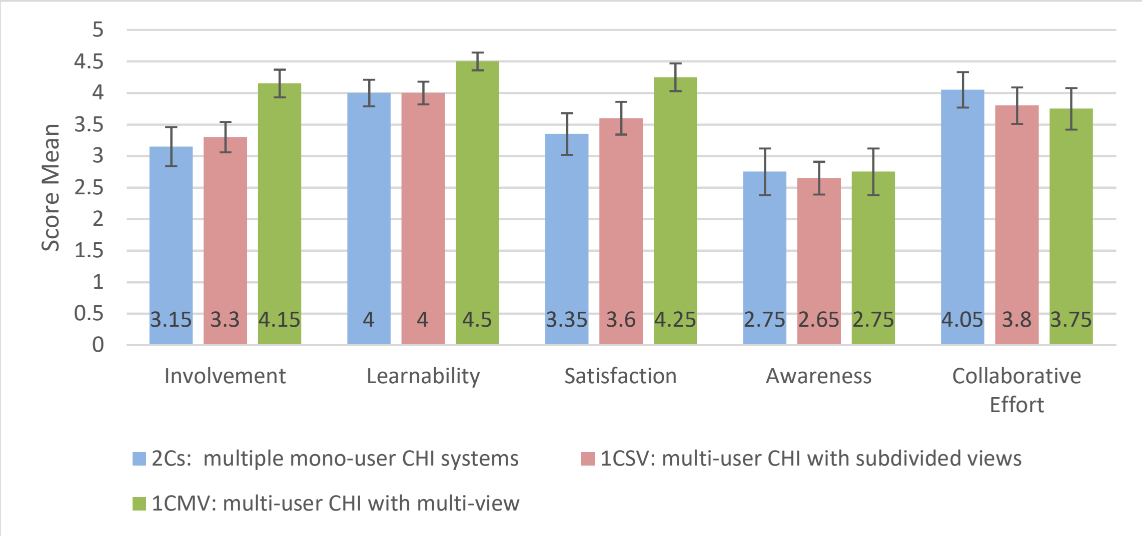


Figure 72: Average and standard deviation of subjective criteria: involvement, learnability, satisfaction, awareness, collaboration effort.

- Involvement

The result of questionnaire shows that the average of the involvement of 1CMV is 4.15, higher than the other two conditions, as shown in Figure 72. The result of Friedman test show that the difference among three conditions is ($p=0.017<0.05$) significant. A Wilcoxon signed-rank test shows that the difference exists between 2Cs and 1CMV ($p = 0.025<0.05$), as well as between 1CSV and 1CMV ($p = 0.033<0.05$). So, with 1CMV, participants could feel more involved during experiment and feel more concentrated.

- Learnability

For 1CMV condition, the average of learnability is 4.5. This value is 4 for the other two conditions, as shown in Figure 72. The result of Friedman test show that the difference among three conditions is ($p=0.001<0.05$) significant. A Wilcoxon signed-rank test shows that the difference exists between 2Cs and 1CMV ($p = 0.004<0.05$), as well as between 1CSV and 1CMV ($p = 0.01<0.05$). This indicated that in 1CMV condition, user feel easier to use the system than in the other two conditions.

- Satisfaction

The condition of 1CMV has an average of 4.25 in satisfaction, as shown in Figure 72, higher than the other two experimental conditions. The result of Friedman test show that the difference among three conditions is ($p=0.002<0.05$) significant. A Wilcoxon signed-rank test shows that the difference exists between 2Cs and 1CMV ($p = 0.001<0.05$), as well as between 1CSV and 1CMV ($p = 0.03<0.05$). This indicated that in condition of 1CMV, participants feel more satisfied than in the other two conditions.

- Awareness

The condition of 1CMV has an average of 2.75 in awareness, as shown in Figure 72. Both Friedman test for three conditions and Wilcoxon signed-rank test between any two of the conditions show no significances.

- Collaboration effort

The condition of 1CMV has an average of 3.75 in Collaboration effort, as shown in Figure 72, lower than the other two experimental conditions. Both Friedman test for three conditions and Wilcoxon signed-rank test between any two of the conditions show no significances.

Table 7: Subjective measurements of COLLAB_PACMAN simulation game. (*: p<0.05 significant; **: p<0.01 highly significant)

	Involvement (Max 5)	**Learnability (Max 5)**	**Satisfaction (Max 5)**	**Awareness (Max 5)**	**Collaboration effort (Max 5)**
2Cs	3.15	4	3.35	2.75	4.05
1CSV	3.3	4	3.6	2.65	3.8
1CMV	4.15	4.5	4.25	2.75	3.75
Significant (p)	2Cs -1CMV: * 1CSV -1CMV: *	2Cs -1CMV: ** 1CSV -1CMV: *	2Cs -1CMV: ** 1CSV -1CMV: *		

To summarize the comparisons under different subjective criteria. From the Table 7 we can oversee the results. In the condition with 1CMV, participants have more involvement, learnability, and satisfaction. These differences are significant through statistics analysis. Using 1CMV, the awareness and collaboration effort are lower than the other two conditions.

V.1.7 Discussion

- Efficiency of task

Four variables, Finish time (Time), Number of question/answer pairs (Num_QnA), Sum of response time of all question/answer pairs (Time_QnA) and Ratio of communication time to finish time (Time_QnA_devidedby_Time), are all significant to represent the efficiency of task. Both time and number during the task, as well as the communication rate, decrease from 2Cs, 1CSV to 1CMV. Obviously from our results, these variables have all reached the significance levels. Users can finish the task by using less time and less communication. So, users achieve more efficiently during the collaborative task using the multi-view system (**H1**).

- The usability of Multi-user CHI system

According to the taxonomy of applications in the field of collaboration, DMU, and CHI in II.5.1, we categorize our approach of multi-user CHI in this experiment as Table 8.

This multi-user CHI can be quickly established because it is a simple mechanism of multiple views. Anaglyph is based on color filter of red and cyan. The color differentiation makes use of color distortion of only on red or on cyan. The disadvantage of anaglyph is obvious because of its effect of filtration. From the results we can see, the learnability and satisfaction of the multi-user CHI have more than 4 points. The differences between multi-user system and other systems can be confirmed through the significant data test. So, the multi-user system has a better performance in usability (**H2**) than the other two experimental conditions.

Table 8 : Multi-user CHI in COLLAB_PACMAN simulation game is categorized in collaboration, DMU, and CHI.

	Collaboration (Coupling)			**DMU**	**CHI**					
					Multi-view				Multi-interaction	
					Multi-view mechanism (-based)			Multi -POV (VR)		
	Tight	Mixed	Loose	Multi-representation	Filter	Time	Space		Multi-device	Multi-interaction
COLLAB_PACMAN		×		×	×				×	

- Performance of collaboration

From quantitative measurement about the performance of collaboration (**H3**), multi-user CHI archives good performance considering the criterion of involvement. These results of evaluation of collaboration reveal that during the experiment, users feel involved in this co-located collaborative scenario.

The criteria of awareness and collaborative effort do not have significant results. For awareness of each other's positions and tasks being done, uses has different feedbacks according to their roles. For a player who always focus on asking questions and judging the pass with responses, he/she may always feel unsafe and the demand of mutual awareness may keep on a high level. For a helper, because of the differences of the experimental conditions, he may have feeling of different demands of knowing of player's position. Users have less collaborative effort to make at an average level using multi-user CHI, but this difference is not significant.

V.2 Experiment of COLLAB_MAZE_3D simulation game

As mentioned in Figure 65, in this section, a 3D collaborative multi-user CHI system and a multidisciplinary task with quantitative measurements are tested in the experiment of COLLAB_MAZE_3D simulation game, using the application developed in IV.3.2.3. This experiment has a comparison between different CHI experimental conditions of multiple users' collaboration in 3D design activities. The criteria of the hypotheses **H1**, **H2**, and **H3** are evaluated.

V.2.1 Description of experiment

The experimental study is designed to explore the advantages of collaborative work in the virtual reality environment. To simulate the collaborative work during industrial design and its optimization work using DMU, a 3D collaborative game is designed.

As shown in Figure 73, multi-view shutter glasses & polarized filter for visualization is applied, accompanied by multi-interaction techniques of keyboard, mouse, and tracking system. To realize a collaborative scenario, COLLAB_MAZE_3D simulation game is used in this experiment.

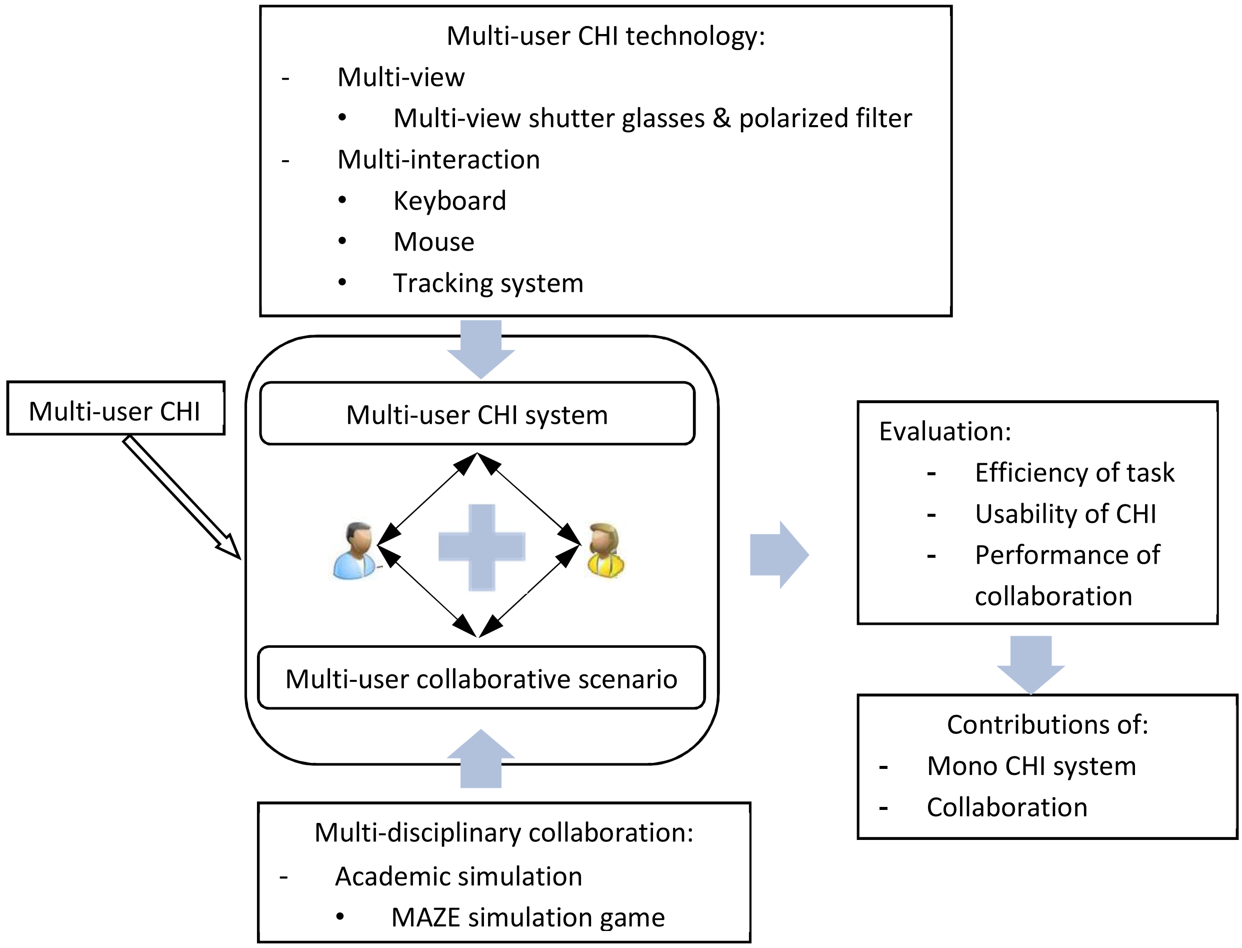


Figure 73 : Experiment scheme of COLLAB_MAZE_3D simulation game.

As we described in IV.3.2.3, COLLAB_MAZE_3D lets two users collaborate in a 3D environment to find the way to exit the maze. Two different elements of "Gold" and "Bombs" in a maze are displayed respectively to two users. One of them must navigate in the maze and collecting "Gold" at the same time. The other user need to share the information on the maze that only he/she can see to help the first user. He/she can remind the first user: 1.the "Bombs" that needs to be avoided; 2. The highlighted correct path to go outside the maze. They should communicate with each other complementary information on constraints to proceed the task.

V.2.2 Experimental conditions

This experiment is carried out by a group of two users under two viewing conditions, Figure 74:

- Multiple mono-user CHI systems: Two screens with multiple mono-user CHI systems and one view for each user. For example, the player can see the maze with golden coins Figure 74.a whereas the helper can see the highlighted way Figure 74.b.
- Multi-user CHI system: A screen with multiple overlapping views (Multi-view) for each user Figure 74.c.

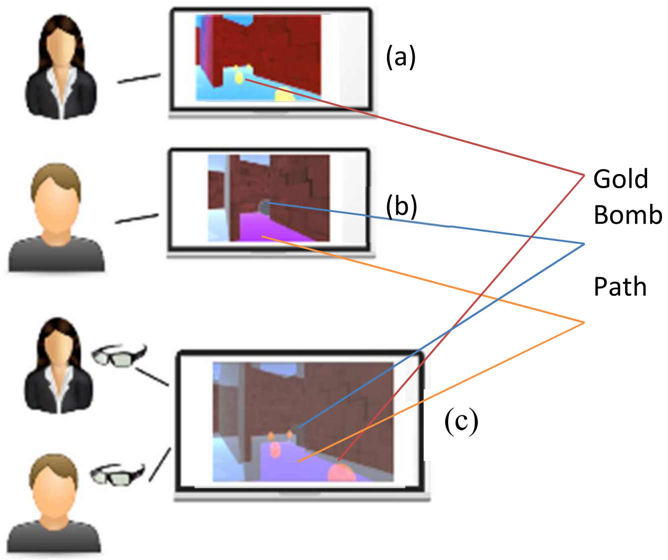


Figure 74 : Two experimental conditions: Left: multiple mono-user CHI systems condition; Right: multi-user CHI condition.

V.2.3 Hypothesis

Various criteria (efficiency, learnability, involvement, satisfaction, awareness, and collaboration effort) related to hypotheses **H1**: Efficiency of task, **H2**: Usability of CHI system, **H3**: Performance of collaboration will be investigated. These criteria are used to prove the following hypotheses.

H1: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Efficiency of task**.

> **H1.1**: Participants will finish task more quickly with multi-user CHI system than with multiple mono-user CHI systems.
>
> **H1.2**: Participants spend less communication time with each other with multi-user CHI system than with multiple mono-user CHI systems.
>
> **H1.3**: The percentage of the time for communication is smaller with multi-user CHI system than with multiple mono-user CHI systems.

H2: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Usability of CHI system**.

H3: Multi-user CHI, which allows multiple users to work collaboratively with different representations of a Digital Mock-Up, has influence on the **Performance of collaboration**.

V.2.4 Experimental protocol

10 groups of participants (i.e. 20 students) have attended the experiment. The duration of the experiment ranged from 50 minutes to 90 minutes.

1). Introduction (5-10 min):

Before the real test, participants must undergo a preliminary training. The purpose of this preliminary training is to make participants understand what is the experimental process.

Participants are served as "player" and "helper" separately. The "player" is positioned in the projector screen and the "helper" plays the game with computer (multiple mono-user CHI systems), as shown in Figure 75. Both participants move in the maze by the mouse. For starting experiments, Participants must finish the training without the problems of movement and hit no bombs at the same time.

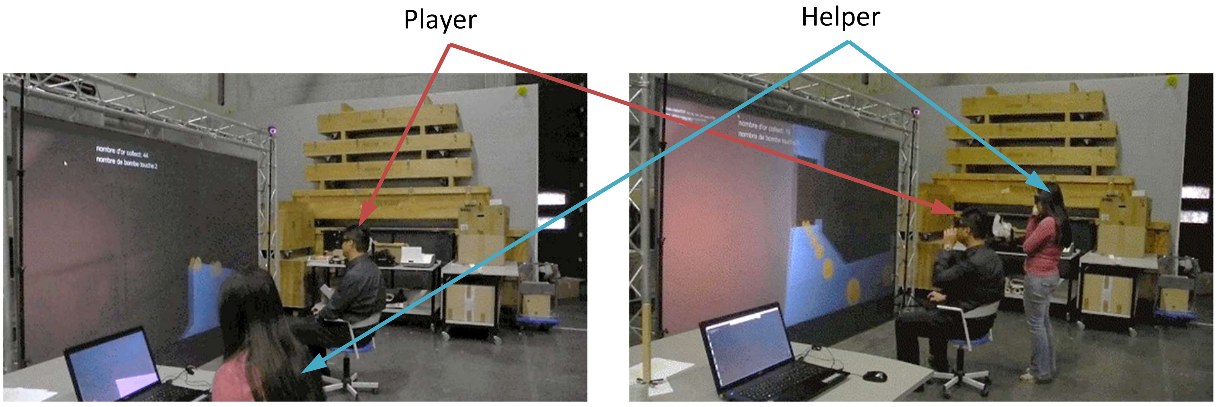


Figure 75 : Experiment conditions: Left: multiple mono-user CHI systems; Right: multi-user CHI.

2). Test phase (30 min):

In experiment, each group of participants will do 4 tests with the 2 view conditions we mentioned in V.2.2. Four maze maps with similar difficulty will be used in our experiment for two sections.

- In the first section, players and helpers try to collaborate with multiple mono-user CHI systems.
- In the second section, participants play the game in virtual environment with the multi-user CHI system.

3). Feedback of experiment (10 min)

Both participants must complete a questionnaire at the end of each experimental section. Four questionnaires are collected for each group of participants.

V.2.5 Measurement

Both objective measurement of task efficiency and subjective measurement of users' involvement, learnability, satisfaction, awareness, and collaboration effort during the experiment are evaluated.

For objective measure, we calculate the time to complete the task and the communication time for each participant during the task:

- **Finish time:** the length of the task completion time during a collaborative task;
- **Communication time**: how much time each participant spent on communicating with the partner;
- **Error committed**: an error of the task occurred when players meet a bomb in our experiment. This factor is measured by the number of bombs that are touched by player during the task.

A questionnaire is used to measure the subjective variable which is described below:

- **Involvement**: participation level of the participants in their activity;
- **Learnability**: ease of learning;
- **Satisfaction**: user's acceptance of the performance of tool or system;
- **Awareness**: The willingness and the degree of knowledge of collaborator’s position and special need;
- **Collaborative effort**: how much work that two collaborators provide.

V.2.6 Results

In this chapter, we will compare and discuss the performance of each group of participants in two experimental conditions.

1) Subjective measurements

Involvement, learnability, satisfaction, awareness, and collaboration effort are investigated by questionnaire with a Likert scale from 1 to 5 points. Since the data do not respect normal distribution, a non-parametric statistical hypothesis test, Wilcoxon signed-rank test as mentioned in III.2.3.2 is used to analyze the differences is significant or not.

- Involvement

The result of questionnaire shows that the average of the involvement of multiple mono-user CHI systems condition is 3.95, while for multi-user CHI condition it is 4.53, as shown in Figure 76. Wilcoxon signed-rank test proves that there is a significant difference between two experimental conditions ($p=0.032<0.05$). So, with multi-user CHI system, participants could feel more involved during experiment and feel more concentrated.

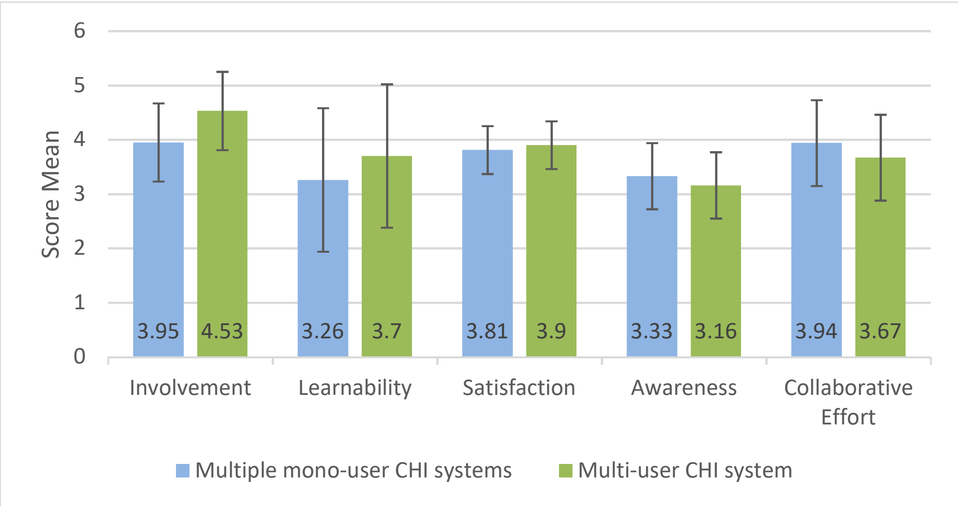


Figure 76 : Average and standard deviation of subjective criteria: involvement, learnability, satisfaction, awareness, collaboration effort.

