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A Concurrent Workflow Management Process for Integrated Product Development

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SUMMARY *This paper describes a systematic concurrent workflow management (WM) process for integrated product development. WM consists of planning and scheduling teams' activities to support cooperative and concurrent works. This paper first explains process re-engineering, flowcharting and various workflow practices in concurrent engineering (CE) to come up with a general process for WM. The WM process is based on an information infrastructure containing models of product requirements, enterprise organization and resources, including the workflow activity. Finally, technologies supporting WM such as work process modeling, performance analyzing, process re-engineering strategies to redesign the process and activity management—real-time task's monitoring—are introduced.*

1. Introduction

Concurrent engineering (CE) is a systematic approach for considering all aspects of a product's life cycle management including the integration of planning, design, production and related phases. CE needs a number of experts from multi-disciplinary groups to cooperate in a computer network environment. In order to organize a cooperative team and direct its efforts, it is necessary to model the enterprise process and decompose it into workflow activities. It is also necessary to develop concurrent schedules that can overlay these activities in parallel by allowing one workflow activity to overlap with another. This is essential to achieve time compression and optimal performance (with respect to meeting customer and company interests, such as X-ability considerations) for the product's design and development.

Workflow management (WM) is an analysis or a study of the business process in an enterprise or a company so as to optimize the flow of 'product', 'work', 'organization' and 'resource' (Fig. 1). The 'optimizing workflow' means determining an effective distribution of the aforementioned elements. The traditional workflow for product development (commonly referred to as an 'as-is workflow' is mostly serial. Such a process has loose organizational structures, does not share product models and/or lacks necessary cooperative tools. Many problems can occur with this mode of operation; the one that impacts the most is that it elongates the product development cycle time. CE concepts can be used to alleviate such problems. CE sets up a new matrix-based organizational structure and lets the parallel teams work cooperatively under a com-

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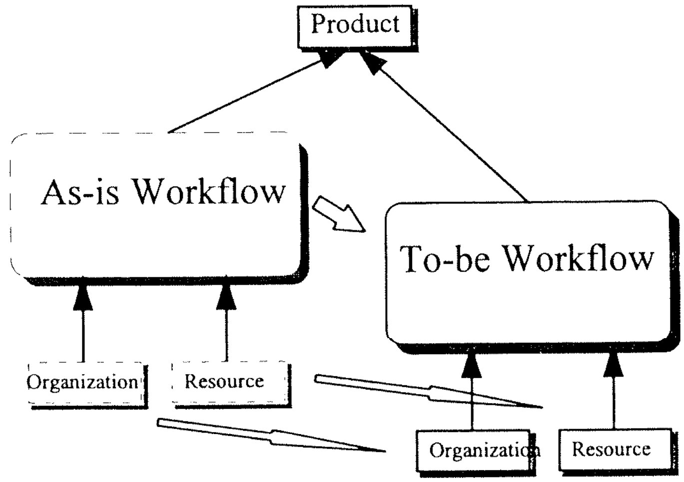

FIG. 1. Two kinds of workflow for product development.

puter network environment, thus shortening the life cycle time [1]. The authors call this mode of workflow management a 'to-be workflow'.

There has been ample research on WM for product development and related fields [2–12]. Each idea seems to give some new advice; some leads to a partial solution but none provides a unified approach to integrated product development [12, 14, 15]. In this paper, a method for optimally scheduling a concurrent workflow process is developed. Section 2 explains WM and its application in CE. Section 3 examines some supporting technological concepts towards an information infrastructure of a concurrent WM process.

2. What Is WM?

Process re-engineering and WM are two different concepts. Both process re-engineering and WM deal with current (as-is) and redesigned (to-be) processes. Process re-engineering is directed towards determining the wastes and reworks of an existing process in order to determine a better performing process. In most traditional organization, product development is a serial process. A serial process gives rise to a serial workflow. A concurrent process gives rise to a concurrent workflow. Thus, in a traditional process, WM would mean managing a serial process for product development. How to re-engineer and, at the same time, manage a workflow process so that product design and development can be accomplished in less time (i.e. efficiently) and with less effort (i.e. effectively) is the key question. This section attempts to examine this WM question from a number of perspectives.

2.1 Workflow Modes of Product Development

Whether one is dealing with an 'as-is' or a 'to-be' process for re-engineering, the traditional product development phases or tracks are often serial. In other words, the phases generally run in a serial mode. An example is a planning phase followed by a concept design phase, a detail design phase, a process planning phase and finally a manufacturing phase. What is different between a serial and a concurrent product development process is the organizational set-up, management style and the manner in which scheduling of tasks and resources are accomplished. Although, in a traditional product development scenario, phases are not concurrent, engineers from different domains could work together (during any stage) to solve problems jointly [14].

Figure 2 shows two modes of product development: 'traditional' and 'concurrent'. The workgroups chosen for this illustration are 'marketing', 'design', 'process', and 'production'. The life-cycle phases chosen for this illustration are 'requirement', 'design', 'process planning' and 'manufacturing'. These workgroups and phases represent a set of identifying names and the foregoing four categories are for illustration purposes only. The actual workgroup names and numbers would differ depending on the subject company's organizational practices, life-cycle phases and team preferences.

