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Toward Definitions of a Concurrent Product Design, Development, and Delivery (PD^3) System

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This article describes a concurrent engineering wheel-set and explains the basic principles on which this very subject is founded. The concurrent engineering approach to product design development, and delivery (PD^3) has two major themes. The first theme is establishing a *concurrent product and process organization* (PPO). This is referred herein as "*process taxonomy*." The second theme is applying this process taxonomy (or methodology) to design and develop a total product system. This is referred to as *integrated product development* (IPD). Each theme is divided into several essential parts forming major arms of the so-called concurrent engineering wheel-set [1].

The first theme called product and process organization (PPO) has nine arms. The second theme named integrated product development (IPD) has ten arms. The materials in these two CE themes are brought together to balance the interests of both the customers and the companies. The arms of the PPO theme are manufacturing competitiveness Life-Cycle Management; Process Re-engineering, CE techniques, Cooperative Work-groups, System Engineering, Information Modeling, The Whole System, and Product Realization Taxonomy. The arms of the IPD theme are Total Value Management, CE Metrics and Measures, Concurrent Function Deployment, Product Development Methodology, Frameworks and Architectures, Decision Support Systems, Intelligent Information System, Capturing Life-cycle Values, Life-cycle Mechanization, and IPD Deployment Methodology [2].

In a Concurrent Engineering (CE) system, each modification of the product represents a taxonomical relationship between specifications (inputs, requirements, and constraints), outputs, and the concept it represents. At the beginning of the design process, the specifications are generally in abstract forms. As more and more of the specifications are satisfied, the product begins to take shape (begins to transform into a physical form). To illustrate how a full CE system will work, and to show the inner-workings of its elements, the author defines this CE system as a set of two synchronized wheels. The representation is analogous to a set of synchronized wheels of a bicycle. Figure 1 shows this CE wheel set.

1. CE Wheel-Set

The first CE wheel represents the *integrated product and process organization* theme. The second CE wheel accomplishes the *integrated product development* theme. The two wheels together harmonize the interests of the customer and the fostering CE organization (frequently referred to as an enterprise). Two concentric rings and a hub represent the three essential elements of a wheel. The middle ring represents the CE work-groups, which drive the customer and the enterprise like a human drives a bike. The work-groups are divided into four quadrants representing the four so-called CE teams. These teams are: personnel team, technology team, logical team, and virtual team. The outer ring for each wheel is divided into eight parts. The arms for the first wheel constitute the PPO theme. The PPO theme explains how a CE design process (called herein as CE process taxonomy) provides a stable, repeatable process through which increased accuracy is achieved. The PPO theme starts with manufacturing competitiveness reviewing the history and emerging trends. The remaining parts of the PPO theme describe the CE design process, explain how concurrent design process can create a competitive advantage, describe the CE process taxonomy, and address a number of major issues related to product and process organization. The arms of the second wheel constitute the IPD theme [2].

1.1 First CE Wheel: Integrated Product and Process Organization

The innermost element of the first CE wheel is a hub. The layout of the hub is the same for both wheels. The hub represents four supporting "M" elements: models, methods, metrics, and measures. Models refer to information modeling. Methods refer to product realization taxonomy. They are parts of the PPO theme. CE Metrics and Measures are part of the IPD theme. The complexity of the product realization process (PRP) [3] differs depending upon the (1) types of information and sources, (2) complexity of tasks, and (3) degree of their incompleteness or ambiguity. Other dimensions encountered during this PRP that cannot be

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easily accommodated using traditional process (such as serial engineering) are: (4) timing of decision making, (5) order of decision making, and (6) communication mechanism. The arms of the first CE wheel define a set of systems and processes that have the ability to handle all of the above six dimensions. In the following, some salient points of the arms are briefly highlighted [1].

