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Experiences in developing collaborative engineering environments: An action research approach

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Abstract

Due to the increasing amount of collaborative work in engineering, it is now necessary to create environments that foster the coordination and cooperation among engineering groups. The aim of this paper is to present a methodology to design and integrate 'Collaborative Engineering Environments' supported by tools that enable cooperative work and intellectual capital sharing. The resulting methodology to create 'Collaborative Engineering Environments' was developed and refined through a set of action research cycles applied to three case studies. The experiences and reflections of every case are described to contribute to a better understanding of how collaborative environments should be built up.

Keywords: Collaborative engineering; Action research; Product design; Information and communication technologies

1. Introduction

Strategic thinking in organizations has changed due to the advances in information and communication technologies (ICT). To remain competitive in this changing scenario, companies are focusing more and more on business globalization and collaboration with technological partners across the product life cycle. Market conditions have led to an upgraded concept where collaborative design must be achieved to support virtual product realization in the new information era.

Product development processes are being executed more and more remotely due to market globalization and expansion. Companies should not think only in their local markets but they have to consider potential worldwide opportunities. Under this concept, information and communication technologies (ICT) play a very important role. Technologies involved in product development are becoming more collaborative and integrated from the information point of view. Not only *client–end user* relationship are more globally undertaking but also supply chain (customer–suppliers) operations requires a worldwide conception.

Authors in the field have worked in developing specialized systems to support a specific stage in product development as a first approach to global collaboration. Typical cases are collaborative CAD systems or technologies related to computerized product modelling. An increasing number of organizations are using virtual tools for product development. These systems are characteristically 3-D computer graphic systems with user-interactive control and viewer-centred perspectives. For example, aeronautic industry and various auto manufactures have experienced substantial improvements and reduce design rework, reporting cost savings and reduction in development time as a result of the use of virtual environment technologies and digital models [1,2].

Several systems have been developed to support the collaboration in specific activities within the product life cycle with a major emphasis in CAD stages. Within these systems can be mentioned: Deneb [3], CyberReview [4], Web-based conceptual design [5] and CyberCAD [6]. There are also other systems, which are focused on the integration of coordination tools, workflows and also knowledge and information, like the CyberCO [7], WebBlow [8], P_PROCE [9] and KdCPD [10]. The integration of Internet-enabled collaboration tools is explored in some systems and also in an integrated way. It can be by integration of commercial software applications [11] or through developed applications [12].

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Research efforts are converging into the creation of ''environments'' to support the collaboration among multi-disciplinary teams in product life cycle engineering. However, there are differences and similarities among collaborative engineering approaches. For example ref. [13], identified three major forces that will affect the design community: *speed of information, expansion of scope* and *degree of concurrency.* Understanding the implication of these forces would lead to structural changes in design. The transformations include expanding the scope of design, linking customers and suppliers proactively throughout the entire value chain, and collaborating across boundaries.

The characteristics of collaborative systems, according to Yang and Xue [14] are:

- Collaboration among product development partners, data modelling, system architecture design and security management are recognized as the four key issues in developing Web-based manufacturing systems.
- Web-based manufacturing systems have been developed and used for supporting different product development life-cycle activities.
- Among all the problems to be solved the open architecture, dynamic distributed data and system modelling issues are considered critical.

Many definitions and names have been given to collaborative systems, such as collaborative engineering environment [15], collaborative design environment [16], Web-based manufacturing system [14], virtual collaborative environment [17], virtual workspace system [18] and collaborative development environment [19], among others. However, the common idea is to enable collaboration and interaction among partners on the development of a project regardless of their locations and incorporating information and tools according to a design activity. The reason is that product and services are nowadays being developed by project workteams distributed into different areas of a company or associated to several companies onto a common project and not necessarily in the same location.

Although many collaborative systems have been developed, many problems need to be solved for developing the next-generation collaborative systems. Among these problems, the following issues were identified by Xue and Xu [20]: open architecture distributed data modelling; open architecture distributed system modelling; accessibility and security of modules; geometric and non-geometric modelling; design library modelling; and collaboration of product development. Additionally, as reviewed by Xie et al. [11], the research on and implementation of Internet-based systems are far behind industrial expectation for product development processes. Therefore, it is necessary for industries to understand the development conditions and current available technology so that they can properly select the best strategy for developing Web-based collaborative environments.

The main purpose of this paper is to contribute to a better understanding of the development conditions and current available technology for developing, what the authors of this paper call, 'Collaborative Engineering Environment' (CEE). To achieve this goal, the paper describes the experiences acquired during the development of three case studies representing such environments.

The experiences presented here are the result of an evolving learning loop. Every case led to reflections that cognitively nurtured the planning of the following case in a recursive fashion. This learning process was structured and systematic and followed the basic principles of the action research methodology.

2. Action research

Action research (AR) is a research strategy classified as an inductive approach (as opposed to a deductive one) and it refers to the involvement of researchers as co-practitioners in the setting where the research is made [21]. Gill and Johnson [22] typify AR as an 'ideographic method' that 'emphasises the analysis of subjective accounts that one generates by ''getting inside'' situations and involving oneself in the everyday flow of life'.

Since the phrase was coined by Lewin in the 1940s [23], many definitions and concepts of AR have been proposed. The following concepts help to achieve a better understanding of this important methodology:

- '(AR) aims to contribute both to the practical concerns of people in an immediate problematic situation and to the goals of social science by joint collaboration within a mutually acceptable framework' [24].
- 'AR is undertaken by participants in social situations to improve their practices and their understanding' [25].
- 'AR is collaborative, critical and self-critical inquiry by practitioners (e.g. teachers and managers) into a major problem or issue or concern in their own practice. They own the problem and feel responsible and accountable for solving it through team work and through following a cyclical practice' [26].
- 'AR is a flexible spiral process which allows action (change, improvement) and research (understanding, knowledge) to be achieved at the same time. In most of its forms it does this by: (a) using a cyclic or spiral process which alternates between action and critical reflection and (b) in the later cycles, continuously refining methods, data and interpretation in the light of the understanding developed in the earlier cycles' [27].
- 'AR embodies a strategy for studying change in organizations. This strategy involves the formulation of a theory, intervention and action-taking in order to introduce change into the study subject, and analysis of the ensuing change behaviour of the study subject' [28].

Most writers on this topic state or assume that action research is cyclic, or at least spiral in structure. One crucial step in each cycle consists of critical reflection. The researcher and other team members live the action first and then critique what has already happened. A well known cycle is that of Kemmis and McTaggart [29], where action research occurs through a dynamic and complementary process, which consists of four essential 'moments': *planning*, *action*, *observation* and *reflection*. The improved understanding emerging from the critical reflection is then used in designing the later steps.

Although AR has its origins in social sciences, it has been used in several fields. From our interests, it is interesting to point out that AR has been studied as a method for information systems research for many years [30]. The cycles provide a useful way of thinking in describing an AR process. Researching a particular issue usually involves going through a number of cycles. This allows practices and understandings to be refined or changed over time. For these reasons, the authors of this paper have used the AR as research methodology for the ideation, implementation and refining of a structured method to design and integrate CEE. The AR spiral process allowed action (CEE implementations) and research (refine methodology) to be achieved at the same time. As a result of this research, the authors have formalized a *methodology for design and integration of CEE*, which will be detailed in Section 3 of this paper.

The experiences presented in this paper follow the structure of the AR model, that is, every case study is described following a plan–act–observe–reflect cycle (as shown in Fig. 1). The fourth cycle is presented as a topic for further research. For the planning stages in this specific research, the authors of this paper implements the methodology for the design and integration of CEEs. The 'planning' is not a separate and prior step; it is embedded in the action and reflection.

Before going through, the next section explains the methodology for designing and integrating CEEs, noticing that although the methodology was being improved on a cycle-by-cycle basis, it is presented in its final shape for space reasons.

3. Methodology for design and integration of CEEs

There are several technical challenges in collaborative engineering: (1) definition of a collaborative integrated product development process among the different companies participating in product life cycle activities; (2) establishment of environments that foster the coordination and cooperation among engineering groups; (3) integration of applications and tools to enable exchange of information and knowledge among engineers in an effective and efficient manner. Therefore CEEs, with an underlying methodology, must be designed and developed to train and cultivate 'Communities of e-Engineering Practice'. These integrated environments must enforce four dimensions of e-engineering:

- *Process*: How engineering (design, manufacturing, supply, procurement and service) is realized in a global environment using e-technologies.
- *Information*: How information have to be structured and shared between all the engineering teams in a global e-engineering environment.
- *Organizational*: How cultural diversity and behaviour affect global engineering activities and how teams can be organized based on core competencies to achieve global e-engineering.
- *Technology*: How different e-technologies and e-applications can be integrated to implement global e-engineering.

Consequently, a methodology has to be followed for the design and integration of the environment and the applications. A sequence of activities is proposed, as shown in Fig. 2, and explained in the following sections.

3.1. Determine the company requirements and model AS–IS development process

Identify the company requirements for product, process and/or facility development using a reference model, or capturing the process used by companies under evaluation (using, for example, ISO-9000 procedures, quality documentation, interviews, questionnaires or other techniques). Once the type of process development has been defined, an AS-IS model can be defined. A workflow model will be built on further stages, based on the identified activities from this stage, which are required for a specific design process.

