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DEVELOPMENT OF ENGINEERING DESIGN METHODOLOGIES AND SOFTWARE TOOLS TO SUPPORT THE CREATIVE PROCESS OF DESIGN IN A DISTRIBUTED ENVIRONMENT

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Abstract

It is a challenge for designers in traditional organisations to work together in teams to achieve a consensus based solution space optimality [1] and this challenge is further compounded by the dispersion of the design information, design personnel and knowledge across the extended enterprise environment. Extensive work has been carried out on passive information management systems for design, however, very little work has been carried out in the much-needed area of proactive, holistic knowledge management and presentation systems required by the extended enterprise. In this paper we propose an agent-based system to access, retrieve and present information (both visually and auditorially) to distributed design teams, in such a way that their collective conceptual space is expanded [2], learning strategies are supported [3] and design solutions are optimised [4]. This agent based information system will support the distributed design process whilst considering human and ICT protocols, for the purposes of enhancing design, learning, creativity, communication and productivity.

Keywords: Agent based systems, distributed design teams, design models

1 Introduction

Evolving information and knowledge residing within an enterprise is typically captured in data, knowledge and case bases which have to be trawled regularly by the designer, (research has shown that 47% of a designer's time is spent retrieving and managing information [5]). While this data is made accessible via a graphical user interface, current user interfaces only respond to direct manipulation, i.e. the computer is passive and always waits to execute highly specified instructions from the user. It provides little or no proactive help for the complex task of carrying out actions such as searches for information that may take an indefinite length of time. Descriptive models of the design process suggest that design engineers are goal focused, tend to pursue a single design concept and attempt to optimise their original idea rather than generate new ones [6] [7]. Furthermore, the increasing volume of information being produced means that designers generally have to go hunting for the information that they require. Arias also claims that designers working on one specific are of a project generally have a limited awareness of how the work of other designers working in the same project impacts on their own work. "The large and growing discrepancy between the amount of relevant knowledge and the amount that any one designer can possibly remember imposes a limit on progress in design" [17]. Notwithstanding, if information is not easily accessible, design engineers are unlikely to seek or share knowledge and expertise and as a result, at best are likely to generate local rather than global solution optima [6]. These problems have the potential to be particularly augmented in the extended enterprise environment because of the distribution of knowledge and information, the inherent dynamic nature of design information, the virtual communication processes and the increased complexity of products [4].

The work presented in this paper is being carried out under a project entitled I-DIMS[1] (Intelligent Agent Based Collaborative Design Information Management and Support Tools). This project, (which is still at an early stage in its progression) has been initiated to address the problem of collaborative design, and to investigate and develop a holistic approach to knowledge management for the design process, by developing intelligent agent based systems. These systems will be coupled with case based reasoning and evolving semantic web science, to enhance the creativity of the designers in the design team by supporting the synthesis and internalisation of external information and knowledge across the enterprise. It is envisaged that the realisation of these objectives will be achieved by developing intelligent collaborative agents which understand the problem space as described by the designers in semantics (either verbally, graphically or textually). These agents will then trawl through existing data, knowledge, and case bases, and filter, encode and then present the relevant information and knowledge (both graphically and auditorially) to designers operating within an extended enterprise environment. Additionally, information and knowledge will be tailored to designers' learning strategies [8] so that this relevant external information and knowledge can be readily internalised, thereby resulting in an expansion of the optimal solution space of the collective design team. In this paper a design process model entitled the 'phase activity loop framework' will be described. This model forms the basis for the proposed integrated design model that will support design methodologies and software tools (developed to operate within a distributed design environment). Following this, a brief technical description of the main supporting technologies that the I-DIMS project proposes to integrate into the distributed design model, in order to address the problems associated with distributed design will be presented. The paper will then proceed to explain the I-DIMS information system architecture, which has been proposed to facilitate the integration of the main technologies with the design model. Finally the paper will conclude with the testing and validation of a software design tool, within a distributed environment that incorporates the proposed design model

2 Phase activity loop framework

The basis for the design model (proposed in the I-DIMS project) arises from previous research that has been carried out by members of the I-DIMS team in the area of life cycle design. This research proposed a model to describe the generic evolution of design, see figure 1. This design model represents the transformation of information through four generic stages of design (namely *requirements definition, functional definition, general design* and *detailed design)*, i.e. the transformation of information from more *abstract* statements of requirements to more *concrete* details on the final design. This information transformation process can be described by; (a) the *degree of embodiment* and (b) the *solution space*. The vertical axis describes the degree of *embodiment of a design*, which ranges from the general to the specific stages. In the early stages of embodiment, the solution space is very large, however, as the design evolves, this solution space becomes increasingly narrow until there is one specific solution remaining i.e. the final design.