- *Manufacturing Competitiveness:* Price of the product is dictated by world economy and not by a country's market edge alone. Those companies that are global can quickly adapt to the world's changing marketplace and position themselves to compete globally than locally. This arm outlines what is required to become a market leader and to compete globally. Successful companies have been the ones who have gained a better focus on eliminating waste, normally sneaked into their products, by understanding what drives product and process costs and, how value can be added. They have focused on a product and process delivery system—how to transition process innovations into technical success and how to leverage the implementation know-how into big commercial success. Many have chosen to emphasize high-quality flexible or agile production in product delivery rather than high-volume (mass) production.
- *Life-cycle Management:* Today, most companies are under extreme pressure to develop products within time periods that are rapidly shrinking. As the market changes, so do the requirements. This has a chilling effect on managing the complexity of such continuously varying product specifications and handling the ongoing changes within the shrinking time periods. The ongoing success of an organization lies in its ability to: continue to evolve; quickly react to changing requirements; reinvent itself on a regular basis; and keep up with ever-changing technology and innovation. Many companies are stepping up the pace of new product introduction, and are constantly learning and bracing new ways of engineering products more correctly the first time, and more often thereafter. This arm outlines life-management techniques, such as change management, and process improvement to remain globally competitive.
- *Process Re-engineering:* The global marketplace of the 1990s has shown no sympathy to tradition. The reality is that if the products manufactured do not meet the market needs, demands decline and profits dwindle. Many companies are finding that true increase in productivity and efficiency begin with such factors as clean and efficient process, good communication infrastructure, teamwork, and a constancy of shared vision and purpose. The challenge is simply not to crank up the speed of the machines so that outputs (per unit of time) are increased or doubled, but to change the basic machinery or process that produces the outputs. To accomplish the latter goal, this arm describes several techniques to achieve competitive superiority such as benchmarking, (continuous process improvements) CPI, organizational restructuring, renovation, process re-engineering, etc.
- *CE Techniques:* The changing market conditions and international competitiveness are making the time-to-market a fast shrinking target. Over the same period, diversity and complexity of the products have increased multi-folds. Concurrency is the major force of concurrent engineering. Paralleling describes a "time overlap" of one or more work-groups, activities, tasks, etc. This arm describes seven CE principles to aim at: Parallel work-group; Parallel Product Decomposition; Concurrent Resource Scheduling; Concurrent Processing; Minimize Interfaces; Transparent Communication; and Quick Processing. This arm also describes the seven forces that influence the domain of CE as agents (called here the 7Ts) namely: talents, tasks, teams, techniques, technology, time, and tools.
- *Cooperative Work-groups:* It has been the challenge for the design and manufacturing engineers to work together as teams to improve quality while reducing costs, weight, and lead-time. A single person, or a team of persons, is not enough to provide all the links between: human knowledge and skills; logical organization; technology; and a set of 7Cs coordination attributes. A number of supporting teams are required, some are virtual or at least are virtually collocated. For the waltz of CE synthesis to succeed, CE teams need clear choreography. This arm describes for the first time the four collaborative teams that are essential for managing a CE organization. Examples of collaborative features include capabilities of electronic meeting such as message-posting and interactions through voice, text, graphics, and pictures.
- *System Engineering:* Most groups diligently work to optimize their subsystems, but due to a lack of team incentives, they tend to work independently of each other. This results in a product which is often suboptimized at each decomposed level. System engineering requires that product realization be viewed as a "system-centered" problem as opposed to "component-centered." Systems Engineering does not object to the idea of compartments or division of work, but it emphasizes that the interface requirements between the divisions (interdivisional) and across the levels should be adequately covered. That way, when the time comes to modernize other components of a system, one has the assurance that previously introduced technologies and processes will work logically in a fully integrated fashion, thereby increasing net efficiency and profitability.
- *Information Modeling:* A successful integrated product development (IPD) requires a sufficient understanding of the product and process behaviors. One way to achieve this understanding is to use a series of reliable information models for planning, designing, optimizing, and controlling each unit of the IPD process. The demands go beyond the 3-D CAD geometric modeling. The demands require schemes that can model all phases of a product's

