Concurrent Engineer-To-Order operation in the Manufacturing Engineering Contracting industries

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Abstract: This paper presents the concurrent Engineer-To-Order (ETO) concept. ETO is a Make-To-Order operation that starts with a product specification and finishes with delivery of a customised product. By synchronising the production activities in a product development process, a concurrent ETO operation can effectively improve and assure the product development lead time. This paper defines its relevance to other contemporary manufacturing operation concepts and proposes a concurrent ETO operation framework. It details the interactions among the sales, production, engineering, and manufacturing operations with a focus on hierarchical planning, incremental scheduling, and operation control.

Keywords: concurrent engineering; hierarchical planning; incremental scheduling; operation control; enterprise systems; Make-To-Order (MTO); Engineer-To-Order (ETO).

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1 Introduction

1.1 Manufacturing Engineering Contracting (MEC)

Manufacturing Engineering Contracting (MEC) is a vital element of today's manufacturing industry. It provides design related manufacturing services to Original Equipment Manufacturers (OEM). A great variety of manufacturing companies heavily engage in engineering contract work, especially in the sectors of computer, automobile, office automation, telecommunication, consumer electronics, industrial, and medical products. Among these, the Electronic Manufacturing Services (EMS) sector is the largest subindustry. Most manufacturing engineering contractors operate in a comparable business environment and adopt a similar business process. They are highly agile, lean and quick in response. By and large, they are engaged in the OEM business and work closely with customers to develop a particular product, as opposed to only manufacturing. Many provide complete design, engineering, and manufacturing services that are vertically integrated with component capabilities to optimise its OEM customers' operations and time to market.

Manufacturing engineering contractors apply the concepts of mass customisation, concurrent engineering and lean manufacturing to their operations. They need to actively shorten development lead time, reduce operation costs and improve processing capability to stay competitive. Their business process usually starts with a product specification and goes through the phases of bidding, contracting, product and process design, tooling, fabrication, assembly and testing. Some of these phases may have a recursive process. For instance, development of an end product for OEM often requires engineering tools (tooling) that themselves in turn may go through steps of bidding, contracting and design, followed by fabrication, assembly and test. The process repeats if the tooling also requires its own tooling, resulting in a nested hierarchy of business processes. Product and process complexity creates more challenges for production planning, costing, scheduling and leadtime prediction. Moulds, dies, jigs, and fixtures are the typical engineering tooling. They are used to either harness a production line or produce components such as frames, housings or small parts for an end product. Tooling plays an increasingly important role in many industries at both operational and strategic levels, because it is getting more costly, technologically intense, and often with a less predictable as well as long leadtime. Without loss of generality, this paper will often use tooling operations or tooling industries to exemplify the discussion of concurrent ETO operation.

1.2 Classical ETO

Classically speaking, ETO is a product development process that starts with a product specification and finishes with an engineering design as its deliverable. It is usually limited to an engineering design process that involves the tasks of engineering analysis, concept design, architectural design, detailed design, prototyping and manufacturing process design. It does not include the manufacturing phase of materials acquisition, fabrication and assembly. In a classical ETO operation, product functionality is the major design focus. Various prototypes may be created in the design process to verify the product design in progress, but prototypes are seldom a deliverable item. The design and standardisation of a manufacturing process may be a development focus as well, when intended for batch/volume production. Prototypes however, are not made with a standardised manufacturing process, which usually occurs only at a later time.

1.3 Two stage operation approach

While a typical end product such as a notebook, cell phone and digital camera is a standardised design for volume/batch production, the engineering development project for such a product or tooling is mostly one of a kind. Traditionally, most manufacturing engineering contractors would take a two stage approach to their operation that separates engineering/tooling development from their production. The first stage is considered an R&D phase and is focused on design of the end product as well as its manufacturing process including development of required production tools. Only after product and process designs are finalised will the second stage begin, when a manufacturing order is received.

A classical ERP system is designed for the second stage of operation; which is repetitive manufacturing of products with a well tested product and process design. A classical ERP system requires a Bill Of Materials (BOM) to drive Material Requirements Planning (MRP) and a process plan to drive Capacity Requirements Planning (CRP). MRP calculates time phased materials requirement and CRP estimates plant capacity requirements over time. Most ERP systems operate in a Make-To-Stock (MTS) mode. They are readily applicable to the Assemble-To-Order (ATO) and Build-To-Order (BTO) operations as well, where both BOM and manufacturing process plan are in existence. Typical ERP systems are not applied to the ETO and the DTO (Develop-To-Order) operations however, because BOM and manufacturing process plans are not available beforehand to drive production planning. ETO and DTO operations in most manufacturing companies are left to a blackbox approach (Krishnan and Ulrich, 2001). Some companies began to use a Product Data Management (PDM) system for product data and workflow management.

1.4 ETO for tooling

ETO for tooling is a unique product development process. Unlike a typical product development project, tooling development engages in both engineering and manufacturing processes and it results in delivery of a final artefact of a very small quantity. It usually makes no prototype and does not standardise the product and process design, because there is no further tooling production activity. From a tooling point of view, every activity in the development process is a production activity. It includes engineering analysis, concept design, assembly design, BOM creation and detailed design in the design phase; plus material acquisition, fabrication, assembly and testing in the manufacturing phase. A tooling ETO operation often plans for (and executes) both design and manufacturing activities in concurrence, in order to shorten the *production* lead time. A challenge to the production operation however, is that work plans are uncertain when a production order is issued. Work planning itself is also a production activity. Usually work is incrementally created and dynamically scheduled for frequent release in small increments, leading toward a hierarchy of partial work plans for concurrent design and manufacturing.

