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Towards applying principles of concurrent engineering to the efficient design and development of construction facilities

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Abstract

The paper describes a set of supporting principles for concurrent engineering (CE) and its application to the construction industry. CE is gaining worldwide attention. The paralleling of lifecycle activities in design and construction of buildings and steel structures is being deemed necessary by more and more civil industries [1]. A design and construction example of a building (and design and fabrication of steel structures) is used in this paper to illustrate many aspects of these CE principles. The principles help the construction project team, first, to define how to decompose the activities and, secondly, how to arrange these decomposed activities so that 'best concurrency and simultaneity' can be achieved.

Keywords: concurrent engineering (CE) principles, concurrent engineering (CE), concurrency, simultaneity, time-to-market, building architectural design, facility construction

Introduction

The concept of concurrent engineering (CE) was initially proposed as a potential means to minimise product design, development and delivery time [2]. Since then, many definitions of CE have emerged in the literature [3–6]: e.g. Zhang & Zhang [6] list over 123 papers dealing with this subject. Today, CE is much more encompassing. Expectations range from a modest productivity improvement [7] to a complete pushbutton-type automation [8, 9], depending upon the views expressed.

CE is a paralleled approach, replacing the time-consuming linear process of serial engineering and expensive prove-outs. CE is intended to encourage property builders and developers, from the start, to consider the 'total job', including cost management, subcontracting, and procurement and supply functions [3, 10].

CE has a major impact on construction process set-up and the way an organisation conducts the architectural design, procurement and fabrication (ADPF) business. As shown by Prasad [8], CE replaces the traditional sequential 'over the wall' approach with a simultaneous design-and-manufacture approach with parallel, less interdependent processes. It aims at reducing the total effort, including investment in constructing a property from architectural design to erection, while meeting the needs of the contractors, owners, regulatory civil bodies, and industrial clients [11, 12].

The four major phases of a typical product design and development (as shown in Fig. 2.26 of [8]) have been detailed into eight tracks for architectural design, procurement and fabrication (ADPF) (as shown in Figure 1), running in parallel. Figure 1 shows the different tracks of the construction process. These tracks are: inception and project definition; architectural design; structural engineering and analysis; property specifications; cost management; procurement and supply; fabrication, assembly and erection; and finally facility management. The 'facility management' track is an ongoing coordination track that runs for the full construction lifecycle. This 'facility management' track also provides normal project management functions, tasks sequencing, cooperation, and central support to the other tracks.

These eight tracks are not unique to a particular construction facility (such as buildings, bridges, roads, factories, etc.). Individual tasks breakdown, their identifying names and time-overlaps may differ from property to property. Table 1 describes some of the key elements of these major lifecycle construction phases. This is based on published results and from an in-depth analysis of what has been commonly practised among several big companies in the UK [1] and USA [13]. Kamara *et al.* [14] list 54 references dealing with CE and construction.

Key drivers for CE

Prasad [8] has chosen to divide forces that influence a CE domain into seven agents (referred to there as seven Ts): talents, tasks, teams, techniques, technology, time, and tools. One of the primary team issues in CE is the decomposition of tasks. The people issue is the composition of teams. 'Teams' are often used to solve the problem cooperatively. 'Technology' issues arise from increased needs for higher operational efficiency and effectiveness. Examples of popular technologies in CE are soft prototyping, visualisation, facility management, integrated design and construction (IDC), design for constructability (DFC), design for erectability and fabricability (DFEF), multimedia, electronic data interchange (EDI), etc.

'Tools' mean software, hardware, and networks that make CE practical in today's world of multinational corporations, multipartner projects, and virtual corporations. From the 'time' point of view, CE is an initiative of the (property's) construction community that has the goal of reducing the cycle-time for the architectural

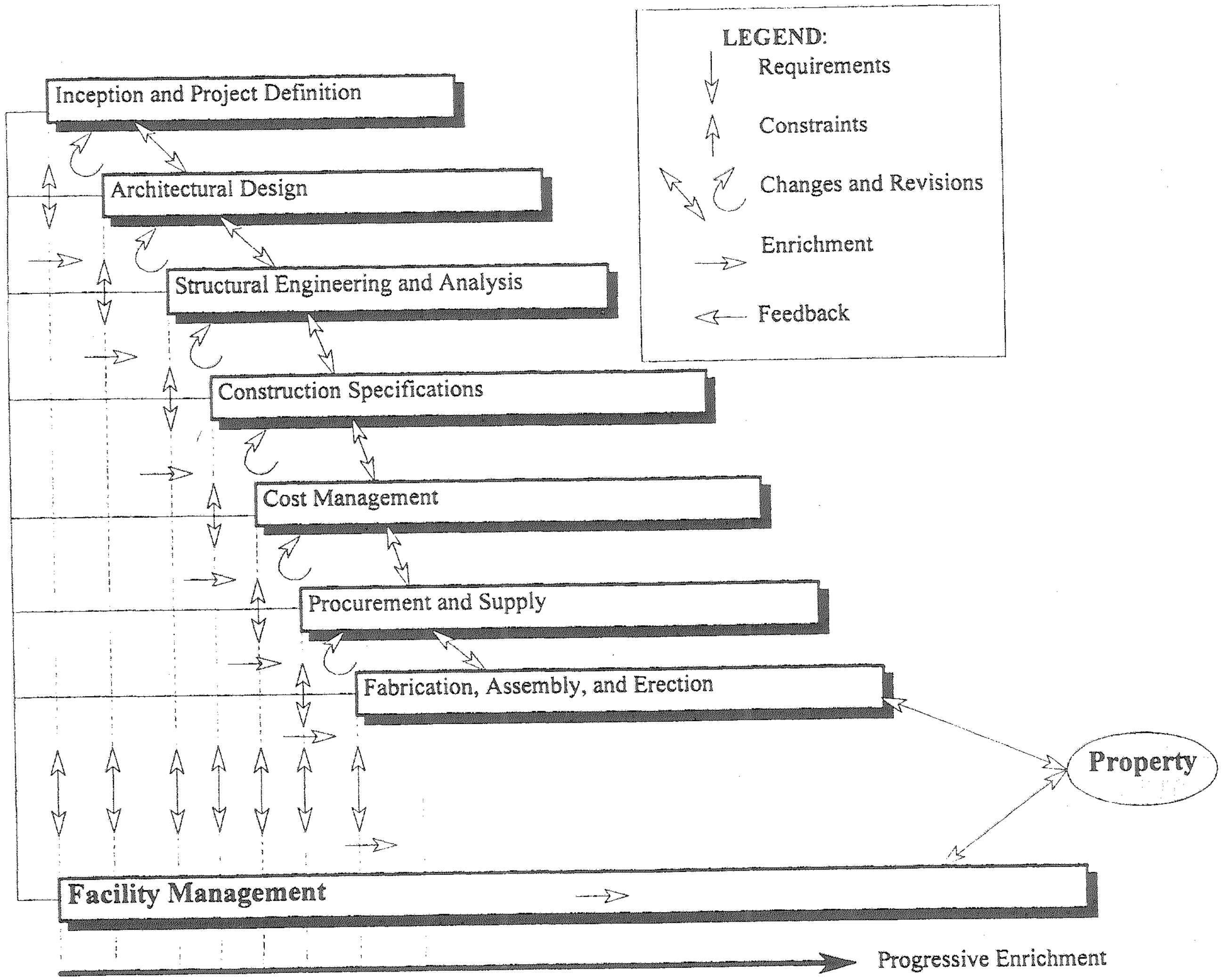

Figure 1. Concurrency during architectural design, procurement and fabrication processes

design, fabrication, assembly and erection of the property by allowing teams of construction engineers to develop architectural design modules concurrently with other perspectives [15]. 'Training' also plays an important role in CE. A popular word in the business press is 'reengineering', meaning, in short, revamping the processes by which to satisfy clients' needs.

Timing and cost are important considerations in architectural design, procurement and fabrication (ADPF) systems. A lot rides on the timing of decision making and problem discovery. Approximately 80% of a typical product's lifecycle cost is driven by decisions made in the first 20% of the programme effort [16, 17]. Designers have traditionally attempted to produce economical solutions by concentrating their efforts on producing structurally adequate frames, minimising steel weight. This often proves counterproductive in terms of the actual cost of the overall project. Savings in materials can be easily lost (many times over) by increased production and site costs [18, 12].

Once an ADPF process is decomposed into a set of tracks, and a track is decomposed into a set of activities, they become one full spectrum of steps leading to a desired property realisation. The staggering of their 'steps' start-points and overlaps is indicative of partial information-sharing. Orders are indicative of their precedence. The extent of overlap between any two consecutive construction activities is indicative of the degree of dependency that may exist between them [19]. In general, there will be greater affinity and dependence between pairs of activities, which are adjacent to each other. The farther away the activities are positioned from each other, the lesser the degree of affinity or the need for information transfer among them: e.g. an 'inception and project definition' track would be more closely related to an 'architectural design' track but would have little bearing on construction activities such as those belonging to a 'fabrication, assembly and erection track. Similarly, a 'fabrication, assembly and erection' track would be closely related to 'cost management' and/or 'procurement and supply' track but less sensitive to activities belonging to farther tracks such as a 'structural engineering & analysis' track. The construction costs depend substantially on the connection and the connec-

Table 1 Major lifecycle construction phases and their details

Major lifecycle phases	Typical details of a phase
Inception and project definition	Assessing customer, market research, business case development, needs identification, briefing, scope definition, formation of study team, etc.
Architectural design	Schematic design, space arrangement, risk assessment, option evaluation, packaging, feasibility assessment, design synthesis, gardening synthesis, performance evaluation, feedback
Structural engineering, HVAC and decision analysis	Structural analysis, environmental analysis, M&E analysis, appraisal, design review, design standards, design for constructability, design for buildability, design for erectability, design for fabricability, etc.
Construction specifications	Materials management, types of material, quantity, bill of parts, bill of materials, bill of processes, precast parts, volume and space calculations, (work, kitchen, living, wet areas), energy management, heating & power consumption, etc.
Cost management	Cost planning, cost modelling, cost estimating, reporting, forecasting, analysis, contingency management, lifecycle cost management, value management
Procurement and supply	Strategy options, procuring standard components, use of preferred suppliers, bidding and negotiation, contract administrations, contract drafting, scheduling, and signing.
Fabrication, assembly and erection	Procure resources, mobilise facilities, licensing, construction planning, regulatory planning, monitoring, execution, subcontractor logistics, commissioning and inspection.
Facility management	Facility repair, rental, landscape, maintenance, HVAC, furnace tune-up, plumbing, ventilation control, inspection, etc.

tion-related costs; thus a greater emphasis on the fabrication, assembly and erection costs at the design stage would inherently give more efficient design [18]. On the other hand, if the tracks and construction activities were completely independent, they can all be aligned along the left margin of the diagram, keeping the precedence intact. The time-to-market in that case would be dominated by tracks that take the longest time to finish. This is a case of a true 'simultaneity' or a 'simultaneous engineering' situation.