life cycle from cradle to grave. The different aspects of product design (planning, feasibility, design, process-planning), process design (process-execution, production, manufacturing, product support), the human behavior in teamwork, and the organization or environment in which they will operate, all have to be taken into account. Five major classes of modeling schemata are defined: [1] (a) product representation schemes and tools for capturing and describing the product development process and design of various interfaces, such as design-manufacturing interface; (b) schemes for modeling physical processes, including simulation, as well as models useful for product assessments, such as DFA/DFX, manufacturability evaluation on in-progress designs; (c) schemes for capturing requirements or characteristics (product, process, and organization structure) for setting strategic and business goals; (d) schemes to model enterprise activities (data and work flow) in order to determine what types of functions best fit the desired profitability, responsiveness, quality, and productivity goals; and (e) schemes to model team behavior, because most effective manufacturing environments involve a carefully orchestrated interplay between teams and machines.

- *The Whole System:* Often while designing an artifact, work-groups forget that the product is a system. It consists of a number of subassemblies, each fulfilling a different but a distinct function. A product is far more than collection of components. Without a structure or "constancy-of-purpose" there is no system. The central difference between a CE transformation system and any other manufacturing system, such as serial engineering, is the manner in which the task's distribution is stated and accomplished. In a CE transformation system, the purpose of every process step of a manufacturing system is not just to achieve a transformation but to accomplish this in an optimal way. This arm proposes a system-based taxonomy, which is founded on parallel scheduling of tasks and a breakdown of sturctures for product, process, and work to realize a drastic reduction in time and cost in product and process realizations
- *Product Realization Taxonomy:* This constitutes a "state of series of transformation" leading to a complete or a mature design. Product Realization Taxonomy involves items related to design completeness, product development practices, readiness feasibility, and assessing goodness. In addition, CE requires these taxonomies to have a unified "product realization base." The enterprise integration metrics of the CE model should be well characterized and the modeling methodologies and/or associated ontology for developing them should be adequate for describing and integrating enterprise functions. The methodologies should have built-in product and service accelerators. Taxonomy is comprised of the product, process descriptions, classification techniques, information concepts, representation, and transformation tasks (inputs, requirements, constraints, and outputs). Specifications describing the transformation model for product realization are included as part of the taxonomy description.

1.2 Second CE Wheel: Integrated Product Development

The second CE wheel defines integrated product development (IPD) [2]. IPD in this context does not imply a step-by-step serial process. Indeed, the beauty of this wheel (integrated product development) is that it offers a framework for concurrent product design, development and delivery (PD^3) system. A framework within which the CE teams have flexibility to move about, fitting together bits of the jigsaw as they come together. CE teams have opportunity to apply a variety of techniques contained in this theme (such as: Concurrent Function Deployment, Total Value Management, metrics and Measures, etc.) and have opportunity to achieve steady overall progress toward a finished product.

- *Concurrent Function Deployment:* The role of the organization and of the engineer is changing today, as is the method of doing business. Competition has driven organization to consider concepts such as time compression (fast-to-market), Concurrent Engineering, Design for X-ability, and Tools and Technology (such as Taguchi, Value Engineering) while designing and developing an artifact. Quality Function Deployment (QFD) addresses major aspects of "quality" with reference to the issues it performs, but quality is one of the many functions that need to be deployed. With conventional deployment, it is difficult, however, to address all aspects of Total Values Management (TVM) such as X-ability, Cost, Tools and Technology, Responsiveness and Organization issues. It is not enough to deploy just the "Quality" into the product and expect the outcome to be the "World Class." TVM efforts are vital in maintaining a competitive edge in today's world marketplace.
- *CE Metrics and Measures:* Metrics are the basis of monitoring and measuring process improvement methodology and managing their effectiveness. Metric information assists in monitoring team progress, measuring the quality of products produced, managing the effectiveness of the improved process, and providing related feedback. Individual assurances of DFX specifications (one at a time) do not capture the most important aspect of concurrent engineering—the system perspectives, or the trade-off across the different DFX principles. While satisfying these DFX principles in an isolated manner, only those which are not in conflict are usually met. Concurrent engineering views the design and evaluates the artifact as a system, which has a wider impact than just sub-optimizing the sub-systems within each domain.
- *Total Value Management:* The most acclaimed slogan for introducing a quality program in early corporate days