- Learnability

For the multiple mono-user CHI systems condition, the average of learnability is 3.26. This value is 3.70 for multi-user CHI condition, as shown in Figure 76. Wilcoxon signed-rank test prove the significant difference between the two experimental conditions ($p=0.030<0.05$). The conclusion is that multiple mono-user CHI systems the multi-user CHI system is easier to use than the multiple mono-user CHI systems.

- Satisfaction

The condition of multiple mono-user CHI systems has an average of 3.81 in satisfaction, as shown in Figure 76. The condition of multi-user system has an average of 3.95 in satisfaction. Wilcoxon signed-rank test shows no difference (p=0.854>0.05) between these conditions.

- Awareness

The condition of multiple mono-user CHI systems has an average of 3.33 in awareness, as shown in Figure 76. The condition of multi-user system has an average of 3.16 in awareness. Wilcoxon signed-rank test shows no significant difference (p=0.577>0.05) between the two experimental conditions.

- Collaboration effort

The average of the collaboration effort of multiple mono-user CHI systems condition is 3.94, while for multi-user CHI condition it is 3.67, as shown in Figure 76. Wilcoxon signed-rank test proves that there is not a significant difference between two experimental conditions (p=0.176>0.05).

Table 9: Subjective measurements of COLLAB_MAZE_3D simulation game. (*: p<0.05 significant; **: p<0.01 highly significant)

	Involvement (Max 5)	**Learnability (Max 5)**	**Satisfaction (Max 5)**	**Awareness (Max 5)**	**Collaboration effort (Max 5)**
Multiple mono-user CHI systems	3.95	3.26	3.86	3.33	3.94
Multi-user system	**4.53**	**3.7**	**3.95**	**3.16**	**3.67**
Significant (p)	*	*			

To summarize the comparisons under different subjective criteria. From the Table 9 we can oversee the results. In the condition with multi-user system, participants have more involvement and learnability. These two differences are significant through statistics analysis. Using multi-user system, the satisfaction of the collaboration is higher, and awareness and collaboration effort are lower.

2) Objective measurements

The sum of helper's communication time, the sum of player's communication time and finish time of each test are calculated during the experiment. The ratio of participants' communication time to finish time is calculated after that. The number of touched bombes is counted at the end. Since the data do not respect normal distribution, a non-parametric statistical hypothesis test, Wilcoxon signed-rank test as mentioned in III.2.3.2 is used to analyze the differences.

- Finish time

Finish time can be used to represent the collaboration efficiency. A significant difference between two experimental conditions (p=0.008<0.05) is calculated with Wilcoxon signed-rank test. The average finish time for multiple mono-user CHI systems condition is 563.74s and it is 451.4s for multi-view condition, as shown in Figure 77. The player could finish the task more quickly by using the multi-user CHI system.

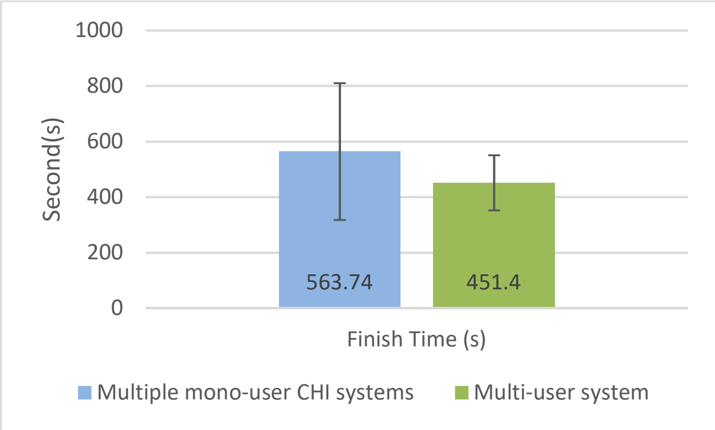


Figure 77 : Average and standard deviation of **Finish time**.

- Player's communication time

Players spend an average of 39.94s to communicate with helpers in multiple mono-user CHI systems condition, which is 8.82% of finish time. However, the average of communication time in multi-view condition is 10.67s, which is 2.51% of finish time as shown in Figure 78. Wilcoxon signed-rank test shows a significant difference between two conditions. ($p=0.009<0.05$ for communication time, $p=0.007<0.05$ for ratio of play's communication time to finish time.)

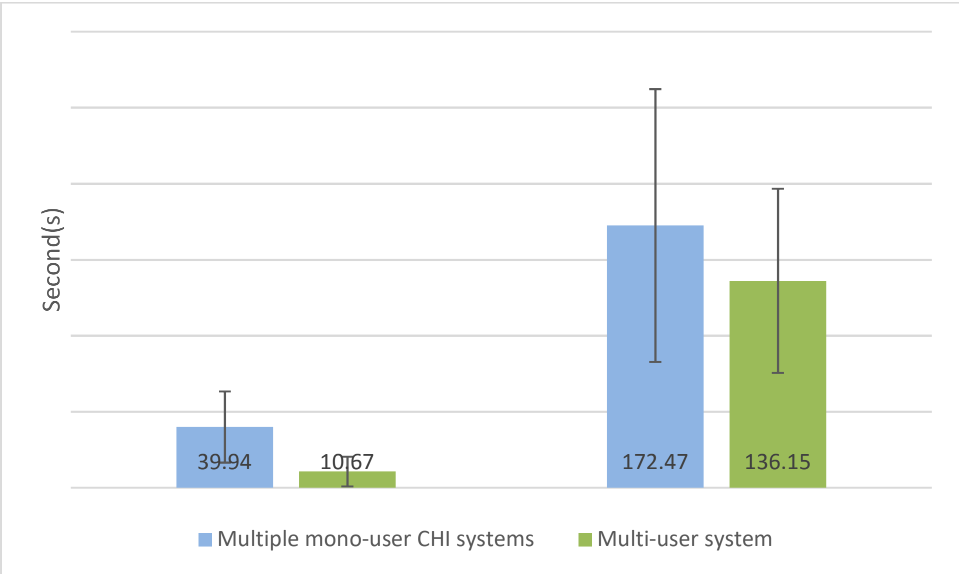


Figure 78 : Left: average and standard deviation of **player's communication time** in two conditions; Right: average and standard deviation of **Helper's communication time** in two conditions

- Helper's communication time

As in chapter II.2.1, communication time and the ratio of communication time to finish time of helper are analyzed. Helpers spend an average of 172.47s to communicate with players in multiple mono-user CHI systems condition, which is 31.45% of finish time.

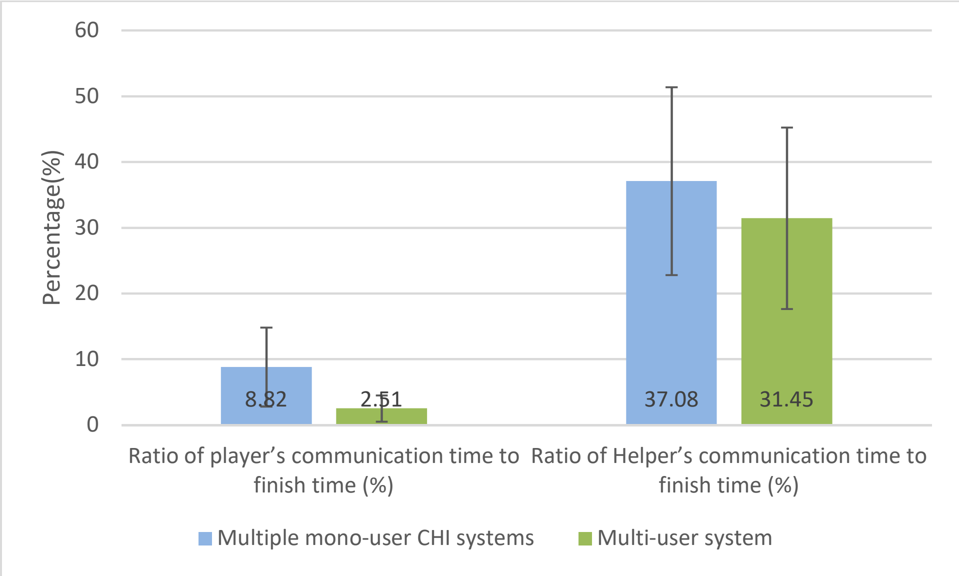


Figure 79 : Left: average and standard deviation of the **Ratio of player's communication time to finish time**; Right: **Ratio of Helper's communication time to finish time**

The average of communication time in multi-view condition is 136.15s, 37.08% of the finish time, shown in Figure 79. The result of Wilcoxon test shows a difference of communications between two conditions ($p=0.028<0.05$). However, the Wilcoxon signed-rank test shows no difference in ratio of communication time between two conditions. ($p=0.074>0.05$). So, the difference between two kinds of communication time may be caused by shortened of finish time.

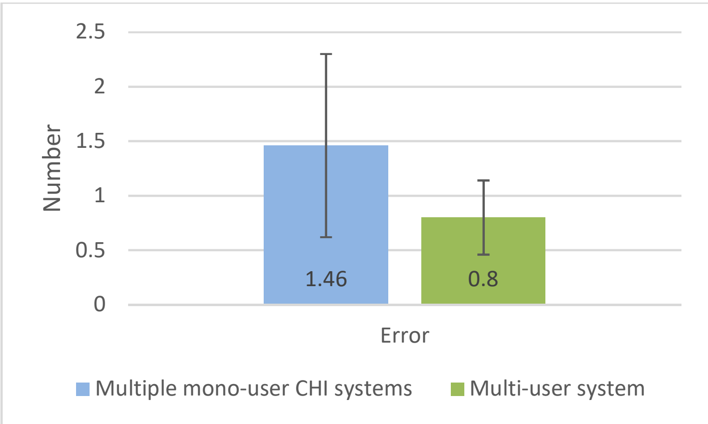


Figure 80 : Average and standard deviation of the **Error committed** between two multi-view condition and multiple mono-user CHI systems condition.

- Error committed

In multiple mono-user CHI systems condition, player touches an average of 1.46 bombs each game. Meanwhile, player touches 0.8 bombs in multi-view condition. The result from Wilcoxon signed-rank test shows a significant difference between two conditions ($p = 0.041<0.05$). Therefore, the multi-user CHI system could reduce the error incidence rate, as shown in Figure 80.

To summarize the comparisons under different objective criteria. From the Table 10 we can oversee the results. In the condition with multi-user system, participants finish the task quicker, have less communication and commit less errors. The Ratio of communication time to finish time (%) of both player and helper is less than the other experimental condition. The difference of the Ratio of Helper's communication time to finish time (%) is not significant.

Table 10: Objective measurements of COLLAB_MAZE_3D simulation game. (*: p<0.05 significant; **: p<0.01 highly significant)

	Finish Time (s)	**Player's communication time (s)**	**Ratio of player's communication time to finish time (%)**	**Helper's communica tion time (s)**	**Ratio of Helper's communication time to finish time (%)**	**Error**
Multiple mono-user CHI systems	563.74	39.94	8.82	172.47	37.08	1.46
Multi-user system	451.4	10.67	2.51	136.15	31.45	0.8
Significant (p)	**	**	**	*		*

V.2.7 Discussion

- Efficiency of task

For efficiency of task (**H1**), although the ratio of communication time to the finishing time of helpers is not significant (**H1.3**), the result of other variable: finish time (**H1.1**) and communication time (**H1.2**) are significant to represent the efficiency of collaboration. From our analysis results, these variables have differences between two working conditions. On the other hand, the difference between helpers' communication time is not significant. From these objective data analyses above, we found that users achieve the collaborative task more efficiently with the multi-user CHI system than without it. Users can finish the collaborative task with less communications during the use of multi-view device.

- Usability of Multi-user CHI system

According to the taxonomy of applications in the field of collaboration, DMU, and CHI in II.5.2, we categorize our approach of multi-user CHI in this experiment as Table 11.

Table 11 : Multi-user CHI in COLLAB_MAZE_3D simulation game is categorized in collaboration, DMU, and CHI.

<table>
<tr><th rowspan="4"></th><th colspan="3" rowspan="3">Collaboration (Coupling)</th><th rowspan="3">DMU</th><th colspan="6">CHI</th></tr>
<tr><td colspan="4">Multi-view</td><td colspan="2" rowspan="2">Multi-interaction</td></tr>
<tr><td colspan="3">Multi-view mechanism (-based)</td><td rowspan="2">Multi-POV (VR)</td></tr>
<tr><td>Tight</td><td>Mixed</td><td>Loose</td><td>Multi-representation</td><td>Filter</td><td>Time</td><td>Space</td><td>Multi-device</td><td>Multi-interaction</td></tr>
<tr><td>COLLAB_MAZE_3D</td><td></td><td>×</td><td></td><td>×</td><td>×</td><td>×</td><td></td><td>×</td><td>×</td><td></td></tr>
</table>

The multi-user CHI in this experiment adopts the mechanisms of polarized filter and time-based shutter glasses as the multi-view system, keyboard, mouse, and tracking system as multiple interaction system. Polarized filter and time-based shutter glasses generate four views, each two of which can give a user a multi-POV of an 3D object. In a VR environment, this multi-user CHI system can realize two 3D views for two users. The control metaphors of mouse buttons and the metaphors of hand markers of tracking system in this experiment. According to Personas of user, the functions that can be realized by rolling the mouse wheel button and the motions of selecting an object with tracking system are different, as described in IV.2.2.

For usability (**H2**), from the analysis of learnability of the system, the significant difference between both conditions indicated that participants can learn quickly of the multi-user CHI system. There is no significant difference in terms of collaboration satisfaction for the both conditions, however, the collaboration satisfaction level may depend on participants themselves.

- Performance of collaboration

For Performance of collaboration (**H3**), from the results we can see, users feel more involved in this co-located collaborative experiment with multi-user CHI system. This difference is confirmed with the significance test result.

The criteria of awareness and collaborative effort do not have significant results. Users have less awareness of each other's existence using multi-user CHI system. This means the user can focus on his/her own activity instead of worrying about each other. Multi-user CHI system allows user to have individual working phases, as well as collaboration when it is necessary. But the difference of this criterion is not significant. Users make less effort to collaborate using multi-user CHI, but this difference is not significant.

V.3 Experiment of MUG collaborative design

This experiment of design application of collaboration with multi-user CHI, mug design developed in IV.3.2.4, is conducted in this section. The aim of this experiment is to evaluate the usability of CHI (**H2**) and user performance of collaboration (**H3**) under the specific examples of early collaborative design activity in industry.

V.3.1 Description of experiment

V.3.1.1 The study of collaborative design with Persona method

The Persona method was created by Cooper (Cooper, 1999) and it was mainly used in the field of product design. Personas are an archetype of users that take the form of a card with a photograph of the persona, his name, sociological, demographic, and psychological information which can be embellished with storyboard to promote realism (Long, 2009). The Persona method is a tool for design process considering the aspect of identified target users. As representations of users, with behavior, attitude, personal motivation, and intentions, they allow designers to understand the needs of future users as to the use of a technology (Brangier and Bornet, 2011).

Personas are commonly created at the beginning of the design process and are used during the entire design process. They can be used in different manners, depending the nature of the project and the designers' preference (Chang et al., 2008; Matthews et al., 2012). They are materialized based on ethnographic research, interviews, and user observations (Pruitt and Grudin, 2003). Following the collection of data on the users, an analysis is realized. A list of behavioral data and demographic variables is drawing up to determine the main trends. Depending on the behavior pattern, different personas will be defined. These personas will be used to represent a group of people with this pattern (Goodwin, 2002, 2001).

The entertaining aspect of this method is the fact that it allows designers to stimulate their creativity and encourage the development of innovative ideas (Pruitt and Adlin, 2010). Indeed, it allows designers to distance themselves from their way of apprehending the product since they no longer reason from their point of view but from that of the personas (Spool, 2007). In the design process, they improve the generation of ideas which are more numerous, more original, and more flexible than a condition without personas (Liem and Brangier, 2012).

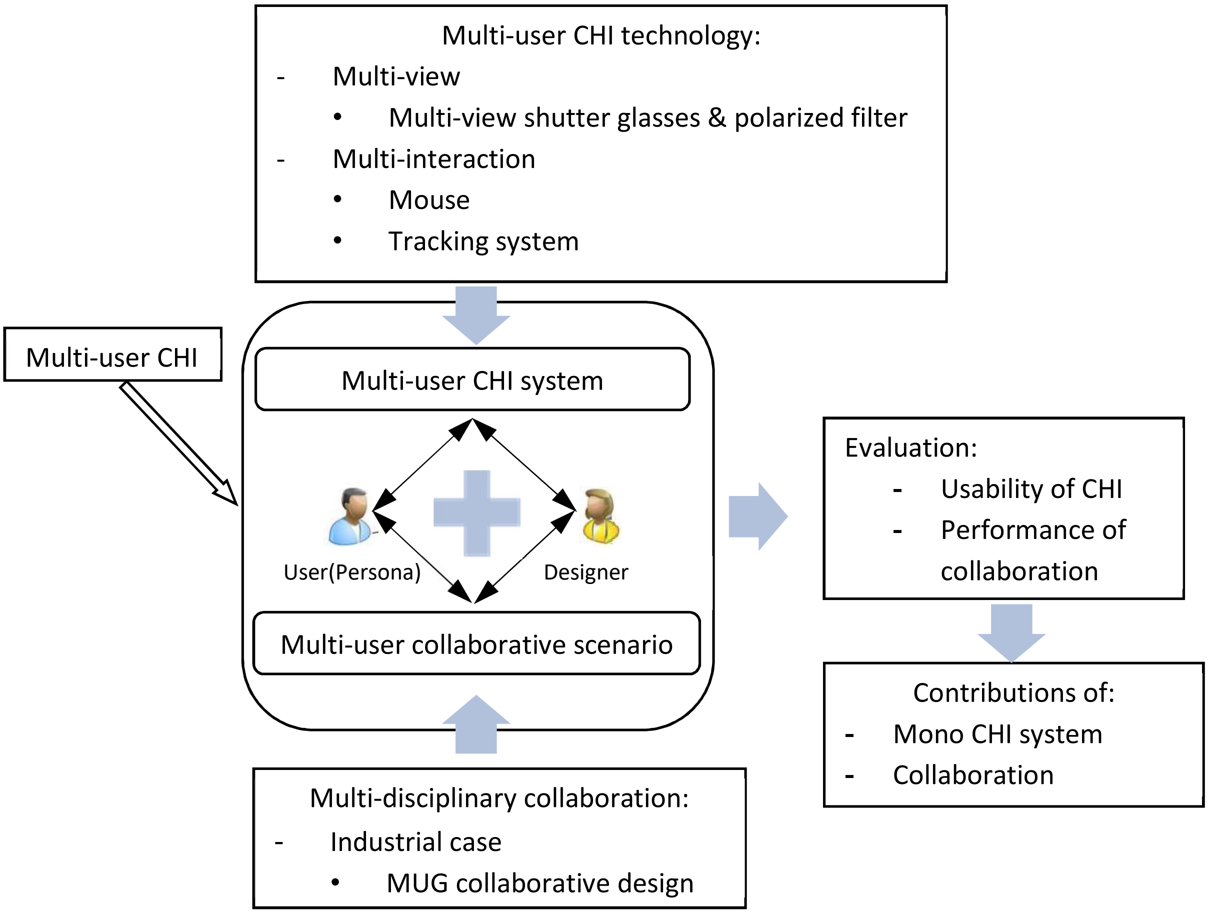


Figure 81 : Experiment scheme of MUG collaborative design.

In our study, we show the interest of persona during a collaborative design case in a virtual environment. In collaborative work, two or more users often have different "Personas" because of their various specialties. A working environment which allows two Personas to collaborate in real time may help during the early design activities. Considering our multi-user CHI system, an experiment of testing the support of collaboration and the working style between Persona has been conducted.

V.3.1.2 Experiment scheme

This experiment is designed to explore the multi-user CHI performance and feedback of different Personas in an early stage of MUG collaborative design. The scheme of experiment as shown in Figure 81, multi-view shutter glasses & polarized filter for visualization is applied, and accompanied by multi-interaction techniques using mouse and tracking system.