Measure of concurrency (MOC) or overlap

Let us denote the activities in a track, A-set, as $a_1, a_2, a_3, \ldots, a_{i-1}, a_i, a_{i+1}, \ldots a_{n-1}, a_n$.

Where A-set is the activity set:

$$\text{A-set} \equiv \cup [a_1, a_2, a_3, a_4, \ldots, a_i, a_j, a_k, \ldots, \ldots a_n] \quad \ldots(1)$$

Let us also assume that these activities are arranged concurrently, meaning that their start and end times are staggered. If we denote (see Figure 2):

ts_i as the start time, the time when an *i*th activity, a_i, starts;

te_i as the end time, the time when an *i*th activity, a_i, ends ....(2)

Then, duration of an *i*th activity (also called lead-time, d) can be expressed as:

$$d_i = (te_i - ts_i) \quad \ldots(3)$$

If we denote c_i as the 'measure of concurrency' between any two consecutive activities, a_i and a_{i-1}, the measure of concurrency or overlap can be expressed as:

$$c_i = 1. - (ts_i - ts_{i-1}) / d_{i-1} \quad \ldots(4)$$

where d_{i-1} is the duration of an activity a_{i-1} in Figure 2. Using eqn (3), d_{i-1} can be expressed as:

$$d_{i-1} = (te_{i-1} - ts_{i-1}) \quad \ldots(5)$$

As shown in Figure 2, $(ts_i - ts_{i-1})$ is the time-delay in the start of an activity, a_i, with respect to its predecessor activity a_{i-1}. If the two activities, a_i and a_{i-1}, are arranged:

(a) serially, then $ts_i = te_i$-1 and $c_i = 0$ ...(6)
(b) completely overlapping, then $ts_i = ts_{i-1}$ and $c_i = 1$ ...(7)

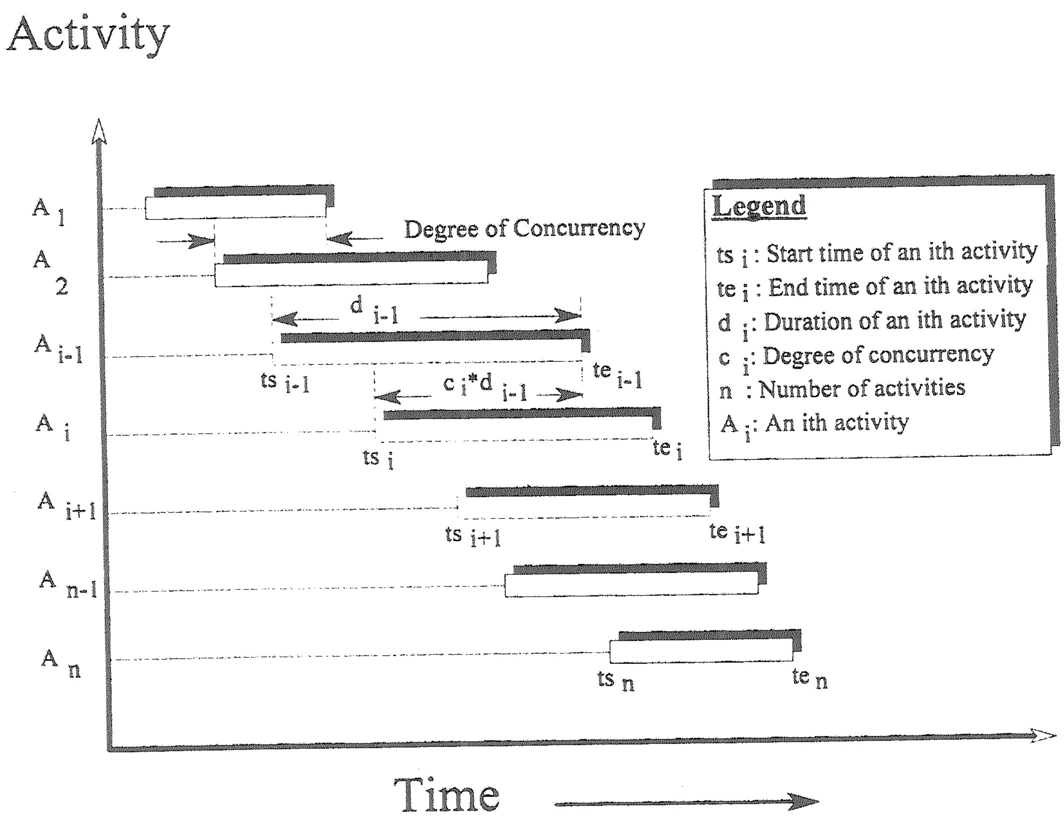

Figure 2. Defining measures for concurrency and overlap

For a partial overlap, c_i may range between 0 and 1. Based on the definitions of c_i, the cycle-time for designing and developing a property, whose activities a_i through a_n when arranged in parallel, can be expressed as follows:

If T_i is the clock time of an ith activity, the time a_i takes from start (t=0) to finish, then T_1, T_2, T_3, T_4, ... T_n, can be expressed as:

$$T_1 = d_1,$$
$$T_2 = \{d_2 + d_1 * (1\text{-}c_2)\},$$
$$T_3 = \{d_3 + d_1 * (1\text{-}c_2) + d_2 * (1\text{-}c_3)\},$$
$$T_k = \{d_k + d_1 * (1\text{-}c_2) + d_2 * (1\text{-}c_3) + d_3 * (1\text{-}c_4) + *** + d_{k\text{-}1} * (1\text{-}c_k)\}, \quad ....(8)$$
$$T_n = \{d_n + \sum_{i=1}^{i=n-1} d_i * (1.\text{-}c_{i+1})\} \quad ....(9)$$

Eqns (8) and (9) provide a basis for computing the total property's construction time, T_k^*, if the activities in the A-set are arranged concurrently. The term d_i * (1.- c_{i+1}) represents a time delay, a fraction of the time-duration (d_i) when two activities, a_i and a_{i+1}, do not overlap with each other.

$$T_k^* = \text{MAX}\,[T_i;\ i=1, 2, ..., k, ., n.] \quad ....(10)$$

It is clear from eqn (9) that the total cycle-time, T_k^*, depends upon the duration of each activity, d_i, and its 'degree of concurrency or overlap', c_i.

- The shortest cycle-time, T_k^S can be reached when $c_i = 1$; for $\forall\ i$; i=1, k, i.e. when each and every one of the activities (a_1 through a_k) is scheduled to start simultaneously, meaning that the starting point of each activity is aligned to the leftmost point as far as possible in Figure 2.
- The longest cycle-time, T_k^L will occur when $c_i = 0$; for $\forall\ i$; i=1, k meaning, when each and every one of the activities, a_1 through a_k, runs serially.

The idea of 'best concurrency and simultaneity' is to align each construction activity step to the farthest left of the diagram (Figure 1), satisfying the following three Ms:

(a) maintain the precedence of the activities, a_i that were decomposed, i. e.

$$t_{si+1} \geq t_{si} \text{ for } \forall\ i;\ i=1, n\text{-}1 \quad ....(11)$$

(b) maximise the horizontal overlap between the consecutive activities, a_i and a_{i+1}, i.e. maximise (d_i * c_{i+1}) for $\forall\ i$; i =1, n-1 ....(12)

(c) maximise the independence of the decomposed activities, a_i and a_{i+1} in the A-set, meaning, $a_i \cap a_{i+1} \approx 0$ for $\forall\ i$; i = 1, n-1 ....(13)

where ∩ denotes an intersection of the adjacent activities in questions in the A-set. The terms t_{si}, d_i, and c_{i+1} are defined in eqns (2)–(4).

The paper describes a set of fundamental principles for achieving this 'best concurrency and simultaneity' when applied to the construction industry. A building construction process example is introduced in the next section to familiarise readers with basic civil engineering nomenclatures and terminology. The same terms are used in the remainder of the paper to illustrate the abstract nature of these fundamental principles. The seven principles help construction project teams define:

(a) how to decompose the activities in the A-set, and then
(b) how to arrange these decomposed activities in the A-set so that 'best concurrency and simultaneity' can be achieved.

The concurrent approach is gaining worldwide attention at the moment [6]. The paralleling of lifecycle activities is being deemed necessary by more and more building and civil engineering industries to adapt quickly to changing market conditions and to achieve shrinking 'start-to-finish' construction targets [20]. In the next section an example of a building design and construction is described, and the following section uses the decomposed set of tasks from this example to maximise c_i, minimise d_i, and minimise T_k*.

A building design and construction example

Most building and civil engineering industries introduce a new architectural design every 2-3 years at a cost of several millions of dollars/sterling in each construction property. The new construction project in the USA now ranges between 2 and 3 years [12]. Construction is generally the responsibility of the builders or contractors, with properties sold through one or more of their real-estate marketing agents or brokers. The completed products of construction are assembled and erected on site and are usually fixed in space.

It is usually not possible to make major alterations after a facility is completed and is in use, except at great cost. This makes it necessary, therefore, that designs are done 'right first time' to eliminate any costly alterations downstream [14] and incur additional transportation costs. A building has a structural system, which can be composed of one or more multistorey structural assemblies. The major elements of a building property are as follows:

- Storeys and architectural style: It encompasses the structural assemblies as well as the building itself and the different products used during its construction. It includes major architectural designs for outside storey-bays, one or more structural assemblies, such as a foundation, a substructure, a superstructure, or a frame. An architectural group often designs them.
- Styling: is done by a central architectural design staff with support from structural analysis divisions and outside contractors. They come up with the architectural design of the outside elevation, look and feel, and interior designs mostly from aesthetic considerations.
- Detail architectural design of the interior, exterior parts, interior rooms, living spaces, kitchen and utilities, accessory room, lighting and comforts: The layout design of rooms and panels is done by the CAD/CAM shop contractors.
- Structural analysis is proposed by the design engineers but often performed by the analysts or contractors.
- Structural assembly: A structural assembly is composed of many structural elements, which may be a column, beams, walls, slab, etc. A structural element may contain reinforcements, connections, joints, steel, concrete, etc.
- Foundation: A foundation may be composed of one or more of the pilecap, pile, slab, openings, groundslab, substructural elements, etc.
- Substructures: Substructures may consist of one or more of the substructural elements, precast beams and columns, precast concrete partition wall panels, precast retaining walls, plinth panels, etc.
- Superstructures: Substructures may consist of one or more of the superstructural elements, building entrances and stair flights, beams, facades.
- Frames: Frames may consist of one or more beams or columns, steel structures, openings (doors, windows, vents, etc.), bar reinforcements, fabric reinforcements, formwork, etc.
- Accessories: Accessories consist of heating, ventilation and air-conditioning (HVAC), central air cleaner, gas and water supply, central humidifier, evaporators, water heaters, communication system, electrical, fire alarm, security system, sump pump, garage door opener, other advisory/alert system, etc.
- Others: An entire project is supported by thousands of second- and third-tier contractors and suppliers that provide interior parts, bolt in parts, and hundreds of other components and materials.