simply was to provide the most value for the lowest cost. This changed as the competitiveness became more fierce. For example, during the introduction of traditional TQM programs in 1990, "getting a quality product to market for a fair price" was the name of the game. The new paradigm for CE now is TVM: to provide the total value for the lowest cost in the least amount of time and, which satisfies the customers the most and lets the company make a fair profit." Here use of value is not just limited to "quality." To provide long lasting added value, companies must change their philosophy toward things like *x-ability*, responsiveness, functionality, tools and technology, cost, architecture, etc.

- *Product Development Methodology:* A systematic methodology is essential in order to be able to integrate (a) teamwork, (b) information modeling, (c) product realization taxonomy, and (d) measures of merits (called CE metrics), and to quantitatively assess the effectiveness of the transformation. This may involve identification of performance metrics for measuring the product and process behaviors. Integrated product development methodology is geared to take advantage of the product realization taxonomy.
- *Frameworks and Architectures:* In order to adequately support the CE–4Ms (namely: modeling, methods, metrics, and measurements), it is necessary to have an architecture that is openly accessible across different CE teams, information systems, platforms, and networks. Architecture consists of information contents, integrated data structures, data states, behavior and rules. An architecture not only provides an information base for easy storage, retrieval, and tracking version control, but can also be accessed by different users simultaneously, under ramp-up scheduling of parallel tasks, and in synchronization. We also need a product management system containing work management capabilities integrated with the database. This is essential because in CE there exists a large degree of flexibility for parallelism that must be managed in conjunction with other routine file and data management tasks.
- *Capturing Life-cycle Intent:* Most C4 tools are not really "capture" tools. In static representation of CAD geometry, configuration changes cannot be handled easily, particularly when parts and dimensions are linked. This has resulted in loss of configuration control, proliferation of changes to fix the errors caused by other changes, and sometimes ambiguous designs. By capturing "design intent" as opposed to "static geometry," configuration changes could be made and controlled more effectively using the power of the computer than through traditional CAD attibutes (such as line and surfaces). The power of a "capture" tool comes from the methods used in capturing the design intent initially so that the required changes can be made easily and quickly if needed. "Life-cycle capture" refers to the definition of the physical object and its environment in some generic form. "Life-cycle intent" means representing the life-cycle capture in a form, which can be modified and iterated until all the life-cycle specifications for a product are fully satisfied.
- *Decision Support System:* In CE, cooperation is required between CE teams, management, suppliers, and customers. A knowledge-based support system will help the participating teams in decision making and in reflecting balanced views. Trade-offs between conflicting requirements can be make on the basis of information obtained from sensitivity, multicriterion objectives, simulation, or feedback. The product realization taxonomy can be made a part of the decision support system (DSS) in supporting decisions about product decomposition by keeping track of what specifications are satisfied, ensuring common visibility in the state of product realization, including dispatching and monitoring of tasks, structure, corporate design histories, etc.
- *Intelligent Information System (IIS):* Another major goal of CE is to handle information intelligently in multimedia—audio, video, text, graphics. Since IIS equals CIM plus CE, with IIS, many relevant CE demands can be addressed and quickly processed. Examples include: (a) over local or wide area networks, such as SQL, which connects remote, multiple databases and multimedia repositories; (b) any needed information, such as recorded product designers' design notes, figures, decisions, etc., can be made available on demand at the right place at the right time and (c) any team can retrieve information in the right format and distribute it promptly to the other members of the CE teams.
- *Life-cycle Mechanization:* Life-cycle mechanization equals "CIM + Automation + CE." Life-cycle mechanization is arranged under a familiar acronym: CAE, for CIM, Automation, and CE. Since CAE also equals IIS Plus automation, the major benefits of mechanization in CAE come from removing or breaking barriers. The three common barriers are: (a) integration (this is a term taken from CIM), (b) automation, and (c) cooperation (which is a term taken from CE). CE provides the decision support element, and CIM provides the framework and architecture plus the information management elements. *Life-cycle Mechanization* refers to the automation of life-cycle functions or creation of computerized modules that are built from one another and share information from one another. This includes integration and seamless transfer of data between commercial computer-based engineering tools and product-specific in-house applications. This tends to reduce the dependency of many CE teams on communication links and product realization strategies, such as decomposition and concatenation.
- *IPD Deployment Methodology:* The purpose of this arm is to offer an implementation guideline for product redesign and development through its life-cycle functions. IPD implementation is a multitrack methodology. The tracks overlap, but still provide a structured approach to organizing product ideas and measures for concurrently