3.2. Assessment of AS-IS model, and model TO-BE development process

The AS-IS business process model represents how a process is currently executed, before any ideas for improvement arises. The use of graphical representations helps identifying duplicated information, parallel activities and information sent to other departments in order to make analysis to become more efficiently. There are four domains in the identification of the integrated product development environment: process, information/knowledge, organization and resources. Afterwards, the TO-BE process is modelled (if any modifications are proposed for making the process more efficient) capturing the process-redesign team's analysis of the integrated product

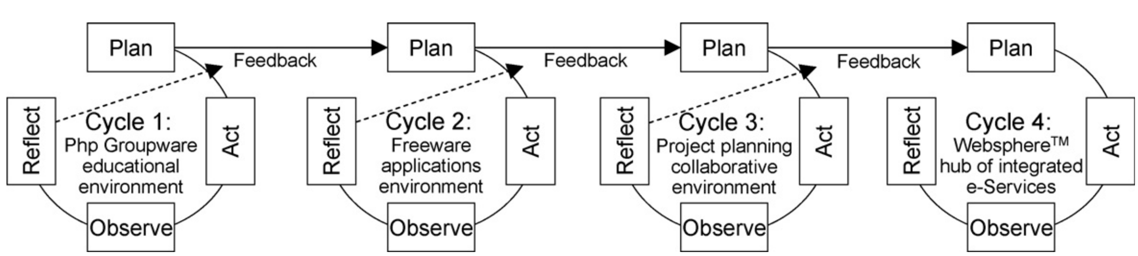

Fig. 1. Learning cycles of the action research approach.

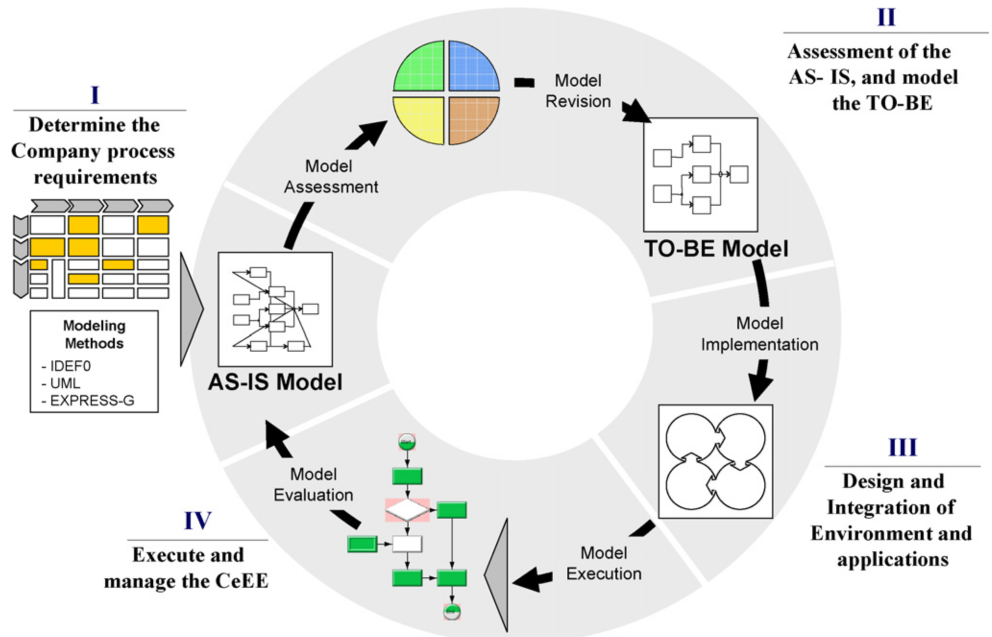

Fig. 2. Methodology for design and integration of CEEs.

development domains. This TO-BE process model will be the base model used to define the workflow in further stages.

3.3. Design and integration of environment and applications

After the model is identified, and the AS-IS model is understood (or TO-BE model, if it is the case) four main steps must be followed in order to integrate CEEs:

3.3.1. Modelling the workflow:
Workflow modelling allows analyzing the whole process development and visualizing how it works. The model also helps identifying possible information flow problems, duplicated activities and unnecessary activities, as well as showing which are the core activities and core resources in the industrial environment.

3.3.2. Selection and integration of e-engineering applications:
Several computer based information systems have been introduced to support integrated product and process development, which integrates all the activities, methods, information and technologies to conceive the complete product life cycle. Table 1 shows a taxonomy for these systems that has been proposed [31]: functional (e.g. CAD, CAM, CAE and rapid prototyping tools), coordination (e.g. workflow and project management), collaboration (e.g. CSCW, computer supported cooperative work) and information management (e.g. PDM and knowledge based engineering systems). For each type of product or process, the tools into the categories may change, but in general these categories include the tools necessary to enable the integrated product development supported by information technologies.

3.3.3. Connect environment and application using standard and Web protocols:
It is important to consider that integration with suppliers and customers is an important issue to improve the collaborative product development, allowing increasing efficiencies, reduction of time-to-market and high quality through the cooperative working of partners involved. Two groups of connections can be identified. First group includes marketing information exchange (e.g. Web pages, e-catalogues) or interconnection of manufacturing/production information (e.g. e-request for quotation, enterprise resource planning, on-line capacities),

Table 1
Computer applications classification

	Functional	Knowledge/information management	Collaboration	Coordination
Aim	To carry out and support specific functions	To share and manage Information and knowledge	To Interact and communicate	To manage and control tasks
Definition	Function oriented systems that support engineers in specific tasks.	Product information and knowledge management systems to enable the exchange of product and manufacturing information and knowledge	Collaboration systems to foster cooperation among engineer	Coordination systems to support sequencing of activities and flow of information

Table 2
Legend for methodology implementation in CEE developments

Steps	Methodology steps description	Shortcut
Action research: planning		
Step I	Define the company requirements and model the AS-IS of the development process	Step I. AS-IS
Step II	Assess the AS-IS and model the TO-BE	Step II. TO-BE
Step III	Design and integration of environment and applications	Step III. Environment
Sub-step III.1	Modelling the workflow	III.1—Model
Sub-step III.2	Selection and Integration of e-engineering applications	III.2—Integrate
Sub-step III.3	Connect environment and application using standard and Web protocols	III.3—Connect
Sub-step III.4	Definition of performance measures and monitoring techniques	III.4—Monitor
Action research: act & observe		
Step IV	Execute and manage the CEE	Step IV. Execute
Action research: reflect		
Reflection	Assess the result of the evaluation of the whole action and research process, which may lead to the identification of a new problem and hence a new cycle	

and the second group includes the information exchange between partner's functional tools (e.g. CAD/CAM/CAE files).

3.3.4. Definition of performance measures and monitoring techniques:

In the monitoring phase, the definitions of 'what' to monitor are defined but it is not monitored yet. The measurable parameters are defined in order to allow managers to coordinate, track and control the process in a further execution phase. The project plan (or the workflow model) has to be considered, in order to have a guideline for associating all the measurable data. For example, the resources involved in each activity (human and technological), which are important for cost estimations (important measurable parameter) and also for workload analysis. Furthermore, assigned dates and time are analyzed, in order to control delays or precedence problems based on unfinished activities. Similarly, the input and outputs from the activities are parameters to be controlled, in order to manage the information flow as well as availability for further activities, being an important issue to avoid delays or lack of information to perform the business process activities.

3.4. Execute and manage the workflow

After the environment is technologically integrated and implemented, it has to be managed and the loop for continuous process management is closed by the use of monitoring techniques. It provides external visibility into what is occurring when the business process is being executed. The process management tracks events and data from the workflow environment execution and provides both real-time and historical tracking of what is occurring in the workflow engine. Finally, an improvement process is performed, in order to analyze a possible new TO-BE model (the current process in execution is converted now in the AS-IS) and maybe new design improvements can be proposed to improve the business process.

4. Case studies: action research cycles

Based on the action research approach, and a rough methodology for designing CEEs, the experience cycles started. The main purpose was to satisfy the real need (action) and the enrichment of the methodology (research). The pilot project execution was carried out in this way: plan, corresponds to the configuration of the environment, according to the steps I–III (see Fig. 2). Afterwards act and observe are performed in stage IV of the methodology, which represents the implementation and the execution of the environment. Then, reflection includes the feedback and experiences documentation to make modifications to the previously used methodology for designing the environment. The methodology is summarized in Table 2.

As AR suggests, the results from previous experiences serve as starting point for a next AR cycle. Additionally, results obtained throughout the cycles increase knowledge about the subject under study. Fig. 3 depicts a general overview of the spiral followed in the development of the research, showing the evolution of needs and complexity of results. The set of lessons learned from previous experiences have contributed to define objectives of further cycles in order to justify, prove or reject some assumptions previously made. The cycles were developed in such a way that knowledge has progressively evolved until reach the current knowledge that has allowed authors to determine a minimum set of requirements to develop CEE.