A major corporation generally has architectural design facilities at many states and engineering and analysis and construction plants in many cities and counties. Many of its plants are spread throughout the USA (e.g. the midwest and south). Operations within a construction group are supported by an extensive contractor network or a supply chain.

Other groups within a construction unit must support the eight following groups: project definition group; architectural design group; structural engineering and analysis group; specification group; cost management group; procurement and supply group; fabrication, assembly & erection group; and facility management group: e.g. architectural design support groups may seek a balance between piece cost, transportation cost, fabrication, assembly and erection cost, energy consumption, and safety regulations; the project planning group may balance investments with budgets; marketing groups may seek competing concerns, such as appearance, building content, building quality, usability, transportation cost, and numerous other issues.

These groups are often matrixed to each other to address these concerns. Since many of these project groups are independent of each other, no one manager is likely to own the right or control the total construction project. Funding and control of resources are usually decided through committees. Each group thus ends up doing (suboptimising) its own things, with lack of overall coordination between groups. The problem is typical of a situation where groups have too much independence but not enough coordination. Systems engineering and QFD models are often employed to simplify problems in such cases [21].

How property (product) complexity is handled today

Construction facility is the most complex product that a multidisciplinary team has to deal with. This was shown in a survey carried out by the Benchmarking Partners Team [22] (see Figure 3.) As indicated, construction engineering is at the top of the list in the 12 industrial sectors surveyed that have the largest manufacturing complexity. The problem of product complexity in the construction sector has been addressed [1] by:

- eliminating custom-build options
- favouring standard solutions (such as precast concrete panels, precast retaining walls, plinth panels, formwork, precast standard beams and columns, etc.)
- overcoming the problem of site production, using prefabrication or preassembly
- forming partnerships for production in a mutual effort to overcome this complexity

Another avenue investigated to reduce product complexity is by means of decomposition [23]. It is the complexity of the products (buildings) or of the construction (e.g. 'fabrication, assembly and erection') processes present in the system that compels a property's builder to look for their (product and process) logical breakdown structures. This breakdown is necessary to exploit any inherent concurrency, so that the individual construction activities can be overlapped (run in parallel). Physical-based decomposition is one way to achieve this parallelism, as shown in Figure 4 [8]. Perspectives represent the first level of physical-based description (PhD). PhD is also commonly referred to as 'product holistic decomposition' for short [8]. Other possible levels of PhD (into which the product can be decomposed to exploit concurrency) are: hierarchy; multiplicity; alternatives; characteristics; and projects (see Figure 4). It should be noted that 'decomposition' is not intended here to mean clustering the problem parameters in different ways. A typical case of this type occurs when a problem is decom-

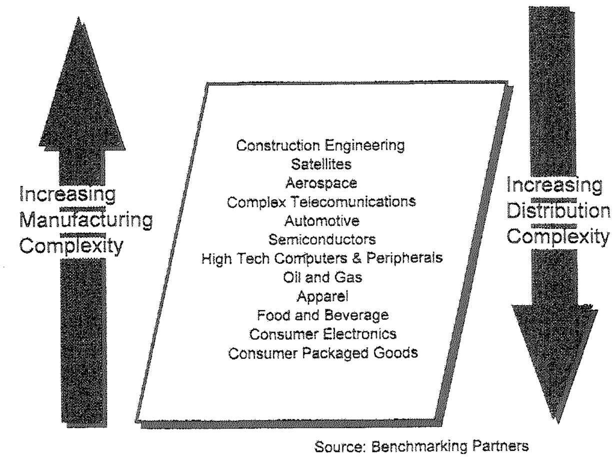

Figure 3. Raking of industrial sectors based on manufacturing complexity

posed simultaneously into a number of ways (such as program phase, subsystem, and discipline). The term 'decomposition' is used here to mean 'product holistic decomposition (PhD)'. Parameters are not fragmented into separate decomposed sets. All parameters belonging to a particular class or a part family stay together (after decomposition) and collectively influence the decision-making process.

$$\text{PhD A-tree} = \forall\ [\{\text{A-perspectives}\}, \{\text{A-hierarchy}\}, \{\text{A-multiplicity}\}, \{\text{A-alternatives}\}, \{\text{A-characteristics}\}, \{\text{A-projects}\}] \quad ...(14)$$

where the brace $\{x\}$ denotes the activity set of quantities of type x. An activity tree (short form is A-tree) comprises several activity sets. The following are examples of some typical decomposition scenarios of a PhD A-tree [8].

Perspective

An architectural design problem usually involves multiple perspectives. Each may have its own set of constraints and could interact with each other. At the highest level, different work-groups can operate in parallel on separate competing perspectives of property lifecycle concerns. Such concerns are often required for property evaluation or assessment. These perspectives include the intellectual process of commonality or class-hierarchy between different families of construction properties, such as:

- size-wise (cubic space, living area, elevation, etc.)
- model-wise (colonial, modern, traditional, multi-level)
- storey-wise (two bays, four bays, six bays, eight bays, etc.)

$$\begin{aligned} P_{\text{size-wise}} &= \{\text{cubic space, living area, elevation}) ...\} \\ P_{\text{model-wise}} &= \{\text{colonial, modern, traditional, multilevel, ...}\} \quad ....(15) \\ P_{\text{storey-wise}} &= \{\text{two bays, four bays, six bays, eight bays, ... }\} \end{aligned}$$

where 'P' denotes the perspective.

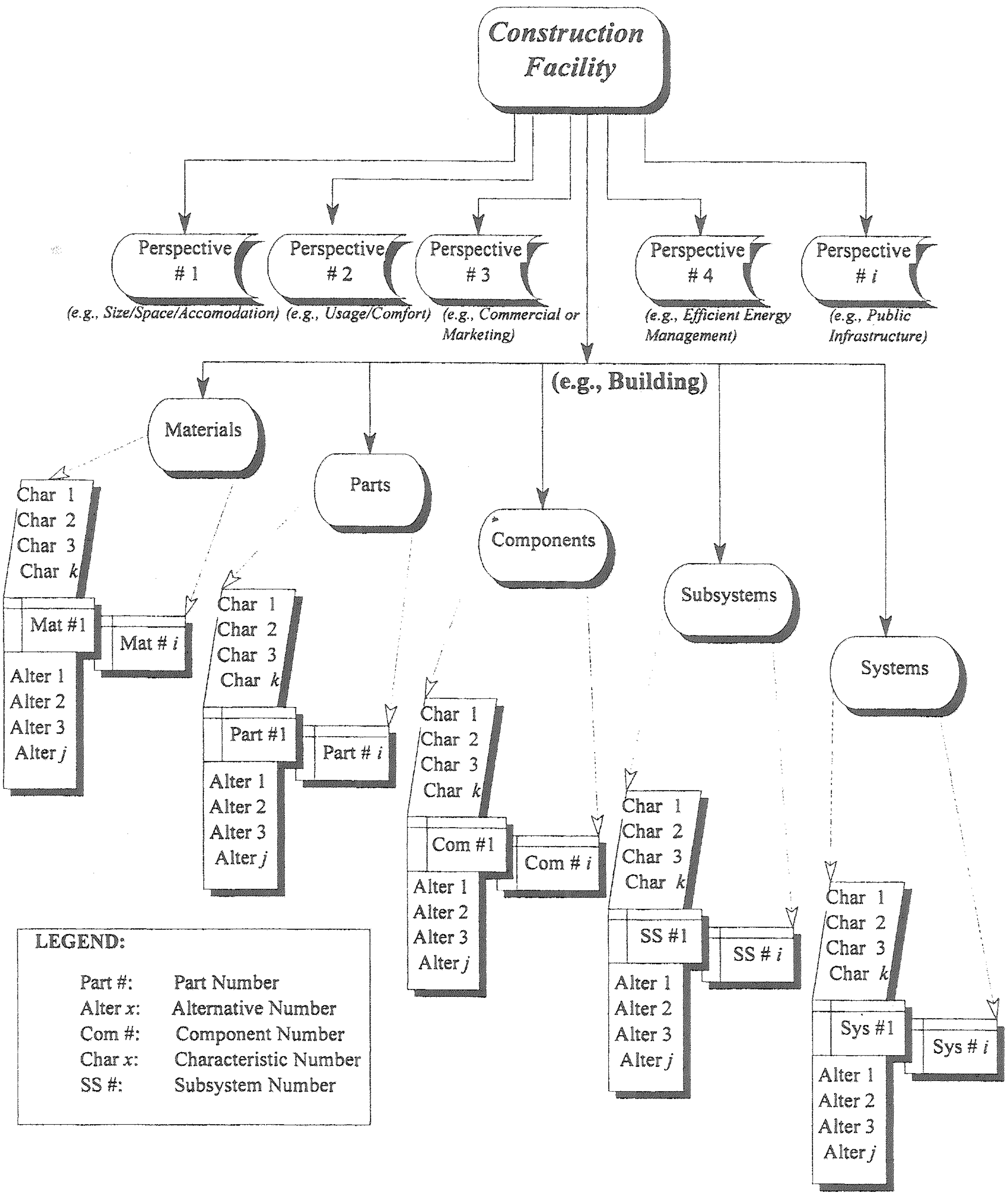

Figure 4. Areas of concurrency during construction facility (product) synthesis (bottom-up representation)