performing the associated tasks. Concurrency is built in a number of ways, depending upon the complexity of the process or the system involved. This arm proposed [2] a set of "Ten Commandments," which serves to guide the product and process iterative aspects of IPD rather than just the work-group collaborative aspects during the development cycle. The CE teamwork in the center of the wheel ensures that both local or zonal iterative refinements and collaborative refinements take place during each concurrent track.

2. A Synchronized Wheel—Set for CE

All of the above arms of CE put together create a synchronized wheel-set for CE, as shown in Figure 1. The teamwork, with four cooperating components (technological teams, logical teams, virtual teams, and personnel teams), is in the middle. The 4Ms (models, metrics, measurements, and methodology) form the hub of this wheel. It has four arms: Information Modeling; Product Realization Taxonomy; Measures of Merit; and Product Development Methodology. The two outer rings, which are the same for both wheels, makes the wheels a synchronized set. The teams in the middle ring are the driving force of the methodology (listed in the hub) and the controller of the technologies (listed on the outer ring). The emphasis of a team-centered wheel for CE is a departure from a conventional function-centered approach. Outer rings of each wheel contain the remaining arms of integrated product and process organization (PPO theme) and integrated product development (IPD theme), respectively. The idea of this middle ring is to provide a team-centered 7Cs (Collaboration, Commitment, Communications, Compromise, Consensus, Continuous Improvement, and Coordination) interplay across layers of enabling technologies and methodologies. Everything is geared toward cutting and compressing the time needed to design, analyze, and manufacture marketable products. Along the way, costs are also reduced, product quality is improved, and customer satisfaction is enhanced due to the synchronized process. There is, however, a finite window in which the benefits of time compression and cost