One persona is testing the usage of the mug in the specific usage scenario restituted virtually by a series of actions to meet the requirements of user preferences. Another persona is more interested in design analysis data, e.g. size, thermal analysis. They should communicate to proceed the design task.

Both formative evaluation and summative evaluation are adopted during the experiment. An open-question interview was given to the participants, as well as a subjective measurement of users' involvement, learnability, satisfaction, awareness, and collaborative effort during the experiment.

V.3.2 Experimental protocol

The experiment requires 2 participants (one will play the role of the user and the other will play the role of designer). They are asked to be recorded during the experiment by camera.

10 participants are recruited for the experiment to form 5 partnerships. Participants are students in master degree at the Image Institute. They are all male, between 19 and 23 years old. They are novice in product design.

1). Introduction (5-10 min):

They are firstly introduced with the object and procedure of the experiment. Then in a training scenario, they are asked to manipulate virtual objects. They must be taught how to do the following: Catching an object, moving it, dropping it, returning it, etc. A training task is to be tested several times to make the collaborators familiar with our equipment. As soon as the participants are ready, the experiment starts. During the training program, the participants could learn:

- How to use the system;
- What are their collaborators able to see and to interact;
- What and how to ask their collaborator to do;
- How to understand the requirement of their collaborator.

2). test phase (20 min):

The tasks that we ask the group of participants to achieve during this "product user/designer" experiment are listed below in Table 12. These 4 tasks are intended to represent situations of use of the products.

3). Feedback of experiment (20 min)

Participants are asked to fill a questionnaire and have a recorded interview to gather their points of view about the experience.

Table 12 : Experimental tasks of MUG collaborative design

	Product User	**Product Designer**
Get ready	The user gets sit in the vehicle.	
Task 1: Put the mug in the cup holder *He must put mug into the cup holder*	He opens the cup holder; he takes the mug initially placed on the dashboard and tries to put it into the cup holder, but the initial size of the mug is not suitable. The user may require changing the size of the mug.	the designer changes the size (especially the diameter) of the mug immediately when the user asks him.
Task 2: Put the tea bag into the mug *The user must grab the tea bag and put it in the mug*	Leave the mug on the cup holder and place the teabag in the mug. The user may require the mug to be transparent to see if the teabag is inside the mug.	The designer can make the mug transparent under the requirement of the user.
Task 3: Catch the folder *The user is asked to grab the folder*	the user must take the folder from the dashboard, but the height position of the mug on the cup holder may block the folder.	The designer changes the size of the mug (specially its height the cup holder) so that the folder can pass over the mug without any collision.
Task 4: Color change *The user is invited to test different colors of the mug*	The user is asked to observe the color of the mug and analyze how its reflection on the windshield affect the vision. Different colors are available to let user to compare and choose.	The designer changes the color of the mug under the requirement of the user.

V.3.3 Measurement

In the questionnaire, a scale from point 0 to point 4 is used for each question. Using a questionnaire, we can measure the variables adapted to our research question based on literature (Gerhard et al., 2001; Harms and Biocca, 2004; Hrimech and Merienne, 2010; Snowdon et al., n.d.)

- **Involvement**: the participants' feeling of how well they participate in their activities.
- **Learnability**: the quality that a system offers at the level of ease of learning.
- **Satisfaction**: user's acceptance of the performance of the tools or system.
- **Awareness**: the ability to communicate directly, users of shared systems should be made generally aware of each other's presence and activity.
- **Collaborative effort**: how much work that two collaborators provide to accomplish a specific task in a collaborative context.

V.3.4 Results

The main results of this case-study are highlighted in this chapter. From background investigation questions in the questionnaire, we can find out that 50% of the participants have experience in projects with design activities. But only 20% of them have been involved in collaborative design activities with other people. Thus, the opinions and performances of these participants may have practical implications in multi-user system and the way of collaborative design. The visualizations of different functional interface for each participant are shown in Figure 82.

From the result, we can explore that this experiment allowed us to identify elements about the co-activity between users and designers related to the use of the multi-view system on the one hand, and elements of improvements of this system on the other hand.

1) The main result of qualitative interviews of participants:
    - Collaboration between users and designers:

From the familiarization phase, spontaneous exchanges between users and designers become noticeable. These exchanges make it possible to agree on the modifications of the model and continue throughout the experiment. Through the observation on the participants during the experiment, the user gives directions to the designer "*a little bit*" "*it's ok*" so that he can modifies the design parameters of the mug to meet his request. User guidance allows designers to modify the settings of the digital mock-up of mug as required, but designers can also propose spontaneous changes to arouse user's interest in things they might not have thought of, such as color changes for example "*I didn't know that you could change the color, it's good to be able to do it*".
Users and designers raise the interest of this device for design. Regarding their Personas in this experiment, they express different points of view.

Figure 82 : User and designer during the experiment of MUG collaborative design.

For the users, it is very interesting to be able to communicate with the designer. Being involved in a design project is not common, and it is interesting for them to be able to express their opinion on the product to its designer: "*speaking with the designer make him closer*". On the other hand, seeing live modifications encourages users to express their needs in terms of the design, something generally difficult for a non-expert in the domain: "*it's very interesting to see the live changes, it helps to verbalize the thoughts*". Users appreciate the fluidity of the experiment and the scope of possible modifications: "i*t's great to see the object changes lively*". The device is also appreciated by users, who can project themselves in the context of using the product: "*it helps to project different things to more than one user*".

On the designers' side, the contribution of the presence of users is undeniable. This allows them to think differently and consider elements they would not have thought alone, such as the trouble of the reflection of the mug on the windshield, depending on the color "*we see things we didn't necessarily* *see without the user* ". Finally, designers appreciate the time saving of this tool that allows to reduce iterations. The presence of users and live modifications is deemed relevant to save time in design "*this tool give the opportunity to reduce iterations and to collect user impressions in live*".

Finally, the playful aspect of multi-view system is appreciated and encourages both parties to participate in compare to a product test situation without digital support "*it's nice to manipulate an object with virtual reality!* "

Users and designers also mentioned difficulties and improvement points for the whole system.

- Difficulties and areas for improvement

On the user side, the main difficulty lay in interactions with the virtual model. Indeed, some actions were hardly feasible and not very fluid, like putting the mug on the cup holder "*it falls when it is placed on it*". Tracking latency was also mentioned. An embarrassment also resided in the field of view because the objects to be caught were displayed on the screen and behind the user's hand, which did not allow the user to see them correctly.

For designers, the major difficulty was the lack of information on the view of users. Indeed, users had a view of the car with all its attributes, while the designers saw the mug with design information. Therefore, they could not assist users in adjusting the modifications to the object. In addition, designers have told us to add more parameters to vary, such as more choice of color or shape of the mug.

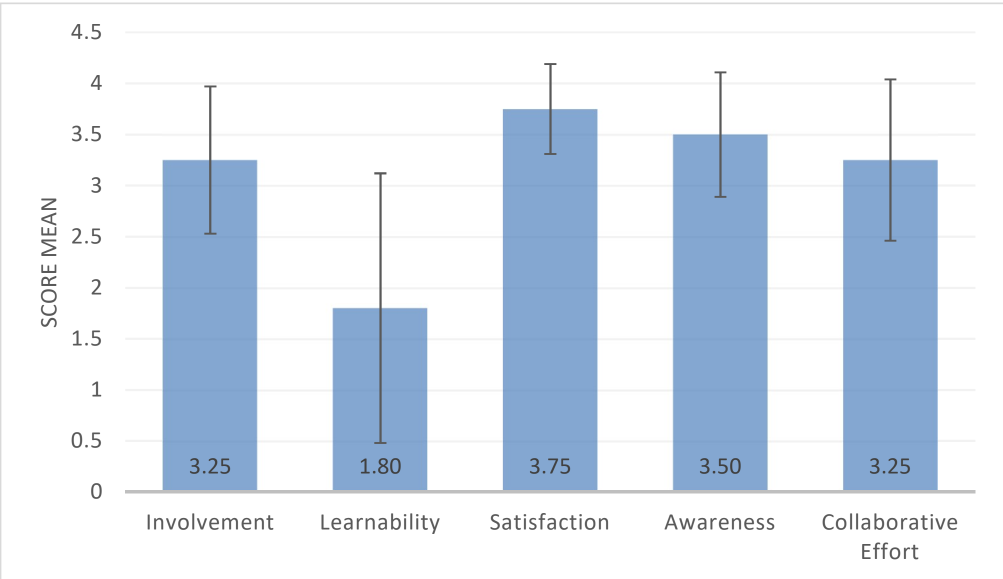


Figure 83 Score means of the variables in the quantitative questionnaire of the experiment.

2) The main result of representative themes of the quantitative questionnaire are shown in Figure 83 and are listed below:

- Involvement

The questions about the impression of the experiment are asked. The results show positive feedbacks of the general impressions. An average score of “Excellent” and “Interesting” impressions is up to

3.25/4. From the frequency analysis in Figure 84, over 85% of the participants is beyond a “fair” score in involvement. Thus, during this experiment, participants are highly involved in the collaborative work.

- Learnability

In terms of the ease of learning of the multi-user system, as well as the collaborative scenario, a mean score of 1.8/4 (4 means very hard learnability) is present. In the questionnaire, 20% of the participants think the experiment task is very easy to complete. Half of the participants have some difficulties about the collaborative task or troubles with hardware.

From an analysis comparing users and designers, users appear to consider the collaboration task easy to complete. They achieve an average score of 1.4/4. However, designers usually have trouble with the learnability of the scenario that they got 2.2/4 point.

- Satisfaction

The questions about the concept of collaborative working styles in the experiment scenario receive high marks. Participants seems like the way the multi-user system works. A score of 3.75/4 (4 means very satisfied) has been given for the satisfaction of the usability of the system. In Figure 84, 75% of the participants are very satisfied with the collaboration style during this kind of design activity, in which collaborators can exchange multi-disciplinary information in real time.

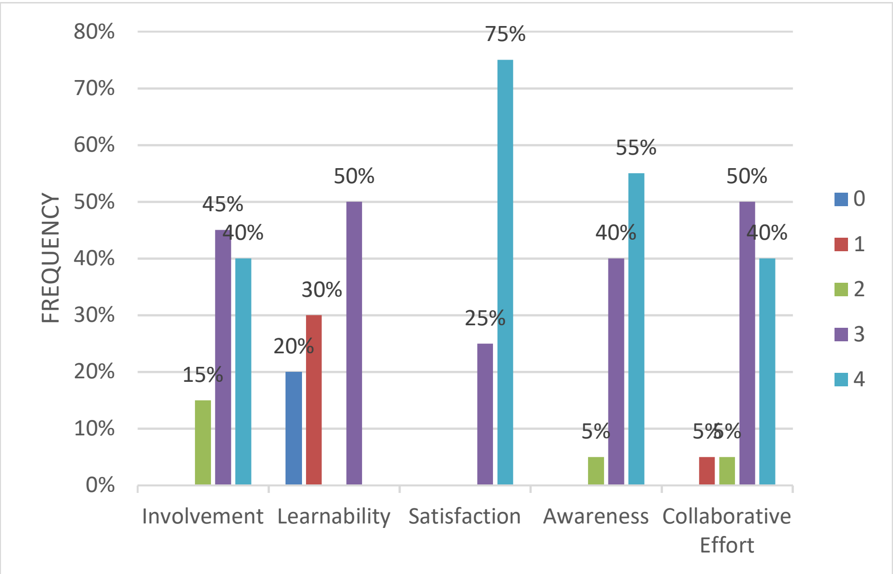


Figure 84 Frequencies of the scores of variables in the quantitative questionnaire of the experiment.

- Awareness

For each participant, the awareness of the collaborator is questioned, as well as the confidence of the collaborator. During the experiment, participants show great awareness of their collaborators. Through frequent communications, the awareness of collaborator reaches a high mark of 3.5/4 (4 means knowing very clearly about one’s collaborator) and the score of the confidence of one’s collaborator is 3.5/4 (4 means very confident).

- Collaborative effort

The effort that collaborators provide to accomplish the experiment task during the communication between the two of them is questioned. The result shows an average of 3.25/4 (0 means having tough difficulties) for the collaboration difficulty. Participants don’t meet terrible communication problems and they have high evaluation of the contributions of their collaborators.

V.3.5 Discussion

- Usability of Multi-user CHI system

According to the taxonomy of applications in the field of collaboration, DMU, and CHI in II.5.2, we categorize our approach of multi-user CHI in this experiment as Table 13.

Table 13 : Multi-user CHI in MUG collaborative design case is categorized in collaboration, DMU, and CHI.

	Collaboration (Coupling)			**DMU**	**CHI**					
					Multi-view				Multi-interaction	
					Multi-view mechanism (-based)			Multi -POV (VR)		
	Tight	Mixed	Loose	Multi-representation	Filter	Time	Space		Multi-device	Multi-interaction
MUG collaborative design		×		×	×	×		×	×	×

We will first discuss the evaluation of the usability of multi-view system (**H2**). From the experimental results, we find the quantitative criterion on the usage of the system, usability, is slightly below the median, which means that participants have problems with use of the system. Users felling of experiment remains easy, while designers have difficulties in operating the system. Also from the interview responses, there are many recommendations about technical improvements of the tracking system and interaction system. The limitation of the tracking system mainly appears on: only a few markers can be tracked (four); the version of tracking cameras cannot allow a fly stick to be captured, thus most of our interactive motions must be created by the combination of markers and mouse buttons. So, the complex operation of the interaction devices could be a technical problem which affect the user experience. Also, during our experiment, usually the user is acting as a driver who is sitting on a chair. However, designer must stand up and walk around to catch up with the changes of the user. Since the tracking cameras have a limited working field in space, sometimes designer walks out of the tracking field and gets lost from tracking system. That’s why we set up a long-time training program to keep the participants to be familiar to our devices before the experiments.

From quantitative questions about usability (**H2**), users feel easy to learn the multi-user CHI. Users find interested of this CHI and have high remarks on the satisfaction.

- Performance of collaboration

Then we will discuss the concept of collaboration and its evaluation results. Since our participants have little experience in collaborative design activities with a partner, they seem curious and interested in the multi-view and multi-representation collaborative working style. From the interviews, we can conclude that participants have positive comment on the synchronization of changes in design activities. One’s change can be synchronized and visualized in real time to the other participant. This shortens the time of checking modifications in another user’s visualization. A time saving in design process can be realized among several experts. Compared to traditional design activities, transferring, checking, and re-designing will cause a waste of time. From quantitative questions about the performance of collaboration (**H3**), criteria of involvement, awareness, collaborative effort all perform positive effect. These results of evaluation of collaboration reveal that our concept of introducing multi-view system into early collaborative design is feasible. The advantage of co-located face-to-face communication is obvious during the experiment.

Personas method lets participants act as some special users of a product. However, in future tests, it is better to include expert designers into experiment to make more persuasive and authoritative evaluation.

V.4 Experiment of CAR ergonomic evaluation

An experiment of collaborative ergonomic evaluation with multi-user CHI, using the CASE_OF_CAR application developed in IV.3.2.5, is conducted in this section. The aim of this experiment is to evaluate the usability of CHI (**H2**) and user performance of collaboration (**H3**) under the specific examples of evaluation activities of ergonomics in automobile industry.

V.4.1 Description of experiment

V.4.1.1 The study of ergonomic evaluation in car industry

In automotive industry, the ergonomic analysis of the driver’s posture and visual field in the car cockpit is one important stage along its design optimization. Ergonomist often needs to work besides the driver to deal with some anthropometric measurement. During a simultaneous measuring activity, the driver, and the ergonomist, they are provided with views in different orientations. They are also concerned about completely different professional information.

From the section of the state of the art, it can be inferred that the analysis of driver's posture and visual field accords with the issue of collaborative CHI with double views. In current industrial processes, the analysis of driver's posture and visual field of view (FOV), which involves two or more experts from different professional views (e.g. designer and ergonomist), is often realized in using physical car mockup or using the virtual car mock up (e.g. immersion VR system). The current approach for the evaluation of analyzing a driver’s posture and visual field in industry is often conducted in two steps:

1. Verbalization:

The ergonomist questions the driver: what blocks the lower visual field? The driver responds: the dashboard is too large so that it limits my lower visual field.

2. Geometry analysis:

The ergonomist notes the positions of the eyes for each driver when the driver answers his verbal question. The ergonomist must either use tools to conduct a real measurement, or make a screenshot of the side view of the car and driver to record the scene, as shown in Figure 85.

To determine which parts of the automobile truly limit the lower visual field, the ergonomist needs to launch a geometric calculation, which is a time-consuming post-processing after the evaluation. From the geometric calculation results, the ergonomist may realize that it was the other part than dashboard (verbalization of the driver) limiting the driver's lower vision (e.g. tip of the steering wheel, the lower edge of the front windshield, or the tip of the hood) that had blocked the driver's lower visual field.

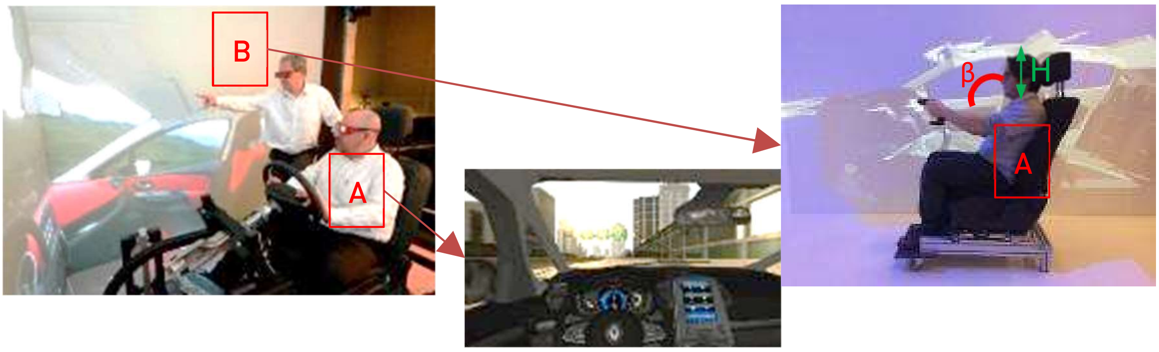


Figure 85 : Design of a project review of designer and ergonomist: A. a designer is driving a car in driver's view; B. an ergonomist can see ergonomic data, e.g. height from shoulder to roof/ angle between head and arm, on user A in real time.

We may notice the drawback of this approach is the verbalization of the driver who may contain an error, which is often due to very personal reasons. Ergonomist's side view is different from the driver's front view. From a side view, it is not easy to check driver's personal error in real time. During the post-processing, the ergonomist can no longer ask another question (otherwise rephrase the question) to the driver to check again the response. Because it is no longer at the time of evaluation in the cockpit and the driver is no longer there. Therefore, all the data associated with this driver should be rejected. This is a waste of time and data of the evaluation.

The approach with multi-view system that we proposed for the same evaluation combines the former two steps (Verbalization plus Geometry analysis) occur simultaneously:

The ergonomist always asks the same question to the driver. The driver tells him for example that it is the dashboard blocking the lower visual field according to the driver's front view. However, the view provided to the ergonomist allows him to see from the side view of the driver plus enriched technical measurement data.

V.4.1.2 Experiment scheme

This experiment is designed to explore the multi-user CHI performance and feedback of different experts in an ergonomic evaluation of CAR design. The scheme of experiment as shown in Figure 86, multi-view shutter glasses & polarized filter for visualization is applied, and accompanied by multi-interaction techniques using mouse and tracking system.

One user, a designer, is adjusting the positions of the car seat and the driving wheel in the specific usage scenario restituted virtually by a series of actions to meet the requirements of user preferences. Another user, an ergonomist, is more interested in ergonomic factors, e.g. driver's FOV. They should communicate to proceed the evaluation task.