2.1.1 Traditional product development mode. In a traditional product development mode, the respective life-cycle engineers do their own work in phases (called herein a 'main-activity' job), and the information (only after the main-activity job is completed) is passed serially on to the next department or group. Main-activity, in a workflow process, represents a set of tasks for a phase (that are identified as core or as a primary set of activities) that ought to be performed to complete that phase. In a traditional mode, each department works somewhat independently of each other and the information is passed to the next department only after the completion of all of its assigned (department's) tasks. This passing of information between the two consecutive departments or groups is normally a one-time transfer. A backward pass is required when a rework or a revision on the main-activity is desired or requested during the course of product development/refinement. In a traditional workflow process, main-activity represents the tasks for only one distinct phase (department or group).

2.1.2 Concurrent product development mode. In a concurrent mode of product development, the workflow moves vertically among the workgroups (within its own phase) but also moves horizontally across its neighbouring phases. During the main-activity for a phase, all members of the multi-disciplinary groups work together on tasks for that phase. In a serial workflow mode of product development, the information (while the main-activity tasks for a phase are in progress) flows primarily among other workgroups of the same phase. In a 'concurrent' workflow mode of product development, in addition to main-activity, two additional work activities take place simultaneously. They are named here as pre-activity work and post-activity work for that phase. The main-activity work for a phase discussed here represents the same set of tasks that take place in a serial WM process for that phase.

Pre-activity work is done before the main-activity phase, to support the requirements of some downstream activities or workgroups (including the main-activity) and to carry out some initial pre-works of its own. Post-activity work is done before completion of the main-activity work tasks, to support the upstream activities (including the main-activity) and to carry out some of its post-activity tasks. Unlike the as-is case, in a to-be mode, a series of transfers may take place while the information is being built up during a main-activity phase.

2.2 Method of WM

Traditional project management is based on identifying a set of critical paths. It determines what combinations of resources (manpower, tasks and schedules) would make the product life-cycle time the shortest or the total cost the lowest [11]. The

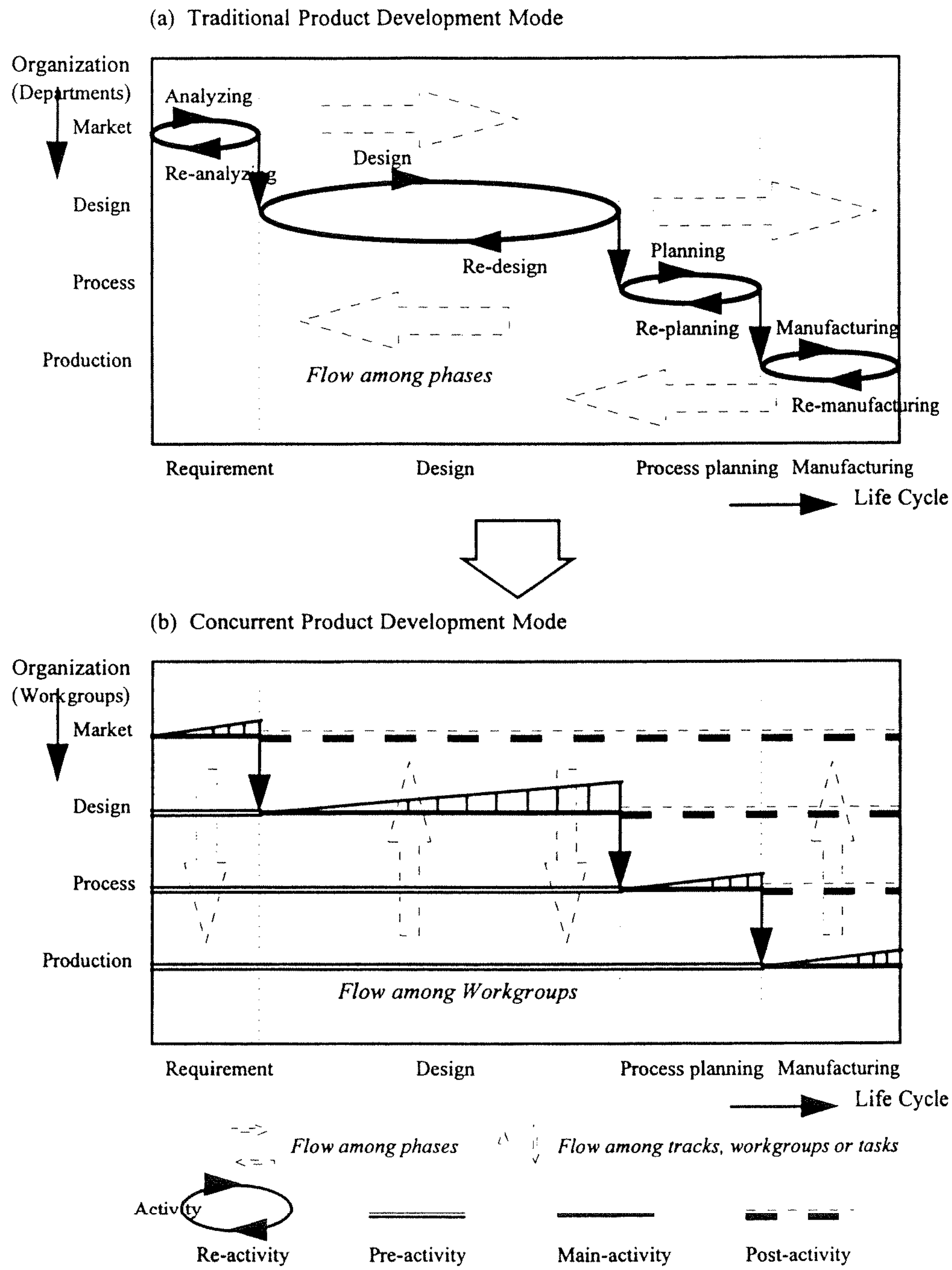

FIG. 2. (a) Traditional and (b) concurrent product development process.