1.5 Objective

This paper is intended to define the concept of concurrent Engineer-To-Order (ETO) operation and present a foundation for design and development of an effective concurrent ETO operation system. This paper describes the concurrent ETO concept in detail and discusses its relevance to other contemporary manufacturing operation concepts in Section 2. It proposes a concurrent ETO operation framework in Section 3 and explains interactions among the production activities in the integrative sales, engineering and manufacturing process in Section 4, with emphasis on concurrent planning, incremental scheduling and operation control.

2 Research background

2.1 Product life cycle

From an enterprise operation point of view, a product life cycle can be properly divided into eight major phases, beginning with customer intent and ending with product disposal. These are:

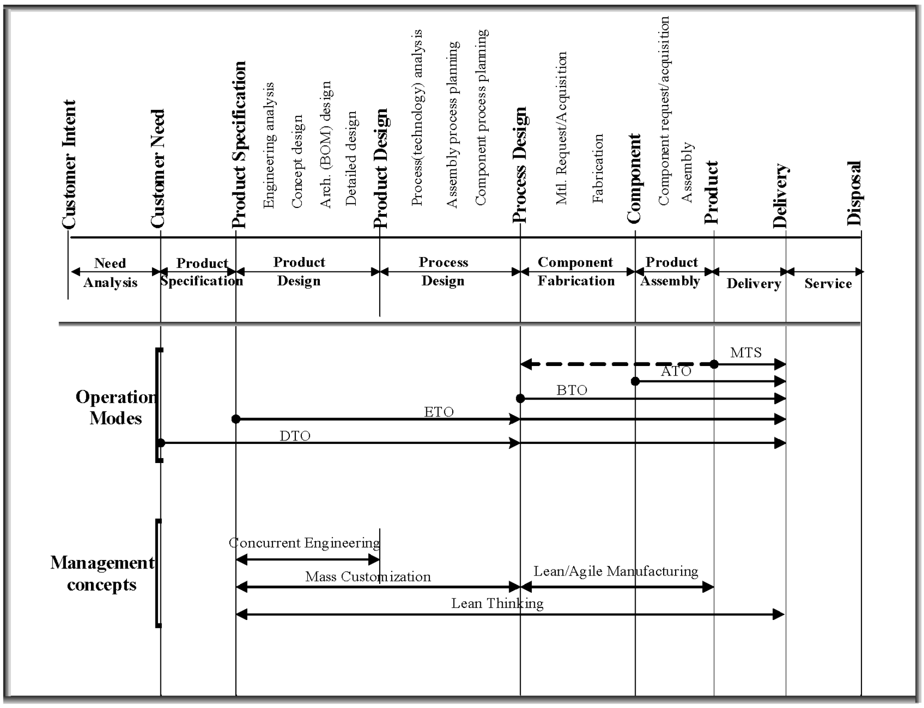
1 need analysis
2 product specification
3 product design
4 process design
5 component fabrication
6 assembly
7 delivery
8 service.

As depicted in Figure 1, need analysis is the first phase and starts with customer's intent and ends up with listing of specific customer needs. Product specification is the second phase of the life cycle that translates the needs into a technical specification for the end product. Product design is the third phase and starts with a product specification and stops with the product designed. It involves engineering analysis (for a technical solution), conceptual design, architectural design and detailed design. Process design starts with a product design and stops with a manufacturing process developed. It involves (processing) technology analysis, assembly process design and component process design. Tooling is considered at the processing technology analysis stage and it may trigger its own product and process design. Component fabrication starts with a manufacturing order which comes with a detailed design and a manufacturing process plan for the component and stops with the component made. It may involve material acquisition as an activity of the fabrication operation. The assembly phase starts with components made and stops with the final product completed. It may include components acquisition and product test activities in the assembly process. Delivery is the phase that transports a finished product from the factory (or warehouse) to its customer. The service phase is the last phase and is controlled by the customer until its disposal. The first four phases typically are considered engineering/design tasks, while fabrication and assembly are viewed as manufacturing tasks.

2.2 Operation modes

Make-To-Stock (MTS) and Make-To-Order (MTO) are two generic operation modes commonly used in the manufacturing world. MTS produces products in volume. A central planning system is used to prepare and issue production orders that fabricate components and assemble products according to a demand forecast and inventory updates. Components and finished goods are kept in inventory, according to a company's inventory policy, which usually is designed to minimise delivery lead time and overall operation costs. However, the customer is mostly limited to what is available in the inventory. Pricing is a marketing tool to move finished goods from inventory. Back orders may be accepted when a product is out of stock, but little customisation is intended. MTO on the other hand, accepts only back orders and thus keeps no inventory of finished goods. MTO aims at customising products to meet individual needs. The price for each product is estimated and negotiated at the time of contracting. It typically costs more and has a longer delivery lead time. Depending on the entry point of operation in the product life cycle, an MTO operation may be further classified into Assemble-To-Order (ATO), Build-To-Order (BTO), Engineer-To-Order (ETO) and Develop-To-Order (DTO) modes.