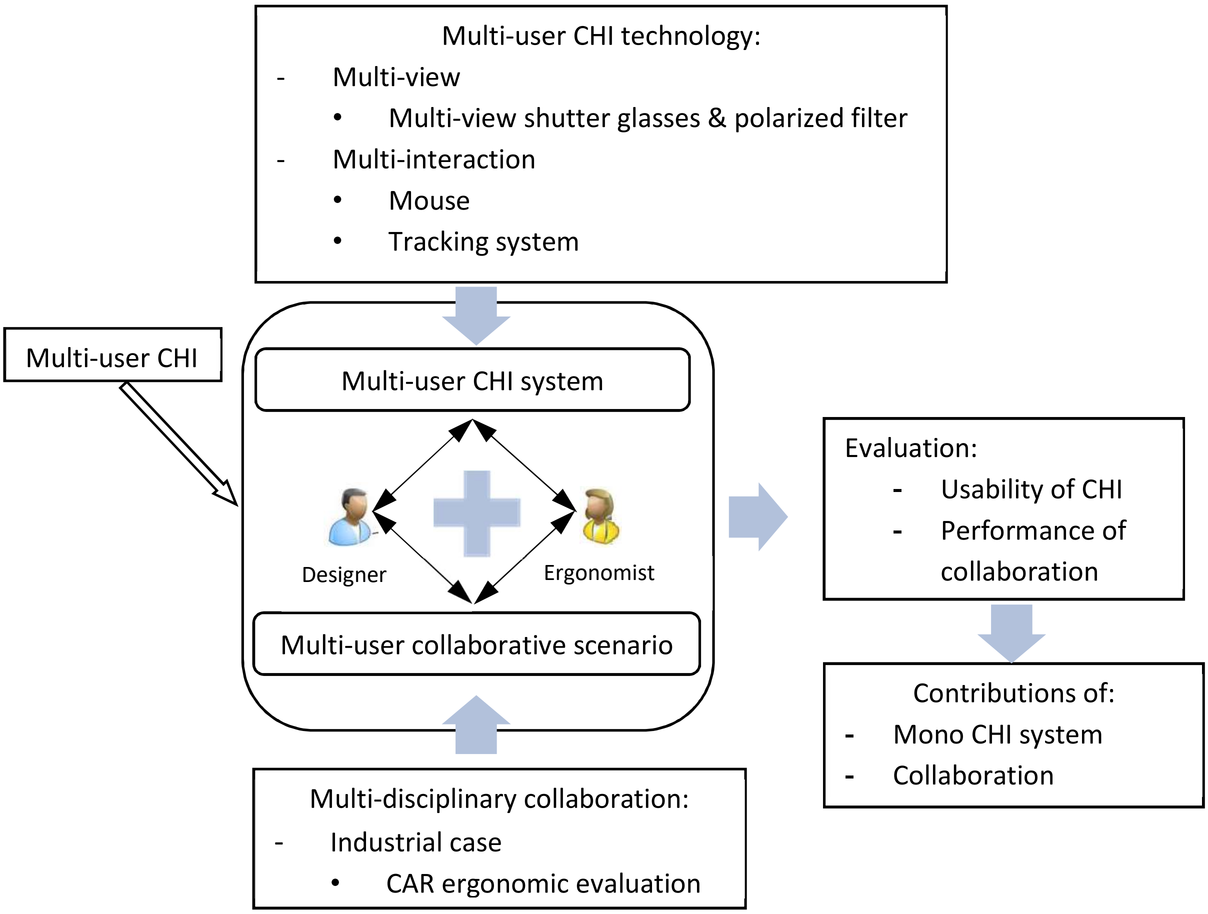


Figure 86 : Experiment scheme of CAR ergonomic evaluation.

We propose a scenario that combines Verbalization & Geometry analysis for a co-located synchronous ergonomic evaluation using multi-view system. The ergonomist can realize at once which object blocks the lower visual field by several tools developed, which consist: 1. displaying a snapshot of driver's FOV on a virtual screen; 2. darkening objects out of FOV (in Fig. 3); 3. calculating the value of FOV; 4. highlighting the part that blocks the lower visual field and displaying the bottom edge of FOV on it. These tools may help ergonomist increase the reliability of designers' answers and save the time for post-processing.

V.4.2 Experimental protocol

The experiment requires 2 participants (one will play the role of the driver and the other will play the role of ergonomist). They are asked to be recorded during the experiment by camera.

1). Introduction (5-10 min):

Participants are asked firstly to answer a questionnaire about some basic questions including their height, 3D visual experience and motion sickness.

Participants are firstly introduced with the object and procedure of the experiment. Then in a training scenario, they are asked to manipulate virtual objects. They must be taught how to do the following: reaching an object, choosing from virtual menu, reading numbers, controlling mouse and wand, etc. A training task is to be tested several times to make the collaborators familiar with our equipment. As soon as the participants are ready, the experiment starts. During the training program, the participants could learn:

- How to use the system;
- What are their collaborators able to see and to interact;
- What and how to ask their collaborator to do;
- How to understand the requirement of their collaborator.

2). test phase (30 min):

The tasks that we ask the group of participants to achieve during this "driver's lower visual field evaluation" experiment are listed below in Table 14.

Table 14 : Experimental tasks of driver's lower visual field ergonomic evaluation

	Designer	**Ergonomist**
Get ready	The designer gets sit in the vehicle.	
Task 1: Traffic cone *Verify lower field view when traffic cone is blocked*	He can see the traffic cone until it goes out of his lower visual field, then he stops the ergonomist from moving it; Answer ergonomist's questions.	Move the traffic cone towards the car; Stop when designer says that he cannot see the traffic cone; Ask questions to the designer and verify his lower visual field by the tools developed.
Task 2: Rear end of the front car *Verify lower field view when the rear end of the front car is blocked*	He can see the rear end of the front car until it comes too close that it goes out of his lower visual field, then he stops the ergonomist from moving the front car, as shown in Figure 87.a; Answer ergonomist's questions.	Move the front car towards the designer, as shown in Figure 87.b; Stop when designer says that he cannot see the rear end of the front car; Ask questions to the designer and verify his lower visual field by the tools developed.
Task 3: Visible pedestrian crossing *Verify lower field view of the pedestrian crossing*	He can see the numbers on each line of the pedestrian crossing. Answer ergonomist's questions.	Ask the designer the number of the pedestrian crossing that is in his FOV. Ask questions to the designer and verify his lower visual field by the tools developed.

The participant will well position himself in the car with his familiar driving experience. He will answer the questions from the question set asked by the ergonomist. According to the answers, only one main question or extra questions will be asked by the ergonomist. From the perspective of ergonomist, since the ergonomist can see which parts blocking the lower visual field, if the participant has a incorrect answer, the ergonomist will ask the rephrased questions from the question set to help the participant to correct.

Question set:

- Main question:
  What blocks the lower visual field?

- Extra questions:
  (a) Which part in details (position, color) blocks the lower visual field? (which part of steering wheel/dashboard/hood blocks?
  (b) Answers may be the tip/bottom/left/right/ of steering wheel/dashboard/hood.)
  (c) Do you want to slightly move your head back and forth to confirm the part that blocks the lower visual field?
  (d) Why do you think it is this part but not others that blocks the lower visual field?
  (e) Are your sure about your answer?

There are 5 cars with different models and visual situations to be tested.

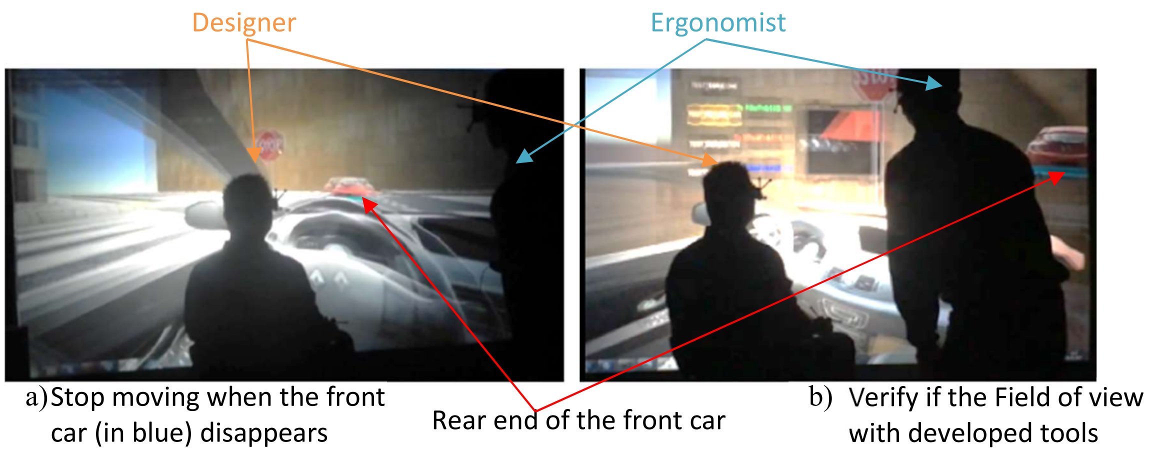


Figure 87 : Designer and ergonomist verify the rear end of the front car.

3). Feedback of experiment (20 min)

Participants are asked to fill a questionnaire and have a recorded interview to gather their points of view about the experience.

V.4.3 Results

This experiment has been tested with some experts from automobile industry as well as some academic ergonomists. Due to the unavailability of the devices, we have not a quantitative experiment with more participants. From the subjective feedbacks of users, we find that the learnability of the devices is affirmed. The use of mouse and wand is easy to understand. The illumination condition of the devices has been mentioned by users. Because of the combination of shutter glasses and polarized filters, the luminosity is decreased that it may be darker in user's eyes. Both industrial experts and academic ergonomists are interested in the collaborative manner that the user as ergonomist helps the designer with the verification of the field of view in real time. They think it will be less effort for an ergonomist to get the human factor data during the collaboration.

V.5 Synthesis of experiments

As we described in the introduction section, the user interface setup in interactive product design may have an influence on the productivity of designers. In the co-located collaborative design activities, multiple users from different domains must communicate in real time. Their collaboration will be affected by the collaboration tools, which is a multi-view CHI system as we proposed.

These experiments test the multi-user CHI system in collaborative working conditions. According to the scientific scheme that we have proposed in chapter III, the evaluations of multi-disciplinary collaborative work supported by multi-user CHI system can be modularized with multi-user CHI system, multi-user collaborative scenario, evaluation method and discussion. The choice of multi-user system techniques and collaborative scenarios of form an experiment scheme is flexible and replaceable. The multi-view system in experiment of COLLAB_PACMAN adopted anaglyph technology which is limited to number of views and visible colors. The multi-view solution to other experiments archive a four-view system which can be used in two 3D visualizations. But the limitation of markers for tracking system brings some problem with quickly mastering the interactive activities. With shutter glasses and polarized filters, there exists a decrement of the brightness of displayed images.

Table 15 Results of experiments respond to the hypotheses

	H1: Efficiency of task			**H2**: Usability of CHI system		**H3**: Performance of collaboration		
	Finish Time	Communi-cation Time	Error	Learna-bility	Satisfa-ction	Involve-ment	Aware-ness	Collaboration effort
Exp 1	×	×		×	×	×		
Exp 2	×	×	×	×		×		
Exp 3				×	×	×	×	×
Exp 4				×				×

The experiment results show academic significances of the efficiency of task, usability of CHI and performance of collaboration. As show in Table 15, two academic game simulations show that during the multi-user CHI system working condition, the objective measurements represent better efficiency (**H1**). Subjective measurements of these experiments show that the multi-user CHI system brings different contributions to collaborative criteria (**H2**, **H3**). Qualitative user analysis in MUG experiment show that users of multi-user CHI system express generally positive impressions and comments (**H2**, **H3**). Expert users' feedback of the CAR ergonomic evaluation experiment has also the responses to (**H2**, **H3**).

These experiments responses to the proposed scientific question. These are positive influence on the Efficiency of task, the Usability of CHI system, and the Performance during a collaborative work among users with different representations using multi-user interface. Form the Table 15, we can make a synthesis that the **H2** of experiment 1, the **H1** of experiment 2, the **H2** and **H3** of experiment 3 is strong validated. The other validations of the criteria in all the experiments are less strong validated, as show in Figure 88.

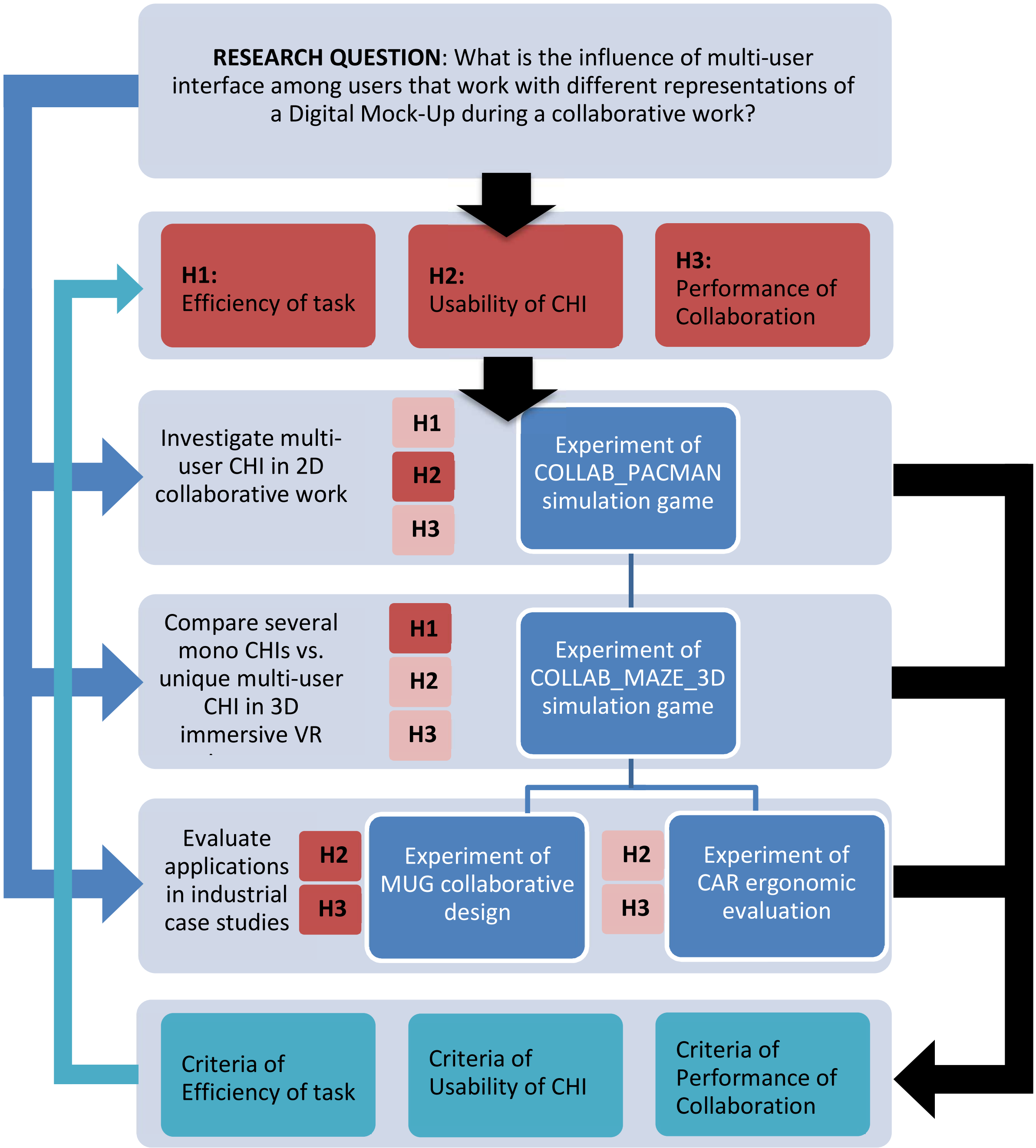


Figure 88 : Validated hypotheses in the experimental plan: hypotheses are strong validated (in dark red); hypotheses are less strong validated (in light red);

Chapter VI Conclusion and perspectives

In this chapter, a general conclusion is made on the research work carried out during this thesis. Starting from a summary on the contributions, their limitations are discussed, and the perspectives are proposed for future work.

VI.1 Proposed research question

In this thesis, we have been interested in the development and application of multi-user CHI in the context of multi-disciplinary collaborative works. Through this research work, we have investigated the industrial need of multi-disciplinary working environment and the techniques of building a multi-user CHI system. We have tried to better understand the impact of this system on the efficiency of task, the usability of CHI and the performance of collaboration.

The main research question asked in this thesis was: " What is the influence of multi-user interface among users during a collaborative work with different representations of DMU?". To answer this research question, several double user CHIs were build according to different technologies and various interaction scenarios are developed and experimented to evaluate its influence. Hypotheses of the influence have been proposed on the efficiency of task, the usability of CHI and the performance of collaboration. Through experiments, the contributions of multi-user CHI have been summarized in the improvement of a multi-user CHI, as well as the influence on collaborative work.

VI.2 Contributions

The main aim of this thesis is to study the influence of multi-user CHI on the multi-disciplinary collaborative work. To carry out the study of this research problem, we have decomposed the work of this thesis in several parts.

VI.2.1 State of the art

A state of the art in three scientific areas: collaborative, DMU, and CHI is analyzed. The definition of collaboration and the need of Concurrent Engineering (II.2.2) in current industrial product development processes are discussed. The characteristics of multi-representation (II.3.2) of DMU and its need of CHI to support collaborative works are discussed, especially for co-located simultaneously multi-disciplinary collaborative works (II.3.4). The different mechanisms (II.4.4II.4.4.2) to create multi-user CHI are introduced. The intersection of collaboration, DMU, and CHI (II.5) is emphasized in this thesis. The applications for the intersection of these three areas (II.5.3) are presented and analyzed under different criteria.

VI.2.2 Multi-user CHI system

To build a multi-user CHI system, the development is described respectively in multi-output system and multi-input system. For the visual output aspect of a multi-user system, we proposed to use auto-stereoscopic displays system (e.g. Holografika), anaglyph filter, polarized filter and multi-view shutter glasses combined with polarized filter. We developed several different devices as the input of a multi-user system, including keyboard, mouse, and tracking system. Multi-interaction metaphors for different users have been defined with mouse and tracking system.

VI.2.3 Multi-user collaborative scenario

Four collaborative applications for multiple users have been created. COLLAB_PACMAN simulation game adopts the multi-view anaglyph filter visualization technology. COLLAB_MAZE_3D simulation game is created under multi-view shutter glasses & polarized filter visualization technologies and multi-interaction techniques of keyboard, mouse, and tracking system. In these two simulation games, users should communicate to proceed a collaborative task. Two industrial cases, MUG collaborative design and CAR collaborative design have been created according to the industry need of multi-disciplinary collaboration in early collaborative design with Personas and ergonomics in automobile industry.

Four collaborative applications for multiple users have been created. COLLAB_PACMAN simulation game has been experimented under the multi-user CHI developed with the multi-view anaglyph filter visualization technology. COLLAB_MAZE_3D simulation game has been experimented under the multi-user CHI developed with multi-view shutter glasses & polarized filter visualization technologies and multi-interaction techniques of keyboard, mouse, and tracking system. In these two simulation games, users should communicate to proceed a collaborative task. Two industrial cases, MUG collaborative design and CAR collaborative ergonomic validation have been created. According to the industry need of multi-disciplinary collaboration in early collaborative design with Personas, an expected user and a designer can discuss the design of a mug collaboratively in the application of MUG collaborative design. Through the application of CAR collaborative ergonomic validation, a car body designer and an ergonomist in automobile industry can collaborate to validate the field of view of a driver in a car.

VI.2.4 Evaluations

A scheme of the methodology for evaluating the contribution to a multi-user system and the multiple users' experiences is proposed in Figure 89. The multi-user CHI is composed of a multi-user hardware/software system and a multi-disciplinary collaborative work scenario.

Hypotheses that multi-view and multi-interaction CHI supporting system can help multiple users in a collaborative co-located and real time working condition in: Efficiency of task (**H1**), Usability of CHI system (**H2)**, Performance of collaboration (**H3)** have been proposed. The methods of measurement during the experiment are quantitative objective measurement and subjective measurement, as well as qualitative user analysis. For each hypothesis, there are several criteria to be measured. For H1: Efficiency, criteria to be measured are Finish time, Communication time, Error committed, etc. For H2: Learnability and Satisfaction are criteria to be measured for usability of CHI. For H3: performance of collaboration, we usually consider involvement, awareness, and collaboration effort as criteria.