foregoing principles—described in Section 2.1—apply to any process under consideration (for example, an as-is or a to-be WM process). The best performance is usually realized by scheduling the identified activities or worktasks in parallel and by maximizing the utilization of available talents/resources. In traditional project management, organizational structure is not normally changed, while in CE, a workgroup normally re-engineers the as-is process based on a set of new 7Ts (talents, tasks, teamwork or team structure, techniques, technology, time and tools) [1]. This re-engineered process

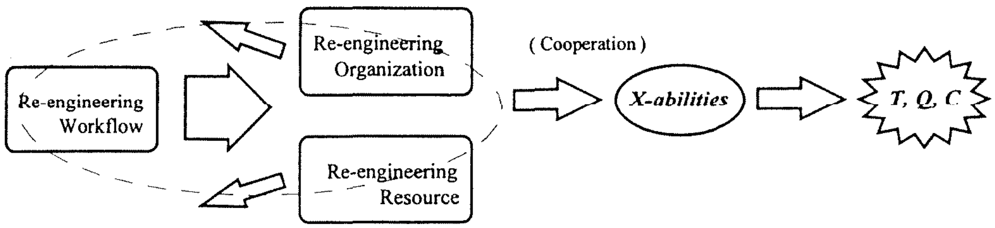

FIG. 3. Methods of re-engineering the work process.

is expected to account for product's quality at each phase of product development for example, X-abilities would be kept in sight while the design workgroups working on the design phase. Re-engineering the workflow, re-engineering the organization and re-engineering the resources are typical approaches to work process re-engineering (Fig. 3) [14]. Cooperation is the key feature of a concurrent WM process. With cooperation, the joint teams can improve X-abilities and satisfy customers and the company's interests (with respect to a multitude of performance factors, such as time, quality and cost) simultaneously.

3. Stages in Managing a Work Process

Generally, there are four stages in managing a work process, they are described as follows (Fig. 4).

Stage 1: Work process modeling

Work process modeling is the first step in managing a workflow. The ensuing model should contain all the information necessary and could incorporate the underlying

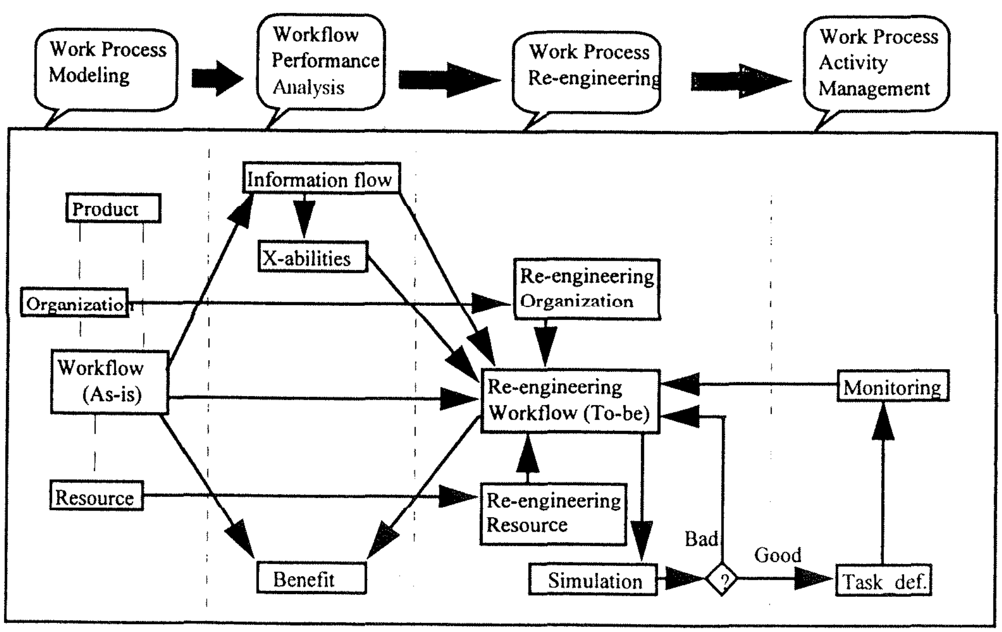

FIG. 4. Flow for scheduling the process.

principles of CE. A work process typically contains information of the following types—normally captured as submodels:

- product submodel (including PtBS—product breakdown structures);
- workflow submodel (including WBS—work breakdown structures);
- organizational submodel (including constancy-of-purpose management styles [1] and organizational charts);
- resource submodel (including matrix of teams and flexible reporting structures).

The main task of this stage is to model the current (as-is) workflow process, which is the concatenation of the above four submodels.

Stage 2: Workflow performance analysis

A work process is made up of a number of activities that are related to each other. In order to improve the performance of a re-engineered process, the teams must understand the dependencies and constraints among the identified activities. In addition, the customer and company interests (for example, performance, X-abilities, cost savings, benefits, etc.) need to be identified and analyzed.

Stage 3: Work process re-engineering

As mentioned earlier, workflow process re-engineering can be realized by organization re-engineering, resource re-engineering or workflow re-engineering. The team could also perform dynamic simulation on the process to identify elements that need re-engineering.