The first experience in this research was a CEE for a mechatronics product development between US and Mexican Universities using Groupware technologies. In this case, the design was carried out in one country and the manufacturing in another. The main finding in this cycle was related to collaboration technologies. The second pilot project was focused on the use of low cost technologies for collaboration, and it was launched in order to improve last experience through the use of shareware tools and achieving, therefore, a more dynamic environment. The third project was based on the coordination needs that previous cycles have shown. It was based on the experiences form the e-Hubs Project, where the use of workflows for content driven processes was tested. Finally a fourth cycle, planned for further research, will try to integrate robust technologies and will work in the implementation of a CEE for engineering maintenance operations for a Mexican cement company. In this case, a commercial tool was proposed to be used (IBM's WebSphere^{TM} Technologies),

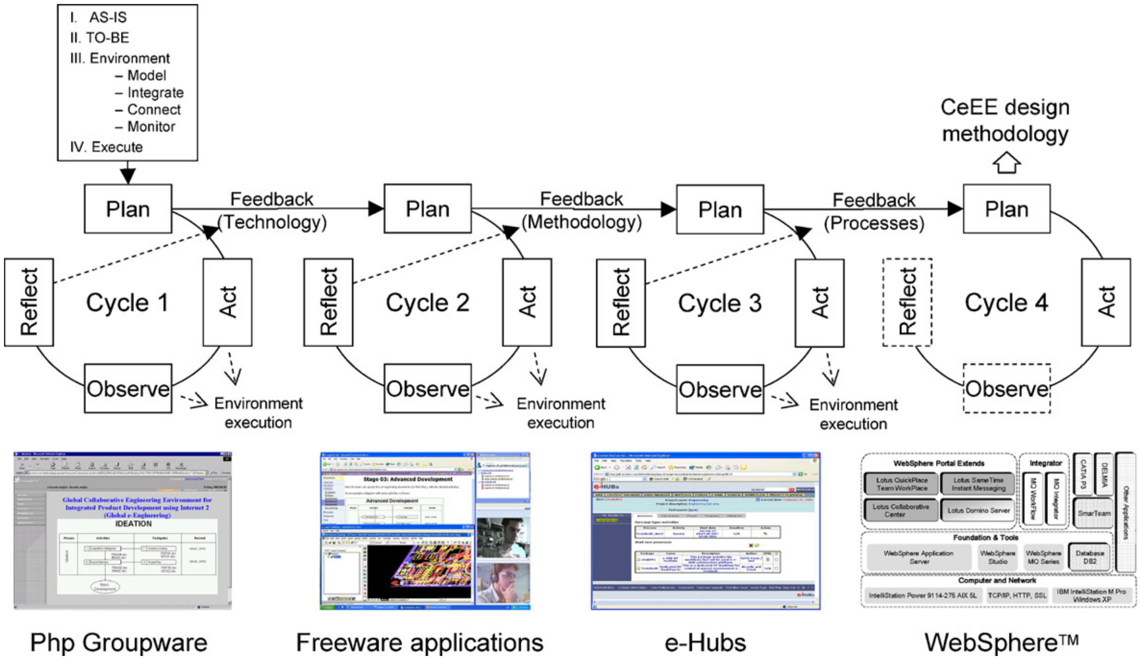

Fig. 3. The research undertaken using action research spiral.

which includes several modules that support functionalities not supported by the tools used in the previously developed prototypes (previous cycles). The following sub-sections will describe the case studies in detail and Table 2 provides the terminology for case studies' structure.

4.1. Cycle 1: Php groupware Technologies

The purpose of this cycle was to design and integrate a: *Global CEE for Integrated Product Development using Internet-2* (*Global e-Engineering*) [17]. This UC-MEXUS[1] project intended to support the remote development of High Tech Products, as well as education cooperation.

4.1.1. Cycle 1: Planning

4.1.1.1. Step I. AS-IS. In this scenario, there was no current process under execution. The idea was to introduce a new methodology for High-Tech products development. Consequently, an original model or a current process to be analyzed (in order to be improved) did not exist.

4.1.1.2. Step II. TO-BE. In order to concurrently design electronic products integrating electronic and mechanical knowledge a structured way of doing the design stages was proposed. These stages were followed to assist students and engineers to design and collaborate with an established set of specific methods and tools, allowing the collaborative product development within US and Mexican students.

Four domains of the model were assessed: process, information, organization and technology. The process domain was identified, and the sequence of activities was defined. The information domain includes the procedures, instructions and formats which constituted the documentation of the development process. Each stage from the methodology has a defined set of documents, which allow partners to execute the activities. The organization domain was considered through the definition of responsibilities for the activities execution. The technology domain was defined through the identification of required methods and tools, to support integrated product development process.

4.1.1.3. Step III. Environment

The technology to be considered in this scenario was evaluated. In the early project stages, a complete development of an environment prototype was carried out. The selected technologies for the first software were Hypertext Preprocessor (PHP), MySQL database and Apache Web Server. The system was finished, but some issues in the testing stage showed that the software developed was not the best option for this application. Among the limitations found were the difficulty to do maintenance, it was not standard and it was not easily modifiable. In this way, a Webmaster must be constantly coordinating and maintaining the system, increasing costs, and reducing efficiency and autonomy for the Software users.

As a consequence, a new research about collaborative applications was performed and some standard applications were analyzed. The chosen application was PHPgroupware (http://phpgroupware.org/) because it offers a standard groupware, which can be personalized, that is, it can be reprogrammed to be adapted to a specific application.

After the domains were identified, the sub-steps from this stage of the methodology were executed:

4.1.1.3.1. Step III.1—Model. Based on the TO-BE model assessed on the previous stages, now the work assignment to the

[1] UC MEXUS (The University of California—Institute for Mexico and United States) Workshop of I2 Research Projects—UC Riverside, 2003.

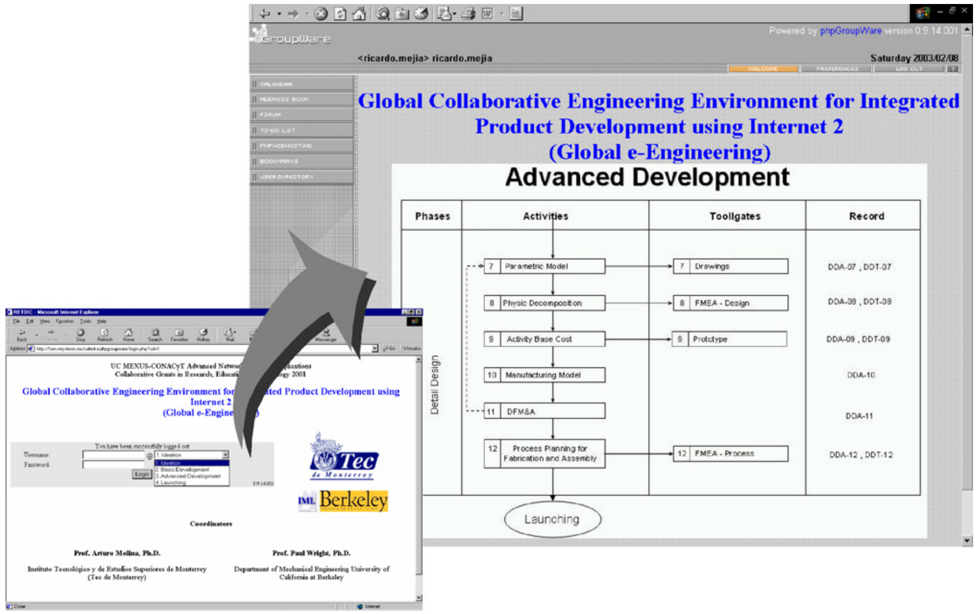

Fig. 4. Stages of product development process in the high tech product.

CEE users would be defined. Due to the platform specifications, a lack of processes management or workflow tools forced a different form to represent the process sequencing. A set of HTML pages were developed and integrated into the environment. This is the way groupware systems are configured in order to personalize the environments to the purposed application.

For this scenario, the integrated product development process was divided in its main four stages, specifying the sequence of activities to be performed by the users, and the required information that each step requires to be performed and the information generated as a result. In order to access to the environment, users must introduce a username, password and select actual project stage. The stages are available as the project advances; if information from pervious stages is not complete, next stages are unavailable (see Fig. 4).

4.1.1.3.2. Step III.2—Integrate. In this case, the technology requires configuring a server in order to allow the Internet access to the environment. The storage space limits depends on the hardware in the server where the installation will be installed.

Several Web-based tools were developed to support the Integrated product development process [32]. Some examples are: (A) The Manufacturing Advisory Service (MAS), which is a tool for finding a good fabrication method for a part while still at the conceptual level of design, (B) SMT-Advisor, helps users to analyze the manufacturability of any printed circuit board (PCB) according to the capabilities of the SMT line at Tecnológico de Monterrey and (C) Ducade, for supporting the electronic and mechanical components assemblies design.

The technologies used in this case are summarized in Table 3. The information management tools and the collaboration tools are capabilities of PHP technology. From the other side, the functional tools are the methods and tools recommended for use by the integrated product development process.

4.1.1.3.3. Step III.3—Connect. For this scenario, no marketing information exchange was required because the partners were Universities (UC-Berkeley & Tecnológico de Monterrey) using their own capabilities for design and manufacture. The only need of information exchange was the information exchange between partner's functional tools as CAD software and DUCADE system.