Figure 1 Summary of relevant enterprise operation concepts



As shown in Figure 1, ATO is an operation mode that engages in final product assembly using readymade components, which usually are inventoried and shared among products. BTO engages in both component fabrication and final product assembly. It does not intend to keep components in inventory. Product configuration and modular design are the keys to an ATO as well BTO operation. Both ATO and BTO operations assume that product and process designs are in existence. Starting with a product specification, ETO is the operation mode that engages in product and process designs. It may include manufacture of the product design if it is one of a kind, but the two (design and manufacture) processes typically occur in sequence. A concurrent ETO is an ETO operation in which both design and manufacture processes occur in parallel, in order to optimally minimise the product development time that spans a product specification and delivery of the final product. DTO is similar to ETO, except that it starts (usually working closely with the customer) one step earlier, at the stage of specifying a customer need or defining a product specification. From an operation planning point of view, DTO can be reduced to an ETO problem by treating need analysis and product specification as an engineering design activity.

2.3 Related manufacturing operation concepts

2.3.1 Mass customisation

Mass customisation is an operation philosophy with which products are designed and made to customer's need/specification and yet the operation runs at the efficiency of mass production (Pine, 1993). The philosophy may be applied to configuration or customisation of a new product and process design (Yassine et al., 2004; Jiao and Tseng, 2004). From an operation point of view, the aggregate demand for tooling could be tremendous for a major manufacturing engineering contractor, though each tooling is designed and made one of a kind. In fact, the tooling operation of some manufacturing contractors has grown to an unprecedented size that matches its counterparts in batch/mass production. It is fairly common now a days, to see a tooling operation of more than five hundred workers, that routinely handles many dozens of customer orders, resulting in hundreds of deliverable items and tens of thousands of components and production tools to be designed and made concurrently. To better deal with the size and volume, many tooling operations have turned to the concepts of mass customisation, aiming at improving operational efficiency and minimising reliance on skilled workers.

Mass customisation is particularly relevant to today's tooling industries, since many deliverable items and their respective tooling share similar product structures and manufacturing processes, while having differences. Anderson (2004) identified the three ways of mass customisation as modular, adjustable, and dimensional. However, the need for tooling customisation goes beyond the three customisation methods, because typical tooling cannot be readily made with modular components, product configurations, or adjusting dimensions. To effectively mass customise tooling, manufacturing engineering contractors need to organise their corporate expertise into a knowledge base (of formulas, rules, templates and reference models) for repeat use in the process of bidding, contracting, work planning, product design, process design, shop floor execution and changes management. Mass customisation can be an effective means to realising lean and agile manufacturing as well, when generic work elements and processes are properly standardised. A comprehensive knowledge base of sales/product/process models along with an effective classification system can greatly facilitate tooling operation management and improve resources utilisation. Thus it reduces waste for a concurrent ETO operation.

2.3.2 Lean manufacturing/thinking

Lean thinking is a philosophy that focuses on creating value through its value stream by eliminating wastes (Womack and Jones, 2003). The value of a product is evaluated from the customer's point of view. The value stream may reach the product's entire supply and service chains. A waste is an activity that consumes resources but creates no values.

It may exist in many forms in an enterprise, such as a mistake which requires correction, an idling resource waiting for work, a processing step that is superfluous, a movement of employees or transport of goods from one place to another without real purpose, or production of an item that no one wants. As shown in Figure 1, lean thinking is an expansion of lean manufacturing that has traditionally focused on the manufacture phase of component fabrication and product assembly. In the tooling industries, a short- term goal of lean manufacturing is to minimise resource idling and Work-in-Process (WiP) waiting in a queue, until the problem of frequent rework and engineering changes can be better managed. A change or rework may appear in many different forms, depending on the stage at which a product is in its life cycle. A customised product may be recalled or repaired (by the vendor) at its service stage, returned at the delivery or tryout stage, reassembled at the test stage, rebuilt at the fabrication stage, redesigned at the design/engineering stage, or redefined at the specification phase. A repair or change in product specification usually is not considered a waste, if it is a request made and paid for by the customer. Even so, it may cause a chain of changes to be made. This may incur waste in the process, depending on the management of the product lifecycle data and development process.

2.3.3 Concurrent engineering

Concurrent engineering is a concept that aims at shortening product development lead time (Prasad, 1996) by performing engineering activities in parallel when feasible, such that slack times on critical paths are eliminated and unnecessary engineering iterations are avoided. Aside from development of various colocation techniques and making managerial/cultural changes in individual companies, much of the concurrent engineering focus has been directed to concurrent manufacturability evaluation of a product design in progress (Anderson, 2003). More recent research studies of concurrent engineering have it focused on product development collaboration. Shen (2003) presented an overview of the collaborative design environment that focuses on knowledge sharing. Swink (1999) identified a list of factors that negatively affect the manufacturability of a new product design and emphasised the importance of the development teams' integration processes to assuring product manufacturability. Gao et al. (2003) proposed a PDM based approach to sharing product data for enterprise integration from the conceptual design stage on. Chandra and Kamrani (2003) presented a knowledge based system for managing complex product design work flows. Fine et al. (2005) proposed a quantitative approach to implementation of a 3D concurrent engineering paradigm involving product, process, and supply chain design. A survey of internet based information sharing and visualisation technology for collaborative product design and manufacturing was reported in Zhang and Xue (2002). Concurrent engineering does not concern itself with process design, production planning or manufacturing. Process design and production planning are considered premature at this juncture, because product design has not been finalised and demand is unknown. From a classical concurrent engineering point of view, manufacturing will occur only at a much later time. Therefore, concurrent engineering has been largely applied to ensuring that a product design is somehow possible to produce. It does not consider concurrent execution of engineering and manufacturing activities.