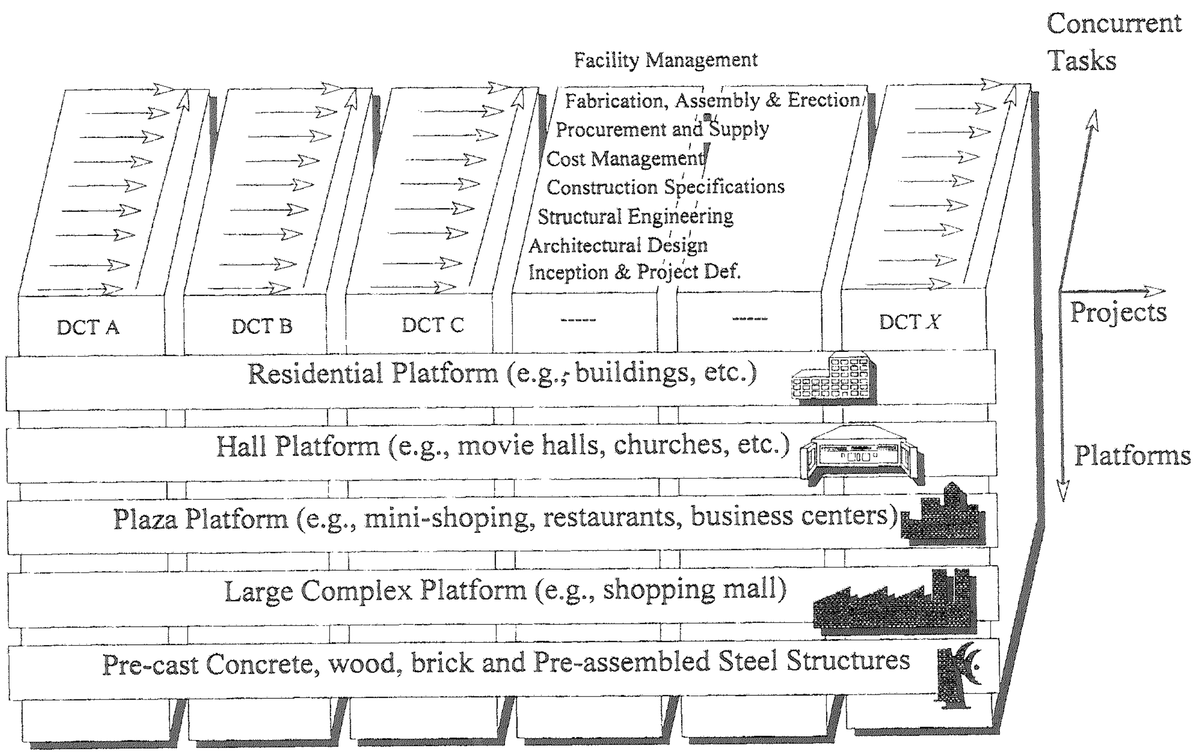

Figure 5. A 3-dimensional concurrent triad (construction, fabrication, assembly & erection example)

A class-hierarchy can be based on the usage (private or public enclosures, commercial property (shopping plaza, stores, etc.), infrastructure (bridges, roads, highways) and factories). One perspective commonly used during organisation and management of information is a combination of size, usage and marketing perspectives. For the construction industry this has transformed into a triad spanned by three axes, shown schematically in Figure 5.

(1) The vertical axis shows the division by platform types. The common platform types for buildings are large shopping complex (mall), plaza (minishopping), restaurants, business office centres, halls (movie halls, churches, etc.), residential property, etc. The subclasses of business office centres can be single-storey, multistorey, multipurpose buildings, etc. Structural assembly (steel frame, wood, brick, and concrete) is also categorised as a type of a platform, since it cuts across all major building types.

(2) The horizontal axis lists the division by model types. In the case of residential building, examples of typical models are colonial, modern, or traditional styles. There is usually a design and construction team (DCT) responsible for each construction project. They are generically named here as DCT A, DCT B, DCT C, DCT D, ..., X, etc.

(3) Concurrent to each project, there is usually a third dimension, now commonly called 'centres'. These centres perform activities, such as architectural design centre, structural engineering, construction specifications centre, cost management centre, procurement & supply centre, fabrication, assembly & erection centre, and facility management centre. They are either dedicated services to a project or matrixed across several projects, e. g. DCT A, DCT B, DCT C, etc.

Defining a property (product) breakdown structure (PtBS) tree to perspectives attaches additional meaning and order to the complex building architectural design process [18]: e.g. a passenger automobile's basic product structure (four wheels, four–eight cylinders, reciprocating gasoline engine in front, round steering wheel, two–four doors, one–two rows of seats, interior instrument panel, trims, etc.) has not changed much in 3 decades [8]. Many new models have been introduced, but these have inherited the basic concept of the automobile. Similarly, in a construction facility, the basic structure (elevation, landscape, water, electric, gas, and HVAC supply) has not changed.

Hierarchy

The physical property or the 'construction unit' may be divided into several logical, hierarchical blocks or classes, depending upon its complexity. The advantage of this logical division is that different people can work in parallel in these different hierarchical blocks. The associated teaming between groups of people in a large construction or fabrication industry is discussed later. If separate construction project teams are assigned to each class and subclass, they can work concurrently. A PtBS example for a civil engineering property-class is shown in Figure 6.

$$\text{PtBS A-tree} = \cup [\{\text{building system}\}, \{\text{building subsystems}\}, \{\text{building components}\}, \{\text{building parts}\}, \{\text{building materials}\}, \{\text{building characteristics}\}] \quad ....(16)$$

The PtBS activity tree can be superimposed on work groups involved in the construction property's system design, with supporting construction subteams dealing with subsystems design and another set of construction subteams handling the remainders, such as components, parts, architectural design, materials, form features, etc. A nested routing workflow model can be drawn, starting from the bottom and showing the activities of each of the PtBS's trees leading up to the system flow model as information builds up. Some dependencies can exist between the branches.

An important job of the CE work-groups is to recognise and manage interdependency between the PtBS

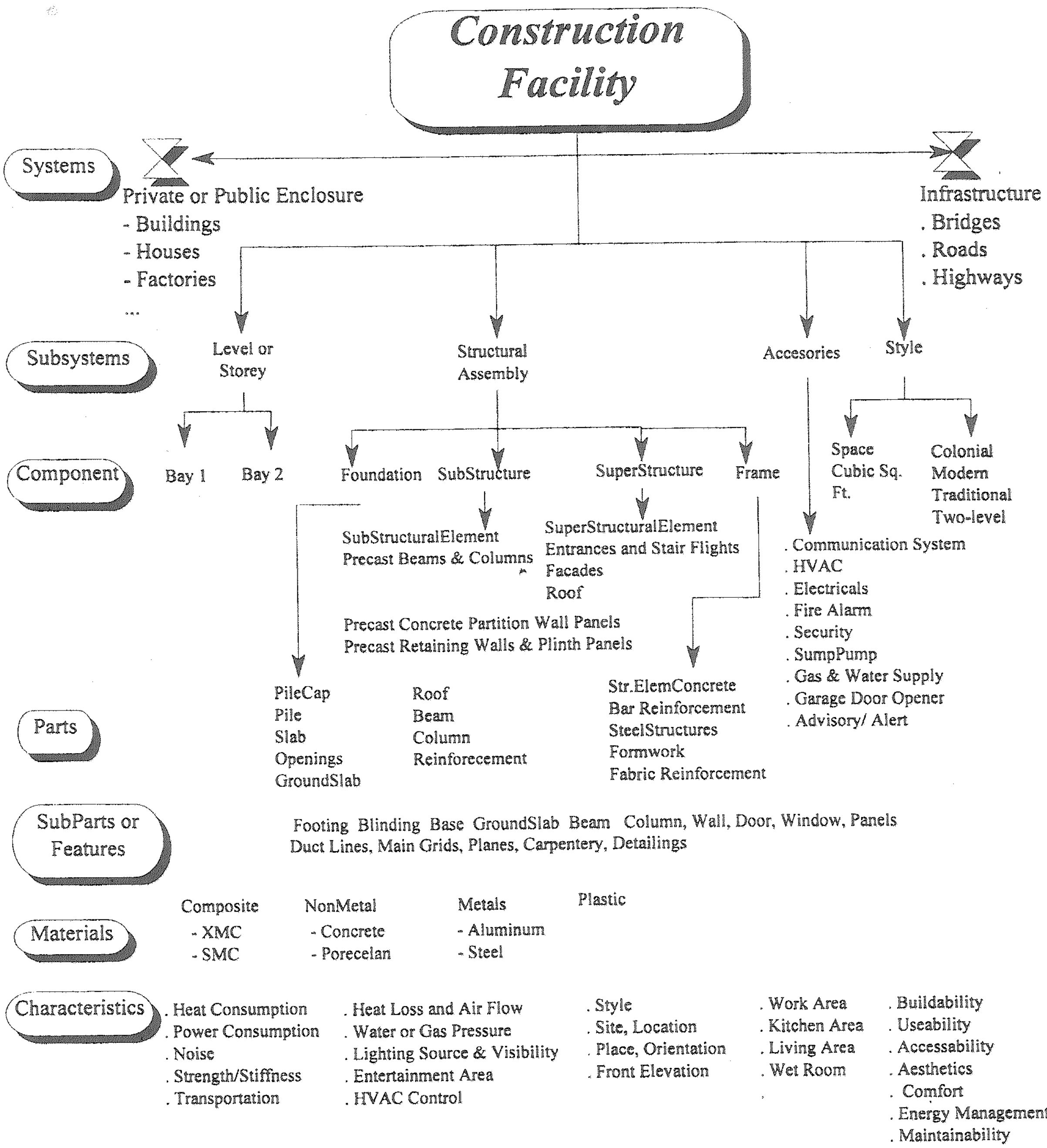

Figure 6. Areas of concurrency in a construction facility top-down decomposition: an example

nodes. Establishing common interface standards for communications and dictionary definitions (standard) of problem parameters and checkpoints can allow parallel groups to work concurrently. Checkpoints are essential to ensure the smooth coupling of completed activities. This is accomplished by staggering the PtBS tree, as shown in Figure 4: e.g. the system level activities can begin only when activities for subsystem track are already well underway. The subsystem-level activities can begin only when tasks for component's track are well underway, and so on. PtBS organises a product hierarchy by using a step-wise refinement and differentiation technique.

Step-wise refinement adds hierarchy to the structure, and differentiation adds details at a particular level. Product or process features, materials, attributes, and parameters, provide the lowest level of hierarchical abstraction. The amount of granularity present at each level is usually a function of the property and the construction process complexity and their knowledge, such as structural knowledge of connections, joints, members, equipments, architectural design cases and needs. Object knowledge for a property (i.e. building, site, space, pipe, duct, topology, opening, etc.) provides attributes (door, window, etc.), structures, assembly, and their relationships. Functional knowledge produces evidence for hierarchical decomposition (systems, subsystems, components, parts, ..., etc.).