4.1.1.3.4. Step III.4—Monitor. For this scenario, and due to the lack of a coordination system, no performance measures were defined. The automated monitoring was not possible, and conventional managing tools were used for the management of the project (breakdown of activities and Gantt charts) and for

Table 3
Computer applications for the PHP-environment integration

Functional	Knowledge/information management	Collaboration	Coordination
Web Based applications used: MAS, SMT-advisor, Ducade	Files uploads	Tools available are: mail, chat, forums, shared spaces, news, user index	Design stages are conformed by a sequence of activities in order to assure the information flow along product development process
Engineering stand-alone applications used: Pro-Engineer, electronic workbench			The defined structure in the environment allow process flows and control of instructions, formats, methods and tools

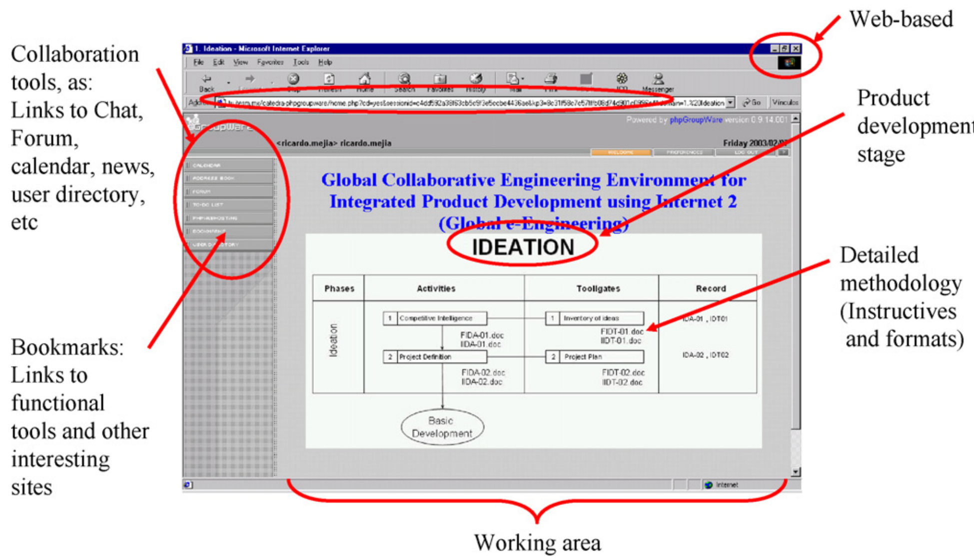

Fig. 5. Php groupware characteristics.

process documentation (instructions, formats, methods and tools).

4.1.2. Cycle 1: Act and observe

4.1.2.1. Step IV. Execute. After conducting the previous activities and with the identified technology, the integration and implementation of the CEE is carried out.

The last version of the CEE prototype is shown in Fig. 5. All the identified technologies are referenced from the process model, and the application can be linked (if it is a Web-based functional tool) or simply referenced or recommended by the process model (in this case, embedded information HTML pages).

To fulfil all of the above issues, the system developed offers different applications on each stage and activities of the project. The members can access these methodological sections in different geographical locations and the environment allows them to: organize their project activities (time and resources); participate in creative ideas across distances; establish coordinated actions for specific task in order to take decisions in critical points during the product design process; and keep up-to-date and share project information like records of every activity, product models and simulation reports.

4.1.3. Cycle 1: Reflect

The objective of this environment was to create a shared space to support remote interaction among engineers in developing a High-Tech product. However, the functionalities of the *Cycle 1* environment were not enough to produce a fully integrated CEE due to some limitation on the basic technologies to be integrated. Authors consider that a CEE should cover the basic technological categories as mentioned in Table 1 (functional, information management, collaboration and coordination) to properly support engineering tasks accomplishment.

Nevertheless, this environment allowed interaction among partners, based on a structured engineering process, being able to provide users with their corresponding activities based on a predefined methodology. During the assessment of the environment, the following technological issues arouse:

- Functional tools could only be integrated as links. That means only Web-based systems could be linked to the main process. Some applications could not be integrated but can be referenced or mentioned, as a suggestion throughout the main process (High tech product development).
- The knowledge and information management area was reduced to a file repository or a basic storage on a Web space.
- The environment provided access to some collaboration tools that groupware systems usually offer, such as chat and forums. This was a key issue that had to be further tackled.
- The coordination technologies were intended to be covered by publishing the methodology. Design stages were conformed by a sequence of activities in order to assure the information flow and control of instructions, formats, methods and tools.

Hence, one of the main lessons learned to be considered in a further cycle, is to enhance the CEE beyond an information sharing Web-space. Real time interaction was detected as a primarily need to be further researched through exploring different communication set of tools to be integrated.

4.2. Cycle 2: Freeware applications

This cycle was executed to explore a broader range of collaboration tools, because the last cycle (Php-groupware scenario) had shown that collaboration tools already integrated in groupware were limited. Several tools were tested, and this scenario allowed one to visualize what public-domain tools may offer. Within these categories MSN™, Yahoo™ and NetMeeting™ can be included. They

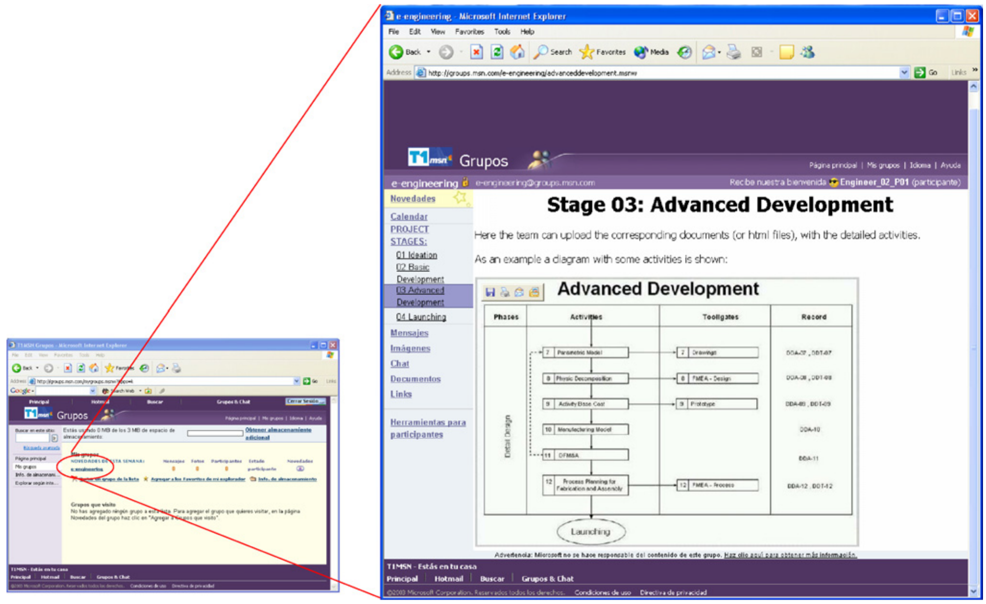

Fig. 6. Stages of product development process in freeware environment.

provide a huge variety of collaboration tools. In this case, the MSN application was selected to demonstrate the concepts.

4.2.1. Cycle 2: Planning

4.2.1.1. Step I. AS-IS. In this scenario, as well as the previous one, there was no current process under execution.

4.2.1.2. Step II. TO-BE. The main goal of this scenario was to test the variety of accessible collaboration tools, and since the integrated product development process was intended to be included in this scenario, this model was selected as the TO-BE model.

4.2.1.3. Step III. Environment

Considering the availability of these tools, some of the next steps were carried out in order to design an integrated environment.

4.2.1.3.1. Step III.1—Model. In this scenario, it was necessary to create a shared space using MSN groups; however, in those environments there is a lack of workflow tools. Hence, the environment was configured to display, in a static way, the flow of activities, the methods and the tools required for each activity (Fig. 6). A menu was created, with the integrated product development stages, according to the pre-defined methodology (same as used in first cycle of AR). Also, links to the documentation (procedures, instructive and formats) were generated. The documents were uploaded, and instances of the delivered documents (registers) were able to be uploaded in a pre-defined file structure.

4.2.1.3.2. Step III.2—Integrate. Table 4 displays the freeware applications used to configure an e-engineering environment. As illustrated, it integrates space to upload information, configure methodological steps, calendar, e-mailing and chat, among other services. Some specific tools (functional tools) were shared through ‘applications sharing’ and allowing control and interaction through video/audio conferencing as well as drafting with a common whiteboard.

This kind of scenarios is an example of the execution of one activity into the product life cycle. Here, users need some input information (i.e. electronic CAD design, specifications, etc.), and they must deliver a specific output (CAD model reviewed or engineering change proposed). The management and monitoring tools are supposed to be controlling the execution

Table 4
CEE based on freeware tools

Functional	Knowledge/information management	Collaboration	Coordination
Engineering stand-alone applications were used: mechanical desktop, design explorer, electronic workbench Some CAD tools allow collaboration (e.g. CATIA, AML)	MSN groups: file uploads, picture publishing, customized html frames (with the project information)	MSN group: chat, calendar, forums MSN messenger: instant messaging, application sharing, audio/video, whiteboard	A lack of a formal coordination tool is a disadvantage. Stand alone applications as MS Project were used An approach is the structure defined in the environment created: MSN groups: calendar, customized html frames (with the project information)

of this task, and the common information (i.e. uploaded in this shared environment) is centralized.

4.2.1.3.3. Step III.3—Connect. The key issue in connecting applications is the exchange formats among functional tools. In this kind of environments, the transferring of information between computer applications can be managed through file uploading from the environment. Nevertheless, this stage was not executed, because connectivity efforts were not required.

4.2.1.3.4. Step III.4—Monitor. The monitoring stage was not executed as well, because there was not a coordination system able to track and control the defined performance indicators.

4.2.2. Cycle 2: Act and observe

4.2.2.1. Step IV. Execute. Different tools had been used to foster collaboration, but the problem of integration was still a key concern. Hence, as shown in Fig. 7, a combination of different tools through the Internet were used to execute a specific task in an electronic product design.

The users of this CEE (MSN group) http://groups.msn.com/e-engineering were joined through e-mail accounts (in this specific case, Hotmail.com accounts were created). They defined groups of four engineers and one Project leader. The point to tackle was then the 'integration' of all the required applications into a common 'environment', providing the necessary tools to the project team. The integration platform should allow the coordinated and simultaneous execution of project tasks.

4.2.3. Cycle 2: Reflect

Cycle 2 environment was primarily made with the objective of interacting with more powerful collaboration technologies. It also covered the other basic technologies (functional, information management and coordination) but in a more simple fashion (similarly to cycle-one in some cases) due to the capabilities of the selected technology.