[1] The I-DIMS project is funded by the IRC (Irish research Council) set for science, engineering, and technology

These stages are not discrete events within the design process, rather, the designers engage in a set of decision-making cycles continuously improving the design at each level of abstraction

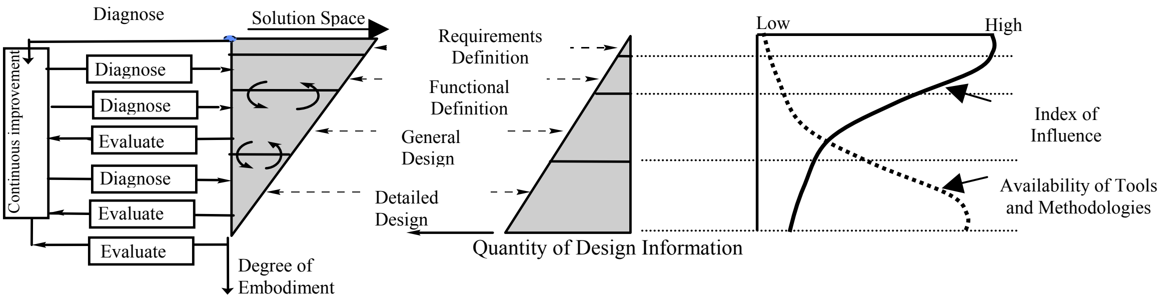

Figure 1. Generic evolution of design [4]

It should be noted that decisions made in the earlier stages of the design process have the largest influence on the final design [9] [7] [12]. This is compounded by the fact that there are few methodologies and tools available to provide assistance. Hence, the amount of information on which to make concrete decisions in the earlier stages of design is limited and abstract. It is therefore extremely important to develop methodologies capable of both qualitative and quantitative reasoning in order to support the decision making process in these earlier design stages.

Furthermore, the design of products requires a more holistic view of the design process, i.e. a life cycle view [10]. Consequentially, it is proposed that the life cycle *design process* can be represented by a tri-axial information transformation space, i.e. design phase, activity and loops axes, see figure 2. The design phase axis describes the degree of embodiment of the candidate design as described in figure 1. The activity phase can be viewed as the *instrument* or *mode* of information transformation in each phase of the design process, hence a problem solving cycle is adopted to describe the *activity axis* of the design transformation space, i.e. the steps *analyse*, *synthesise* and *evaluate* [7]. The design phase and activity axes define the boundaries of a *design process plane.* It is implicit in this plane that problem solving occurs explicitly at different levels of abstraction in the design process. This affects the types of problem solving that can occur, and hence the types of tools and methodologies that can be used. For example, in the requirements definition phase, the problem solving cycle consists of; abstract analysis, synthesis and evaluation of verbal design requirements. It may use qualitative reasoning tools such as Analytical Hierarchy Processing (AHP), Fuzzy Reasoning or Constraint Based Reasoning to aid the decision making process.