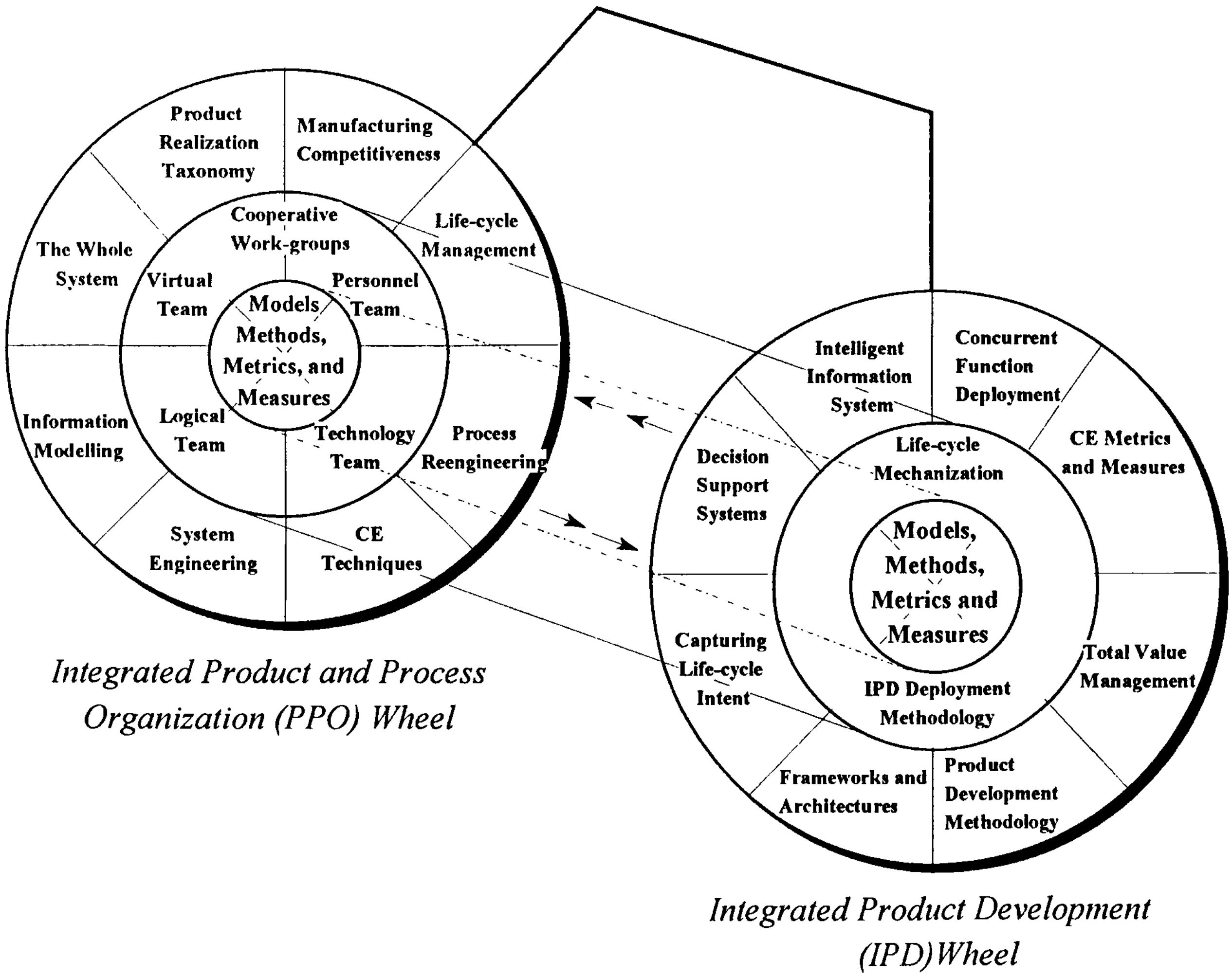

Figure 1. A synchronized set of CE wheel.