Stage 4: Work process activity management

The activity management stage starts when a set of tasks for each activity is well established and a member of the workgroup for each task is identified. Normally, it consists of real-time monitoring and controlling of tasks during product development. Activity management should have the capability to adjust the workplan or its schedule to account for unexpected situations.

The traditional workflow is a serial process. In the following sections, some key technologies for modeling a work process are introduced.

3.1 Work Process Modeling

Work process modeling is a complex concept, especially when it is developed in the context of CE. A good work process model should possess the following qualities [14].

3.1.1 Composite tree structure. A work process is not just a group of activities. As described earlier, product (P), organization (O), resource (R) and workflow (W) are the four primary components of a work process model. Component P is the outcome of a W process. Components O and R are the supporting elements for a W process to realize P. Figure 1 pictorially depicts this relationship, which can be expressed as

$$P = f(O, R) \qquad (1)$$

Such relationships can be described using a language such as EXPRESS-G as shown in Fig. 5.

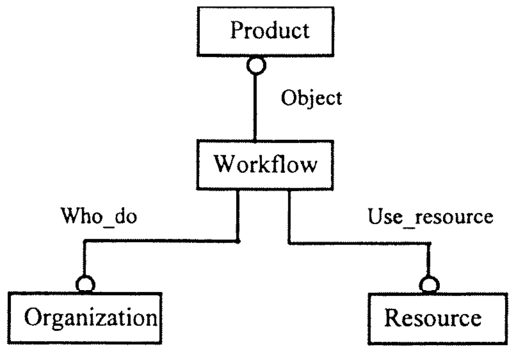

FIG. 5. Relationships among P, O, R and W in work process modeling.

3.1.2 Hierarchical decomposition. A work process may range from a small activity—such as 'editing a file'—to a large engineering activity—such as 'developing a new type of airplane.' Because CE is directed towards studying team cooperation among life cycle phases and perspectives, one could decompose the original product development problem into hierarchical sets so that there are not many interfaces that are in common among these decomposed sets. A workgroup could then sort out the common interfaces based on dependency rules so that all activities chosen for a set belong to a particular hierarchical set. If an activity is further decomposed into tasks, a workgroup would know which task belongs to which activity set—thus maintaining a hierarchy by association. For example, if a team has to describe an assembly, the following steps can be followed.

- In accordance with a product's assembly relationship, the entire work process could be divided into a hierarchical structure: for example, product (or systems), subsystems, components, parts, features or materials, etc. [16].
- A set of interface (cooperation) points can be established at the common boundaries, which could be different for each structure. For example, at the part stage, the 'manufacturability' may be important, while at the subsystem or component stage the 'assemblability' or the 'subsystem performance' could be the key considerations [14, 15].

3.1.3 Parallel distribution of tasks. The work process model employs a parallel distribution of tasks in addition to deploying parallel workgroups. In this way, while a workgroup is working on a task, another workgroup can be working on another task, belonging to the same track. If the work tasks require collaboration, these two workgroups can work concurrently and will be able to collaborate as a team for that stage of product development. Some of the common modeling tools such as IDEFx and Petri Nets are not suitable for this purpose. They are process-oriented tools or are based on event-oriented methods. Using these tools, it is difficult to describe the concurrent characteristics or overlaps among the tasks.

3.1.4 Information flowcharting. Information flowcharting (IFLOW) is an icon-based modeling method, for describing a production system or a process and for distinguishing them from simple modeling templates [14, 17]. IFLOW is different from the IDEF type of modeling tools, since in IFLOW, the model shows 'who (a person or a group) does each activity' and the 'time sequence in which these activities are performed'

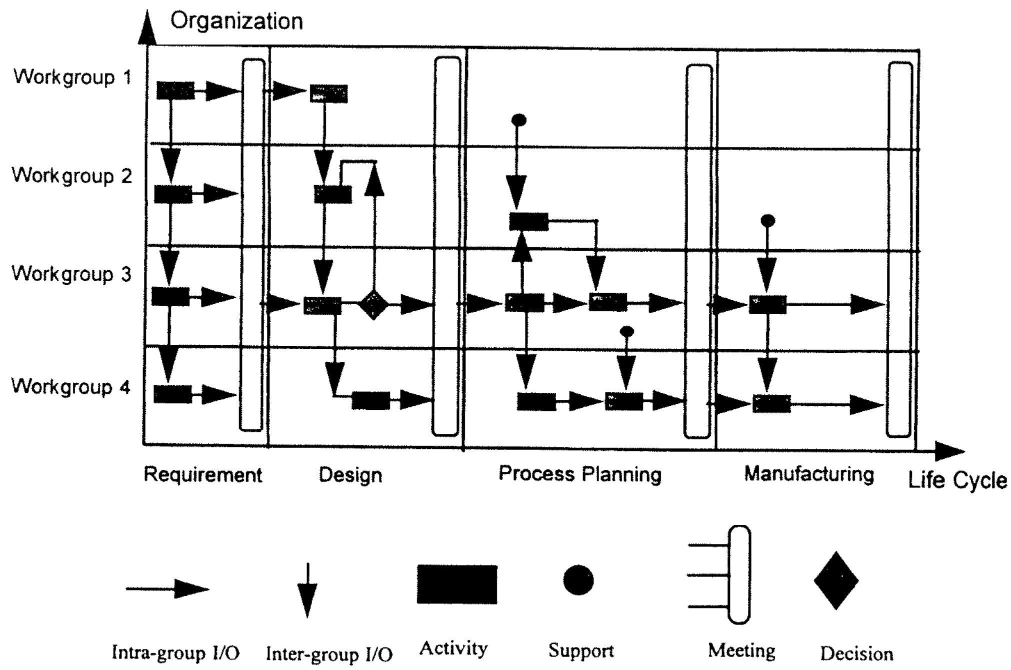

FIG. 6. Information flowcharting.