Tooling operations in the MEC industries have extended the classical concept of concurrent engineering to the entire product design and manufacture phases. In tooling industries, concurrent engineering and manufacturing activities are a common practice for leadtime compression. However, the practice of concurrence complicates the already complex tooling operations in several dimensions. First of all, both product and process design tasks are a production activity, but their task plans and schedule are not detailed before hand. Only after a production order is being decomposed can partial work plans be created, scheduled and then released for execution. As a result, operation planning and scheduling is tediously incremental, control is convoluted, and lead time feasibility is difficult to evaluate.

To speed up the development process, partial work plans for product and process designs in an ETO operation environment are habitually created and approved, on the fly, for immediate execution. Many changes are expected to arise in both product and process designs. While changes management is a complex task in itself, changes also compound the problem of operation planning and control. It also adds new challenges to cost and lead time management. Product Data Management (PDM) and Collaborative Product Development (CPD) are a contemporary solution to product data and workflow data management. It manages and enables sharing of product life cycle information in timely manner to eliminate slack times. However, existing PDM systems do not present a solution to concurrent operation of engineering and manufacturing activities.

2.4 Related ETO operation studies

A number of recent research efforts were attempted to address ETO operation related issues. Little et al. (2000) underlined the importance of design capacity and load factor in their proposed reference model that outlined a sequential development process in which MRP was used to plan for manufacturing activities after completion of the design task. Giebels et al. (2001) proposed an implementation scheme for concurrent manufacturing planning and control using multiagent concepts to handle a changing manufacturing environment. Tianfield (2001) presented a life cycle product development model, which formalised the serial nature of the product development process by using information substitutive concurrency and detours. Jin and Thomson (2003) recognised some unique features of ETO operations and proposed an MRP based framework, by considering finite capacity scheduling and partially defined BOM and manufacturing process plans. It did not detail how finite capacity scheduling works with uncertain product/process information.

In a concurrent ETO operation environment, bidding is an essential element of the integrative product development process. ETO bidding consumes engineering resources and is an integral part of a concurrent ETO operation. Furthermore, ETO bidding commits resources and thus changes resources availability. Since delivery promise is largely committed at the bidding process, each active bid must be accounted for in master production scheduling and its timephased resources requirement must be included in capacity planning and scheduling. When a bid is accepted, its lead time and resource requirement become a firm commitment for production. To minimise development lead time, an ETO operation must engage in hierarchical work planning, incremental scheduling, and concurrent execution of engineering and manufacturing plans.

3 Concurrent ETO operation framework

3.1 Engineering as a production activity

The application of mass customisation concept has fundamentally changed the MEC industries from a projectbased to a production centred operation, evidenced by their operation planning, material routings, labour size, organisation structure and efficiency expectation. It has also largely diluted the importance of a traditional tooling concept that relies on a veteran toolmaker (master) for leading a tooling team. As a result, manufacturing engineering contractors are able to manage the engineering design process as a production activity. As the expertise of product, component, material, and operation is being increasingly formalised and integrated, manufacturing engineering contractors are expected to continuously reduce turnaround time, better integrate business processes, and make their operations more transparent, accountable, and predictable. In addition to challenges put before a conventional manufacturing operation, today's manufacturing engineering contractors are facing the following operation reality:

- innovation and technology intensive competition at project/tooling level
- continued pressure on lead time reduction due to shortened product life cycle
- concurrent operations of production orders (for both engineering and manufacturing)
- management of frequent changes and numerous engineering iterations at the production stage
- constant tradeoff decisions among cost, lead time and quality between laterally or vertically related work plans
- integration of hierarchical planning and incremental scheduling.

3.2 Concurrent operations

The concept of concurrent operations goes beyond manufacturability evaluation of a product in design from a traditional concurrent engineering sense. A concurrent ETO operation is geared toward running an ETO operation at the efficiency and cost effectiveness of a mass production operation while continuously minimising the product development lead time. By treating engineering as a production activity, a concurrent ETO operation engages in concurrent planning and execution of sales, engineering, material acquisition and manufacturing activities. The consideration for concurrent execution of the engineering and manufacturing activities makes an ETO operation very different from a traditional, sequential product development process. To speed up the development process, all engineering and manufacturing activities are created on the fly and immediately released for execution in small increments. Thus, a concurrent ETO operation must support hierarchical planning along with incremental scheduling to manage the dynamics of production activities on the shop floor. Capacity requirement and its planning must be dynamically planned and adjusted as well. Outsourcing is therefore often used as a capacity buffer for shortterm adjustment. In addition, raw materials are mostly one of a kind and are possibly unavailable in inventory. Summarised below is a set of common attributes required of a concurrent ETO operation:

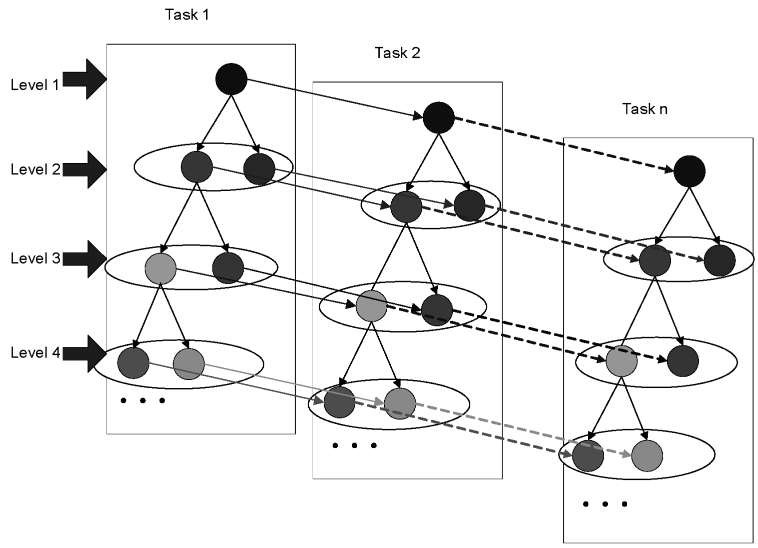
- project based operations integration
- concurrent execution of sales, engineering and manufacturing operations
- integrative decomposition of project's work, budget, lead time and quality
- incremental work planning and scheduling
- handling frequent managerial and technical changes
- engaging in mass product/process customisation
- close collaboration with customers, suppliers and subcontractors
- management of product lifecycle data and history.

3.2.1 Project based operations integration

Project is a common thread for work management in any ETO environment. The concept of project based operation was discussed in Aurich and Barbian (2004) in relation with optimal flexibility of a production system. Kovacs and Pagnanelli (2003) presented an operation infrastructure for largescale engineering projects in virtual enterprises. Project work decomposition is an essential planning function for an ETO operation. A tooling project usually starts with bidding, which eventually leads to a customer order containing one or multiple deliverable items. Most likely each item is specified with a work statement, milestones, resources requirement, cost breakdown and quality expectation. As part of quality assurance, it is fairly common that a product specification was prepared in the bidding process activity and accepted as a part of the contract. For effective management of work content at the production stage, each deliverable item usually is decomposed into a set of tasks (and released as work orders) when a deliverable item in the customer order is converted into production orders. Each task is assigned to a task manager with a work statement, budget, quality specification, resources and due date. In turn, a task may be further broken down to smaller tasks, each again assigned to a task manager with a work statement, budget, time limit, resources and quality specification. The decomposition process continues until task elements reach a granular size of 'operation' that is readily defined with a standardised operation procedure and that can be mapped to a specific resource (machine and/or worker) instance (type). Task plans are subject to changes and decomposition, until each task is sufficiently defined and successfully completed.

As illustrated in Figure 2, a work plan for a deliverable item can be envisioned as a hierarchy of interrelated work plans, of which a component (fabrication) process plan for example, should be situated at the bottom level. The term of process plan is defined in a concurrent ETO operation environment as a network of related operations organised to design, manufacture, or test a component (or assembly) of a deliverable item. A task manager is a person who creates, appends and modifies a task plan at a prefixed granularity level. Until its completion, a task plan continues to evolve, as work elements are being added, deleted or modified. It is a task manager's responsibility to plan and allocate resources accordingly, subject to his/her resources allocation and time constraint for the task. A task manager is also responsible for scheduling and release of individual work elements, after they are approved. In light of the dynamic nature of product and process design in progress, approved work elements might be kept from releasing to accommodate last moment changes. When a work element is released, its resource, time and quality allocations become a constraint to its manager. Note that some elements of a work hierarchy can be planned and executed in parallel, while others may be subject to temporal, technical and/or other constraints. When feasible, it is desirable to organise task managers for a production order in a hierarchy that reflects the company's organisation structure. This streamlines the chain of commands, as task managers at all levels make frequent tradeoff decisions and communicate with their upper or lower task managers for approval, when a deviation exceeds its limit.

Figure 2 Hierarchy of interrelated work plans



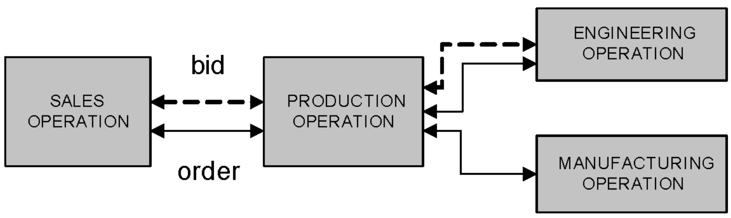
3.2.2 Concurrent execution of sales, engineering and manufacturing operations

Most manufacturing engineering contractors contemplate sales opportunities around the clock to fill its production pipeline and/or optimise its resources utilisation. A research study of the MTO bidding process is reported in Kamrani (2003) and Veeramani and Joshi (1997). In an attempt to quickly turn around a quotation, most ETO contractors face two major challenges: lead time and cost estimation. These challenges affect each other and both depend on available capacity within the customer's time frame of need. It becomes more complicated when outsourcing is considered as an extended capacity. Capacity planning in a concurrent ETO operation considers not only existing customer orders but also pending orders in the bidding process. Each customer or pending order is at a different stage of completion and thus the requirement and timing for resources are uncertain in varying degrees. In particular, each bid has a different perspective of success and should have it reflected in resource reservation accordingly, tying to its historic success with the customer and ongoing negotiation. Both pricing and delivery promise in a quotation are highly timesensitive. They can vary dramatically over a small time horizon, depending on resources availability and the perspective of other active bids and incoming bid opportunities in that time interval. Contractors may also use pricing and delivery promise as a tool to attract a desired order, entice a strategically important customer, or transform the company's business positioning, which further complicates operation planning, scheduling and control. In any concurrent ETO operation environment, bids must be surely incorporated into capacity planning and scheduling, to reflect the dynamic nature of demand and resource availability at varying levels of granularity over the planning horizon.