Architectural design cases or case histories provide additional evidence of breaking the hierarchy into alternatives, characteristics, etc. During the differentiation technique, different characteristics and alternatives can be assigned to a PtBS tree, as shown in Figure 6. The PtBS tree drives the product or the process design to a manageable set of units and nodes that can be worked on independently by the work groups or the concurrent construction subteams.

The illustrations in Figure 6 show how a hierarchy of system decomposition would look if we started with an architectural system assembly of a construction facility and worked our way down from this top level. Each decomposed element combines with other decomposed elements of about the same level to make up the next larger level. Strategy (what services to render and to whom) and processes (how to convert inputs to outputs and how to deliver outputs to the customer) practically determine expected quality level, productivity, costs, and profitability.

Multiplicity

Within each different hierarchical group (e.g. a part or a component group), multiple parts or compo-nents going into the final product may be worked on simultaneously.

$$\{\text{Parts}\} \text{ of a PtBS A-set} = \cup \{\text{part\_1, part\_2, part\_3, ..., part\_}n\} \quad ....(17)$$

Similarly, the teams in the work groups may work concurrently on a multiplicity of models used to represent an architectural design enrichment in a particular discipline: e.g. the geometry of parts may be modelled, first in the early architectural design stages using a sketch, then by means of a solid model using CAD/CAM tools, and later by an orthographic projection drawing. As such, a decomposed element of a PtBS tree can be a quantified set.

Alternatives

Within one hierarchy level, a group of architectural designers guided by its hierarchy leader may work on several alternative ideas in parallel.

Characteristics or aspects

Each alternative idea may involve integrating some lifecycle aspects, meaning the validation of its output through compliance from multiple characteristic views, where each characteristic view may represent a different lifecycle aspect such as safety, noise, waste, earthquake vibration, energy consumption, heating, ventilation and air-conditioning (HVAC), structures, space, etc. Each lifecycle concern may further be looked upon from different viewpoints, from well-defined ones (e.g. structural analysis, fabricability), to ill- or vaguely defined ones (e.g. usability, constructability, erectability). Building construction subteams from different contracting agencies and suppliers may be needed to support these aspects or viewpoints. These construction project subteams can work in parallel on each characteristic view.

Projects

Multiple projects, such as predictive analyses, structural analysis (FEA), QFD [21], design for constructability/erectability/fabricability, and safety analyses, may be required to evaluate product compliance with functional specifications (such as cost, safety, waste, transportation, and energy consumption). Many structural analysis subteams may be working in parallel to determine the integrity of the architectural design with respect to these construction specifications. Additional details, increased accuracy, and other aspects of alternative architectural designs, may be considered as typical examples for projects.

The next section describes a set of enabling principles for concurrency and simultaneity. The information is extracted from an automobile case history [8] and applied to the construction industry in a generic form, so as to be applicable across many other constructed facilities.

Best concurrency and simultaneity

Concurrency and simultaneity are the major force of CE. There are seven enabling principles to achieve the best concurrency and simultaneity in CE.

Parallel work-group

Parallel work-groups were one of the key elements of the concurrency described by Prasad [8, 9] and Krishnan [19]. Paralleling describes a 'time overlap' of one or more activities in the A-set, tasks, etc. CE is structured around multifunctional teams that bring specialised knowledge necessary for the project.

Multidisciplinary project team

The multidisciplinary set-up (called design and construction team (DCT)) is composed of several distinct project subunits specialising in a variety of areas:

- property planners (T_{pp}), clients or owners
- structural engineers, HVAC engineers and analysts (T_{se})
- architectural designers (T_{ad})
- consultants & regulators, contractors & partners (T_{cc})
- cost estimators (T_{ce})
- materials suppliers, procurement (T_{mp}) teams
- fabricators, assemblers, and erectors (T_{fe})
- facility operators (T_{fo})

In the above, eight concurrent sets of teams are intentionally chosen to show the actual correspondence with each of the eight concurrent tracks of Figure 1. Each track is responsible for developing and integrating its own aspect to the construction's lifecycle, as the project requires. However, there could be as many activities/track (referred to here as A-set) and teams (referred to here as DCT-set) as needs arise: e.g. experts from the structural engineering field must be involved in specifications development to identify, as early as possible, opportunities to improve construction process fabricability, reliability, and safety.

A building's construction process is not a CE process unless it involves all parties responsible for its fabrication, assembly and erection, regardless of whom they report to administratively. Subcontracting companies must be included as participants in the CE teams, at least until the construction specifications have been determined, validated, and are somewhat firmed up. The property's builders or owners tell the contractors or consultants exactly what client wants are. The consultants are able then to communicate upstream to the contractors or suppliers what parts or materials they would require to construct the facility correctly.

For the establishment to construct a unit or property that satisfies the regulatory and safety requirements, all project participants have to know what is expected from the others, in what time frame. Proper communication links have to be in place. This will ensure a complete integration of client needs and usage of the property with contractors' and suppliers' construction capabilities. With such integration, the consultants can influence architectural design requirements before they are frozen. Structural, weight, regulatory, and safety specifications can be stated in joint terms that the contractors and fabricators can effectively satisfy and that are reasonably stable and unlikely to undergo any significant change.

Inclusion of outside contractors or trade partners

An effective inclusion of outside contractor or consultant partners in cooperative construction is frequently one of the under-emphasised issues relating to implementation of a CE process. In today's environment, because of the growth in the complexity of investments, goods and services (buildings, bridges, etc.) and the increased reliance on ready-to-assemble prebuilt building parts and problem-free procurement methods to construct them, partnership has become an increasingly important issue. The building and civil engineering industries often rely on outside contractors or partners to supply materials, services, and products, in various specialised forms and shapes. Many examples exist [13].

It will do little good for a construction company to adopt a CE environment (or to control its facilities design and construction process) without including its contractors or trade partners, if a major or significant portion of its facility is built by outside contractors or suppliers. Establishing a partnership can be strategically very important. It can eliminate or minimise the need for building Code regulators or in-house inspection. By establishing some type of partnership, where the certification programme is a part of the deal, one can ensure the procurement of quality incoming materials and building parts. In that case, the cost benefits of inspecting incoming materials and sorting out defective parts for return to vendors must be weighted against the contractor's cost of acquiring defect-free parts.

Successful partnership requires a harmonious communication environment characterised by rapid, accurate and 'paperless' business transactions. Other claimed benefits of partnership include greater satisfaction to the customer, simplified recycling, fewer computer entries, smaller inventories, and greater economy of scale. The increased use of electronic commerce technologies, such as electronic data interchange (EDI), via wide area networks, value added networks, and electronic vendor bulletin boards, is paving the way for making such partnership painless. They are widely used in the automobile industry to exchange purchase orders, shipping notices and payments, particularly with first-tier supply-chain partners that deliver directly to OEMs. A first-tier supplier of instrument panels, for example, may be required to deliver a product within a few hours of receiving an order, and deliver it in the assembled order needed on the assembly line. This close partnership has directly reduced inventory across industry.

Figure 7 shows a bidirectional sandwiched structure for an integrated design and construction (IDC) system. In one direction, IDC-sets are supported by the client on the top and the infrastructure (organisation) at the bottom. In a perpendicular direction, DCT-sets are sandwiched between the architectural design and construction process, on one side, and tools and technology on the other side.

$$\text{IDC-set} = \cup\,[\{\text{clients and owners}\}, \{\text{architectural design}\}, \{\text{construction process}\}, \{\text{tools}\}, \{\text{technology}\}, \{\text{construction company infrastructure}\}, \{\text{DCT-set}\}] \quad \text{.... (18)}$$

where $\cup$ indicates a union of several sets and DCT stands

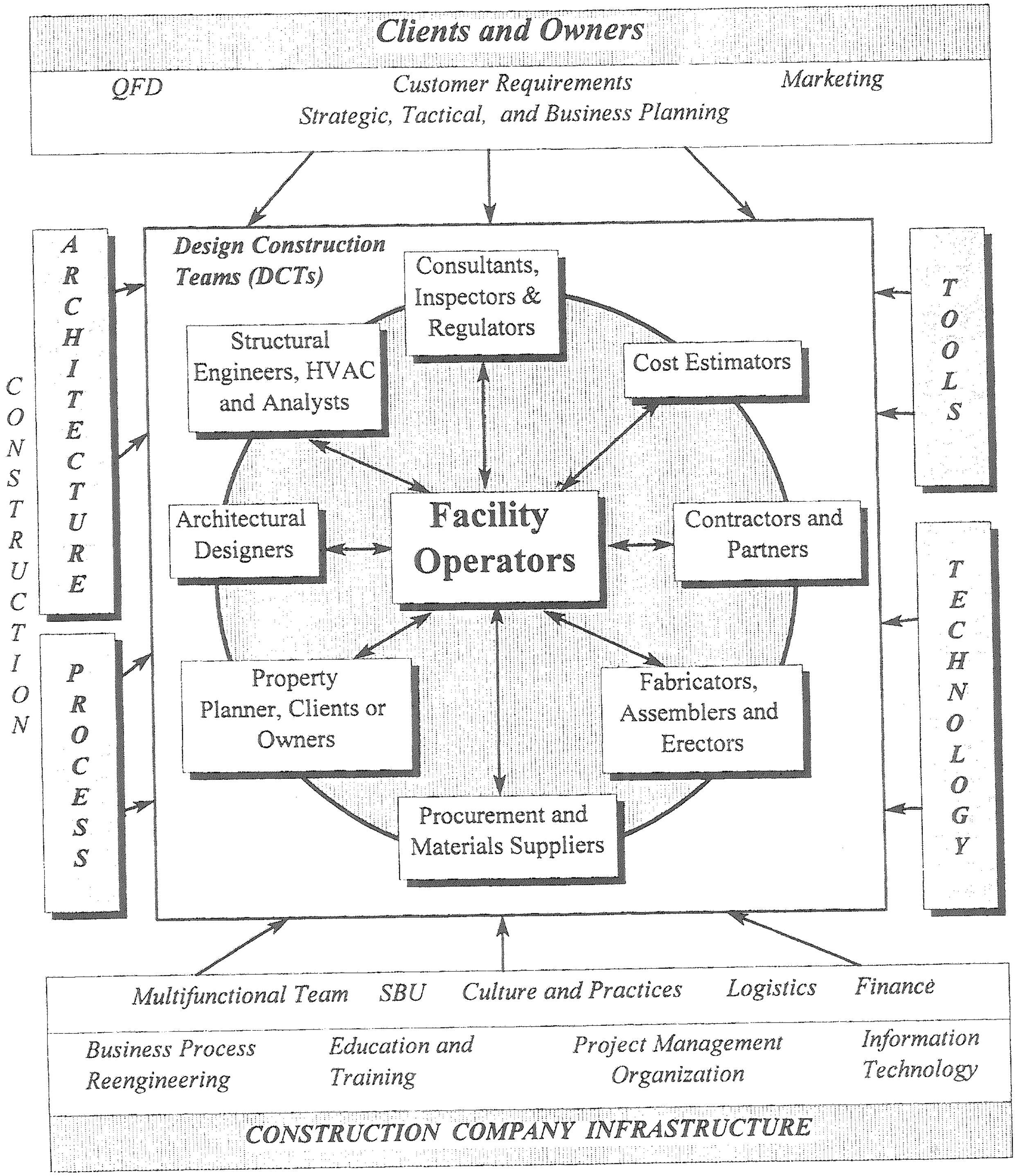

Figure 7. Example of a typical design and construction team (DCT)