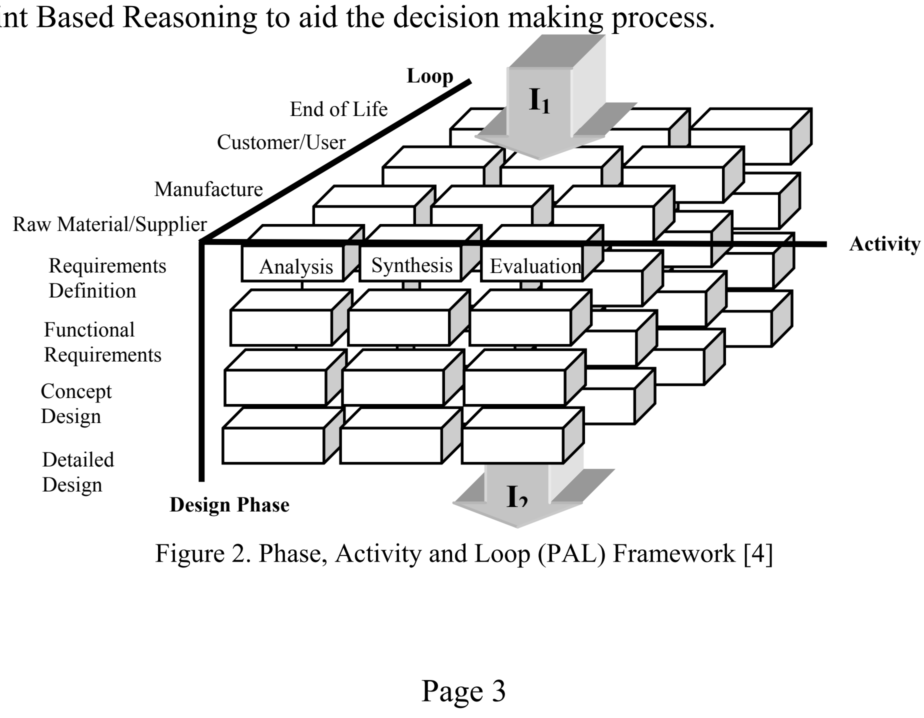

Figure 2. Phase, Activity and Loop (PAL) Framework [4]

In contrast, the problem solving cycle in the detailed design phase can be highly specific, for example, the use of Finite Element Analysis (FEA) to analyse stress distribution in a design. The *design information loops* (used to describe the third axis of the transformation space) represent the source of information for each life cycle phase of the product and also acts as a focus for life cycle methodologies and tools. The *activity* and *loop* axes bound a *life cycle problem-solving plane*. This plane ensures the analysis, synthesis and evaluation of life cycle information throughout each phase of the design process. ICT tools must be embedded within this design process to support the communication of information between members of distributed teams and between all phases in the design process.

In summary, the resulting model in figure 2, called the PAL framework, is proposed as a life cycle design framework to facilitate the development of methodologies and tools to aid life cycle design decisions. These methodologies and tools must be embedded in an appropriate ICT infrastructure to support the distributed nature of information and processes associated with PAL. The PAL framework forms the basis for the description of the product design process within the I-DIMS project

3 Integrated design model for distributed design

The IDIMS project seeks to take a holistic view of the design process in the context of emerging new products and distributed design environments and to ensure that the designer has appropriate tools and methodologies available (supported by an appropriate ICT infrastructure) to ensure effective design of products. Figure 3 summarises the relationship between the core research themes of the IDIMS project, which will be integrated with the PAL framework design model. The model illustrated in figure 3 proposes the development of new *ICT infrastructure and protocols* coupled with well-founded *human protocols* to support design methodology, tools and information and knowledge sharing as well as the communication and management of information within distributed design environments.