3.3 Proposed framework

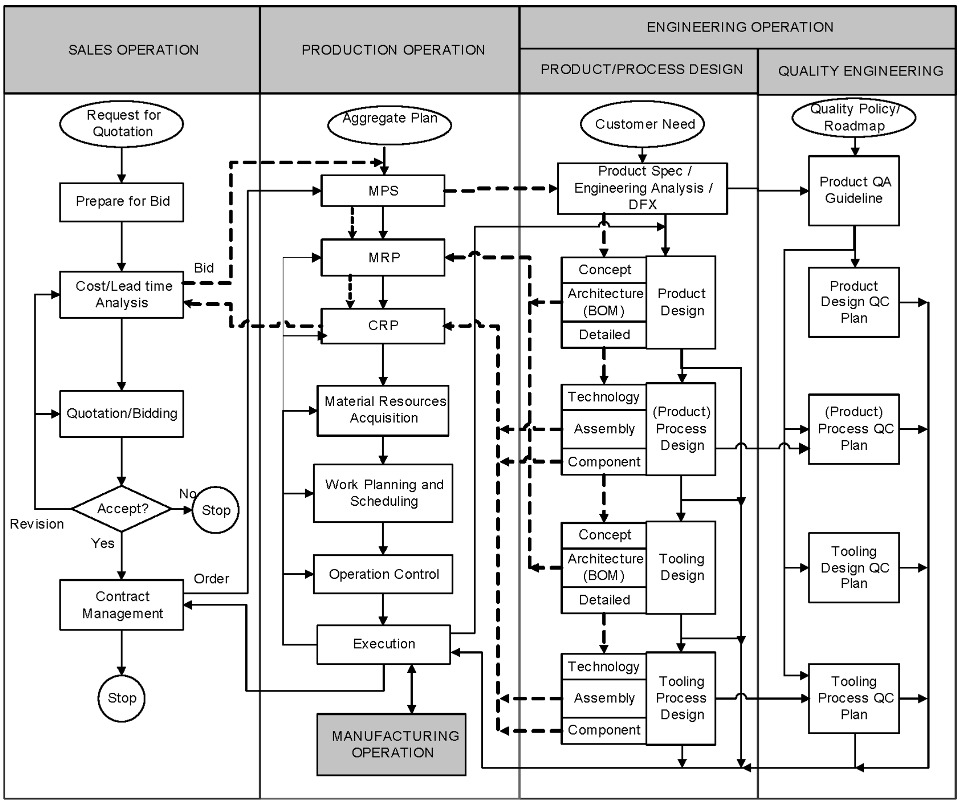
The proposed concurrent ETO operation framework is sketched in Figure 3. The sketch identifies four major business processes and shows how they relate to one another. The sales operation in the proposed framework is the driving force and is typically triggered by a request for quotation from the customer. Each sales process is a production activity and collaborates closely with the production operation. For each bidding activity, the production operation coordinates with the engineering operation for preparing a product specification, conducting an engineering analysis and estimating product costs. Based on the engineering data, the production operation estimates resources requirement and evaluates development lead time for each bid item. When a bid is submitted, the production operation reserves the estimate of resources requirement for the proposed time period. After a customer order is accepted, the sales operation converts the order into production orders and releases the orders to the production operation. The production operation then plans and organises the engineering and manufacturing operations for each production order.

Figure 3 Concurrent ETO operation framework sketch



As detailed in Figure 4, a sales process goes through the steps of bid (opportunity) evaluation, cost analysis, lead time estimation, quotation preparation, bidding, negotiation, order acceptance and contract management. In the bidding process, multiple versions of a product specification and quotation may be prepared in sequence or in parallel with a possibly different solution technology, until the bid is accepted or terminated. From a bidding point of view, the most difficult task is lead time and cost estimation, which both require participation of various technical personnel. Some prepare a product specification and conduct an engineering analysis, while others assess work contents and evaluate resources requirement for availability and costing. Most customers expect each quotation to come with a detailed breakdown of work, material, labour and cost. The breakdown usually becomes a part of the contract and thus deserves a careful deliberation in the bidding process. While bidding is often a complex task in an ETO operation, the details greatly facilitate the management of contracts in the production phase, which begins when the contract manager translates a customer order into production orders and issues each order to a production manager. The contract manager continues interacting with the customer and the production manager to oversee progress, changes, payments and work plans derived from the order, until delivery of the customer order.

Figure 4 Concurrent ETO operation framework



The proposed production operation works with an aggregate plan (AP) and manages production orders that are initiated by contract managers. It handles Master Production Scheduling (MPS), Material Requirements Planning (MRP), Capacity Requirements Planning (CRP), resources acquisition, work planning and scheduling, operation (shop floor) control and work execution. An AP is an annual plan for product offering, service (demand) forecast and resources requirement. As a constraint to the production operation, a corporate structure is in place that organises resources (machines and workers) into a hierarchy of managerial layers to match the demand forecast. In volume production, MPS enrols only independent items derived from customer orders. The proposed master production schedule includes every deliverable item in an active bid, for three reasons. First of all, bidding itself is a production activity in a concurrent ETO operation. Secondly, bidding triggers engineering activities. Thirdly, bidding commits production resources, in the light of acceptance. In a bidding process, the proposed master production schedule is used to drive the MRP and CRP functions if a reference product/process model is available. However, MRP is limited to estimating material cost and delivery lead time for each BOM item. Similarly, CRP is reduced to an appraisal of time phased resources availability and delivery promise. The work planning and scheduling function is a critical production operation element which decomposes production orders and prepares production plans to release for execution or further decomposition. The operation control function supervises engineering and manufacturing activities on the shop floor and addresses deviations from production plans in quality, cost and schedule. The execution function monitors shop floor activities, follows the work planning and approval process, and collects realtime production data. It also manages product lifecycle documents, tracks resources utilisation, updates objects' status, and reports critical events to shop floor supervisors and/or production managers for operation control. The work planning/scheduling and operation control functions are further explained in Section 4.