In our experiments, two academic game simulations, COLLAB_PACMAN simulation game and COLLAB_MAZE_3D simulation game, show that under the multi-user CHI system working condition, the objective measurements represent better collaborative efficiency. Subjective measurements of experiments show that the multi-user CHI system brings different contributions to collaborative work. Qualitative user analysis in MUG collaborative design experiment shows that positive impressions and comments are generally expressed by users on the multi-user CHI system

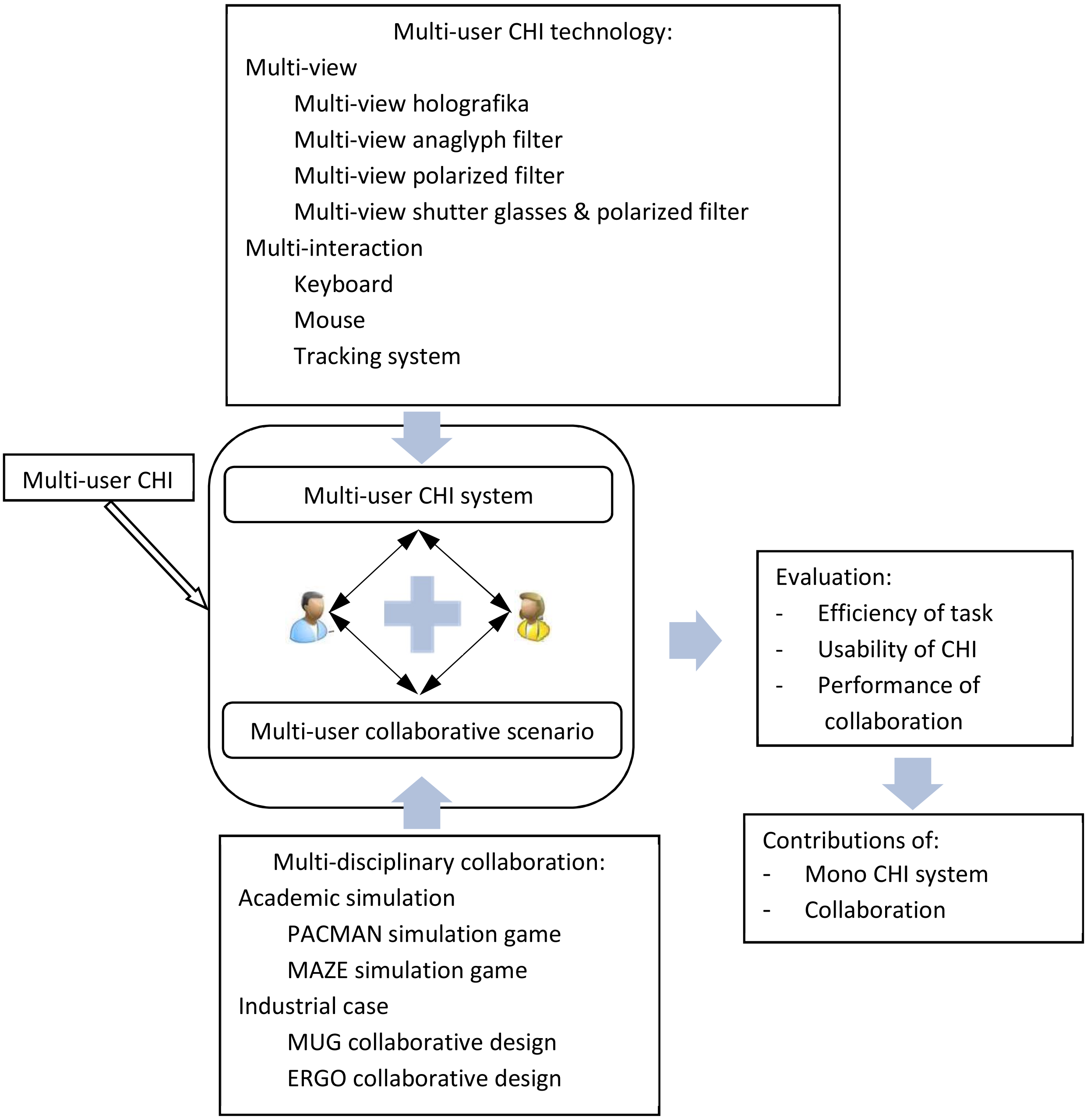


Figure 89 : Scheme of evaluation of multi-user CHI.

VI.2.5 Scientific publications

All the research results are presented in the scientific publications in journals and international conferences, as listed below:

- Journals:

Bo Li, Ruding Lou, Frédéric Segonds, Frédéric Merienne. Multi-user interface for co-located real-time work with digital mock-up: a way to foster collaboration?. International Journal on Interactive Design and Manufacturing, Springer Verlag, 2016, pp.1-13.

Bo LI, Hongyi ZHANG, Ruding LOU. Study of efficiency of multi-view system in multi-disciplinary collaboration. Special issue of the journal Research and science today.

Bo Li, Frédéric Segonds, Céline Mateev, Ruding Lou, Frédéric Merienne. Multi-representation DMU interaction through multi-view system: an experiment to enhance early collaborative design. Computers in industry. (under review)

- International conference:

Bo Li, Ruding Lou, Frédéric Segonds, Frédéric Merienne. A Multi-view and Multi-interaction System for Digital-mock up's collaborative environment. EUROVR conference 2015, Oct 2015, Lecco, Italy. 2015.

Bo Li, Ruding Lou, Frédéric Segonds, Frédéric Merienne. Multi-user Interface for Co-located Real-time Collaborative Work with Digital Mock-up. Virtual Concept Workshop 2016 Major Trends in Product Design, Bordeaux, France on 17 - 18, March 2016.

Bo Li, Ruding Lou, Javier Posselt, Frédéric Segonds, Frédéric Merienne, Andras Kemeny. Multi-view VR system for co-located multidisciplinary collaboration and its application in ergonomic design. VRST '17, November 8–10, 2017, Gothenburg, Sweden.

VI.3 Limitations

There are some limitations on both multi-user CHI techniques and performance of collaboration.

When choosing anaglyph as the mechanism of multi-view system, the defect of anaglyph is obvious because its effect of color filtration. Considering screen luminance, it is hard to find a color that can be completely removed by filters by both two filters. If creating multi-user CHI system with shutter glasses and polarized filters, there exists a decrement of the brightness of displayed images. Due to the limitation of markers for tracking system, users have difficulties to quickly master the interactive activities by the interaction metaphors realized with a combination of mouse and tracking system.

As collaborative scenarios using different DMU representation, the two experiments of COLLAB_PACMAN and COLLAB_MAZE_3D simulation games are mostly consistent with the characteristics of the industrial case. But during these two experiments, one of the user acting as helper, has only the observation of the constraints on his domain. He has not conducted a modification or a manipulation like the other user, the player. So, the helper has no interaction with the DMU and the collaboration maybe unilateral. In the industrial case experiment, Personas method lets participants act as some special users of a product. It is better to include expert designers into experiment to make more persuasive and authoritative evaluation.

VI.4 Perspectives

The presented research work is part of the studies on the multi-user CHI. This work has focused on proposing a methodology for the study of the influence of introducing multi-user CHI into collaborative working condition, especially a multi-disciplinary collaboration. There are many perspectives to be realized in the future. Some of them are listed below.

VI.1 Short range perspectives

- Improvement on multi-interaction

For multi-interaction, a Kinect that can capture users' motions in front of a certain screen may be proposed in the next version of multi-user system. Kinect could identify several users and their gestures. We could define a gesture with which different users would get different interaction results.

- Evaluation of CAR collaborative design industrial case

We propose here an experimental prototype for the evaluation of CAR industrial case. The collaborative efficiency and user performance for multiple users during ergonomics design of an automobile could be evaluated by using multi-user CHI.

VI.2 Middle range perspectives

- multi-user CHI for more than two users

There are currently some techniques for creating multi-user CHI for more than two users, however, their industrial application should be further explored.

- Expert evaluation

With the development of virtual tools that can support product design activities, more industrial requirements on the CHI supporting multiple users should be discovered. The multi-user system should be tested for a real product design project during the process of product lifecycle. The feedback from experts will be very important and practical.

VI.3 Long range perspectives

It would be interesting to focus more on the mental and cognitive aspects necessary for the collaborative work process. The work carried out in this thesis paves the way towards the establishment of a multi-user interface and multiple users' human behavior of collaborative work. There is still a lot of work to do in this context, which requires collaboration with specialists in the field of cognitive psychology and ergonomics.

Appendix A Résumé substantiel en langue française

I. Introduction

Les outils actuels de gestion du cycle de vie (en anglais product lifecycle management, ou PLM) des produits industriels reposent généralement sur la stratégie de l'ingénierie concurrente (CE). Certaines étapes du cycle de vie du produit sont menées simultanément en parallèle. Les données techniques sur chaque étape sont partagées. La maquette numérique, l'ensemble de données de toutes les données techniques, a été utilisé par divers experts dans différents domaines. Puisque les données sauvegardées ont une variété de formats, e.g. le format spécial généré par un logiciel au domaine spécifique, la maquette numérique stocke plusieurs formats de données. Chaque expert travaille avec l'une des représentations de données de la maquette numérique. Pour communiquer entre plusieurs représentations, de nombreux travaux ont été réalisés pour améliorer l'interopérabilité entre les logiciels d'ingénierie et entre les modèles dans les activités de conception.

Pendant ce temps, de nombreux outils créatifs ont été développés pour soutenir ces activités de conception. Bien que les experts doivent travailler ensemble sur une unique maquette numérique, chaque expert a sa propre perspective d'une représentation spécifique des données techniques de maquette numérique en fonction de son domaine d'expertise. Une Interaction Homme-machines (IHM) appropriée permet à chaque expert d'avoir une préférence personnalisée : une visualisation correcte de la représentation de la maquette numérique et une manière appropriée d'interagir avec la maquette numérique. Par conséquent, lorsque plusieurs experts travaillent en collaboration, le nombre de IHM augmente en fonction du nombre d'experts.

Avec le développement du groupware et de la technologie d’IHM, il est possible de concevoir des outils et des méthodes plus intuitifs pour améliorer l'interopérabilité de la collaboration entre experts. L’IHM, qui utilise à la fois des technologies multi-vues et multi-interactions, peut être appliquée par plusieurs experts lorsqu'ils travaillent dans des activités de conception collaborative, synchrone et colocalisé. Cette thèse est réalisée dans le contexte des domaines de recherche suivants :

- A. Domaine de l'ingénierie collaborative. Cela concerne les nouvelles stratégies qui sont prises en compte en génie industriel. Au cours du cycle de vie d'un produit, la façon dont les experts collaborent et ce que la collaboration peut apporter au développement du produit doit être discutée.
- B. Domaine de la maquette numérique. Des représentations multiples de données sont contenues dans la maquette numérique. L'interopérabilité de l'échange de données avec plusieurs phases industrielles dans le développement multidisciplinaires de produits doit être discutée.
- C. Domaine de l'interface homme-machine (IHM). De nombreuses technologies d’IHM peuvent prendre en charge plusieurs utilisateurs. Leurs avantages et leurs inconvénients doivent être discutés. De nouvelles technologies pour soutenir le travail collaboratif multi-représentation ont été développées. Leur utilisabilité et l'efficacité doivent être évaluées.

Pour résumer, nos recherches portent sur les domaines de la collaboration, la maquette numérique et l’IHM. Il existe des technologies visant à la conception de systèmes d’IHM pour plusieurs utilisateurs. Selon différents mécanismes, une taxonomie du système d’IHM à utilisateurs multiples sera résumée dans nos études. Principalement, un système d’IHM à utilisateurs multiples est développé à la fois dans un système multi-vue et dans un système multi-interaction. Les problèmes auxquels nous sommes confrontés pour les systèmes d’IHM à utilisateurs multiples sont les suivants :

- Comment concevoir un système multi-vue ?
- Comment concevoir un système multi-interaction ?

Les experts travaillent avec une seule maquette numérique pendant le développement du produit grâce à un système à utilisateurs multiples. Chaque expert peut travailler avec une représentation de cette maquette numérique. En collaborant les uns avec les autres, différents experts peuvent travailler ensemble. Ainsi, les problèmes de recherche pour les comportements des collaborateurs sont :

- Comment le style de travail des experts lorsqu'ils sont colocalisé ?
- Comment un système multi-utilisateur peut-il aider à la collaboration ?

Pour savoir si notre approche satisfait réellement le cas industriel, le sujet de recherche pour l'évaluation est :

- Comment évaluer un travail collaboratif avec une IHM multi-utilisateur ?

Considérant tous les problèmes de recherche mentionnés ci-dessus, notre question de recherche à explorer et à étudier dans cette thèse est la suivante :

« Quelle est l'influence de l'interface multi-utilisateurs parmi les utilisateurs ayant différentes représentations d'une maquette numérique lors d'un travail collaboratif ? »

II. L'état de l'art

Dans ce chapitre, un état de l'art dans trois domaines de recherche : l'ingénierie collaborative, la maquette numérique, et L'IHM est étudié. La définition de la collaboration et le besoin de l'ingénierie concurrente dans le processus de développement de produits industriels sont discutés. Selon différentes conditions de collaboration, les styles de collaboration typiques sont décidés.

Puisque les experts doivent travailler en collaboration avec les modèles et les logiciels, la maquette numérique est largement utilisée dans toutes les activités pendant le cycle de vie du produit. Les caractéristiques de la multi-représentation de la maquette numérique sont discutées. La nécessité d'utiliser la multi-représentation dans l'industrie est étudiée dans la conception précoce et l'ingénierie automobile.

Beaucoup de maquette numérique commerciaux peuvent intégrer la conception, l'analyse et la fabrication. Cependant, un expert n'utilise qu'une partie de la plateforme pour terminer son travail. Des affichages séparés affichent différents domaines d'informations séparément, par exemple un ordinateur portable unique ou un mur d'écran qui rassemble plusieurs écrans séparés. L'expert doit échanger les yeux et le corps pour gérer les fragments d'informations. Cela peut réduire psychologiquement la concentration de l'expert et augmenter la possibilité de malentendu et de complexité de la communication (Guangtao Zhai and Wu, 2014).

Lorsqu'ils assistent à un examen de projet, dans lequel les expressions faciales et les gestes de la main sont importants pour exprimer des idées les uns des autres, les experts ont besoin de plus de communication en face-à-face. Pour éviter le basculement entre la perspective des autres experts et la perspective de sa propre perspective, il est préférable qu'un expert ne puisse avoir sa propre perspective que dans un espace visuel partagé avec les autres. Cela aidera l'expert à communiquer et à collaborer (Agrawala et al., 1997) avec d'autres et aussi à surmonter le sentiment d'isolement qui se produit lorsque les experts utilisent leurs propres IHM, e.g. leurs ordinateurs portables, pour assister à l'examen du projet.

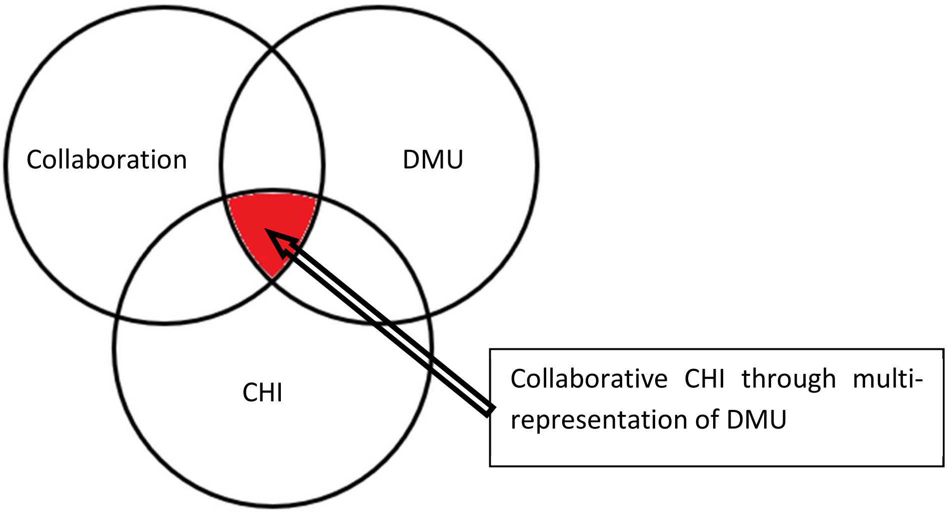


Figure 1 : Intersection de la maquette numérique, la collaboration et l'IHM : l'IHM collaborative par multi-représentation de la maquette numérique

Le positionnement de notre recherche est illustré à la Figure 1. Une IHM collaboratif pour la maquette numérique, soutenant les scénarios collaboratifs multidisciplinaires, sera développé et évalué dans cette thèse. Nous avons discuté de la collaboration dans l'industrie actuelle et le style de couplage collaboratif ; de l'utilisation de la maquette numérique dans les activités de conception pendant le cycle de vie du produit et sa multi-représentation ; d'une IHM qui prend en charge plusieurs utilisateurs et sa réalisation dans une entrée multiple et une sortie multiple, respectivement. L'intersection de la maquette numérique et de la collaboration aboutit à une collaboration multidisciplinaire. En tenant compte des facteurs humains, l'IHM multi-utilisateur qui supporte la collaboration multidisciplinaire est positionnée à l'intersection de la maquette numérique, de la collaboration et d'IHM. Dans cette thèse, nous allons développer de tels outils d'IHM qui permettent à plusieurs utilisateurs d'interagir avec. Les scénarios collaboratifs multidisciplinaires seront créés. Les outils et scénario seront aussi évalués dans cette thèse.

L'étude des applications est résumée dans le Tableau 1 autour des trois champs de recherche, en utilisant une taxonomie de chaque domaine.

En collaboration, le style de couplage collaboratif de la plupart des applications multi-utilisateurs est souple, ce qui signifie que les utilisateurs multiples travaillent en tant qu'utilisateurs individuels. Les applications (b) (g) (i) ont une collaboration de couplage mixte. Seul (b) a un système à vues multiples en 3D immersive mais les deux utilisateurs de ce système regardent une même représentation de DMU. Les scénarios dans les deux autres applications sont multidisciplinaires en visualisation mais manque de multiples dispositifs d'entrée interactifs.

En maquette numérique, les applications adoptent généralement une multi-représentation pour les collaborations de couplage libre. (b) (g) (i) sont les applications qui utilisent des représentations multidisciplinaires de la maquette numérique pour des scénarios de collaboration de couplage mixte.

En IHM, les systèmes d'IHM multi-vues étudiés sont développés avec des mécanismes de filtrage, de temps et de spatiales, même avec les combinaisons de ces techniques. (a) (b) (f) (h) ont des environnements multi-vues 3D immersifs, qui intègrent la réalité virtuelle (RV) dans les scénarios collaboratifs. Dans (a) (b), plusieurs utilisateurs ont plusieurs dispositifs pour interagir avec le système d'IHM. Cependant, les différentes métaphores de l'interaction sont rarement mentionnées et définies.

Nous allons examiner les applications que nous avons trouvées dans le domaine de la collaboration, la collaboration et l'IHM, en utilisant les critères que nous avons présentés auparavant. Une taxonomie des applications est décrite dans le Tableau 1.

En raison de la mise en œuvre de l'ingénierie concurrente dans les activités industrielles et de la nature collaborative, beaucoup plus de collaboration avec divers domaines d'expertise dans l'ensemble du cycle de vie du produit est nécessaire. Lorsque des experts individuels doivent travailler de manière interactive sur les différentes phases du cycle de vie du produit, les styles de couplage sont classés en :

- Couplage serré ;
- Couplage lâche ;
- Couplage mixte.

Les maquettes numériques doivent être partagées entre les différents types de logiciels spécifiques au domaine et entre experts. Il est parfaitement raisonnable de relier la maquette numérique aux activités de ses multiples applications pour les multiples logiciels. Pour réaliser cela, les applications doivent être créées en suivant les caractéristiques de la maquette numérique :

- Multi-représentation

Tableau 1 : Conception collaborative via la maquette numérique

Application	**Collaboration (Coupling)**			**DMU**	**CHI**					
					Multi-view				Multi-interaction	
					Multi-view mechanism (-based)			Multi-POV (VR)		
	Tight	Mixed	Loose	Multi-representation	Filter	Time	Space		Multi-device	Multi-interaction
(a)	×					×		×	×	
(c)			×				×			
(d)			×	×	×	×				
(e)			×	×			×			
(f)			×	×		×		×		
(g)		×		×			×			
(b)		×			×	×		×	×	
(h)	×					×		×		
(i)		×		×	×	×				
(j)			×		×					
(k)			×	×			×			
(n)			×				×			×
(m)	×						×			
(o)										×
(l)				×			×			

A partir d'une DMU, il est également possible de générer des modèles 3D avec un logiciel VR. Ils sont normalement construits de triangles (polygones) et peuvent être convertis en formats propriétaires d'outils DMU. Le dispositif de visualisation normal fournit une vue 2D à l'utilisateur, comme la télévision, l'ordinateur et le smartphone. Par rapport à l'affichage à vue unique, la visualisation multi-vues offre plusieurs vues aux utilisateurs. Deux images 2D légèrement différentes présentes respectivement dans les yeux humains peuvent être fusionnées dans le cerveau humain pour avoir une vision stéréoscopique (Dodgson, 2005). Puisque le modèle de géométrie d'une DMU est habituellement au format 3D, il y aura au moins quatre vues 2D pour que deux utilisateurs aient une vue stéréoscopique d'une DMU. En raison d'une utilisation particulière du système à vues multiples dans plusieurs PDV, la multi-vue peut être utilisée pour générer la stéréoscopie :

- Multi-Point-de-vue (RV)

Comme nous l'avons catégorisé, le système à vues multiples a trois mécanismes :

- Basé sur un filtre,
- Basé sur le temps,
- Basé sur l'espace

Le système multi-interaction a deux phases :

- Dispositifs multimodaux,
- Métaphores multiples

III. Méthode scientifique

Selon l'état de l'art, le positionnement de la question de recherche est à l'intersection de la maquette numérique, la collaboration et l'IHM. Lorsque plusieurs experts travaillent dans une activité multidisciplinaire, les systèmes d'IHM existants ont des problèmes de la visualisation et de l'interaction des représentations multiples dans l'activité collaborative.