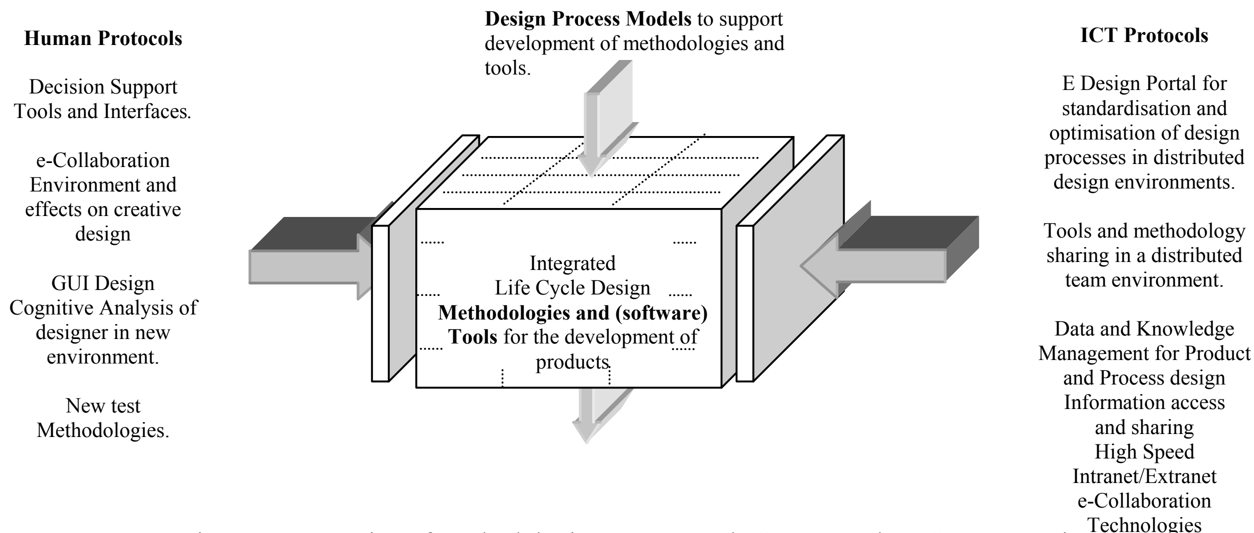

Figure 3. Integration of Methodologies, Human and ICT Protocols to Support Design

Design methodologies and software tools to support creative design

Typically, within collaborative design environments, distributed designers (or distributed design teams) are given design tasks to perform. They generally use design methods, methodologies and tools (including software tools) to develop point solutions, representing local optima, to the task in hand. These point solutions are then combined to create the overall solution, global optima, at each level of abstraction of the design process. The combination of such point solutions can create conflicts, both real and artificial, which can constrain the overall solution. Therefore, methodologies and tools are required to support the transformation of the distributed solution spaces created by distributed designers (or teams) to a consensus based solution space, or set of global optima, at each level of abstraction in the design process. From the description of the PAL framework, the propagation of the solution spaces should be supported both in the forward and reverse directions; hence methodologies and tools must support backward as well as forward propagation of design decisions. The I-DIMS project therefore recognises that it is necessary to develop methodologies and tools, for the definition and propagation of solution spaces, that integrate across all life cycle phases (i.e. horizontal integration in PAL). Furthermore it is necessary to support the integration of these methodologies throughout the design process, (vertical integration in PAL) and to provide a mapping from requirements definition to detailed design for all design parameters and information through an appropriate ICT infrastructure.

Development of ICT systems to support distributed design environments

Hubka's '*general model of the transformation system'* can be used to classify the development of ICT to support the design of extended products within extended enterprises under two interrelated areas: *ICT to support design information management* and *ICT to support design process management*. With regard to ICT to support design information management, it is widely accepted within the design community that knowledge and information must be made available to the designer at an appropriate time in the process. Also as design is becoming increasingly a distributed process, and many designers may be involved in the development of elements of the product, there will be a need to collaborate at all stages in the design process. Some of the critical and inter-linked problems that must be addressed in this regard are the lack of the following: enterprise wide access/sharing of tools and methodologies, enterprise wide access/sharing of information in design, enterprise wide viewing/updating of information, and enterprise wide management of information and resources**.**

The I-DIMS project proposes that the solution to these problems may be in the development of a client/server system that integrates people and computers into the total product design process. Such a system would generate requested information dynamically, display information in a useful manner; electronically maintain control over the created files, automatically update the information and support the distributed methodology and tool operation. Furthermore it is proposed to use the WEB as the backbone of such a system because of its ease of use, scalability, flexibility, and ubiquity. It is planned to investigate the use of distributed virtual reality (DVR) for the transferral and updating of the contents of the virtual environment. It is aimed to use virtual reality modelling languages (VRML) and distributed interactive simulations (DIS) to allow the users to interactively evaluate design concepts using methodologies and tools developed specifically for distributed environments. It is planned to deploy technologies such as JAVA, HTML, XML and to develop agents as the communication and collaboration infrastructure.