The proposed engineering operation has two parallel paths of activities: quality engineering and product/process design. The product/process design path starts with a product specification and goes through the steps of engineering analysis, product design and process design (as well as its tooling development). Engineering analysis is an engineering function that seeks the best technical solution to meeting the product specification. Based on the analysis, product design is the next engineering step that engages in concept design, architectural design and detailed design for a complete definition of the product in design. Concept design breaks down the product function requirement into subfunctional requirements until they collectively reach a compatible solution. The architectural design focuses on an assembly design, by following the breakdowns to construct the product concept into layers of parts and components, defining their relationships, and creating a hierarchy of single layered bills of materials. Detailed design starts with a component identified on the BOM and defines the component's material, geometry, form features, fits, dimensions, tolerances and technical notes such as heat treatment and QC requirement. To a degree, process design is expected to occur in parallel to product design, while product assembly and component are being designed. It starts with a processing technology analysis and develops an assembly plan and process plans for inhouse components. The requirement for tooling is identified at the process design stage. It goes through the same design process, creating both tooling product and process designs. The quality path starts in concurrence with the product/process design track. It creates a QA guideline for the product in design, based on its product specification and a corporate quality policy and/or roadmap. The QA guideline consists of a set of QC and DFX (design for X) requirements for a hierarchy of QC plans to be used for engineering design, material acquisition, manufacturing and testing at various product development stages. The QC plans are work plans to be executed as a production activity, along with other work plans for engineering and manufacturing.

The dashed lines depicted in Figure 4 show the workflow of cost/leadtime analysis in a bidding process. Every bid item starts with the MPS as an independent item. The work flow goes through the activities of product specification, engineering analysis, reference model search, cost estimation and lead time estimation. Product specification is a technical definition of the product, including its functional requirement, physical attributes, dynamic behaviours and operational characteristics. Engineering analysis looks into a technical solution to the product design according to the specification. It may involve, for example, deciding whether a set of engineering (progressive) dies or a continuous die should be used to make a metal part. The specification and engineering analysis are the input to search for a reference model among past product designs in the knowledge base. Of the reference model, the BOM(s) is needed to run MRP that estimates material requirement, cost, and acquisition lead time, and the process plans are used to drive CRP that calculates capacity requirement and timing. Tooling, if required, must be included in the cost/leadtime analysis. A reference model may be modified to better represent the design in bid. A feature based approach to modifying a reference mode was reported in Veeramani and Joshi (1997). If a reference model is not available, engineering personnel must go through tedious steps to painstakingly estimate the material cost and resources requirement. Production personnel on the other hand, have to use the resource requirement to schedule capacity requirement and evaluate lead time feasibility. Based on the manufacturing cost and lead time data, sales personnel then prepare a quotation with delivery promise for each bid item by considering profit margin and slack time. These bid data are the foundation for contract management, production planning, and product/process design when the bid becomes a customer order. Hence, when a bid is submitted, its resources requirement must be reserved in capacity planning and resource availability should be adjusted accordingly. When a contract is accepted, the reservation is then converted into resources requirement in full and earmarked for each item in the contract.

The transoperational solid lines initiated from contract management show the workflow for a production order. Contract management is a sales operation function which issues and manages production orders. Based on a review of its engineering analysis and requirements estimate, each contract item is converted into one or multiple production orders and assigned to a production manager with a budget, due date, product specification and resources allocation. Each contract item is an independent item in the MPS and each production order is a dependent item of the first tier in the MRP. Since design and manufacturing plans are uncertain and BOM is not yet available, the resource requirement estimated in the bidding process is only a reservation reference for initial planning. The reservation is substantiated in the production process, when actual work plans of accurate resources requirement and timing are gradually developed and approved. Initially, material requirement is void as MRP still waits for BOM to be created. The CRP function transfers resources requirement for each contract item to resource allocation for each corresponding production order. The production manager is the planner who develops the first tiered work plan and assigns each work element to a manager. The production manager communicates with (and executes the work plan via) the work managers, who in turn, may further the work decomposition process.

The proposed framework considers three types of work plans for production. These are engineering, manufacturing and quality control. Development of these work plans is considered a special production operation activity, which engages in work decomposition, planning and scheduling. In a concurrent ETO operation, most work plans are partially created and approved for frequent release in small increments. Work development is a recursive process until no work element requires further decomposition. The hierarchy of work plans for engineering, manufacturing and QC processes is determined by prefixing their work's granularity. Creating BOM and planning for manufacturing processes are both an engineering activity. BOM is the basis for planning detailed engineering design work. Manufacturing process plans are the basis for planning fabrication and assembly work. Release of approved work plans is an essential function of operation control, in addition to assuring the feasibility of work plans that are being executed on the shop floor. Each release of a partial BOM is a request for material and triggers the MRP function. Each release of a partial work plan triggers the CRP to evaluate resources availability and capacity scheduling. Quality control in the proposed operation framework is a production execution activity that is defined in a QC plan but is normally integrated into an engineering, manufacturing, or production operation process. A completed work plan for a production order may be reactivated and amended with a new work content, due date and resources allocation, until the contract item is completed and delivered.