This environment really enhanced the real time collaboration through communication technologies provided by freeware systems, but the other technological categories remained without improvements. The main reflections from the execution of this cycle are:

- Through a collaborative functionality called 'application sharing' functional tools (stand alone applications) could be integrated to the process. This functionality enabled a user to remotely control its partner' applications through the Internet. This is a remarkable achievement in collaborative technologies.
- The knowledge and information management area is quite limited due to freeware technology limitations (reduced Web space).
- As well as in the first cycle, the methodology and coordination aspects were the key concern. Information flow and process control should be more structured and automated, to allow monitoring and efficiency in process execution.
- Freeware applications seem to satisfy the needs of focused environments, where collaborative work is required in real time, such as product modelling in product design. In these cases, the designer and the manufacturer should be communicated to work concurrently.

The main learning of this cycle was the need detected of a more elaborated system to manage the engineering process (methodology). Engineers were able to interact with other partners, but the process flow was poorly managed. The enhancement of the

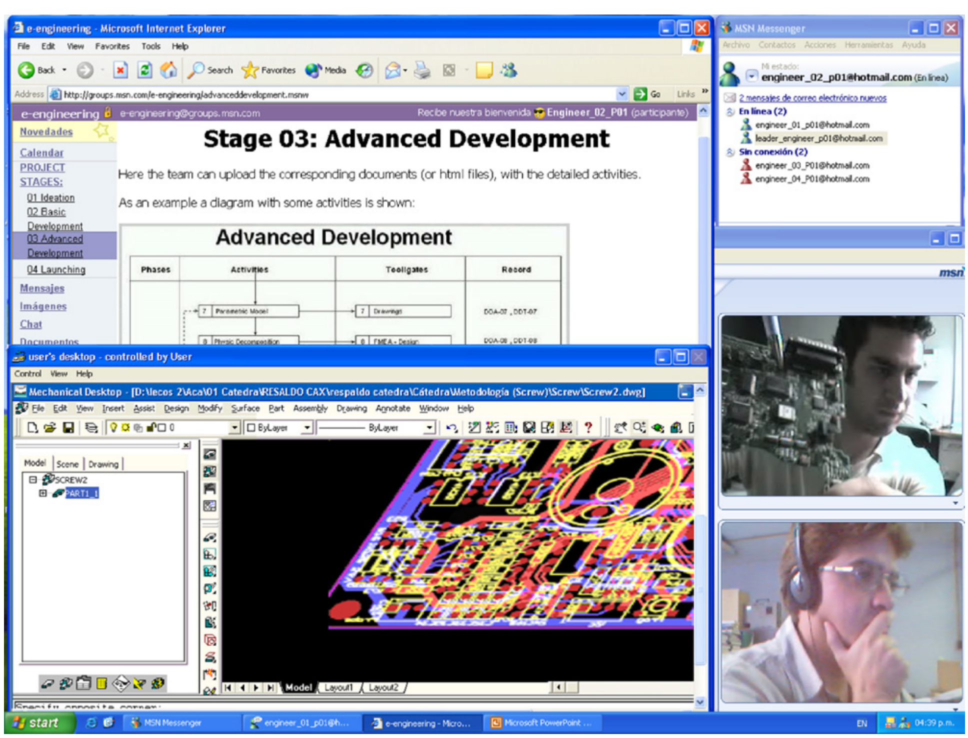

Fig. 7. MSN™ collaborative tools (messenger and groups).

coordination technologies should be considered in a further cycle, to make a more dynamic environment.

4.3. Cycle 3: e-Engineering enabled by Holonomic and Universal Broker services

This cycle integrated the experiences gained in the two prior cycles. The need for more stable and robust platforms guided to the selection of more robust applications. It primarily tackled the engineering process automation (coordination technologies).

This experience was developed in collaboration with the European e-HUBs consortium,[2] funded by the European Commission's IST program in 2002 to develop a Web hosted platform for planning e-engineering projects. The authors were part of the consortium and have participated in the system's requirement specification and integration model (where previous cycles' experiences were included in the contribution). Those specifications were provided to an industrial partner in information technologies (also part of the consortium) and they carried out the construction of a prototype system. The authors of the article were in charge of one of the two "test beds" implementation with industrial and research partners from Mexico and Europe.

The project aimed at a set of Web hosted services that enable projects to be efficiently planned through a so-called e-Hub. The project targeted the conceptual development and implementation of e-Hubs, a novel concept for the realisation of distant co-engineering [33]. A generic conceptual framework was developed and a prototype implementation of the generic concepts was benchmarked in co-engineering processes within the development life cycle and manufacturing process of customized products.

The e-HUBs project ended in summer 2004. The main result was a first generation prototype with unprecedented project planning functionality [34]. The prototype is currently running and some of its functionalities will be described in the following section.

4.3.1. Cycle 3: Planning

4.3.1.1. Step I. AS-IS. For the e-HUBs software prototype, two domain-specific scenarios from different disciplines were evaluated. The first scenario or 'test-bed' dealt with seismic risk assessment procurement in a large construction project, whose client was a Dutch design firm and the engineering service provider was an Italian small and medium enterprise (SME). The second test-bed dealt with the engineering of a structural part for a trailer. In this case, the client was a steel-making company and the engineering provider was an SME cluster in Mexico. The e-Hubs' focus was on project planning where the partners involved had not a standardized process, that is, there was a lack of an AS-IS model.

The strategy followed to generate the TO-BE model was to analyze and improve a planning stage of an already developed project in a company called integration, engineering and construction systems (IECOS). IECOS had made a market analysis for its client to identify potential product for new markets based on the client's expertise—which is metalworking manufacturing. IECOS identified several possible new products and developed a specific project called 'Design process of a Dry-Freight Van for Trailer'. At the end of the benchmarking phase, the client decided to outsource the engineering of the new product to IECOS due to the lack of internal engineering capability and expertise. Hence, the planning process of this project was reviewed, improved and later used as a model.

4.3.1.2. Step II. TO-BE. To create the workflow, the product design scenario was analyzed and an overall evaluation of the generic process for project planning was performed. After that, the original project planning was compared to the real execution. Then, a detailed evaluation was performed comparing each task in order to progressively identify trouble spots and their originators. These issues were useful to determine preventive activities in a project planning workflow, pursuing the prevention of potential problems during project execution.

Information was gathered to prevent issues that could cause problems during project execution. Topics like project duration, project design, parties involved and changes during execution where discussed. However, these topics were too generic and therefore it was necessary to create detailed documents to support a specific domain. For that reason, the testbeds required the design and integration of dedicated workflows to support the collaborative project planning in their specific domains (civil and manufacturing engineering). In the product design scenario, a set of supporting documents were defined based on the experience and knowledge generated (aligned with the PMBOK from the PMI [35]). For example, three supporting workflows for engineering project planning were identified in the product design scenario:

Document A: environment control/external factors: In this document problems detected in execution were grouped, creating a set of fields to be considered by the partners from the beginning of the preparation phases. They were called 'categories' grouping common difficulty spots as technological, market conditions, regulations, etc.

Document B: change management control (*product*): This document intended to guide project planners in negotiating, from the beginning, a set of conditions for dealing with change requests. The workflow managed a flow of activities working upon a set of variables that would guide partners to a discussion of conditions, until an agreement was reached.

Document C: risk identification: Usually between two partners, there are several areas with a high level of risk, for example proficiency, information management, technology, etc. This workflow intended to show users common risk areas in engineering projects. A set of activities would guide

[2] The e-Hubs Consortium consists of: TU Delft (NL), RWTH (GE), Design Solutions (NL), European Dynamics (GR), CKA (BE), GeoDeco (IT), Loughborough University (UK) with affiliated partners Tecnológico de Monterrey/IECOS (Mexico) and NUMA (Brazil), Georgia Tech (USA) and Penn State (USA).

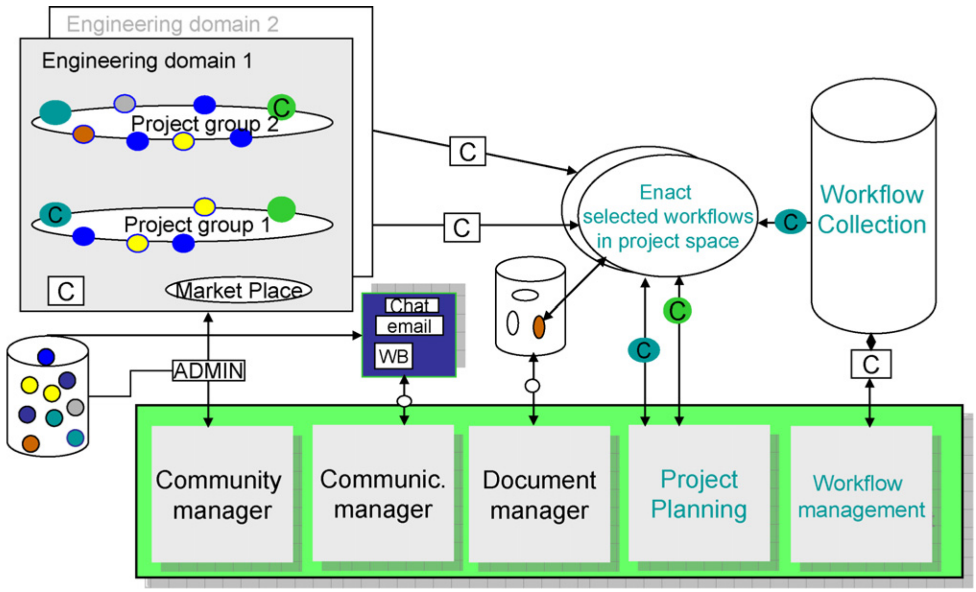

Fig. 8. e-HUBs prototype system architecture [34].

partners to a negotiation process to agree in strategies to prevent or diminish the levels of risk.