Research has shown that one of the major impediments of workflow[2] management systems is its inflexibility to cater to the dynamic nature of the design process. The workflow activities associated with the design process are highly dynamic and usually require the forward and backward propagation of solution spaces. The I-DIMS project recognises that there is a need

[2] Workflow refers to procedures that involve the sequential routing of tasks from person to person, allowing each individual to make a contribution before moving the task onto the next stage.

to develop workflow systems that exhibit intelligence, autonomy and support collaboration within an inter/intranet environment. Furthermore, these workflow systems must support (in addition to depending on) the methodologies and tools developed to support the design of products. Intelligent workflow systems will be developed to guide this process for the individual designer and team and will track decisions made in that process.

Human protocol development for the distributed design environment

The designer's interactions (*Humans* in Hubka's Model) with the design process are crucial to the successful location of the optimal solution. The design process is a basic human cognitive activity that transforms design information from abstract statements of requirements into detailed specifications of the product. Given that design can be described as a problem solving process and considering that engineers tend to solve problems based on '*available knowledge'*, it is important to ensure that appropriate knowledge is available at the correct time in the process [6] [7]. Knowledge can be made available in two ways, i.e. external (established from the experience of others, existing research and new research) or internal (designers own experience and knowledge established through learning) [6]. *Internalised information* is more likely to influence the designer subliminally to make good design decisions [11]. Indeed research has shown that there are strong impacts of learning on the decisions made by the designer [11]. Research has shown that design engineers have strong problem solving skills and are generally poor at creating imaginative ideas and conceptual models, and hence depend largely on the information to which they have 'ready' access [11] [4] [7]. The I-DIMS project proposes to develop data and knowledge management software tools and methodologies that address this weakness in the design process in order to push out the boundaries of the solution space. In an extended enterprise environment information is likely to be distributed within the organisation and across the value chain. It is therefore proposed to optimise the design process by providing design tools that support the synthesis of knowledge and information both externally and internally.

4 Supporting technologies for I-DIMS

The I-DIMS project focuses on the integration of four areas to address the problems associated with collaborative design within an extended enterprise environment. These four areas are follows; design process knowledge (which has already been discussed in the context of the PAL framework in section 2), agent based systems, semantic web technologies, and case based reasoning.

Agent based systems

Agents can generally be defined as software components or programs that work in conjunction with people or represents people and act in their best interests. They have been identified as the next generation model for engineering complex distributed systems [13]. Nwana presents a typology of agents based on three different characteristics, i.e. *ability to learn, ability to co-operate and the degree of autonomy* [14]. Agents must have the ability to *learn* as they react and /or interact with their external environment. Co-operation, a crucial characteristic of agent based computing systems, refers to how agents share information and knowledge with each other and the user. Finally *Autonomy* addresses the ability of the agent to work without human interaction. A key element of their autonomy is their ability to take the initiative rather than acting simply in response to their environment. Nwana's classification results in four types of agents smart agents, interface agents, collaborative agents and collaborative learning agents [14].

Semantic web technologies

Most of today's web technologies are designed for humans to read and not for computers to manipulate *meaningfully*. Providing a semantic set of descriptors for agent based systems allows the computer in someway to understand and process information rather than display text and images as they do at present. Semantic web technologies will use a common data structure that will open up knowledge and expertise to meaningful analysis by software agents thereby providing a new class of tools in which agents can collaborate and retrieve information for the user. For the semantic browsers to function, computers must have access to structured collections of data and sets of inference rules that can conduct automated reasoning in comparison to traditional, poorly scaleable knowledge representation systems that are typically centralised, requiring everybody to have a common definition. Two important technologies for developing the semantic web are already in place; XML and resource description framework (RDF). XML allows the user to add arbitrary structure to documents but says nothing about what the structure means. RDFs encode meaning to the data in a similar way that verbs and nouns do in the English language. Ontologies provide the opportunity to form relations among data sets and enable the computer to manipulate terms more effectively in ways that are more meaningful and useful to the user. Although semantic web technologies are in the research domain they represent a useful opportunity for the retrieval of information for the designer operating in the extended enterprise environment where information is diverse, distributed and highly complex.