(shown in Fig. 6). The method is useful for identifying, analyzing and improving a system or a work process. IFLOW is also an effective tool to describe a to-be process model [14].

3.1.5 Progressive refinement. The process model should be created in such a way that it progressively evolves itself as the product evolves through the various stages of product development. This is shown in Fig. 7. In the beginning, the process model is in the form of a primary model, which contains information about product, workflow, organization and resources as discussed earlier. Later, it converts itself into an information model. Concurrent teams need an information flow model to analyze the tasks' dependence and constraints among the activities. The process model should also be capable of predicting product performance and identifying simulation characteristics. A Petri Net model is an example of a simulation model to simulate a dynamic process. At last, the to-be process is represented by task orders. These models' information is often extracted from their work process models as shown in the first stage which is called the 'primary model'. This primary model should contain as much information as possible.

3.2 Workflow Performance Analysis

This section first introduces a method for analyzing the relationship among activities of a work process, and then evaluates its performance using X-abilities.

3.2.1 Information flow analysis. There might be a number of activities in a complex process and their interdependence (input/output; I/O) may not be clear at first glance. Kusiak and Wang [9] and Kusiak and Larson [10] have introduced a valuable method to analyze the relationship (information flow) among these activities. However, the method does not consider organizational factors. As stated earlier, the goal of WM is not to focus only on sequencing activities in a workgroup but to reinforce the

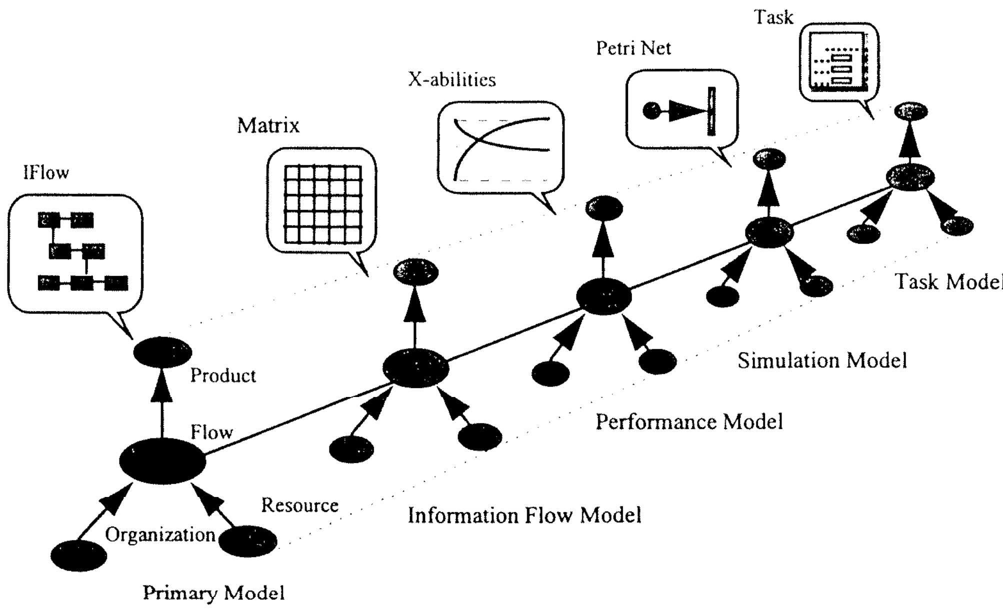

FIG. 7. Evolved models of the process.

cooperation among the workgroups. Considering this viewpoint, an improved method has been introduced [14].

Figure 8 is a relationship matrix (RM) among the activities of a WM process. There are 41 activities in this process. A point in the matrix denotes that an I/O exists between two related activities. For example, the point (2, 12) indicates that there is an input emanating from an activity 2 to an activity 12. An important feature of this RM is that all activities of a group are clustered together. This means RM is divided into a few submatrices, each submatrix represents an affinity relationship between two workgroups. The submatrix on the diagonal denotes the relationship among activities of a single workgroup; we call these submatrices 'intra-matrices' (IM). Other off-diagonal submatrices denote the interactions of two different workgroups; we call these submatrices 'cooperative matrices' (CM). Using a certain algorithm [14], one can arrange activities of each IM in groups and define a set of continuous activities in IM as a cluster for that group.

The aforementioned RM and its ordering are useful to

- facilitate interactions among workgroups;
- track the information flow;
- search for the affinity relationship among all related activities or among the key ones, and so on.

3.2.2 Workflow performance evaluation. In order to improve the process, it is necessary to evaluate the performance of the workflow process. Performance evaluation means measuring the performance of a process. Many researchers have considered 'time' or 'cost' as performance measures [11, 18–20]. Reduction in 'time' and 'cost' are actually the end goals of a CE process. Performance measures are the intermediate means for achieving these goals. One of the aims of CE has been to apply performance measures at an earlier product development phase, so as to avoid reworks and redesigns in the later phases [1].