for 'design and construction team'. An example of a DCT-set was defined earlier. The braces indicate the presence of several sets given in eqn (18). The infrastructure involves a wide range of disciplines, including multifunctional teams, strategic business units (SBUs), culture & practices, business process reengineering, logistics, finance, information technology, education & training, project management, and organisation. As shown in Figure 7, clients help to establish the requirements for IDC including QFD, marketing, strategic/tactical business planning [21]. In the IDC-set system, DCT-set integrates customers' inputs, their products & processes with their own experience in business solutions (tools), knowledge of future directions (technology), and the organisational infrastructure to provide worldwide competitive advantage. The DCT-set that replaces the traditional functional department is often organised along goal-oriented principles. Experts in the field of mechanical, electrical, industrial, chemical and material engineering, as well as a variety of other fields, work together.

Removal of barriers to cooperation and resolution of conflicts is responsibility of the DCT manager [24].

The demands of today's ever-changing international marketplace are immense. Goals are moving targets, undergoing constant changes and shifting in response to market conditions. The diversity of disciplines in CE is essential to leverage core competency in order to address the growing complexity of today's product needs and global fabrication, assembly and erection trends. CE requires a new approach to project management. Each team must work closely with other teams to identify and develop techniques that are more cost-effective, innovative, and simple to use.

Parallel product (property) decomposition

Smith & Browne [25] and Los & Storer [20] describe decomposition as a fundamental approach to handling complexity in architectural design, engineering and construction of a building. Property decomposition means viewing the property construction process as a part of the whole and then overlapping (aggregating) the decomposed A-sets to recreate or reconstruct the whole set (IDC-set) from its parts (A-sets). In other words:

$$\text{Property construction} \Leftrightarrow [\text{decomposing (parts-from-the-whole)} \oplus \text{reconstructing (whole-from-the-parts)}] \quad ....(19)$$

The term 'whole' also includes multiple characteristics of lifecycle concerns (e.g. X-ability). Although not all lifecycle activities are independent, many sets can be decomposed safely: e.g. it is not necessary to delay the start of an activity if the information required for that activity is not dependent on the rest. Owing to an increased global pressure to construct a building or a facility as early as possible, parallel processing in CE is becoming a necessity [14]. The two-step process shown in eqn (19) is in line with the way a contractor builds a property. Most of the time, when a design team comes up with a detailed architectural design of the building, they do it from top-to-bottom, but, when construction starts, the structure is fabricated or erected from bottom-up.

There are, however, many ways a building, a facility, a construction process or work information can be decomposed and overlaid in parallel [23]. If a property, construction process or a work information activity does not affect other parameters (such as safety or regulatory Codes), it can be performed locally; if it does, it can be performed in a distributed fashion. Local or distributed processing, to a large extent, depends on how a property's structure is originally broken up or decomposed [8]. Do the decomposed parts exhibit independent or semi-independent characteristics? Decomposition allows the scheduling of activities to proceed in parallel. In a construction process, usually a high degree of dependencies exists; as such, it becomes even more important that decomposition of construction properties is carried out in the right way.

The two (decomposition + concurrency) allow one to identify activities that can be overlapped or performed simultaneously. They also allows one to formulate strategies leading to their separation, e.g. indexing, alternate decomposition, teaming, or restructuring. Let us assume that an activity set, A-set, has been broken up into activities: a_i, a_j, a_k, etc. There are four possible ways such activities can be related to each other [8]; they are shown in Figure 8. This means that A-set can be split into four subgroups. The corresponding sets for these

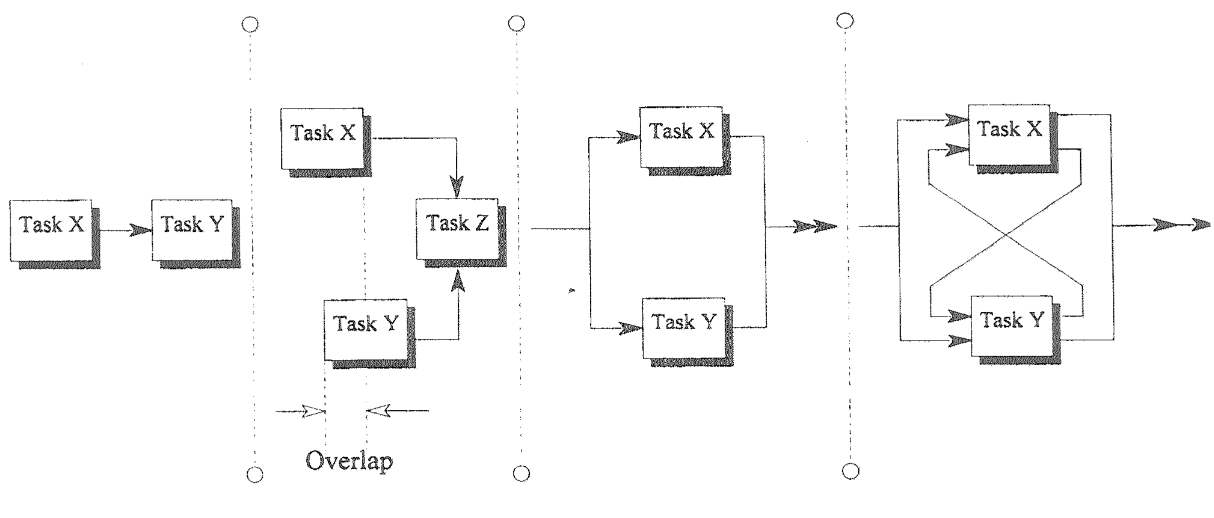

Figure 8. Possible relationships between a pair of activities

four subgroups are:

(a) dependent activities set, $\{A_{dep}\}$;
(b) semi-independent activities set, $\{A_{sin}\}$;
(c) independent activities set, $\{A_{ind}\}$; and
(d) interdependent activities set, $\{A_{int}\}$.

- Dependent activities: A pair of activities (say, a_i, a_j) are said to be dependent, if an activity requires information that is an output from another activity. The information required could be a complete output transfer or it may represent only a portion of the output. If the transfer of information is complete, they are usually run in a series. This is shown in Figure 8(a).
- Semi-independent activities: A pair of dependent activities (say, a_i, a_j) are said to be semi-independent if the transfer of output from one activity to the other is only a partial transfer (pseudo-parallel). The pseudo-parallel structure means that there exist weak interactions among groups of activities. In Figure 8(b), an activity ak is said to be dependent upon activities a_i and a_j since partial outputs from both ai and a_j are used to complete activity a_k.
- Independent activities: A pair of activities (say, a_i, a_j) are said to be independent if no portion of the output from one activity or the other is required for the completion of both activities. Figure 8(c) shows a pair of activities, a_i and a_j, which are independent.
- Interdependent activities: A pair of activities (say, a_i, a_j) are said to be interdependent if a two-way information exchange is required for the completion of the job, meaning that information from one activity (say, a_i) is used to complete the second activity (say, a_j) and the information from the second activity (a_j) is used to complete the first activity (a_i). This is shown in Figure 8(d).

In other words:

$$\text{A-set} = \cup\,[\{A_{dep}\}, \{A_{sin}\}, \{A_{ind}\}, \{A_{int}\}] \qquad ....(20)$$

The symbol ∪ implies a union of individual sets, which are contained within the braces of eqn (20).

Paralleling activities and the amounts of overlap depend upon the types of relationship and the degree of dependency that exists between them [23]. The overlap between two intermediate activities or specifications/outputs represents the timelapse to build the information required for the start of the subsequent activities. Coordinating activities that exhibit dependent $\{A_{dep}\}$ or independent characteristics $\{A_{ind}\}$ is quite straightforward. The dependent activities, belonging to the set $\{A_{dep}\}$, are arranged in series, and independent activities, belonging to the set $\{A_{ind}\}$, are stacked in parallel. For the work groups, however, the challenges of CE are extremely difficult when many activities are interdependent, i.e. those that belong to the set $\{A_{int}\}$, meaning that they are coupled and cannot be separated explicitly either in a series or in a parallel mode. Interdependent (or coupled) activities take more architectural design time and many iterations (of information transfer back and forth) before they finally converge. CE strives for simultaneity and immediacy. In practice, however, mutually independent groups of activities seldom exist. Strategically, decomposing the interdependent activities, which belong to the set $\{A_{int}\}$, into a series of dependent, semi-independent and independent activities ($\{A_{dep}\}$, $\{A_{sin}\}$, $\{A_{ind}\}$) can reduce the size of the working groups and the number of iterations required to obtain a reasonable solution.

Concurrent resource scheduling

Facilitating the transfer of work information among work groups is an essential organisational task of any construction company. Concurrent resource scheduling involves scheduling the distributed activities, A-set, so that they can be performed in parallel. Paralleling is simple for activities exhibiting independent or semi-independent characteristics, $\{A_{ind}\}$, $\{A_{sin}\}$. However, it is not so simple for the dependent activities set, $\{A_{dep}\}$. There are many cases where activities are dependent (not yet coupled) but need to be scheduled in parallel with other activities.

A simple case is that of an overlap. Even though one activity is dependent on another, there is no need to wait until the other task ends: if an activity precedes and generates the information required for a later activity, the next task can start as soon as the required information is made available; there is no need to wait for the completion of the former task. If the two activities are independent, they can be scheduled in any sequence necessary. The other options that address these issues more precisely are: optimal scheduling (minimising time, resource, cost, etc.), backward scheduling (meeting target time), and team-based project management. Sanborn Manufacturing Co. employed a backward scheduling to set up major milestones, consisting of hard and fast dates, and worked back from those dates as a planning mechanism [13].