4.3.1.3. Step III. Environment

As described before, the e-Hubs system prototype has been developed on the substrate of an existing Web hosted collaboration platform. The platform offers all the normal functions typically found in a Web hosted collaboration space, e.g. community building, team communication manager and document management. The process modelling module operates on the basis of these functions but has two added functional modules: workflow management and project planning. Fig. 8 shows the Architecture of the e-Hubs prototype system.

The following steps describe the methodology to create a CEE based on the e-Hubs system prototype, for the product design scenario.

4.3.1.3.1. Step III.1—Model. From the identified supporting documents (detailed workflows for project planning), the workflow model for the system was constructed. The prototype's workflow management module offers a Java based workflow modeller with which the process models can be developed offline and uploaded onto the e-Hub. The program used to design the workflows was JaWE—Java Workflow Editor (http://jawe.objectweb.org/), which generates XPDL files that conform to The Workflow Management Coalition (WfMC) specifications [36,37].

A set of workflows were developed for the definition of a generic process for project planning, and also for engineering specific processes in both scenarios (mechanical engineering areas and civil/construction fields). Fig. 9 depicts one of the workflows developed for the product design scenario for the risk assessment in the dry-freight van for trailer design process.

The e-HUBs platform enables parties to transparently produce rich planning information that exists at the start of project and keeps a document live through execution. This is achieved by the ability of the workflows to invoke external applications, such as saving documents with workflow information based on templates (pre-defined by users). This point will be detailed in the connect step of the methodology.

However, it must be clarified that the exchange of information should not exclusively be done through the workflow system (even through the e-Hub). It is still possible for engineers to freely communicate design information at meetings, by regular e-mail, fax and telephone, as has been mentioned by other authors, e.g. [38]. The main purpose is to minimize (not avoid) the regular interactions.

4.3.1.3.2. Step III.2—Integrate. The applications and tools to support the project planning process were identified. An analysis of the functional tools was carried out in order to identify those Web-based applications (open source or linked

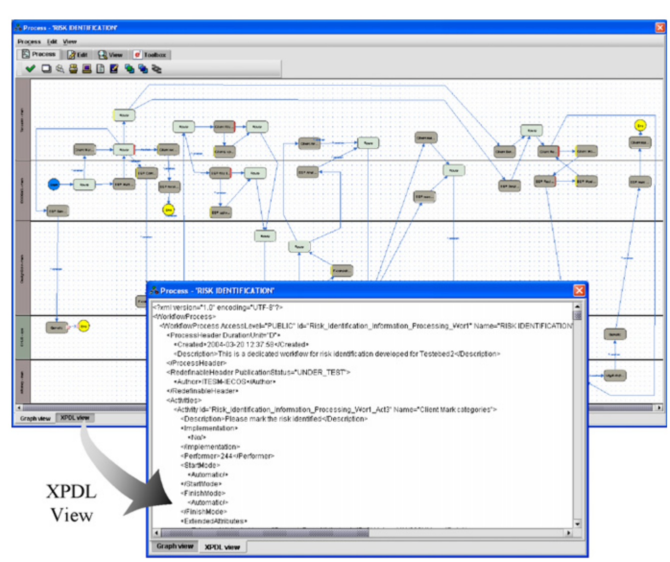

Fig. 9. Workflow graphic view and XPDL view on JaWE.

applications), and stand-alone applications that supports other specific activities.

In the product design scenario, the main functional application required for project planning was an application for saving the information managed through the workflow execution. This data is important to be saved into a document based on templates generating a report (live document) to be considered for project execution.

Two applications used in the seismic engineering scenario exemplify the next step of the methodology (connect). The first of them is the 'eRisk zone', which aims to contact potential clients. The portal requests all the necessary information to perform a simplified seismic risk analysis, provides preliminary results to the user and offers more accurate investigations on demand, to be carried out off-line through a human-based activity. The second tool (also used in the seismic engineering scenario) is the eLEGAL contract editor [39]. This system for e-contracting is the IT-supported creation, negotiation, closing and performance of contracts. It is the process of setting-up, negotiating, signing and maintaining contracts purely in electronic form for establishing a line of communication between parties, in order to agree on a common line of rights and duties.

Table 5 summarizes the taxonomy of applications used in the e-Hubs system. It is important to mention that these technologies can be configured or personalized for new scenario requirements.

4.3.1.3.3. Step III.3—Connect. The e-HUBs prototype is built on pure Java and J2EE technology that provides core platform services, application business logic and integration abilities with external systems. e-HUBs supports all established software services, including:

- Web Server: Apache, IIS
- Application Server: JBOSS, WebLogic
- Database Server: MySQL, Oracle
- OpenLDAP Server: Hosts the Members Centralised Directory.

Furthermore, as a distributed-oriented system, e-HUBs includes features which enable the system to communicate with its own remote instances, as well as, with third party systems, using RSS, XML or SOAP.

The best example to show this functionality is in the seismic engineering scenario, where a connection among the e-Hubs system, eLEGAL and eRisk database was achieved by the e-Hubs functional architecture responsible. Conditions of contract template for engineering service negotiated in the e-Hubs workflows are stored in the eRiskZone database and linked to the eLEGAL contract editor through a particularly developed XML file.

4.3.1.3.4. Step III.4—Monitor. The approach in this case was the workflow activities monitoring. This functionality allows the workflow administrator to know what activities were already closed, and which ones are being executed. However, there was not a specific module to graphically track the workflow execution, as well as performance measures.

4.3.2. Cycle 3: Act and observe

4.3.2.1. Step IV. Execute. The e-HUBs prototype is a Web-based software application supporting online collaboration between clients and engineering service providers (ESPs), for defining and executing engineering projects. The system is currently running on the Web in a temporary server located in http://elf.eurodyn.com:8080/edos/index.do. The main page has public access to predefined communities for general information or public domain information. Then, only registered users can sign-in to the system. Afterwards, private projects (called communities) can be created or accessed. The e-Hubs workbench is accessed by clicking on the desired project. Fig. 10 shows the general characteristics of the main page.

The current version of the e-HUBs prototype supports: specific target markets, member registration, user authentication, user profiling, document repository, dedicated marketing space, online chatting, e-mailing, forums and meeting scheduling. Furthermore, the main modules are also included: workflow and project planning. With these modules, the CEE was customized, designing the specific workflows depending on the scenario's domain. The workflows were created offline with the JaWE tool and then were imported to the system as XPDL files. With the uploaded workflows, its execution was performed and the system started with activity assignment and the environment was running. Fig. 11 shows the sequence of creating, uploading and executing the workflows in the e-Hubs system.

Reports were generated and stored in the system for further analysis or application. Real-time virtual meetings between partners were also possible whereby all other functionalities could be executed simultaneously.

Table 5
e-HUBs prototype's modules

Functional	Knowledge/information management	Collaboration	Coordination
Reports: Application for saving workflow data into a document based on templates	Document manager, templates	Forums, meetings, chat, calendar, e-mail	For this system, a strong set of modules for coordination is an advantage: workflow, project planning
External applications: Stand alone or Web based system from partners: Web-portals, e-legal[a], eRisk zone[a]			*User manager*: For users administration and role assignment

[a] Used in the seismic engineering scenario.

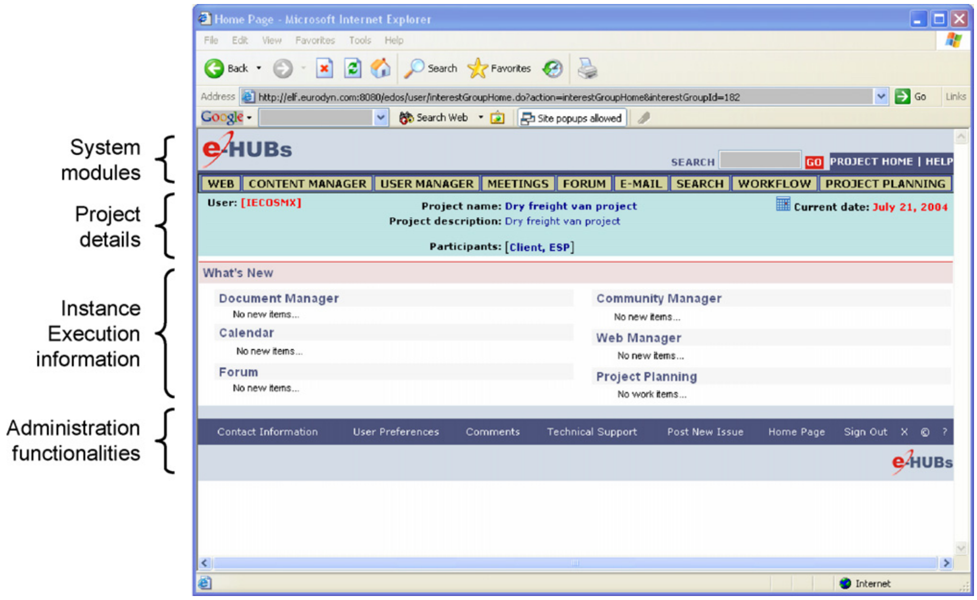

Fig. 10. e-HUBs Web-prototype workbench.