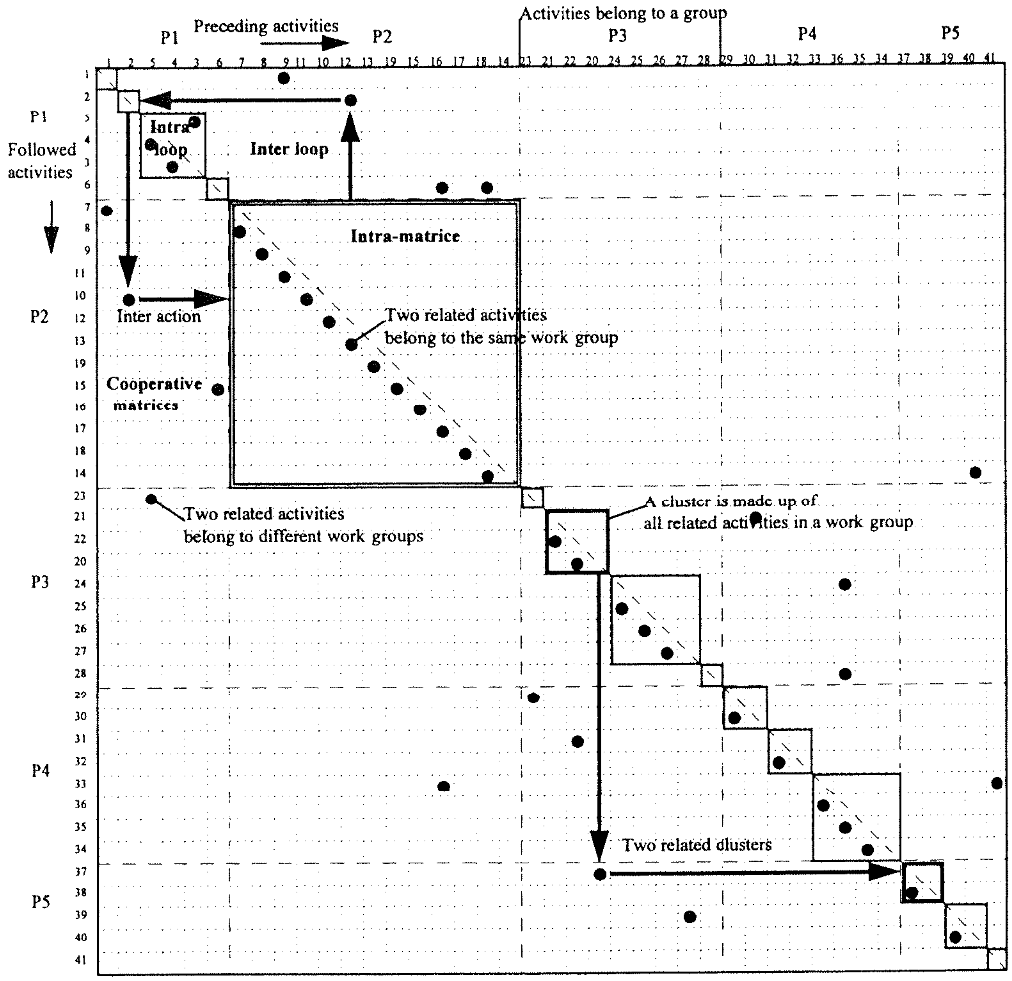

FIG. 8. RM among activities.

X-abilities (in terms of manufacturability, assemblability, maintainability, etc.) are often used to describe the quality (one measure of performance) of a design in product development. There are many factors that influence a process's X-ability performance (Fig. 9). They include integrated environment (IE), supporting tools (ST), design methodology (DM), team organization (TO) and process re-engineering (PR):

- IE: An IE means a distributed network of diverse computers and software—communicating over a virtual network. This improves the design efficiency, reduces data loss due to transfer and exchanges, and also avoids errors arising from multiple models. It includes three aspects: communication, shared product model and a data exchange standard.
- ST: Tools such as quality control, quality function deployment (QFD), total quality management (TQM), tele-conferencing, decision-support systems, knowledge-based engineering (KBE) and knowledge management could be used to support teamwork. Quality control manages the product's requirements and design quality. Tele-conferencing provides communications support for group work and discussion. Decision-supporting tools help in negotiation among multi-disciplinary groups. Knowledge management captures the design process, the

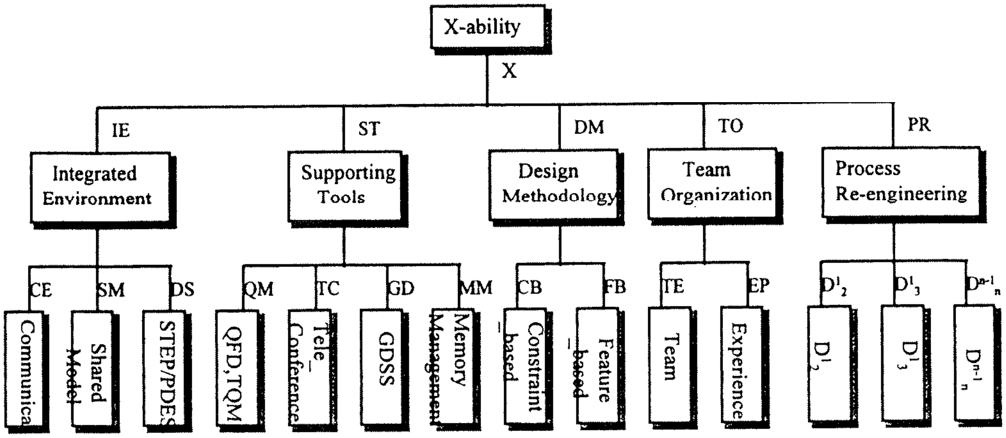

FIG. 9. Factors influencing the process.

history of design evolution and coordinates the efforts of workgroup members working in different places in different time zones [13].