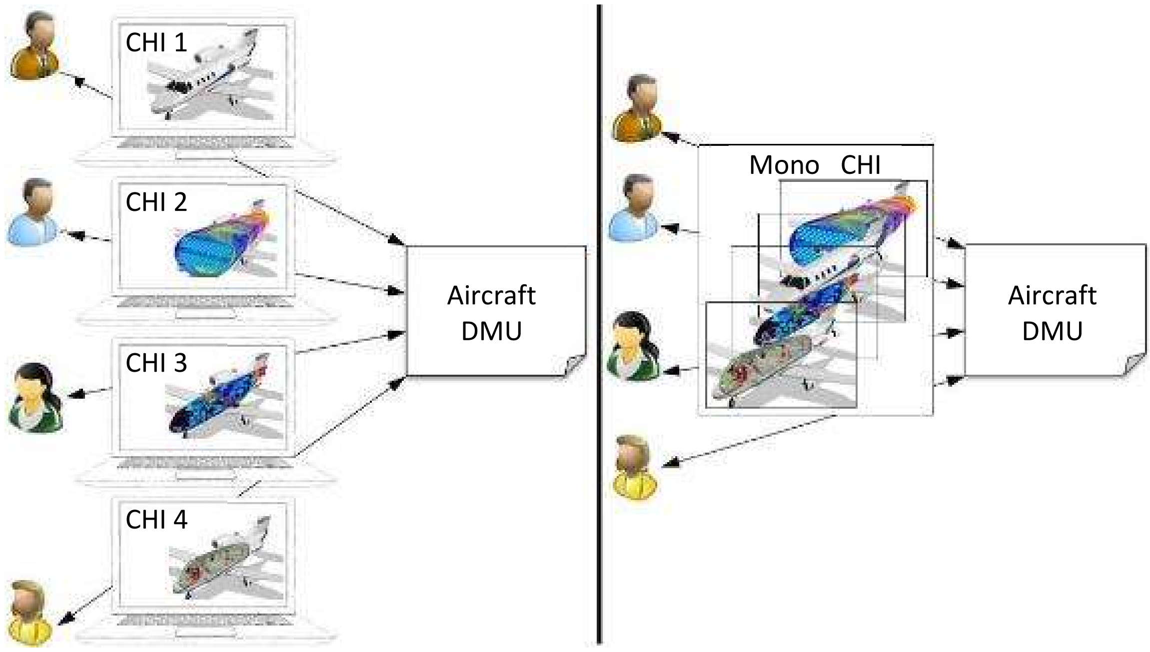


Figure 2 : Une seule IHM multi-utilisateur (à droite) remplace plusieurs interactions homme-machine (à gauche).

Pour améliorer la collaboration des experts dans différents domaines afin de communiquer avec la maquette numérique, un nouveau système d'IHM a été pris en compte, comme illustré dans la Figure 2. Sur la gauche, chaque utilisateur récupère son propre IHM et a ses propres entrées et sorties à travers cette IHM et au total quatre interfaces d'IHM sont utilisés. Sur la droite, quatre utilisateurs adoptent une seule interface homme-machine pour travailler avec la maquette numérique. Cette unique IHM permet à plusieurs utilisateurs de travailler avec les outils qu'il / elle préfère. Ils peuvent obtenir des modifications synchronisées en temps réel. Ils peuvent se sentir libres de discuter avec d'autres experts dans une condition de travail colocalisé.

Pour résoudre ces problèmes scientifiques, ***« Quelle est l'influence de l'interface multi-utilisateurs parmi les utilisateurs ayant différentes représentations d'une maquette numérique lors d'un travail collaboratif ? »***, le schéma suivant est proposé (Figure 3).

Une IHM à utilisateurs multiples, composée d'un système à utilisateurs multiples et d'un scénario de collaboration multidisciplinaire, est proposée. Plusieurs utilisateurs peuvent interagir avec le système d'IHM respectivement. Ils peuvent également travailler ensemble dans un scénario collaboratif, avec une représentation différente d'une même maquette numérique. Pour étudier la question de recherche, une méthodologie d'évaluation de l'efficacité, de la usabilité et de la performance de la collaboration de cette IHM multi-utilisateurs est proposée. Les résultats de l'évaluation peuvent avoir des contributions à la conception d'IHM multi-utilisateurs et à l'amélioration de la collaboration de groupe. La méthode scientifique proposée comprend les étapes suivantes :

- Mettre en place un système multi-utilisateurs utilisant des technologies existantes : multi-vues et multi-interactions.
- Définir un scénario de collaboration multi-utilisateurs en tenant compte de la représentation spéciale adoptée par chaque utilisateur.
- Evaluer l'efficacité de la tâche, l'utilisabilité de l'IHM et la performance de la collaboration par des méthodes d'évaluation.
- Analyser les résultats de l'évaluation et discuter des contributions que la nouvelle IHM pourrait fournir aux critères de conception de l'IHM multi-utilisateur et de la collaboration partagée par plusieurs utilisateurs.

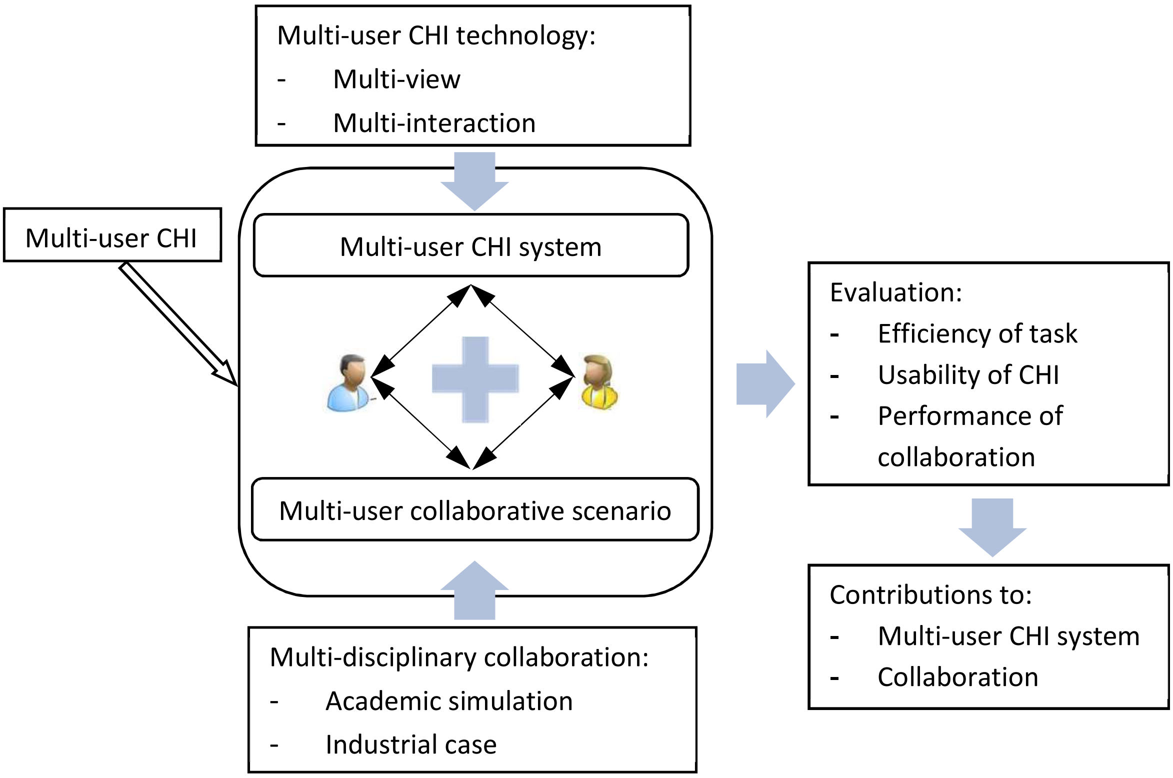


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Figure 3: Méthode scientifique proposée.

III.1 Conception d'un système multi-utilisateur

III.1.1 Multi-vue

Nous avons proposé plusieurs solutions, basé sur les technologies de l'Institut Image du laboratoire LE2I, pour le système multi-vue

- Deux paires de lunettes anaglyphes peuvent être utilisés comme une approche basée sur un filtre pour séparer la lumière mixte de rouge et de cyan. De même, deux paires de lunettes polarisées peuvent être utilisées pour obtenir deux vues à partir d'une lumière mixte en raison des différences de direction de polarisation de la lumière.
- En utilisant le dispositif de Holografika (Balogh et al., 2005) avec une technologie autostéréoscopique avancée, nous pouvons proposer une solution multi-vues basée sur l'espace.

Cet appareil dispose d'un écran qui peut afficher plusieurs images en fonction des différents points avant l'écran.

- Un système combinant à la fois des technologies basées sur des filtres et des technologies basées sur le temps a également été proposé. Deux projecteurs à obturateur actif émettent des images à travers deux filtres polarisés et les deux verres obturateurs actifs reçoivent des images présélectionnées par les filtres polarisés correspondants fixés aux lunettes. Par conséquent, ce système peut fournir simultanément quatre vues simples ou deux vues stéréo pour afficher deux scènes 3D de manière synchrone.

III.1.2 Multi-interaction

Dans notre système d'IHM proposé, plusieurs modalités d'interaction sont disponibles. En utilisant le clavier pour contrôler la navigation de l'objet des scénarios, l'utilisateur a beaucoup de choix de manières d'interaction afin qu'il / elle puisse s'habituer au système. Les boutons de souris sont utilisés pour déterminer un mode de navigation de contrôle dans une scène 3D.

Le système de suivi peut obtenir la position d'espace du point défini sur l'utilisateur (par exemple la tête, la main) ou sur un équipement (par exemple un siège de voiture). Cela peut aider à mettre à jour la position de la représentation virtuelle de l'utilisateur ou de la voiture dans une scène 3D. Les positions de plusieurs utilisateurs peuvent également être capturées avec des systèmes de suivi. En combinant les boutons de la souris, plusieurs utilisateurs peuvent interagir avec les scénarios de sélection, de manipulation et de navigation grâce à des mouvements interactifs prédéfinis.

III.2 Proposition des scénarios de collaboration multi-utilisateur

Comme peut-on voir dans la figure 3, une IHM multi-utilisateur est réalisé en combinant un système d'IHM multi-utilisateur et des scénarios de collaboration multi-utilisateur. En particulier dans un système à vues multiples, les différents mécanismes d'obtention de vues multiples auront un effet sur les images émises finales. Si l'on pense à la couleur d'un pixel en fonction non seulement de ses coordonnées x et y, mais aussi des différents mécanismes des mécanismes multi-vues (MVM). La couleur d'un pixel à plusieurs vues peut être définie comme :

$$pixelcolor_{x,y} = f(x, y, MVM).$$

Avec MVM : mécanismes multi-vues (Filtre ou temps ou espace).

Les représentations des utilisateurs déterminent le scénario de collaboration multi-utilisateur. Les images émises par le système à vues multiples sont liées aux représentations des scénarios des utilisateurs. Considérant les représentations des utilisateurs, nous avons proposé que pour un système collaboratif à vues multiples, la couleur de chaque pixel puisse être définie avec cette formule :

$$pixelcolor_{x,y} = f(x, y, MVM, REP).$$

Avec MVM : Les mécanismes multi-vues (Filtre ou temps ou espace)

REP : Les représentations de maquette numérique

Dans un contexte de travail collaboratif, il est important d'intégrer plusieurs représentations de maquette numérique au scénario de plusieurs utilisateurs dans un système à vues multiples.

Nous proposerons à la fois des scénarios expérimentaux académiques et des scénarios de cas industriels. Pour étudier les styles de collaboration de plusieurs utilisateurs avec une expérience quantitative, des simulations de collaboration multidisciplinaire sont conçues. Chaque utilisateur a sa propre représentation de la tâche de travail. Les deux utilisateurs doivent également collaborer pour terminer une tâche simulée. Ces simulations correspondent aux travaux collaboratifs industriels. Un jeu de simulation académique peut représenter le processus de collaboration entre plusieurs utilisateurs dans la conception de produits industriels, en plus, il peut être évalué avec des critères quantitatifs. Ainsi, nous avons proposé deux scénarios de jeux de simulation pour établir des expériences.

Selon les domaines industriels ayant des besoins de collaboration multi-utilisateurs, les scénarios de conception collaborative multi-utilisateurs ont été réalisés. Un scénario de conception collaborative précoce d'un mug, impliquant les expériences de l'utilisateur et les critères de conception a été proposé. Ce scénario implique les expériences utilisateur et les critères de conception. Un scénario de collaboration pluridisciplinaire entre ergonome et conducteur dans l'industrie automobile a été conçu.

III.3 Évaluation

III.3.1 Hypothèses

L'évaluation est importante pour aider à guider le processus de conception. Puisque nous étudions le système d'IHM plus les scénarios de collaboration multidisciplinaire, la plupart des techniques d'évaluation sont utilisées dans le domaine de l'interface utilisateur.

Dans la Figure 4, pour évaluer comment le système d'IHM multi-utilisateur proposé influence la collaboration multi-utilisateur à travers des représentations de DMU, trois aspects sont liés :

- L'Efficacité de la tâche : le temps utilisé pour terminer une tâche. La communication au cours de la tâche est considérée si la tâche a une collaboration entre les utilisateurs. Les erreurs effectuées pendant la tâche sont également prises en compte.
- L'utilisabilité de IHM : L'utilisabilité est la qualité qu'un système offre au niveau de la facilité d'apprentissage, de la facilité d'utilisation et de la satisfaction des utilisateurs (Nielsen, 1994). Trois facteurs contribuent à l'utilisabilité d'un système : la performance humaine, l'effort cognitif et l'activité collaborative.
- La performance de la collaboration : les performances de plusieurs utilisateurs lorsque les utilisateurs effectuent une tâche en collaboration. Il s'agit des facteurs de psychologie cognitive, tels que l'implication dans la collaboration, la sensibilisation du collaborateur.

Selon ces aspects connexes, dans cette thèse, nous proposons des hypothèses pour répondre à notre question de recherche comme suit :

H1 : L'IHM multi-utilisateur, qui permet à plusieurs utilisateurs de travailler en collaboration avec différentes représentations d'une maquette numérique, a une influence sur **l'efficacité de la tâche**.

H2 : L'IHM multi-utilisateur, qui permet à plusieurs utilisateurs de travailler en collaboration avec différentes représentations d'une maquette numérique, a une influence sur **l'utilisabilité de IHM**.

H3 : L'IHM multi-utilisateur, qui permet à plusieurs utilisateurs de travailler en collaboration avec différentes représentations d'une maquette numérique, a une influence sur **la performance de la collaboration**.

Pour chaque hypothèse, il y a plusieurs critères à mesurer. Comme le montre la figure 4, pour l'efficacité, les critères à mesurer sont **le temps de travail**, **le temps de communication**, **l'erreur commise**, etc. **La facilité d'apprentissage** et **la satisfaction** sont des critères à mesurer pour l'usabilité d'IHM. Dans le cadre de la collaboration, nous considérons généralement les critères de l'**implication**, de l'**awareness** et l'**effort de collaboration** comme critères.

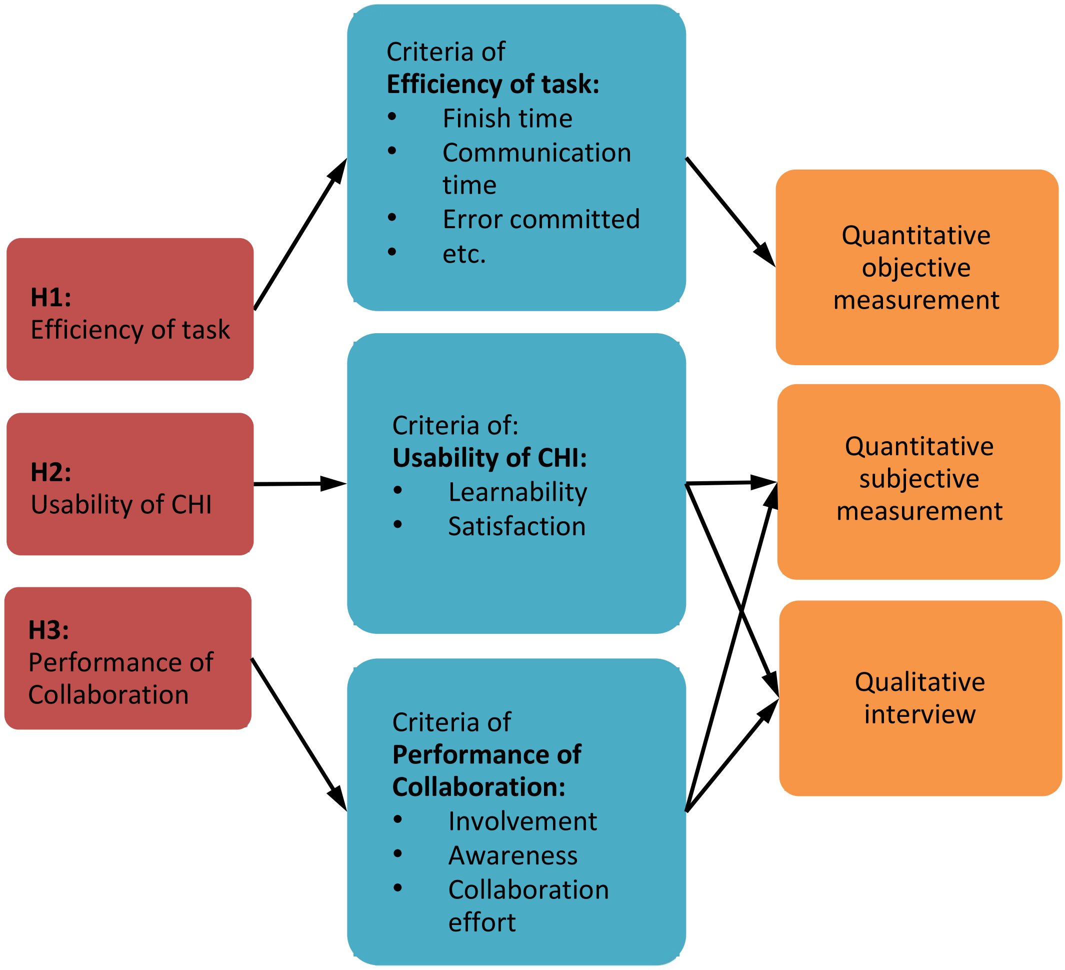

Figure 4: Les critères d'hypothèses et les méthodes d'évaluation

III.3.2 Mesure

Selon la catégorisation de (Hrimech, 2009), l'évaluation consiste en une évaluation formative et une évaluation sommative. L'évaluation formative est utilisée pour affiner la conception d'une technique d'interaction ou d'une métaphore d'interaction. En général, deux méthodes d'évaluation formative sont utilisées : 1. Évaluation en ligne. Des études d'observation seront effectuées sur les utilisateurs (présence simultanée d'un utilisateur et d'un expert en conception). 2. Évaluation hors ligne. Questionnaires, interviews, enregistrements audios et / ou vidéo. L'évaluation sommative consiste à comparer plusieurs techniques au cours d'une même séance d'évaluation. On peut donner comme exemple l'étude de la technique la plus appropriée pour l'accomplissement d'une tâche spécifique. Dans ce cas, les résultats d'une évaluation sommative, qui consiste en un protocole expérimental strict, une sélection de l'utilisateur, etc., sont généralement quantitatifs et l'évaluation du travail collaboratif est analysée statistiquement (Hrimech, 2009).

Dans notre travail de thèse, des méthodes d'évaluation formative et sommative sont utilisées durant notre expérience. Selon différents critères, nos méthodes d'évaluation sont classées : la mesure quantitative (objective et subjective), et la mesure qualitative (entretien).