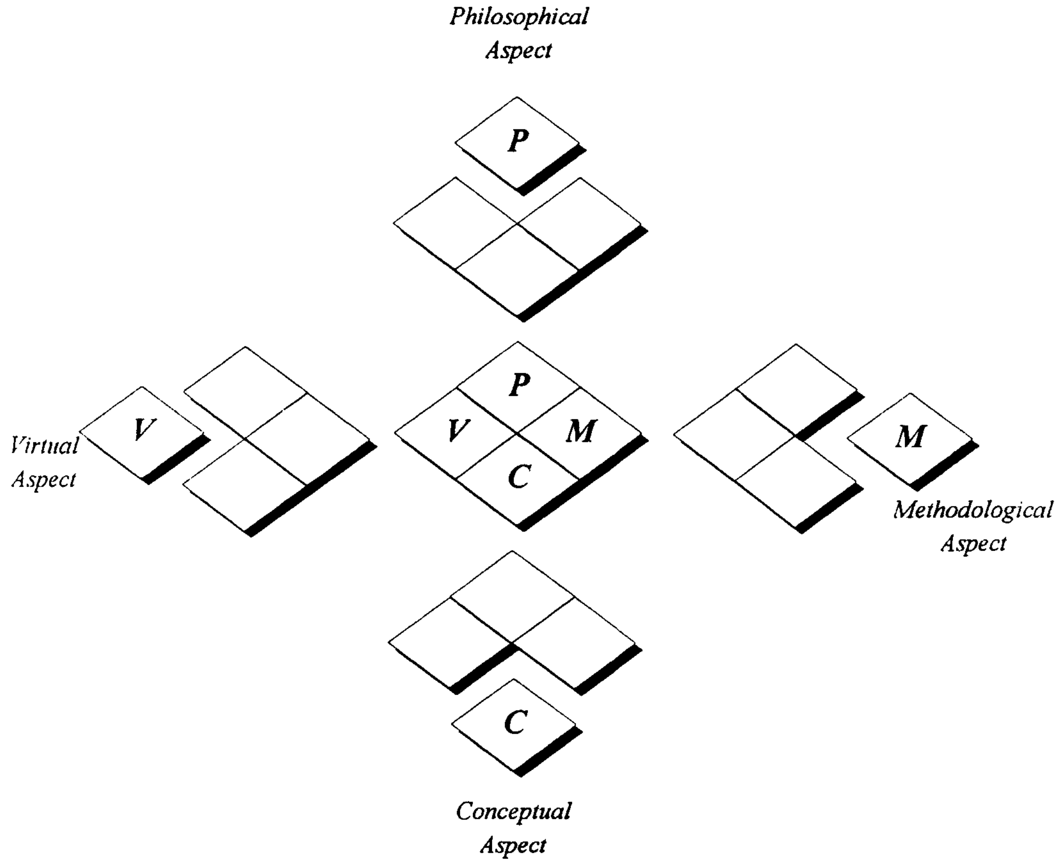

Figure 2. Four aspects of CE.

cutting are available. As more manufacturers reduce lead time, what once represented a competitive advantage can become a weakening source. Fortunately, the CE wheel provides a continuum (dynamic) base through which new paradigms (process, tools, and technology) can be launched to remain globally competitive for a long time.

Before researcher takes a closer look at the different arms of this wheel, it is important to note that all arms are not of the same kind. They emphasize different aspects of CE. The four major aspects are listed below (see Figure 2):

- *Philosophical Aspect:* Personnel CE team governs the philosophical aspects of CE. Philosophical aspect deals with the boundaries of the responsibility and the authority, culture, empowerment, team makeup, program organization, supplier rationalization, management styles or philosophies, change management, workplace orgainzation and visual control, physical proximity (collocation), management and reporting structure, etc. The arms on Coorperative Teamwork and Life-cycle Management emphasize more of this aspect than others.
- *Methodological Aspect:* The methodological aspect of CE is governed by a technology team. Methodological aspect deals with system thinking, approaches to system complexity, system integration, transformation model of the manufacturing system, CE enterprise system taxonomy, integrated product and process development, transformation system for product realization, pull system for product realization, tracks and loops methodology, etc. The arms on Systems Engineering, Whole System, and Product Realization Taxonomy emphasize more of this aspect than others.
- *Conceptual Aspect:* A logical CE team governs the conceptual aspect of CE. Conceptual aspect mostly deals with principles of CE, concurrency and simultaneity, modes of concurrency, modes of cooperation, understanding and managing change, re-engineering approaches, work flow mapping, information flow charting, process improvement methodology, etc. The arms on CE techniques and Process Re-Engineering emphasize more of this aspect than others.
- *Virtual Aspect:* The virtual aspect of CE is governed by a virtual CE team. Virtual aspect mostly deals with capturing life-cycle intent, information modeling, and electronic capture of CE process invariants. These invariants can be transformed into product model class, process model class, specification models, cognitive models, communication through virtual proximity, agile virtual company, artifact intent definitions, etc. The arms of Information Modeling and Life-cycle Management emphasize more of this aspect than others.