- DM: This methodology enables workgroups to consider downstream problems upstream, and lets them deal with these problems at an earlier stage of design development. Constraint-based and feature-based designs are two popular methods. The constraint-based approach allows workgroups to consider downstream factors as design constraints. The feature-based approach lets the teams use features to capture information related to downstream processes [16].
- TO: A product development team (PDT), teamwork and an individual team's talents are important concepts for improving design quality. They comprise some elements of the 7T's [1]. PDT is an organization structure of CE [1].
- PR: This involves redesigning the as-is product development process so as to maximize the degree of concurrency for the decomposed tasks. This increases the use of X-ability in identifying and solving problems as early in the process as possible. Enhancing the coordination among team members and overlapping the tasks based on degree of dependency can increase concurrency. Prasad describes a method to estimate quantitatively a degree of concurrency [16].

The analytic hierarchy process (AHP) method can be adapted to measure the influence of the aforementioned factors on the process's X-abilities [14, 21]. In an example [14], a typical X-ability value of a workflow process in as-is mode is 29.70%, while in to-be mode it is 75.80%. Furthermore, Wang [14] has also built a relationship between the extended duration (Ta) of a process and the X-ability (X_p). The relationship can be expressed through the following function:

$$\frac{Ta}{T} = \frac{1}{\mu_f}\left[(1 + \mu_f)^{(1 - x_p)} - 1\right] \qquad (2)$$

where μ_f is the constant, T is the time duration of a process and Ta is the possible extended duration because of X_p. This function is described in Fig. 10.

3.3 Work Process Re-engineering

Generally, there is no definite algorithm to come up with a to-be flow from an as-is flow. Success depends on the chosen strategies and the teams' experience in applying

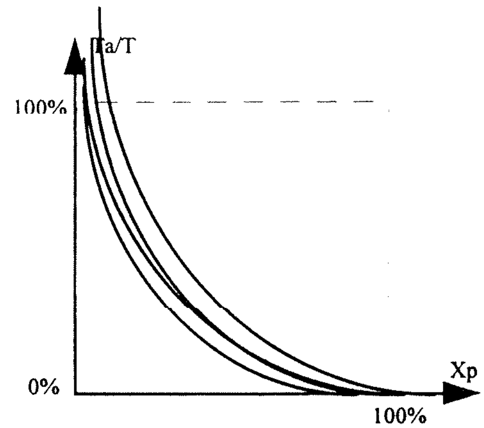

FIG. 10. Relationship between extended duration and X-ability.

value engineering principles. The aforementioned information flow analysis and performance-evaluation methods can be used as a basis for process re-engineering. As mentioned in Section 2, process engineering can be decomposed into re-engineering the organization, re-engineering resources and re-engineering the workflow. This paper now outlines some strategies for achieving workflow process re-engineering.

3.3.1 Re-engineering the organization. This means designing a new organization so as to design and develop a product efficiently and effectively. The traditional organizational structure is often hierarchical, which makes it almost impossible for the teams to consider many life-cycle aspects of product design and manufacturing while making concurrent decisions [1, 7, 22]. The product-oriented organizational structure is sometimes based on a PDT, where members come from different life-cycle domains [1]. This PDT organization forces members to cooperate naturally and to make decisions in concurrence with each other.

3.3.2 Re-engineering resource. Besides common resources, such as computers, equipment, etc., the software environment (such as DM, historical data, experience and solution) also plays an important role. It influences the PD^3 process. For example, the use of 'design for X' serves to improve the design quality. Similarly, when a new automobile is developed, a major portion of its components are carry-over parts. It therefore pays to manage these historical design documents (data, methods, experiences and process knowledge). Re-engineering resources, in this context, means:

- making use of existing resources as effectively as possible;
- improving the design environment (for example, communication, computer-aided design, computer-aided engineering, computer-aided manufacturing);
- adding new resources for key tasks if possible;
- adopting new methods or tools as a part of the product development process.

3.3.3 Re-engineering workflow. This means redesigning the workflow so that the team members can work together during each stage of product development. This could be realized by the following strategies.

- *Cooperation:* Engineers of other domains give advice on the 7Ts as and when they are called upon.

- *Coordination:* Engineers from multi-domains work together on the same object.
- *Group decision:* Once some common problem appears, the affected team members jointly make decisions.
- *Releasing results earlier:* The intermediate results (not the final) from the upstream phases are passed on to the downstream phases frequently.
- *Leveraging experience:* By leveraging experiences from the domain experts, the downstream activity could be started earlier.
- *Pre-work:* If possible, some pre-work should be carried out in advance.
- *Decomposing:* When resources are scarce, decomposing the activity into one or more tasks, and performing them in parallel can reduce the product development time.

It is interesting to point out that re-engineering the organization and re-engineering resources are the foundations for re-engineering workflow. This is because an improvement in workflow cannot be performed without the adequate support of an organization or without the right use of available resources.