- La mesure objective quantitative

Une mesure objective en fonction de l'exécution de la tâche est effectuée. Les critères mesurés de l'efficacité de la tâche, basés sur les littératures (Lissermann et al., 2014), comprennent:

  - **Le temps de travail** : La durée des temps d'achèvement au cours d'une tâche collaborative ;
  - **L'erreur commise** : L'erreur commise pendant la tâche ;
  - **Le temps de communication** : Combien de temps les participants passent-ils à communiquer avec leur partenaire ;
  - **Nombre de paires question / réponse :** le nombre total de communications avec la tâche ;
  - **Somme du temps de réponse de toutes les paires question / réponse :** Une accumulation du temps de réponse de toutes les questions ;
  - **Ratio du temps de communication au temps de travail :** Le pourcentage de temps de communication au temps de travail.
- La mesure subjective quantitative

A l'aide d'un questionnaire, nous pouvons mesurer les variables adaptées à notre Hypothèse 2 et à notre Hypothèse 3 :

  - **La facilité d'apprentissage**:

Il est facile pour les utilisateurs d'accomplir des tâches élémentaires la première fois qu'ils rencontrent le design (Nielsen, 1994).

  - **La satisfaction:**

La satisfaction signifie l'acceptation par l'utilisateur des outils ou de la performance du système (Hrimech, 2009);

  - **L'awareness:**

L'awareness propose qu'en plus de la capacité de communiquer directement, les utilisateurs de systèmes partagés soient généralement sensibilisés à la présence et à l'activité de chacun (Gerhard et al., 2001). Dans notre recherche, nous proposons de considérer l'awareness comme la volonté et le degré de connaissance de la position du collaborateur et des besoins

  - **L'effort de collaboration :**

L'effort de collaboration est la quantité de travail que deux collaborateurs fournissent pour accomplir une tâche spécifique dans un contexte de collaboration (Harms and Biocca, 2004). Cela représente la qualité et la complexité de la tâche de collaboration.

- **L'implication :**

L'implication indique le sentiment des participants de bien participer à leurs activités (Gerhard et al., 2001).

- L'analyse qualitative de l'utilisateur

L'analyse qualitative de l'utilisateur est une méthode d'évaluation basée sur des groupes de discussion, des entretiens, des observations d'utilisateurs et d'autres formes de recherche qualitative. Les scientifiques, les ingénieurs et les rédacteurs techniques déterminent que les caractéristiques des utilisateurs influenceront le développement du produit testé (Pruitt, J.S, & Grudin, 2003). Il est généralement utilisé dans l'analyse ergonomique d'un produit. Dans notre thèse, nous adoptons un entretien qualitatif pour analyser les performances de l'utilisateur et les retours du point de vue de l'utilisateur dans l'expérience.

Dans Figure 4, les critères d'efficacité de la tâche sont évalués par mesure objective. La mesure subjective et l'analyse qualitative de l'utilisateur peuvent toutes deux évaluer les critères d'usabilité d'IHM et la performance de la collaboration.

III.3.3 L'analyse statistique

Une moyenne et une déviation des données de différentes conditions sont comparées. Ensuite, une analyse des différences entre les conditions expérimentales est nécessaire. Dans nos expériences, puisque nous laissons chaque groupe de participants mener des expériences dans des conditions différentes, les échantillons participant à différentes conditions sont liés et dépendants. Lors du choix de la méthode d'analyse, ces échantillons dépendants nécessitent des méthodes d'analyse appariées ou des analyses répétées d'échantillons. Différentes méthodes d'analyse statistique sont adoptées pour comparer les moyennes des échantillons dépendants (Freedman, 2009). Les hypothèses paramétriques doivent être vérifiées avant de tester les données, y compris l'hypothèse de normalité (par exemple, le test de Kolmogorov-Smirnov) et l'hypothèse d'homogénéité de la variance (test de Levene). Si les données respectent à la fois la normalité et l'homogénéité, les méthodes paramétriques de test t apparié et ANOVA à mesures répétées peuvent être utilisées. Si les données respectent la normalité mais pas l'homogénéité, avec des tailles de groupes et / ou des variances inégales, il existe des méthodes, telles que le test de Brown Forsythe et le test de Welch. Si les données ne respectent pas la normalité, des méthodes non paramétriques, telles que le test de Wilcoxon et le test de Friedman, devraient être adoptées. Lorsqu'il existe une différence significative entre plus de deux groupes, un test Post-hoc est utilisé pour la comparaison entre deux des trois conditions (Paramétrique : LSD, Scheffe, etc. Non-paramétrique : Games-Howell).

III.4 Discussion sur les contributions de l'évaluation

La discussion des résultats de l'évaluation portera sur : la technologie, l'usabilité et le facteur humain de la collaboration. A partir d'une mesure objective, le système peut être essentiellement évalué l'efficacité de la tâche pour mettre en évidence les avantages de la technologie d'IHM multi-utilisateur.

L’usabilité du système et les commentaires des utilisateurs sont considérés comme des retours d'utilisateurs importants. Les améliorations futures du système en termes de facteurs humains reposent sur ces rétroactions telles que les inconvénients des dispositifs actuels et les demandes de fonctionnalités possibles.

La discussion sur les performances de la collaboration nous guidera dans la gestion des styles de collaboration avec plusieurs utilisateurs. Les résultats de l'évaluation peuvent influencer l'amélioration de la méthode d'ingénierie collaborative à l'avenir.

IV. Développement technologique

Comme le montre la Figure 5, pour concevoir une interface multi-utilisateur pour plusieurs utilisateurs, nous nous concentrons sur deux aspects principaux, le système d'IHM multi-utilisateur et les scénarios collaboratifs multi-utilisateurs.

D'un point de vue technique, la plate-forme est conçue avec des périphériques et des logiciels. Les périphériques comprennent :

- Le périphérique de sortie : les différents périphériques d'affichage multi-vues que nous avons utilisés pour plusieurs vues. Selon les différents mécanismes, plusieurs types d'affichage sont présentés ci-dessous en détails.
- Le périphérique d'entrée : les dispositifs utilisés pour détecter la position et les mouvements des utilisateurs et les commandes données par les utilisateurs.

Pour le logiciel :

- Echange de réseau : Le périphérique de réseau et le réseau utilisateur-utilisateur.
- Applications : les applications collaboratives que nous avons développées

For the visual outputs of a multi-user system, we developed multi-view with the space-based system, multi-view with anaglyph filter, multi-view with polarized filter, and multi-view with shutter glasses & polarized filter. We developed a different device as the input of a multi-user system, including keyboard, mouse, and tracking system. Multi-interaction metaphors for different users have been defined with mouse and tracking system. The connection between hardware and software, as well as the connection among applications have been developed by using VRPN, IIVR, and Network Management of Unity3D. Four collaborative applications for multiple users have been created. COLLAB_PACMAN adopts the multi-view anaglyph filter technology and it is a 2D simulation game. The other three applications can be executed with immersive system. Two industrial cases have been created according to the industry needs of multi-disciplinary collaboration.

Pour les sorties visuelles d'un système multi-utilisateurs, nous avons développé multi-vue avec le système spatial, multi-vue avec filtre anaglyphe, multi-vue avec filtre polarisé, et multi-vue avec des lunettes à obturateur et filtre polarisé. Nous avons développé un dispositif différent en tant qu'entrée d'un système multi-utilisateur, y compris le clavier, la souris et le système de suivi. Des métaphores multi-interactions pour différents utilisateurs ont été définies avec la souris et le système de suivi. La connexion entre le périphérique et le logiciel, ainsi que la connexion entre les applications ont été développées en utilisant VRPN, IIVR et Network Management de Unity3D. Quatre applications collaboratives pour plusieurs utilisateurs ont été développées. COLLAB_PACMAN adopte la technologie de filtre anaglyphe multi-vue et il s'agit d'un jeu de simulation 2D. Les trois autres applications peuvent être exécutées avec un système immersif. Deux cas industriels ont été créés en fonction des besoins de la collaboration pluridisciplinaire de l'industrie.

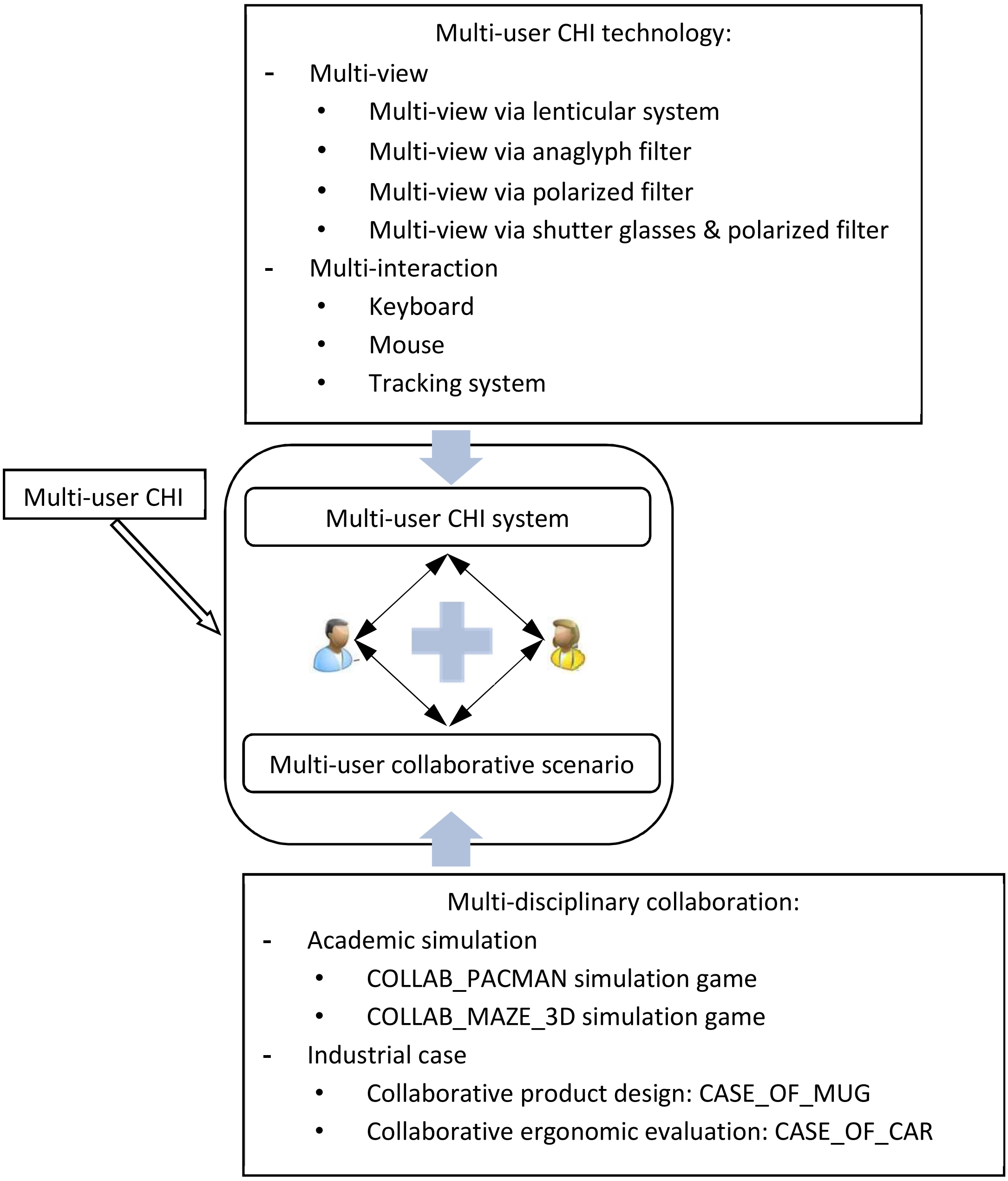

Figure 5: La plateforme d'IHM multi-utilisateur a diverses combinaisons de systèmes d'IHM multi-utilisateurs et de scénarios collaboratifs.

IV.1 Un exemple du système d'IHM multi-utilisateur

Pour fournir une vue stéréoscopique dédiée à deux utilisateurs, un filtrage système basé sur la forme de la lumière et sur la phase temporelle, est proposé. Le système utilise des projecteurs vidéo numériques à haute luminosité. Chaque projecteur est contrôlé par un ordinateur et peut fournir une vue stéréoscopique individuelle en raison de son taux de rafraîchissement de 120Hz. Chaque utilisateur porte une paire de lunettes à obturateur avec lentille oculaire LCD. L'émetteur du signal RF est connecté à chaque projecteur et reçu par les lunettes à obturateur. L'ouverture de l'écran LCD des deux lunettes sur le volet sera synchronisée avec le signal envoyé pour réaliser la multi-vue temporelle de chaque œil. En attendant, pour servir plusieurs utilisateurs, la lumière émise par les deux projecteurs est projetée sur un même écran argenté, mais être séparée par un filtre polarisé pour obtenir une certaine lumière polarisée. Avec les filtres polarisés correspondants sur les lunettes à obturateur, les utilisateurs ne verront donc que l'image émise par le projecteur correspondant aux filtres.

La mise en œuvre de ce système multi-vue est représentée sur la Figure 6, deux projecteurs de DIGITAL PROJECTION TITAN 1080p 3D sont utilisés (Figure 6.a). Chaque projecteur a une fréquence de 120 Hz et une résolution WUXGA (FHD). Chaque projecteur a été connecté à un émetteur Volfoni ActivHub RF50. Cet émetteur peut donner un signal synchronisé à ses lunettes à obturateur correspondantes Volfoni EDGE VR, ce qui permet à l'utilisateur de recevoir deux images différentes dans l'échelle de temps. Lorsque deux verres recherchent des signaux, les signaux des émetteurs doivent être réglés sur deux canaux de signal afin que les signaux n'interfèrent pas les uns avec les autres. Volfoni fournit un logiciel de support pour initialiser le canal des émetteurs et des lunettes à obturateur.

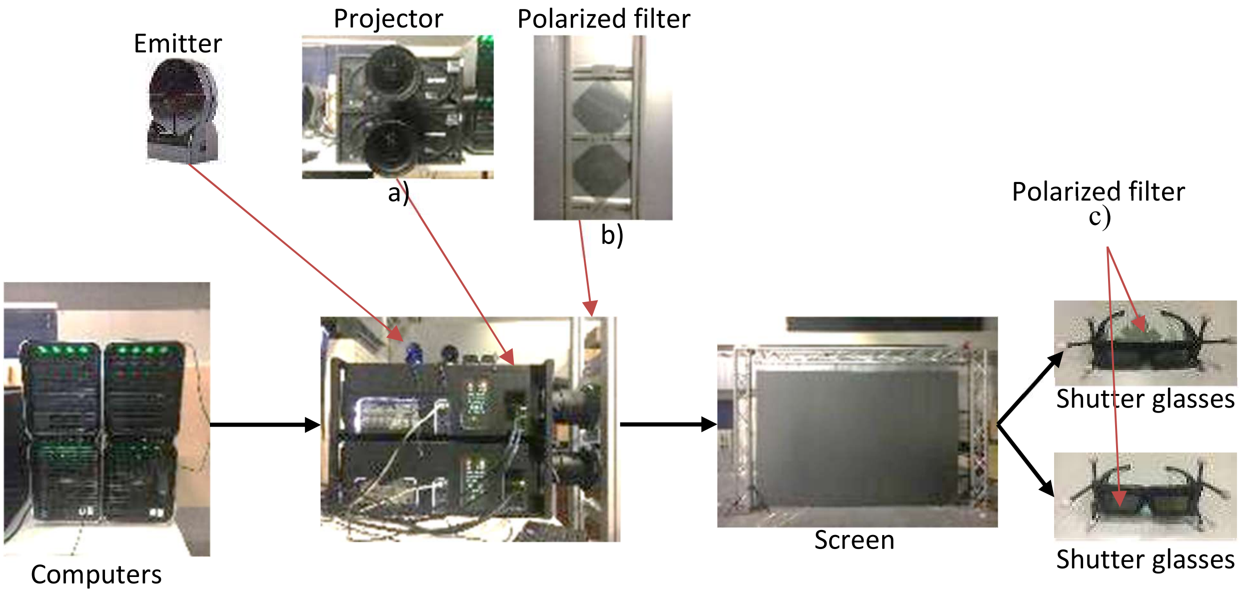

Figure 6 : La mise en œuvre d'une combinaison d'un système multi-vue 3D à deux utilisateurs.

Deux filtres polarisés (Figure 6.b) avec des directions orthogonales sont positionnés devant la sortie des lentilles des projecteurs. Des filtres (Figure 6.c) avec la même direction sont également positionnés devant les lunettes des utilisateurs, de sorte que deux utilisateurs peuvent obtenir de la lumière avec des directions orthogonales.

Pour étudier l'influence de l'interface multi-utilisateur entre les utilisateurs avec différentes représentations d'une DMU au cours d'un travail collaboratif, les besoins des applications en développement sont analysés et répertoriés dans le Tableau 2. Dans les applications mentionnées précédemment dans l'état de la technique, plusieurs utilisateurs travaillent avec :

- Plusieurs Interfaces d'IHM
- L'IHM multi-utilisateur avec une représentation
- Le lâche couplage de collaboration

Les scénarios de notre application sont tous une collaboration de couplage mixte via une seule interface d'IHM multi-utilisateur avec des représentations de DMU. COLLAB_PACMAN et COLLAB_MAZE_3D sont des simulations de cas industriels car nous avons besoin d'applications plus faciles à réaliser.

Table 2: L'identification des besoins pour les applications

Name	Identify needs	Applications
COLLAB_PACMAN simulation game	A control experiment to investigate the impact a multi-user CHI has on collaboration	2D multidisciplinary collaborative task
COLLAB_MAZE_3D simulation game	A control experiment in 3D immersive VR environment to compare: a. several mono CHIs and b. unique multi-user CHI	3D immersive multidisciplinary collaborative task
Collaborative product design: CASE_OF_MUG	Influence on an industrial case study in early product design through collaborative VR tools	3D immersive multidisciplinary collaborative scenario for mug design
Collaborative ergonomic evaluation: CASE_OF_CAR	Influence on an industrial case study in car ergonomic validation through collaborative VR tools	3D immersive multidisciplinary collaborative scenario for car validation

IV.2 Un exemple du scénario de collaboration multidisciplinaire

Une application de conception collaborative précoce est menée entre deux collaborateurs. L'un d'eux est un utilisateur spécifique d'un mug qui a un cadre de caractère typique, comme l'âge, la profession. L'autre collaborateur est un concepteur d'un mug qui peut gérer les différents paramètres fonctionnels et de conception. Le système multi-utilisateur développé prenant en charge la multi-représentation de DMU permet à deux utilisateurs de collaborer en temps réel.

L'idée est de réunir deux collaborateurs dans une même scène pour optimiser la solution de conception et expérimenter l'utilisation d'un mug.

L'utilisateur de le mug expérimente son utilisation dans un contexte spécifique (à l'intérieur d'une voiture) en environnement virtuel (Figure 7.a)

- Manipuler le mug,
- Mettre le mug dans le porte-gobelet,
- Mettez le sachet de thé dans le mug,
- Prendre le document sans renverser le mug.

Pendant ce temps, le concepteur de mug est plus intéressé par les paramètres de conception et les données d'analyse (Figure 7.b), par ex. taille, analyse thermique etc. Si la taille du mug est changée, l'utilisateur et le concepteur de mug verront. Les deux ont d'autres éléments individuels que seulement chacun peut comprendre. L'utilisateur a les accessoires accompagnant l'utilisation du mug. Le concepteur a le panneau d'outil de conception que seulement il / elle peut voir. Si l'utilisateur met un sachet de thé dans le mug, il / elle peut concevoir une poignée pour le mug pour attacher le sachet de thé. L'utilisateur peut demander au concepteur de montrer le mug transparente pour vérifier le sachet de thé (Figure 7.c). Un affichage en temps réel de la taille du mug est montré dans (Figure 7.d). Designer peut utiliser une baguette virtuelle dans le scénario pour sélectionner et contrôler les objets. Les reflets des objets sur le pare-brise peuvent être si dérangeants pour les utilisateurs qu'ils peuvent demander au concepteur de suivre ses conseils (Figure 7.a).