3. Major Attributes of this Synchronized Wheel-Set

No matter what product your company manufactures, this twin wheel-set provides a complete view of CE from all of the above aspects and perspectives. The management perspective, which is a part of philosophical aspect, relates to organization and culture. The twin wheel-set articulates major CE aspects by illustrating the differences between the best methodologies (and taxonomies) and those currently being practiced today.

Examples of major attributes incorporated in the wheel-set are:

- eight fundamental principles on which CE is founded
- seven primary components of concurrency and simultaneity
- CE environment and its five essential components
- seven Cs to ensure cooperation among work-groups
- seven primary influencing agents (called 7Ts) for achieving concurrency and simultaneity
- cooperative work-group environment spanned by four concurrent teams (namely—logical team, personnel team, virtual team, and technological team)

The first wheel (PPO theme) deals with process taxonomy for CE. Process taxonomy is necessary to adequately classify, distribute, and distinguish differences in behaviors of complex enterprise integration systems. The innermost core of this process taxonomy is its foundation, which has four supporting M elements: models, methods, metrics, and measures as mentioned earlier. The following table summarizes the major attributes of this CE wheel-set concept:

Attributes of the CE Wheel-set [1]	How do these attributes benefit CE practitioners?
The CE wheel-set emphasizes, for the first time, the seven primary influencing agents (called 7Ts) for achieving concurrency and simultaneity.	This allows the CE practitioners to look for items that can significantly affect responsiveness and may be root cause for cost, quality, and productivity loss.
The wheel-set features manufacturing competitiveness, life-cycle management, process re-engineering, CE techniques cooperative work-groups, systems engineering, information modeling, and PPO (product, process, and organization) integration issues all described within a unified "process taxonomy" theme.	It allows the CE practitioners to consider a wider view meaning "integrating over the enterprise" while implementing CE. This eliminates the common problem of blindly automating—meaning repeating the same mistakes but doing it more often and more quickly.
Concurrent system tends to operate in one of the two modes. The wheel-set features two such popular modes of concurrency. They are an overlapped pull system and a linked system [1].	It allows the PDT groups to gradually build-up the right information and to link up the process activities with required skills so that the project can be finished on time.
The wheel-set approaches the organization of CE by splitting the system level problem into its mutually separable states, followed by modeling of each state, then the reconstruction of the system definition from the aggregation of the definitions of its constituent states.	This constitutes a "state of series of transformation" leading to a complete or a maturity design.
The wheel-set looks at the product realization process by decomposing its five components (work, product, process, system, and enterprise) into their corresponding breakdown structures so as to exploit the inherent concurrency and independence of the decomposed parts.	The result is a virtual approach to defining multi-disciplinary problems and their solutions for improved productivity.
The wheel-set views the integrated product development as a cooperative work-group environment spanned by four concurrent teams: (namely—logical team, personnel team, virtual team, and technological team).	It allows the PDTs to come up with an effective team design. An effective team is like a peak-performing symphony orchestra: a group of specialists from core CE teams creating an inspirational performance through mutual harnessing and cooperating process.
Cooperation is the key lynchpin of achieving teamwork. The wheel-set incorporates the seven elements (called 7Cs) to this team cooperation philosophy.	Seven 7Cs help identify the extent to which the organizational culture or "self-interest" supports or detracts from achieving a unified product concept (or a common set of company goals).
Benefits of CE stem from few basic principles. The wheel-set facilitates a set of eight fundamental principles on which CE is founded.	The CE practitioners could judge what CE principles to apply and when to apply—what stage of product development.

Attributes of the CE Wheel-set [1]	How do these attributes benefit CE practitioners?
Concurrency is the major force of Concurrent Engineering. The wheel-set includes seven major components that assure concurrency and simultaneity.	CE practitioners could assess what level of concurrency and simultaneity is needed at what stage of product development during its life-cycle.

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