4.3.3. Cycle 3: Reflect

The objective of this cycle was to automate engineering processes execution by a more elaborated system with a more complex architecture. The added value of the e-Hubs is that the process is collaborative and logically ordered. It is also driven by a structured content exchange embodied in a formal project planning model (PPM). This PPM played the role of a methodology to be followed by partners.

Thus, the e-Hubs environment enabled partners to collaborate in more structured manner due to the use of workflows as coordinating technologies. However, the collaboration level acquired in the past cycle was not able to be reached, because the limitations of this technology were similar to the first environment (only chat, e-mail and forums).

The main reflections of the e-Hub Web prototype can be summarized as follows:

- The coordination technologies were covered through the business process management system (workflow and project planning module).
- Functional tools can be integrated. Data can be imported/exported from different applications.
- The functionality of collaboration and information management technologies was limited for being a prototype. This is intended to be improved in a further cycle.
- An important functionality to be considered is a monitoring technology for performance measurement analysis.
- It is a more elaborated system with robust technologies. However, it might create human and organizational barriers for the industrial acceptance of this technology.

The main contribution of this cycle was the importance of using *business process management systems* for supporting the

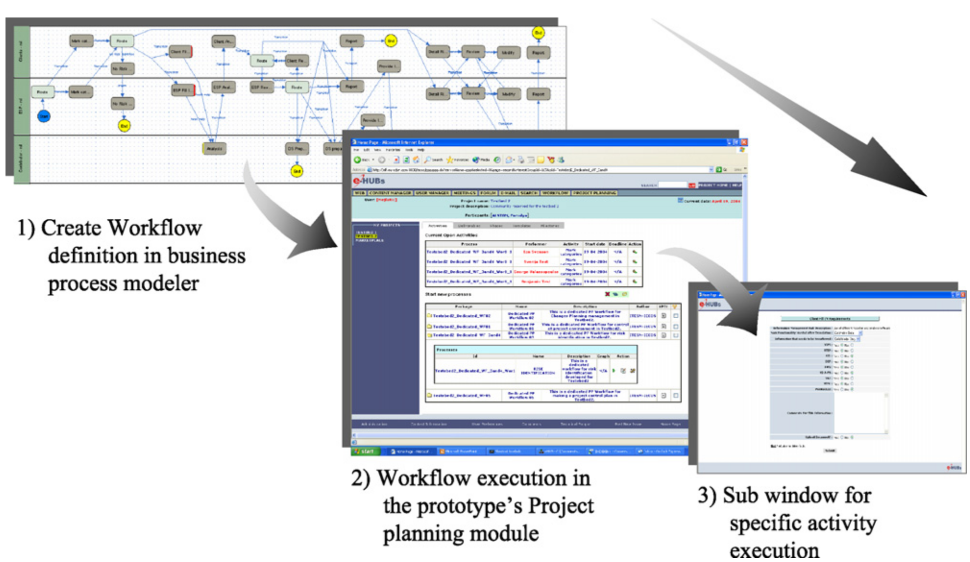

Fig. 11. Workflow design and execution in e-Hubs Web-prototype [31].

Table 6
CEE based on WebSphere™ tools

Functional	Knowledge/information management	Collaboration	Coordination
IBM-PLM tools which are stand-alone: CATIA, DELMIA Additional stand-alone software: (e.g. QFD, IDEF, AMEF) Web-based tools can be included into the WPI-Portal	Database, DB2, SmarTeam	Lotus QuickPlace, Team WorkPlace, Lotus SameTime, Instant Messaging, Lotus Collaborative Centre, Lotus Domino Server	MQ Series: MQ workflow, MQ integrator, HOLOSOFX and Lotus Domino Server

methodologies or main engineering processes. It has open a new way of thinking in the design an integration of CEEs by managing workflow concepts for the engineering processes in industry.

This cycle covered all the basic technologies in different levels (functional, information management, collaboration and coordination) and some of them should be enhanced in a further cycle, integrating all the acquired experiences throughout the three previous action research cycles.

4.4. Cycle 4: Further research with IBM WebSphere™ technologies

Summarizing the experiences acquired in the three previous cycles, it can be concluded that the first cycle has established a Web space with limited capabilities. It integrates all the four categories of technologies but with limitations. The second cycle integrated a set of communication tools to enhance real time collaboration, but the selected technology presented limitations in the other technological categories, similar to cycle one. A very important detection in both cycles was the need of a more structured way of supporting the engineering process management. The third cycle tackled this issue by using the business process management concept through collaborative workflows implementations. It enhanced the coordinating aspect, but the selected technology did not reach the collaboration level acquired in the second cycle. For this reasons, a fourth cycle intends to cover those experiences through the use of a more structured system using a software able to integrate the main technologies (functional, information management, collaboration and coordination) to achieve a more powerful environment.

To explore better alternatives and more powerful technologies, the WebSphere™ application platform from IBM has been identified for developing the system for 'CEEs'. Table 6 shows the structure of the WebSphere™ technologies.

The WebSphere application platform offers tools and technologies with capabilities to cover the defined requirements. WebSphere is based on infrastructure software (middleware) designed for dynamic e-business, providing solutions for connecting people, systems and applications with internal and external resources. Fig. 12 presents a proposed architecture to build a system for creating CEEs.

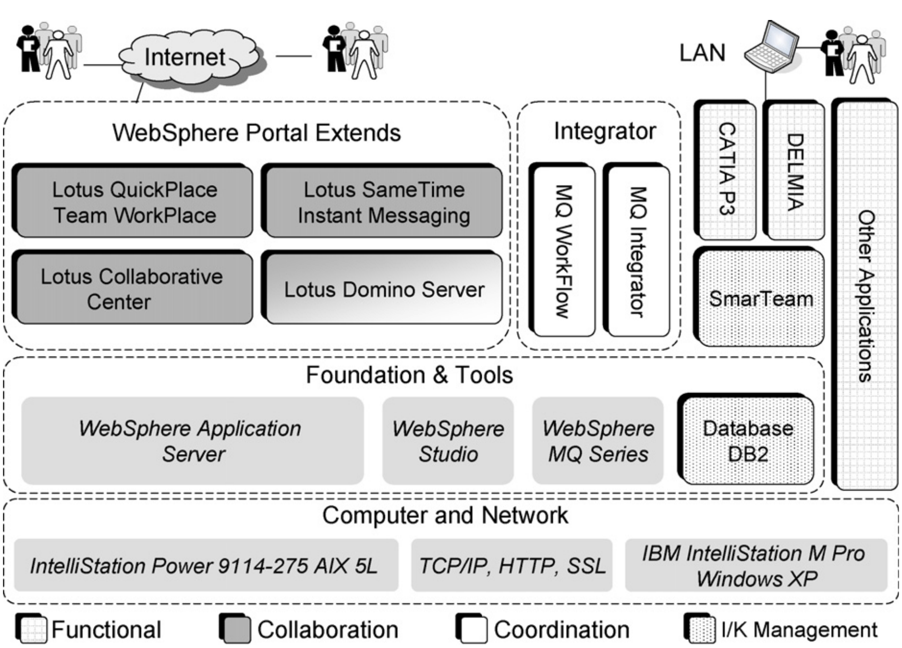

Fig. 12. CEE architecture with WebSphere Technologies.

Table 7
Cycles' outcomes

Cycle	Outcomes
1—Php groupware	*Main achievements*: Environment allowed interaction based on a structured engineering process; Access to some collaboration tools that groupware systems usually offer (chat and forums) *Limitations*: Limited functionalities due to some constraint on the basic technologies; Functional tools could only be integrated as links; The information management area implemented as a file repository or stored on a Web space; The coordination was made by publishing the methodology for the engineering process *Analysis*: This environment has to be enhanced beyond an information sharing Web-space; Real time interaction was detected as a primarily need to be further researched
2—Freeware applications	*Main achievements*: Real time collaboration through communication technologies provided by freeware systems; Functional tools were able to be integrated through "application sharing" *Limitations*: The other technological categories remained without improvements (functional, information management and coordination); The knowledge and information management area was quite limited (reduced Web space); Information flow and process control should be more structured and automated, to allow monitoring and efficiency in process execution *Analysis*: Engineers were able to interact with other partners, but the process flow was poorly managed; A more elaborated system to manage the engineering process (methodology) is needed; The enhancement of the coordination technologies should be considered in a further cycle, to make a more dynamic environment
3—e-Hubs	*Main achievements*: A more elaborated system with robust technologies; Automation of the "engineering processes" by Business Process Management; The process is collaborative and logically ordered using workflow technologies; Functional tools can be integrated. Data can be imported/exported from different applications *Limitations*: The collaboration level from last cycle was not able to be reached, because of the limitations of the technology used (only chat, e-mail and forums) *Analysis*: An important functionality to be considered is a monitoring technology for performance measurement analysis; It might create human and organizational barriers
4—IBM	Not yet implemented

Thus, a fourth cycle will be developed applying this business process management (BPM) concept in a Mexican cement company. The purpose is to start with small environments for specific engineering projects as electrical maintenance analysis for their plants. The final goal is to achieve the business process automation throughout the company, and to work collaboratively with the company staff, the customers and suppliers.

After achieving the set up of this environment, it is important to start considering, in a further implementation, the integration of "emerging technologies" to develop new modules or functional tools in order to help engineers to carry out their collaborative tasks. One of these approaches with some potential is agent based systems, which could be worth to investigate in further applications.