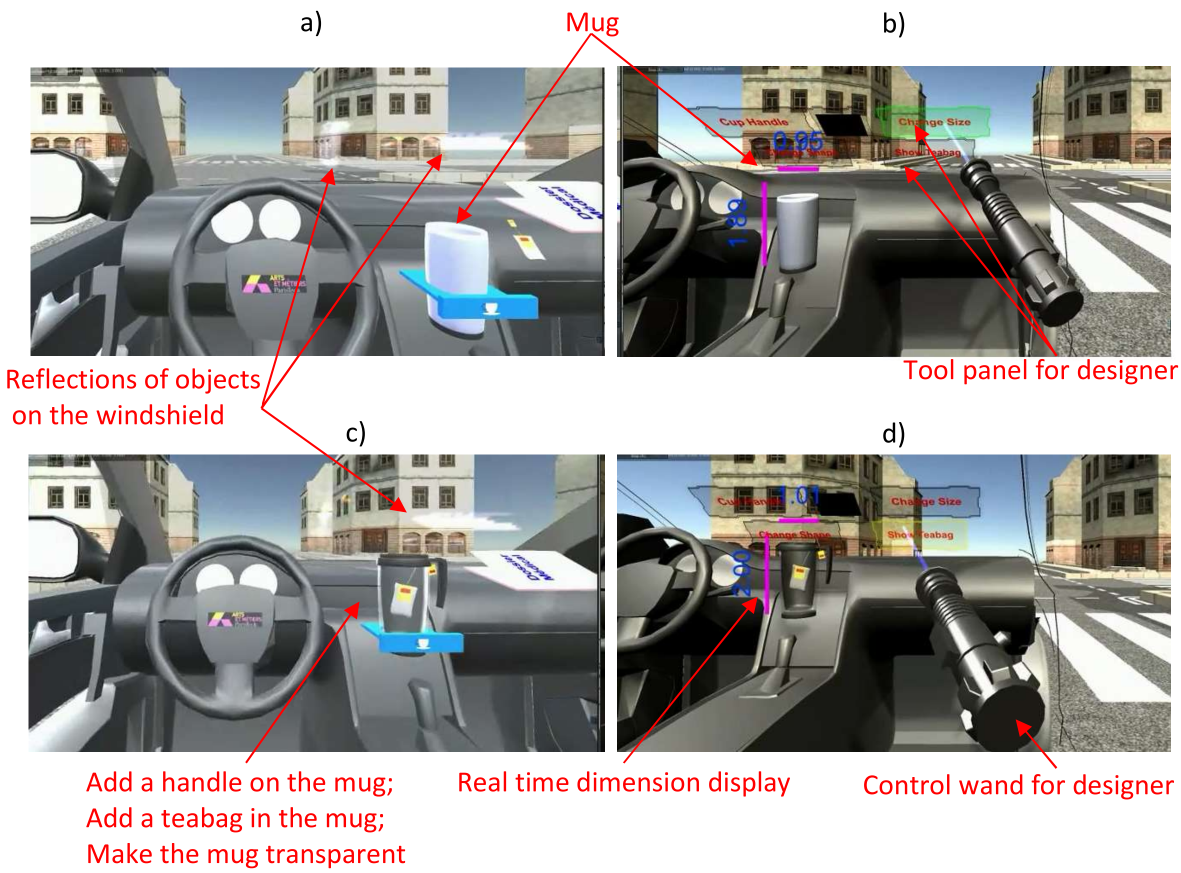

Figure 7 : a) et c): vue de l'utilisateur d'un mug dans la voiture; b) et d): vue de concepteur d'un mug dans la voiture

Cette application implique deux représentations d'une DMU de tasse. Comme affiché avec le système 3D VR, chaque représentation a deux POV pour former la stéréoscopie, 4 vues sont dans le besoin pour ce système à vues multiples.

V. Expériences

V.1 Introduction d'expériences

Au cours des expériences, comme le montre la figure 8, notre question de recherche est d'abord étudiée dans une expérience de jeu de simulation COLLAB_PACMAN, en utilisant l'application qui simule la multi-représentation de DMU et sa tâche multidisciplinaire. Une exploration des différences entre plusieurs interfaces d'IHM, une IHM multi-utilisateur avec des vues divisées et une IHM multi-utilisateur avec des vues fusionnées, est effectuée. Les critères de H1, H2 et H3 sont évalués.

Ensuite, un système d'IHM multi-utilisateur collaboratif 3D et une tâche multidisciplinaire simulant la multi-représentation de DMU avec des mesures quantitatives sont testés dans l'expérience du jeu de simulation COLLAB_MAZE_3D. Cette expérience a permis de comparer différentes conditions expérimentales d'IHM de la collaboration de plusieurs utilisateurs dans des activités de conception 3D. Les critères de H1, H2 et H3 sont évalués avec ce système d'IHM 3D et multi-utilisateur.

Le cas de conception de l'industrie prend du temps à évaluer. Puisque l'efficacité de la tâche nécessite le facteur de temps pour calculer, dans cette expérience, nous n'avons pas besoin de comparer les différentes conditions expérimentales en utilisant les critères d'efficacité. C'est aussi pourquoi nous avons simulé l'activité de conception collaborative de produits en tant que jeu. Une expérience d'application de conception de collaboration avec l'IHM multi-utilisateur est ensuite réalisée. Cette application de conception d'un mug a une maquette numérique d'un mug et un scénario collaboratif multidisciplinaire. Une autre expérience de collaboration avec plusieurs experts pour l'évaluation ergonomique d'une voiture est également proposée. Ces expériences visent à étudier la facilité d'usabilité de l'IHM et la performance de l'utilisateur dans les exemples spécifiques de la mise en œuvre de l'IHM multi-utilisateur dans l'industrie.

Les critères à la fois sur l'utilisabilité d'IHM (H2) et sur la performance de la collaboration (H3) ont des retours sur les hypothèses. Pour répondre à nos hypothèses, ces critères sont analysés avec des méthodes statistiques et discutés après chaque expérience.

V.2 Les résultats

Ces expériences testent le système d'IHM multi-utilisateur dans des conditions de travail collaboratives.

Table 3 Les résultats des expériences répondent aux hypothèses

	H1: Efficiency of task			**H2**: Usability of CHI system		**H3**: Performance of collaboration		
	Finish Time	Communication Time	Error	Learnability	Satisfaction	Involvement	Awareness	Collaboration effort
Exp 1	×	×		×	×	×		
Exp 2	×	×	×	×		×		
Exp 3				×	×	×	×	×
Exp 4				×				×

Selon le schéma scientifique que nous avons proposé au chapitre III, les évaluations du travail collaboratif multidisciplinaire supporté par le système d'IHM multi-utilisateur peuvent être modularisées avec le système d'IHM multi-utilisateur, le scénario collaboratif multi-utilisateurs, la méthode d'évaluation et la discussion. Le choix des techniques de systèmes multi-utilisateurs et des scénarios de collaboration de la forme d'un schéma d'expérience est flexible et remplaçable. Le système à vues multiples dans l'expérience de COLLAB_PACMAN a adopté la technologie anaglyphe qui est limitée au nombre de vues et de couleurs visibles. La solution multi-vues d'autres expériences archive un système à quatre vues pouvant être utilisé dans deux visualisations 3D. Mais la limitation des marqueurs pour le système de suivi pose un problème avec la maîtrise rapide des activités interactives. Avec les lunettes à obturateur et les filtres polarisés, il existe une diminution de la luminosité des images affichées.

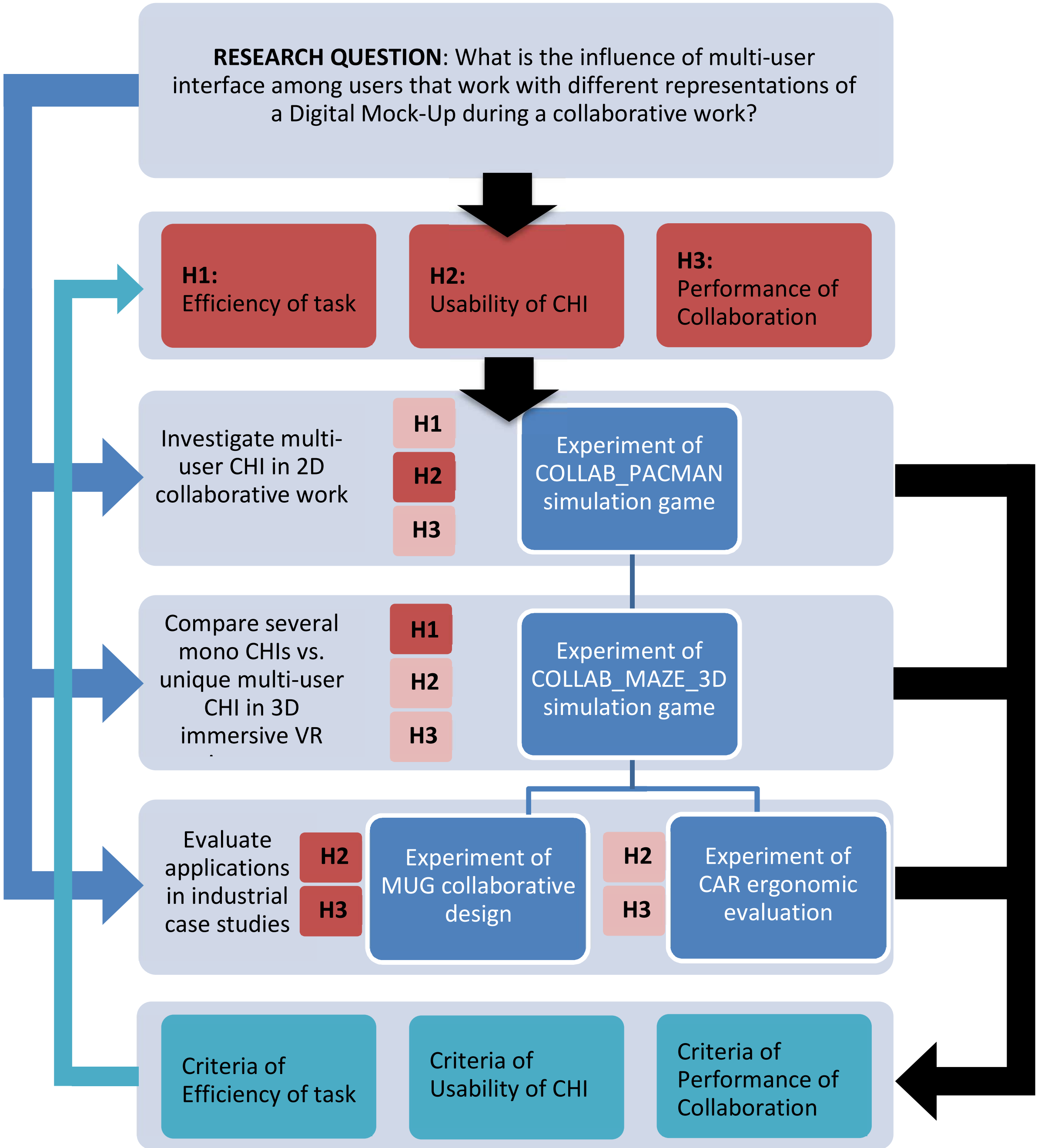

Figure 8 : les hypothèses validées dans le plan expérimental : les hypothèses sont fortement validées (en rouge foncé); les hypothèses sont moins fortes validées (en rouge clair);

Les résultats de l'expérience montrent des significations académiques de l'efficacité de la tâche, de l'utilisabilité d'IHM et de la performance de la collaboration. Comme le montre le Tableau 3, deux simulations de jeux académiques montrent que pendant les conditions de travail du système d'IHM multi-utilisateur, les mesures objectives représentent une meilleure efficacité (**H1**). Les mesures subjectives de ces expériences montrent que le système d'IHM multi-utilisateur apporte des contributions différentes aux critères collaboratifs (**H2, H3**). L'analyse qualitative de l'utilisateur dans l'expérience MUG montre que les utilisateurs du système d'IHM multi-utilisateur expriment des impressions et des commentaires généralement positifs (**H2, H3**). Les commentaires des utilisateurs experts de l'expérience d'évaluation ergonomique de la CAR ont aussi les réponses à (**H2, H3**).

Ces expériences répondent à la question scientifique proposée. Ceux-ci ont une influence positive sur l'efficacité de la tâche, la facilité d'utilisation du système d'IHM et la performance au cours d'un travail collaboratif entre utilisateurs avec différentes représentations utilisant une interface multi-utilisateur. Former le Tableau 15, nous pouvons faire une synthèse que le **H2** de l'expérience 1, le **H1** de l'expérience 2, le **H2** et **H3** de l'expérience 3 est fortement validé. Les autres validations des critères dans toutes les expériences sont moins fortement validées, comme le montre la Figure 8.

VI. Conclusion et perspectives

VI.1 Conclusion

Dans cette thèse, nous nous sommes intéressés au développement et à l'application d'IHM multi-utilisateur dans le cadre de travaux collaboratifs multidisciplinaires. Grâce à ce travail de recherche, nous avons étudié le besoin industriel d'un environnement de travail multidisciplinaire et les techniques de construction d'un système d'IHM multi-utilisateurs. Nous avons essayé de mieux comprendre l'impact de ce système sur l'efficacité de la tâche, l'utilisabilité d'IHM et la performance de la collaboration.

La principale question de recherche posée dans cette thèse était : ***« Quelle est l'influence de l'interface multi-utilisateurs parmi les utilisateurs ayant différentes représentations d'une maquette numérique lors d'un travail collaboratif ? »***. Pour répondre à cette question de recherche, plusieurs interfaces d'IHM à double utilisateur ont été construites selon différentes technologies et divers scénarios d'interaction sont développés et expérimentés pour évaluer son influence. Des hypothèses d'influence ont été proposées sur l'efficacité de la tâche, l'utilisabilité d'IHM et la performance de la collaboration. Grâce à des expériences, les contributions d'IHM multi-utilisateur ont été résumées dans l'amélioration d'une IHM multi-utilisateurs, ainsi que l'influence sur le travail collaboratif.

Un schéma de la méthodologie pour évaluer la contribution à un système multi-utilisateurs et les expériences des multiples utilisateurs est proposé dans la Figure 9. L'IHM multi-utilisateur est composé d'un système matériel/logiciel multi-utilisateur et d'un scénario de travail collaboratif multidisciplinaire.

Les hypothèses selon lesquelles L'IHM multi-utilisateur, qui permet à plusieurs utilisateurs de travailler en collaboration avec différentes représentations d'une maquette numérique, a une influence sur: L'efficacité de la tâche (H1), L'utilisabilité du système d'IHM (H2), La performance de la collaboration (H3) a été proposé. Les méthodes de mesure au cours de l'expérience sont la mesure objective quantitative et la mesure subjective, ainsi que l'analyse qualitative de l'utilisateur. Pour chaque hypothèse, il y a plusieurs critères à mesurer. Pour H1 : L'efficacité, les critères à mesurer sont l'heure d'arrivée, le temps de communication, l'erreur commise, etc. Pour H2 : La facilite d'apprentissage et la satisfaction sont des critères à mesurer pour l'utilisabilité d'IHM. Pour H3 : La performance de la collaboration, nous considérons habituellement l'implication, la sensibilisation et l'effort de collaboration comme critères.

Dans nos expériences, deux simulations de jeux académiques, le jeu de simulation COLLAB_PACMAN et le jeu de simulation COLLAB_MAZE_3D, montrent que sous la condition de travail du système d'IHM multi-utilisateur, les mesures objectives représentent une meilleure efficacité collaborative. Les mesures subjectives des expériences montrent que le système d'IHM multi-utilisateur apporte différentes contributions au travail collaboratif. L'analyse qualitative de l'utilisateur dans l'expérience de conception collaborative MUG montre que les impressions positives et les commentaires sont généralement exprimés par les utilisateurs sur le système d'IHM multi-utilisateur.

VI.2 Perspectives

Le travail de recherche présenté fait partie des études sur l'IHM multi-utilisateur. Ce travail s'est concentré sur la proposition d'une méthodologie pour l'étude de l'influence de l'introduction d'IHM multi-utilisateurs dans des conditions de travail collaboratives, en particulier une collaboration multidisciplinaire. Il y a beaucoup de perspectives à réaliser dans le futur. Certains d'entre eux sont énumérés ci-dessous.

- Les perspectives à court terme
  - L'Amélioration de la multi-interaction

Pour la multi-interaction, un Kinect capable de capturer les mouvements des utilisateurs devant un certain écran peut être proposé dans la prochaine version du système multi-utilisateur. Kinect a pu identifier plusieurs utilisateurs et leurs gestes. Nous pourrions définir un geste avec lequel différents utilisateurs obtiendraient différents résultats d'interaction.

  - L'évaluation du cas industriel de conception collaborative avec l'application CAR

Nous proposons ici un prototype expérimental pour l'évaluation du cas industriel CAR. L'efficacité collaborative et la performance de l'utilisateur pour plusieurs utilisateurs lors de la conception ergonomique d'une automobile pourraient être évaluées en utilisant l'IHM multi-utilisateur.

- Les perspectives à moyen terme
  - L'IHM multi-utilisateur pour plus de deux utilisateurs

Il existe actuellement des techniques pour concevoir une IHM multi-utilisateurs pour plus de deux utilisateurs, cependant, leur application industrielle devrait être explorée davantage.

  - L'évaluation de l'expert

Avec le développement d'outils virtuels pouvant prendre en charge les activités de conception de produits, davantage d'exigences industrielles sur l'IHM prenant en charge plusieurs utilisateurs devraient être découvertes. Le système multi-utilisateur doit être testé pour un projet de conception de produit réel au cours du processus de cycle de vie du produit. Les réactions des experts seront très importantes et pratiques.

- Les perspectives à long terme

Il serait intéressant de se concentrer davantage sur les aspects mentaux et cognitifs nécessaires au processus de travail collaboratif. Le travail réalisé dans cette thèse ouvre la voie à la mise en place d'une interface multi-utilisateurs et au comportement humain de travail collaboratif de multiples utilisateurs. Il y a encore beaucoup de travail à faire dans ce contexte, ce qui nécessite une collaboration avec des spécialistes dans le domaine de la psychologie cognitive et de l'ergonomie.

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L'interface multi-utilisateur pour le travail collaboratif avec les multiples représentations de la maquette numérique

RESUME :

Les outils actuels de gestion industrielle s'appuient généralement sur l'ingénierie concourante, qui implique la réalisation des étapes de gestion du cycle de vie des produits en parallèle et l'intégration des données techniques pour le partage entre les différents experts. Divers experts utilisent des logiciels spécifiques à leur domaine pour produire diverses données compilées via une maquette numérique. Ces experts multidisciplinaires ont tendance à travailler en collaboration pendant le développement de produits. Au cours d'activités de conception collaborative synchrones, telles que les revues de projet et la prise de décisions, les experts de différents domaines doivent dialoguer, négocier et choisir pour résoudre les différences multidisciplinaires. De nombreux domaines tels que la conception collaborative et de l'évaluation des produits avec multiples experts, ont une grande demande de nouveaux outils d'aide à la collaboration. Avec le développement des technologies de l'Interaction Homme-Machine (IHM), il est possible de concevoir des outils et des méthodes plus intuitifs pour améliorer la collaboration co-localisée entre les experts.

Dans cette thèse, afin d'améliorer la collaboration avec des experts de différents domaines et communiquer via la maquette numérique, une IHM multi-utilisateurs avec des représentations différentes lors d'un travail collaboratif a été pris en considération et son influence sur la collaboration multidisciplinaire co-localisée est étudiée. Un schéma de la méthodologie d'évaluation de la contribution à un système multi-utilisateurs et des expérimentations sont proposées. Les résultats des expériences des résultats significatifs concernant l'efficacité de la réalisation de la tâche, l'utilisabilité de l'Interaction Homme-Machine et la performance de la collaboration lors de l'utilisation de l'interface multi-utilisateurs dans les scénarios de collaboration multidisciplinaires. Les contributions et apports de cette interface sont discutés.
Mots clés : Interaction Homme-Machine, collaboration, maquette numérique

Multi-user interface and its use for collaborative work with multiple representations of Digital Mock-Up

ABSTRACT :

The current industrial management tools generally rely on Concurrent Engineering, which involves conducting Product Lifecycle Management stages in parallel and integrating technical data for sharing across different experts. Various experts use domain-specific software to produce various data into Digital mock-up. These multidisciplinary experts have trends to work collaboratively during product development. During co-located synchronous collaborative design activities, such as project review and decision-making, experts from different domains must discuss, negotiate, and compromise to solve multidisciplinary differences. Many areas, such as early collaborative design and multi-expert product evaluation, have a great demand for new collaborative support tools. With the development of Human Computer Interaction, it is possible to devise more intuitive tools to enhance co-located collaboration across experts.

In this thesis, to enhance the collaboration with experts on different domains to communicate with DMU, a multi-user interface across users with different representations during a collaborative work has been taken into consideration and its influence on co-located multidisciplinary collaboration is investigated. A schema of the methodology for evaluating the contribution to a multi-user system and the multiple users' experiences is proposed. Results of experiments show the significances of the efficiency of task, the usability of interface, and the performance of collaboration during the use of multi-user CHI in multidisciplinary collaborative scenarios. The contributions of what multi-user interface brings to the design criteria of multi-user interface and multi-user co-located collaboration are discussed.
Keywords : Computer Human Interaction, collaboration, Digital Mock-Up

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