If the activities in the A-set are independent (i.e. the activities belong to the $\{A_{ind}\}$ set), a pair of activities (say, a_i, a_j) can start immediately, meaning:

$$t_{si} \leftrightarrow t_{sj} \qquad ....(21)$$

The symbol ↔ means that starting time is coincident with respect to timing. The term 'ts' in eqn (21) denotes a time of start for an activity 'a', where A-set is the activity set defined in eqn (1), i.e.

$$\text{A-set} \equiv \cup\,[a_1, a_2, a_3, a_4, ..., a_i, a_j, a_k, ..., ... a_n] \qquad ....(22)$$

Frequently, a 'building, a facility or a construction process' is radically redesigned to achieve parallelism. Paralleling of activities provides the management team with opportunities to reorganise and control the resources applied during CE. These resources fall into

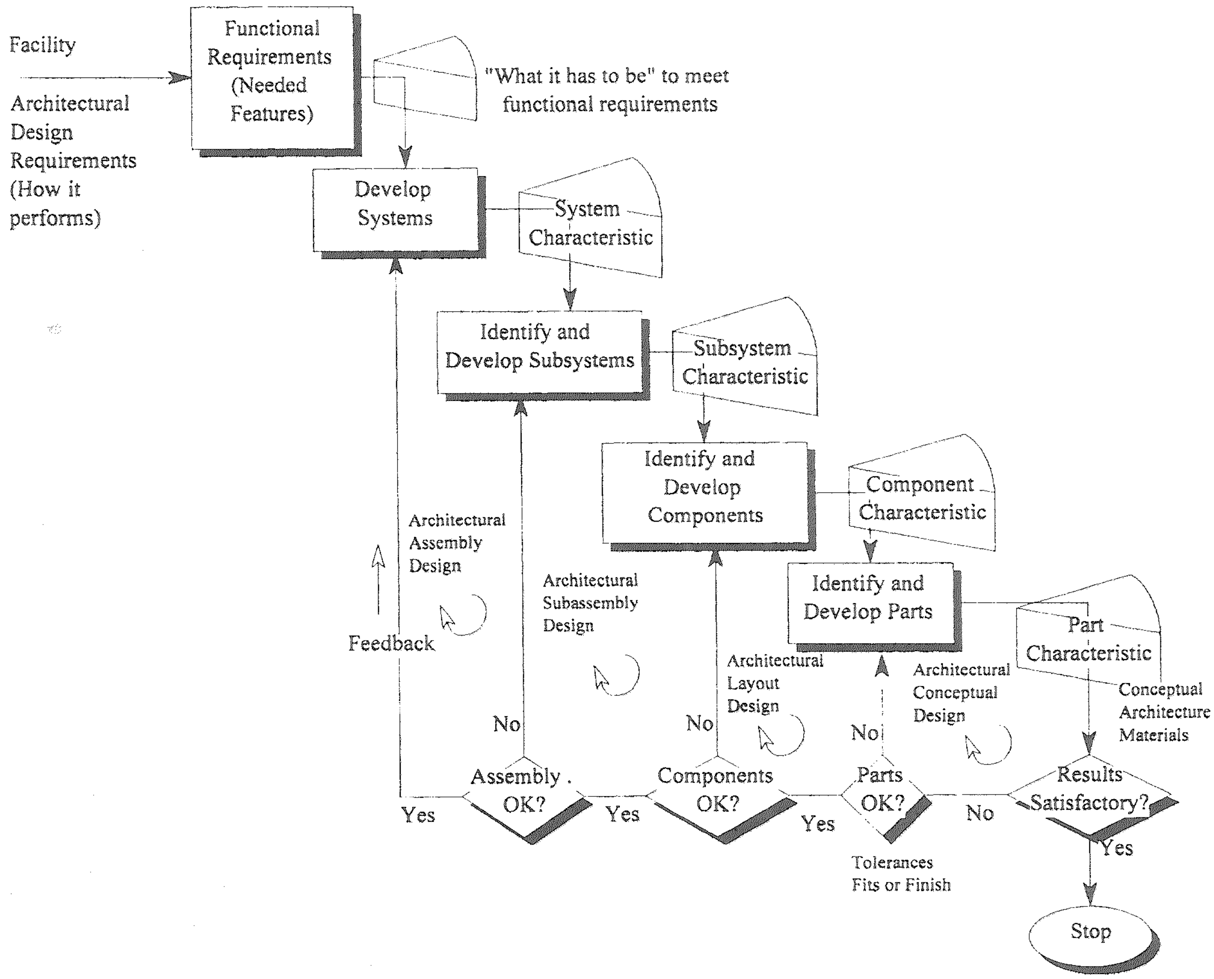

Figure 9. Minimising property (product) interfaces

three main categories: teams (e.g. people, machines (cranes, ladders, etc.)); facilities (materials, etc.), outside firms); tasks (activities or projects they work on, knowledge of the projects, information they need to work with); and time. The trio provides a basis for defining a work break-down structure (WBS). A WBS is really a series of interrelated work tasks initially set in motion by the planning track. New tasks are added or created by the subsequent tracks when put into motion. The latest series of tasks is mostly due to construction specifications, cost management, and procurement & supply tracks. These tasks are over only when that product is finally disposed of at the end of its useful life.

A good WBS contains all three elements: paralleling of tasks, paralleling of teams (work groups) and optimal time schedules. It uses as much knowledge as possible, aggregating the existing evidence for concurrent work scheduling and tasks' decomposition that architectural designers commonly use. Techniques such as optimal resource planning, cost accounting, level balancing, OPT and other load management approaches are considered integral to WBS in achieving concurrent resource scheduling. The types of WBS required within an organisation dictate how the seven Ts should be developed and used. Figures 9 and 10 show how CE activities and work groups should be organised into loops, linked (electronically connected) together by a product (property) breakdown structure (PtBS) and/or (construction) process breakdown structure (PsBS) hierarchy. The construction property decomposition details have been integrated into such loops.

Concurrent resource scheduling is shown in Figures 9 and 10 as a central block, where arrows to and from the nested loops or decision blocks either emanate or terminate. The outer loop starts with the multiple perspectives of architectural design and the innermost loop ends with multiple analyses (or projects). There is a series of nested loops to prune the elements or the information envelope required to build a total design and construction model of the facility.

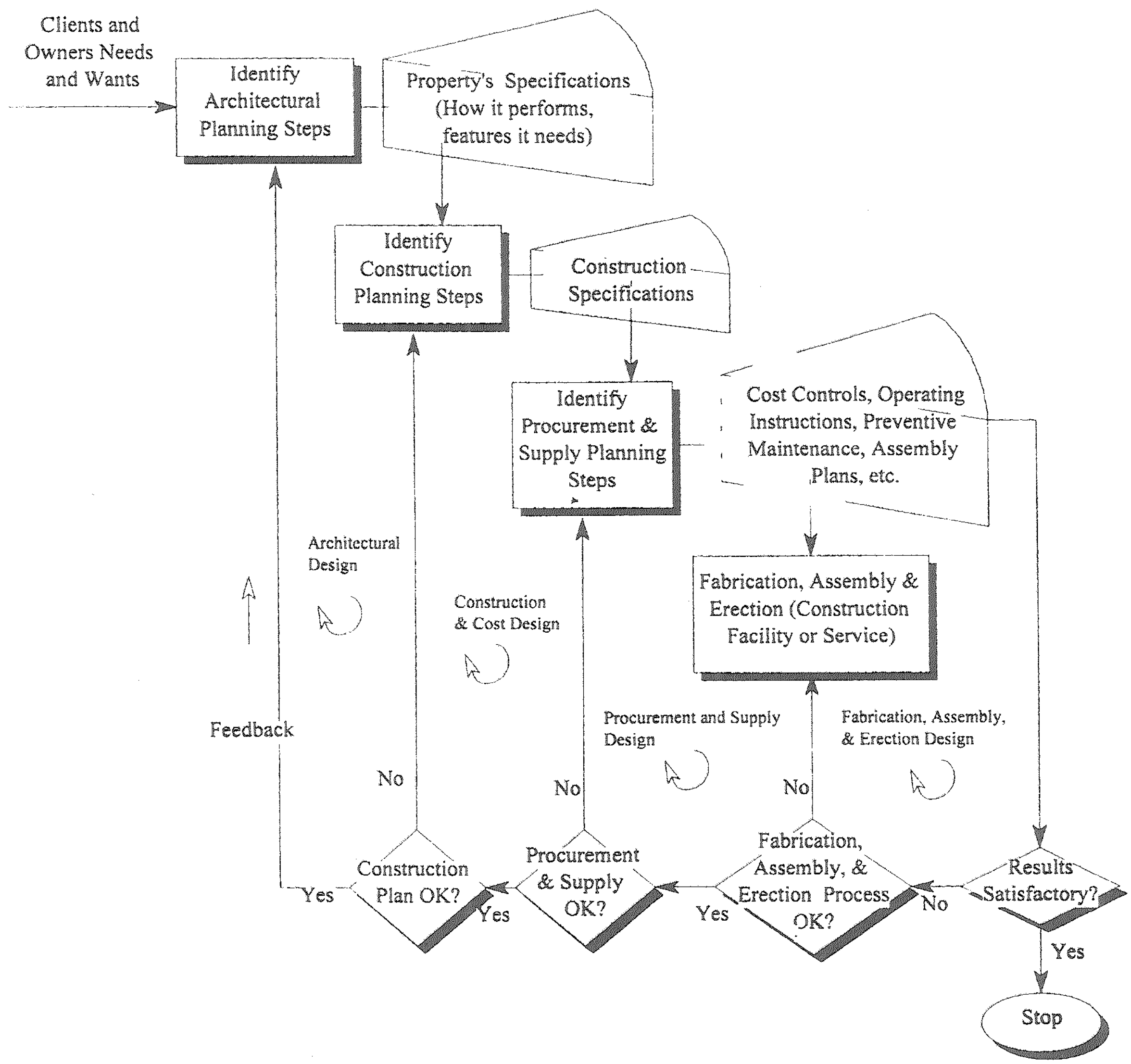

Figure 10. Minimising construction process interfaces

Concurrent processing

Managing time is the fulcrum of CE. Some companies rely on milestones; others use strategic routing and queuing as another way to manage time. Concurrent processing means optimal routing and queuing of activities from both the work-group distribution and information build-up standpoints. This is essential to guide the architectural design of the property and its fabrication, assembly and erection processes toward a safety, quality-build end. Concurrent processing is never easy, particularly in industrial settings where solvable technical problems are impinged upon by cultural considerations. Resistance to change is quite predominant. This is seen, for example, in the automotive industry and, more generally, in companies where the age profile of the technical staff is high. The three most important concepts associated with concurrent processing are: creation of 'variable-driven' product/process models; route management; and queue management.