Using multi-agent system (MAS) technology has proven to properly support a very large domain of applications, in domains such computer integrated manufacturing (CIM), networked organizations and virtual enterprises [40]. MAS represents one of the most promising technological paradigms for the development of open, distributed, cooperative and intelligent software systems [41]. Although there are several developments, such those from [42–44]. They are basically functional tools (to support specific tasks) it is important to investigate they integration in an overall multi-agent environment.

5. Analysis of results: a summary of reflections

From the experiences described in this paper, the first cycle established a shared space to allow interaction among design engineers. The Web-space provided access to some collaboration tools (chat and forums), Web storage and publishing (html) procedures, giving the feedback of a limited collaborative and interactive functionality. After this first cycle, a need for more powerful collaboration tools was identified, being the key issue tackled in the second cycle. The third cycle offered a more complex architecture with a more elaborated system. Its main contribution was the use of collaborative workflows for managing the engineering processes. However, some missing functionalities for performance analysis were detected, as well as the lack of a ready-to-use system. Finally, the search for a more stable platform led the research group to select a more robust technology for a fourth cycle as further research. Table 7 summarizes the most important aspects from the results, by listing the different outcomes from the reflection stage of the three first cycles.

6. Conclusions

The action research cycles have shown a very practical and methodical way of learning from experiences. This research methodology led researchers and users to a common objective of improvement in technologies for collaboration and support of engineering activities. It allowed authors of this paper to identify key issues by using different technologies and working methodologies (business processes). This methodology has led to achieve improvements in the structuring of a proved methodology for the design and integration of CEEs. A set of experiences were structured in such a way that lessons learned were an opportunity to improve further experiences and to enrich the knowledge on CEEs creation. An important remark is that not all the technical shortcomings should be tackled in the next cycle, but it can be done two or three cycles afterwards. Perhaps more importantly, the learning process brought about a methodology for the design and integration of CEEs that will guide researchers and practitioners to build up their customised CEEs.

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References

[1] S.P. Keller, Simulation-based acquisition: real world examples, Army RD&A (1998) 25–26.
[2] G.M. Bochenek, J.M. Ragusa, Virtual collaborative design environments: a review, issues, some research, and the future, International Conference on Management of Engineering and Technology, PICMET 01, 2001.
[3] J.P. Harrison, Virtual collaborative simulation environment for integrated product and process development, in: Proceeding of the IEEE International Symposium on High Performance Distributed Computing, vol. 6–9, 1996, 19–22.
[4] Huang, Q. George, Web-based support for collaborative product design review, Journal of Computers in Industry 48 (1) (2002) 71–88.
[5] S.F. Qina, R. Harrisonb, A.A. Westb, I.N. Jordanovc, D.K. Wrighta, A framework of Web-based conceptual design, Computers in Industry 50 (2) (2003) 153–164.
[6] F.E.H. Tay, A. Roy, CyberCAD: a collaborative approach in 3D-CAD technology in a multimedia-supported environment, Computers in Industry 52 (2) (2003) 127–145.
[7] G. Huang, L. Mak, Agent-based collaboration between distributed Web applications: case study on collaborative design for X, Using CyberCO, Concurrent Engineering: Research and applications 10 (4) (2002) 279–290.
[8] Y. Wanga, W. Shena, H. Ghenniwab, WebBlow: a Web/agent-based multidisciplinary design optimization environment, Computers in Industry 52 (September (1)) (2003) 17–28.
[9] F. Qian, Z. Shenseng, Product development process management system based on P_PROCE Model, Concurrent Engineering: Research and Applications 10 (September (3)) (2002) 203–211.
[10] K. Rodriguez, A. Al-Ashaab, Knowledge Web-based system architecture for collaborative product development, Computers in Industry 56 (1) (2005) 125–140.
[11] S.Q. Xie, Y.L. Tu, R.Y.K. Fung, Z.D. Zhou, Rapid one-of-a-kind product development via the Internet: a literature review of the state-of-the-art and a proposed platform, International Journal of Production Research 41 (2003) 4257–4298.
[12] W.D. Li, J.Y.H. Fuh, Y.S. Wong, An Internet-enabled integrated system for co-design and concurrent engineering, Computers in Industry 55 (1) (2004) 87–103.
[13] M. Tseng, T. Kjellberg, S.C.Y. Lu, Design in the New e-Commerce Era, Cirp Annals-Manufacturing Technology 52 (2003) 509–519.
[14] H. Yang, D. Xue, Recent research on developing Web-based manufacturing systems: a review, International Journal of Production Research 41 (2003) 3601–3629.
[15] W.K. McQUAY, Distributed collaborative environments for 21st Century modeling and simulation, Simulation 76 (2001) 95–96.
[16] W. Shen, Editorial of the special issue on knowledge sharing in collaborative design environments, Computers in Industry 52 (2003) 1–3.
[17] J. Aca, R. Mejía, M. Velandia, E. García, N. Galeano, H. Ahuett, A. Molina, P. Wright, Integrated product development in virtual enterprises supported by Web-based applications, in: L.M. Camarinha-Matos, H. Afsarmanesh (Eds.), Process and Foundations for Virtual Organizations, Kluwer Academic Publishers, 2003 , pp. 361–368.
[18] J. Heckel, The virtual workspace system: an enabling technology for collaborative engineering applications, in: Proceedings of the Workshop on Enabling Technologies for Collaborative Enterprise, Boston, MA, (1997), pp. 10–16.
[19] H.F. Wang, Y.L. Zhang, CAD/CAM integrated system in collaborative development environment, Robotics and Computer Integrated Manufacturing 18 (2002) 135–145.
[20] D. Xue, Y. Xu, Web-based distributed system and database modeling for concurrent design, Computer-Aided Design 35 (2003) 433–452.
[21] M.N.K. Saunders, P. Lewis, Research Methods For Business Students, Harlow Financial Times: Prentice Hall, 2000.
[22] J. Gill, P. Johnson, Research Methods for Managers, third ed., Sage, 2002.
[23] K. Lewin, Action research and minority problems, Journal of Social Issues 2 (1946) 34–46.
[24] R. Rapoport, Three dilemmas in action research, Human Relations 23 (1970) 499–513.
[25] A. Bowling, Research Methods in Health, Open University Press, Buckingham, 1997.
[26] O. Zuber-Skerritt, New Directions in Action Research, Falmer Press, 1996.
[27] B. Dick, Action research: action and research, In the seminar: doing good action research held at Southern Cross University, 2002.
[28] R. Baskervillea, J. Pries-Hejeb, Grounded action research: a method for understanding IT in practice., Accounting, Management and Information Technologies 9 (1999) 1–23.
[29] S. Kemmis, R. McTaggart (Eds.), The Action Research Planner, Deakin University, Geelong, 1988.
[30] R. Baskerville, T. Wood-Harper, A critical perspective on action research as a method for information systems research, Journal of Information Technology 11 (1996) 235–246.
[31] R. Mejía, L. Canché, C. Rodríguez, H. Ahuett, A. Molina, G. Augenbroe, Designing a HUB to offer e-Engineering brokerage services for Virtual Enterprises, in: L.M. Camarinha-Matos (Ed.), Virtual Enterprises and Collaborative Networks, Kluwer Academic Publishers, 2004, pp. 453–460.
[32] A. Molina, J. Aca, P. Wright, Global collaborative engineering environment for integrated product development, International Journal of Computer Integrated Manufacturing 18 (2005) 635–651.
[33] e-Hubs, e-Engineering enabled by Holonomic and Universal Broker Services, Technical Annex-1, Description of Work, IST project: IST-2001-34031, 2001.
[34] G. Augenbroe, e-HUBs: e-engineering enabled by Holonomic and Universal Broker services, in: Proceedings of the eChallenges conference, Vienna, 2004.
[35] PMBOK, A Guide to the Project Management Body of Knowledge, first ed., PMI, Project Management Institute, USA, 2000.
[36] D. Hollingsworth, Workflow management coalition specification: the workflow reference model, WfMC specification, 1994.
[37] WFMC, Workflow Process Definition Interface: XML Process Definition Language, Lighthouse Point FL: Workflow Management Coalition (WFMC-TC-1025), 2002 (available from: http://wfmc.org/standards/docs.htm).
[38] W. Derks, R. Weston, A. West, R. Harrison, D. Shorter, Role of workow management systems in product engineering, International Journal of Production Research 41 (2003) 3393–3418.
[39] T.M. Hassan, C. Carter, M. Hannus, Y. Hyvarinen, e-Legal: defining a frame-work for legally admissible use of ICT in virtual enterprises, in: K.

Thoben, F. Weber, K. Pawar (Eds.), Proceedings of the 7th International Conference on Concurrent Enterprising: Engineering the Knowledge Economy through Co-operation, ICE 2001, Bremen, Germany, (2001), pp. 347–355.

[40] L. Camarinha-Matos, H. Afsarmanesh, V. Marík, Multi-agent systems applications, Robotics and Autonomous Systems 27 (1999) 1–2.

[41] Q. Hao, W. Shen, Z. Zhang, S.-W. Park, J.-K. Lee, Agent-based collaborative product design engineering: an industrial case study, Computers in Industry 57 (2006) 26–38.

[42] T. Madhusudan, An agent-based approach for coordinating product design workflows, Computers in Industry 56 (2005) 235–259.

[43] L. Biegus, C. Branki, InDiA: a framework for workflow interoperability support by means of multi-agent systems, Engineering Applications of Artificial Intelligence 17 (2004) 825–839.

[44] K. Främling, T. Ala-Risku, M. Kärkkäinen, J. Holmström, Agent-based model for managing composite product information, Computers in Industry 57 (2006) 72–81.

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