Case based reasoning

In case based reasoning (CBR) expertise is embodied in a library of past cases, rather than being encoded in classical rules. A case can be defined as a contextualized piece of knowledge representing an experience that teaches a lesson fundamental to achieving the goals of the reasoner. Each case typically contains a description of the problem plus a solution. The knowledge and reasoning process used by an expert to solve the problem is not recorded but is implicit in the solution. CBR systems are highly appropriate for the design process as much of the typical design effort (90%) uses previous knowledge or previous solutions, to generate new designs [4]. To solve a current problem the problem space is matched against cases in the case base for the purposes of retrieving similar cases. The retrieved cases are then used to suggest a solution, which is reused. CBR consists of a four step process i.e. retrieve, reuse, revise and retain.

5 The I-DIMS system architecture

The I-DIMS project proposes information storage and retrieval, expertise sharing and collaboration to support the design of products, by integrating smart agent systems with case base reasoning and semantic web systems. The goal of the I-DIMS architecture is to investigate and develop a system to proactively provide knowledge and expertise specific to current design problems to the designer or design team in the most efficient and intuitive manner. Figure 4 shows the I-DIMS system architecture consisting of the distributed users interacting with distributed interfaces, e.g. distributed GUIs in CAD workstations. Data and knowledge is stored in specifically structured data, knowledge and case bases which are typically distributed in the extended enterprise. It is proposed to develop a set of distributed artificial intelligence based software agents to capture the designers decision-making patterns and behaviours as well the creation of a value chain among agents, (i.e. in which sub assemblies of information are passed from one agent to another each adding value to construct the final piece of information required for the design solution) so that delivery of information to the user is in the way that they want it and at the time that they want it.

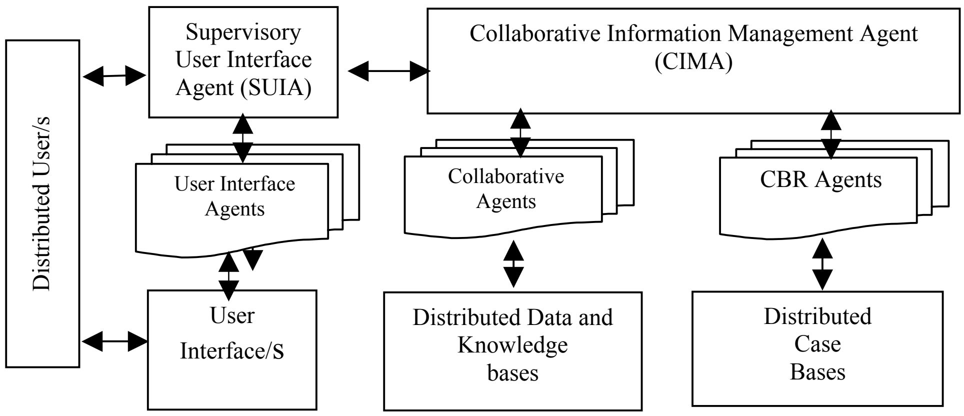

Figure 4. I-DIMS Intelligent Agent Based Information Management System Architecture.

The I-DIMS architecture consists of three types of subordinate agents, i.e. collaborative agents, user interface agents and case based reasoning agents, and two supervisory agents, i.e. the supervisory user interface agent (SUIA) and the collaborative information management agent (CIMA). SUIA is a high level intellectual agent unique to every designer. SUIA will work closely with the designer and learn his/her cognitive models, learning strategies and behaviour. The goal of SUIA is to move the designer away from issuing direct commands to some interface, to a situation where the designer will be engaged in co-operative processes in which human and software agents can both initiate communication, perform tasks and monitor events.