In concurrent processing, activities are staggered (performed simultaneously or overlapped) rather than carried out sequentially. Keeping track of those complex dependencies that vary with time is a critical task in concurrent processing. Appropriate synchronisation efforts between different CE teams have to be made.

If the activities in A-set are performed simultaneously (complete overlap), it implies that a pair of activities, a_i and a_j can start together, i.e.:

$$t_{si} \leftrightarrow t_{sj} \qquad ....(23)$$

If the activities in A-set are overlapped (partial), meaning from timing perspectives:

$$t_{si} < t_{sj} \qquad \text{....(24)}$$
$$t_{ei} > t_{sj} \qquad \text{....(25)}$$

where the symbol ↔ means that the two activities 'coincide with respect to timing'.

Minimising interfaces

This entails reducing all sorts of interfaces required for the 'product realisation process (PRP)' to a bare minimum:

$$\text{Number-of -PRP}_{\text{interfaces}} \Rightarrow \text{Minimum} \qquad \text{...(26)}$$

These include the interface relationship between project definition and architectural design, construction specification and cost management, architectural design and structural engineering, cost management and procurement, fabrication, assembly and erection interface, procurement and supply design, etc. Such interfaces can be very long indeed and tend to depend on the size of the industry and the construction facility and process complexity.

Partitioned design and construction can be facilitated by introducing adequate interface management. The main focus is on identifying various sources of interfaces and determining whether they are actually needed or not. The goal is to reduce the number of design, construction, fabrication, assembly and erection interfaces to a minimum. 'Reducing interfaces' means taking steps to redesign and simplify business systems and processes, search out best practices (three Ps), develop a more competitive workforce, and explore new business methods.

This principle fosters out-of-comfort-zone thinking, relies on value added benefits to both the customer and the business, and focuses heavily on seven Ts. It requires follow through until the new process is firmly entrenched. Unlike organisational restructuring, the 'minimise interfaces' principle involves alterations in the level of abstraction to reconfigureure the subject system. It may involve reconstituting this subject system into a new form or to a new level of abstract descriptions and a new implementation of the altered form. This saves time, reduces architectural design costs, and gets the needed contractors/partners involved early in the process.

Minimising property (product) interfaces

The facility architectural design problem is often decomposed into subdomains, each having its own design variables and constraints.

$$\text{Facility set} = \cup\,[\{\text{system}\}, \{\text{subsystem}\}, \{\text{components}\}, \{\text{parts}\}, \{\text{features}\}] \qquad \text{....(27)}$$

Eqn (27) is very similar to that shown for an automobile, an aerospace and a helicopter example in [8]. Here {features} represents a combination of both {materials} and {characteristics}. These subdomains can be quite independent of each other except in a limited number of common interfaces. The product breakdown structure (PtBS) tree drives the property's architectural design to an interface-driven integration technique.

The PtBS also serves as the model index structure and helps to keep the digital equivalent organised and easier to cross-reference with other indexes. The problems of each subdomain can be solved in parallel and the results brought back to satisfy global needs at a later time. Such a decomposition of architectural design, as represented by the structured PtBS tree, can be achieved in a number of ways: e.g. the architectural design problem can be divided into a four-step process, as shown in Figure 9. The first step is to develop a functional system. It yields system characteristics, which are input to the next step to identify and develop subsystems. The subsystem's characteristics are then input to the third step to identify and develop components. Finally, the components' characteristics are fed into the fourth step to identify and develop parts (see Figure 9).

There are four decision blocks, corresponding to four loops: conceptual design (architectural); architectural layout design; architectural subassembly design; and an architectural assembly design, which checks whether the corresponding architectural design is satisfactory or not. The other aspect of the PtBS tree is the minimisation of interfaces among these five steps: system, subsystems, components, parts, and features. This was illustrated earlier by a building (construction facility) example.

$$\text{Property interfaces} = \cup\,[\{\text{system}\} \cap \{\text{subsystems}\}, \{\text{subsystems}\} \cap \{\text{components}\}, \{\text{components}\} \cap \{\text{parts}\}, \{\text{parts}\} \cap \{\text{features}\}] \qquad \text{....(28)}$$

If a decomposed element is decoupled (or loosely connected), the tasks of interface definition are simple and straightforward. Joints, connections, spacing, finish and fit requirements have little or no impact on conceptual design, assembly, or components' functions. Material types, as represented by the structured bill-of-materials, can often be modified without jeopardising the part, component or assembly function. The convenience of processing architectural design problems in parallel can lead to a converged (constructional) design much faster than is possible conventionally.

However, if decomposed elements of the PtBS tree interfere (beginning and end tasks) or significantly overlap, the interface definitions could be quite complex and intertwined. The major product construction challenge in such cases is to integrate the many (decomposed) subproblem solutions into a well-connected system. Some organisations address this by assigning teams of analysts or conflict resolution engineers to handle the interactions between the decomposed subproblems. The trouble is that such interactions are rarely known in advance or their implications are not well understood. Interface management is the technique used to minimise interfaces. Management implies so preparing the PtBS tree or its content as to preclude possible interfaces between the decoupled elements. Through this approach, the architectural design at the top level supports the next level of architectural design, which supports the next level, and so on. The decomposition is consistent with their interface requirements. This does not prematurely commit the property to a high cost.

Minimising construction process interfaces

As in architectural (product) design, the construction (process design) problem can be decomposed into subdomains. These subdomains can be quite independent of each other, except for a limited number of interfaces. In common with the property's architectural design case, the problems of each construction bay can be solved in parallel and the results brought back to satisfy global needs at a later time. Such a decomposition of a construction plan (a process breakdown structure (PsBS)) is shown in Figure 10. Here the process plan is divided into four stages: architectural planning; construction planning; assembly planning; fabrication and erection (constructional facility or service).

$$\text{Process set} = \cup [\{\text{architectural planning}\}, \{\text{construction planning}\}, \{\text{procurement \& supply planning}\}, \{\text{fabrication, assembly \& erection}\}] \quad ....(29)$$

The first stage is to identify a functional set of architectural planning steps. This yields a property's specifications, which are input for the next stage to identify construction planning steps. The resulting construction specifications are then input to the third stage to identify procurement & supply planning steps. Finally, its outputs are then fed into the fourth stage to obtain a fabrication, assembly and erection (see Figure 10).

There are four decision blocks, corresponding to such four loops: architectural design; construction design; procurement & supply design; fabrication, assembly & erection design.

$$\text{Process set} = \cup [\{\text{architectural design}\}, \{\text{construction design}\}, \{\text{procurement \& supply design}\}, \{\text{fabrication, assembly \& erection design}\}] \quad ....(30)$$

The decision blocks check whether the corresponding plan is satisfactory or not. In essence, PsBS is the manner in which a company architecturally designs and manufactures its products, while PtBS is the means used to describe or capture the inherent complexity of a product.

Minimising computer interfaces

Too many computer interfaces can create problems with the smooth flow of information. Each program has its own data, input, and output format requirements. In order for these programs to run seamlessly, the inputs and outputs of these programs must work in concert with each other. Manual data entry is error prone. Moreover, there should be a single data source from where all inputs originate, so that, if a parameter is changed, the correct value is passed on to all interface programs using them.

Transparent communication

This provides virtual communication between the individual activities that are partitioned (decomposed) and between the team members. Transparent communication involves identification and definition of mission-critical data. All members of CE teams need to have the same common understanding of the frequently used terms and their meanings. It may require definition of 'data dictionary and semantics' as a structured approach to resolving conflicts and for consensus building. The elements that contribute to transparent communications are:

(a) global access
(b) universal product code
(c) electronic data interchange (EDI)
(d) technical memory.

Quick processing

'Quick processing' means performing individual activities as fast as possible, using productivity tools or design aids. It also amounts to speeding up preparation time in building up the information content before and after the execution of an activity. This emphasises the mandate for shortening the pre- and postprocessing time and the time it takes for completing the decomposed activities themselves.

$$\text{Quick processing} \Leftrightarrow \text{minimise } (d_i) \text{ for } \forall\, i = 1, n \quad ....(31)$$

where n is the number of activities in the A-set and d_i is the time duration, defined in eqn (3). There is a difference between the complexity of the philosophies (e.g. product complexity, process complexity, enterprise complexity, or complexity of cognitive behaviour) and the philosophies of their management. An organisation committed to making such complex products in the shortest possible time need not require an equally complex management philosophy. Organisations can still handle all that while following a simple management philosophy.

This simple management philosophy is the philosophy of decomposition, followed by concurrent processing. This is similar to what used to be at one time the European philosophy of 'divide and concur'. To apply this to a complex product, a systematic decomposition of the product and process, (including the seven Ts defined earlier) is required. The latter is discussed further in [8] (Fig. 4.1).

Fast processing can be accomplished through high-bandwidth technology or by building flexibility into the process. Management techniques, which are the product of decades of corporate learning, can be captured as knowledge or rules. With high-bandwidth technology (e.g. object-oriented databases, technical memory, parallel computers, multimedia, X-window) a large amount of information exchange can take place at a very high speed. Using such means, product construction rules can be coded into knowl-edge-based design and construction software programs [9].

Once these knowledge-based programs and technical memories are deployed as useful lifecycle aids, they can provide considerable competitive advantage to companies in terms of construction speed, accuracy in cost estimating, and safety [9]. Not only is the competitive advantage earned through process management techniques retained in this case, but the methods are also readily available for future use, when real-estate market conditions suddenly change or a builder develops a superior architectural design.

Concluding remarks

At the heart of any good architectural design, construction and procurement (ADCP) process, there lies a set of underlying principles for satisfying the interests of the client, the contracting body, and the company. This paper has described a set of seven principles of concurrency and simultaneity (i.e. parallel work group; parallel product decomposition; concurrent resource scheduling; parallel processing; minimising interfaces; transparent communication; and quick processing). The company's focus shows up in applying these seven principles initially to identify construction project teams and then to organise the activities that can be overlapped or performed simultaneously.

The set of these principles provides construction companies with significant competitive advantages and big organisational potential to fabricate, assemble, and erect a quality building or a facility that a client would like to buy in less time and at less cost. CE principles also help construction project teams to formulate significant architectural design and construction process strategies leading to their separation, e.g. indexing, alternate decomposition, teaming, or restructuring.

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