3.4 Work Process Activity Management

Once a new to-be process is identified, the next step is to schedule the tasks among the team members so that they can be executed concurrently. Along with a task usually comes a set of associated requirements such as 'start time', 'finish time', 'cooperative actions' and 'quality targets' to aim for. It is quite possible that many of these requirements for a task cannot be met. Problems with preceding tasks might influence the following tasks. For example, if no necessary data are attainable within an allocated time for a task, a preceding task's finish time would impact the start time of the following task (see Fig. 11). It is, therefore, necessary to monitor the status of the tasks as if they are being carried out in real time, and adjust them, if necessary.

James F. Peters III [23] has introduced a method to analyze the finish time and design quality using a fuzzy clock. In this paper, the authors have also considered the start time and cooperative action, because they influence a task's own finish time and the design quality. Multi-agent technology is adopted here to monitor and control the work status [14]. Figure 12 shows a communication structure between members of the workgroups and the project leader. There are two types of agent, the task agent (TA) and the coordinator agent (CA). The TA is located at each member's node and the CA is at the project leader's node. The TA receives a task from the CA, monitors the status of the tasks being carried out, and reports back to the CA. The CA collects and

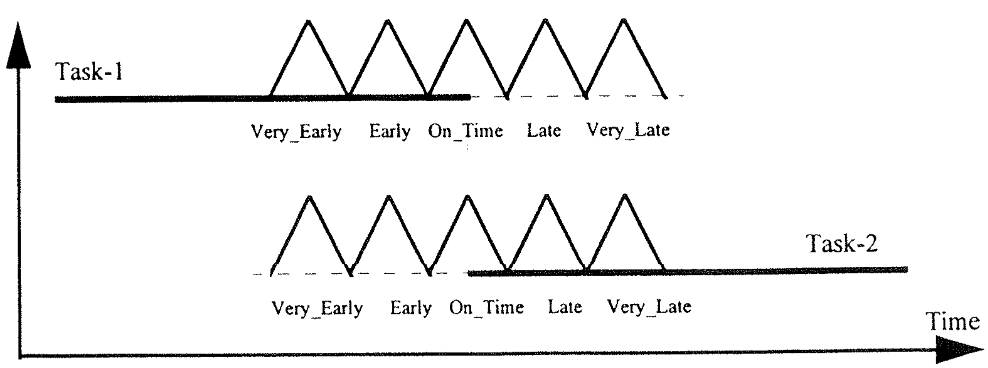

FIG. 11. The influence of time on a task.

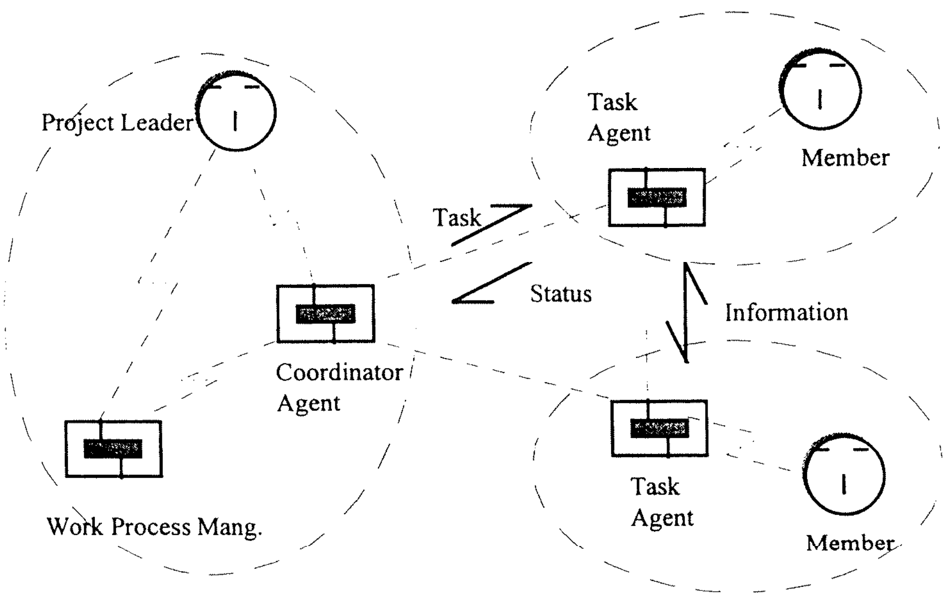

FIG. 12. Work status monitoring using multi-agents.

analyzes the work status of each member and adjusts them according to various strategies [14].

4. Conclusions

CE requires workgroups to work cooperatively as a unified team. WM is an effective method for scheduling and to controlling workflow activities. Leveraging the characteristics of CE, this paper advances a concept of a concurrent WM process, which is made up of process modeling, performance analysis, process re-engineering and activity management. The workflow process model is a composite (representing product, workflow, organization and resources in one model) concept and IFLOW is a useful method for capturing a WM process. An improved RM is introduced in this paper to analyze the interdependence among all activities of a WM process. Since one or more factors influence the WM process, the analytic hierarchy process (AHP) method is studied to evaluate the process's performance (X-abilities) and to measure the benefit of an improved process. The re-engineering work process can be thought of as being composed of re-engineering of the organization, re-engineering of resources and re-engineering of the workflow. Multi-agent technology is adapted here for monitoring and controlling the process's tasks—being carried out concurrently. This paper also proposes some supporting technologies suitable for a concurrent WM process.

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