SUIA will also be responsible for managing and controlling each of the generic subordinate user interface agents each of which has specific responsibilities relating to the HCI domain. When the designer formulates the problem space textually, graphically or auditorially, the relevant subordinate user interface agent will interpret the information and pass it to SUIA. SUIA (based on learned understanding of designer behaviour) will then understand the problem as described by the designer in semantics, configure this problem space and communicate it to CIMA, which then delegates the information retrieval to the subordinate collaborative agents, whose roles are to support the acquisition of information in data and knowledge bases as well as capturing design specific dynamic information occurring in a design project, and CBR agents, whose roles are to proactively retrieve appropriate cases for the design team, as well as to proactively and autonomously perform the retention function (i.e. determine retrieval semantics for the new case and store it) of new cases for the case base. On retrieval of the relevant information and knowledge from the CBR and collaborative agents via CIMA, SUIA will then interpret the knowledge and information and using the relevant subordinate user interface agent present it in a way that the designer can readily internalise the information and knowledge, and productivity is increased. SUIA is crucial and probably the most difficult element to create in the I-DIMS architecture. The I-DIMS research team has already carried out significant work using protocol analysis (will be briefly explained in the next section in this paper) methods to establish cognitive behaviour and learning styles of designers and design teams operating in a collaborative environment. This knowledge will be encoded in SUIA to predict individual and collective designer behaviour.

6 Protocol analysis study for a distributed environment

The I-DIMS research team have investigated the protocol analysis (PA) methodology for testing the effects of distributed design environments on the cognitive processes of design [15]. The objectives of the PA research were the proposal, implementation and results gathering of a new framework based on the protocol analysis technique for the study of distributed and collaborative decision-making processes in a virtual environment. The main goal of the PA research was the evaluation of a distributed design for environment (DFE) tool called the DFE workbench [4]. PA is a qualitative evaluation method for the human cognitive processes. During the PA session, two subjects team behaviour who were co-located was observed firstly, and compared with the subjects team behaviour when they worked in a computer based collaborative environment. The subjects were asked to complete a set of predetermined tasks using the distributed DFE tool, and were observed by an evaluator who recorded the subjects actions using video and audio techniques. The users were then asked to think out loud while they were performing the tasks, describing what they believed was happening. This process of verbalisation reveals the assumptions, misconceptions, inferences and problems that the subjects faced while performing tasks or solving problems [16].

Results of PA test on a distributed environment

For the co-located test both verbal and nonverbal communication were used to design a simple shape from a number of smaller shapes. The user attention was focused on the problem rather than on the other person. It was concluded that nonverbal communication was important from three perspectives i.e. gestures, territorial behaviour and nonverbal aspects of speech. Other nonverbal codes such as facial expression, gaze bodily posture and orientation played an insignificant role because of the nature of the problem. The distributed environment forced people to verbally communicate more since nonverbal communication had to be almost entirely replaced by verbal communication and mouse pointing (as opposed to finger pointing). Gestures normally used in face-to-face communication were still used in the distributed test but were replaced in time (as subjects learned) by mouse pointing and verbal codes. Because the team members had to share the problem of designing the shape in the distributed environment, territorial behaviour was eliminated creating room for non-dominant people to better participate in the problem solving process. In general, both environments supported defined roles of participants: one member of the team prefers to try out ideas without much explanation or to control the mouse while the second member of the team takes the thinker role and gives suggestions, opinions and orientations. The main difference between the two types of environments is that in the distributed environment, an idea is well explained first and executed only if the team gives it a chance of success, whilst in the co-located environment parallel work was favoured (for a more detailed explanation of results see [16]). From knowledge gained from the PA test, the IDIMS project proposes to identify and verify ICT and human protocols developed and hence develop a collective cognitive model that supports distributed cognitive processes of individual team members.

7 Conclusions

Due to designer driven requirements; new product design goals; the increased complexity of products and new design environments, new design support tools are required to support distributed design teams working within virtual environments. The objective of the research presented in this paper is to describe an optimised solution space of the collective dispersed design team, working within a distributed extended enterprise design environment. The I-DIMS project focuses on three integrated areas to address this problem; firstly distributed agent based systems embedded within design tools, secondly the use of agent drive case based reasoning to support the synthesis and management of information for distributed design teams and finally agent based user interfaces. The main results and findings from the I-DIMS project to date presented in this paper, have been; a new holistic view of the design process in the context of distributed design environments; an ICT agent based system architecture, that will support and capture designers decision-making patterns and behaviours within a distributed design environment; and finally, knowledge gained from protocol analysis studies on cognitive processes of design within a distributed environment, that will be used for further development. It is envisaged that as future research by the I-DIMS project progresses to a higher level, ICT solutions and design methodologies will evolve, that will address, and further complement the findings presented in this paper.

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