4 Concurrent operation planning and control

4.1 Hierarchical planning

The proposed ETO operation framework engages in hierarchical planning of finite resources capacity and firm delivery commitment. Hierarchical planning is especially pertinent to concurrent ETO operations. This is because actual production plans and resources requirement are substantiated gradually, as work is decomposed in the production process. The initial resources requirement for each production order is an estimate computed with a reference model in the bidding process. A hierarchical planning approach allows each planning level a certain degree of autonomy, which reflects the managerial nature of a functional organisation structure and provides the robustness required for dealing with local deviations and adjustments.

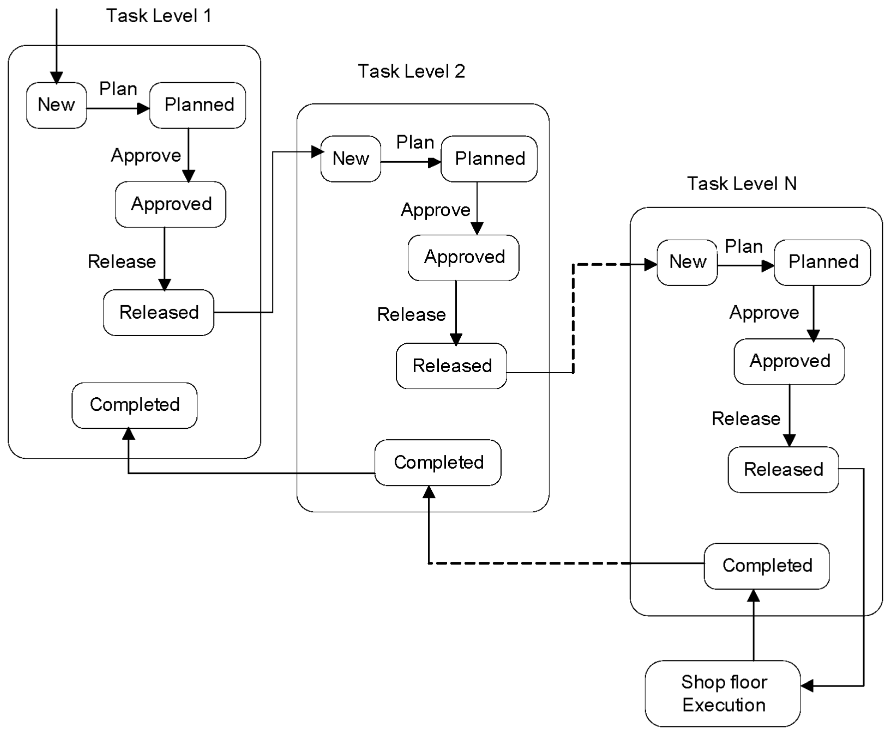
The concept of hierarchical work planning is illustrated in Figure 5 with the level 1 being typically a deliverable order item. A top-tiered work plan for a deliverable item usually consists of design, manufacturing, and testing as its major work elements. The number of planning levels varies, depending on complexity of the deliverable item. Each work element is defined with a specific work statement, scheduled start and end dates, a budget and quality requirement. A work plan at the bottom level usually consists of operations, which are intended for execution by a specialist on the shop floor (whether it is a machine shop or engineering office). Milling a surface, drilling holes, wire EDM cutting, and 2D component design are some of the typical operation types in the tooling industry.

Figure 5 also showsthat each object assumes a different status as it goes through its life cycle. A task is considered new when it is released to a task manger. Its status evolves to 'planned', after it is being worked on. Only approved task plans may be released. A task may go through many incremental rounds of planning, approval, and release before its completion. Note that as work is decomposed, its budget, quality and lead time are also decomposed in parallel. In the iterative process, each work plan must always comply with its allocations and constraints to retain its feasibility, unless a change request is made and approved by its upper manager. The release of an approved work plan triggers the next layer of work planning or sends work elements to a specialist for execution. Work is completed in the reverse hierarchical process. A work plan is completed after all its work elements are completed.

4.2 Incremental scheduling

From a shop floor scheduling point of view, the proposed concurrent ETO operation is a dynamic job shop problem of extreme complexity. Jobs of different types continue arriving at the system, but not entirely in a random manner. In this case, resources requirement is given for each deliverable item and reserved at an aggregate level. Nonetheless, specific routings and timings are not available at the initial production stage. Local lead times are not important, unless a job is on a critical path that affects a delivery promise. Critical paths frequently change over time however, due to new jobs, resources breakdown, delay, QC, rework and changes. Furthermore jobs may constrain one another in multiple ways for technical, temporal, tooling, material and managerial reasons. Job scheduling may have to consider both machine and labour resources. A job may be assigned to a particular resource instance while another is specified only to a resource type level. Some jobs require multiple workers to collaborate in concurrence (e.g., for an assembly operation) or in relay (e.g., for a long EDM operation). Often, components may be bundled together for a common operation in the last minute, to increase resource utilisation. Preemption may or may not be considered for scheduling and resources allocation.

Figure 5 Hierarchical work planning



In such a dynamic, complex operation environment, optimisation techniques are impractical and no heuristics consistently outperform others (Patterson, 1976). Forward scheduling and finite loading however, are the norm. The primary objective for this type of job shop operation is due date feasibility. Hence, a Critical Ratio (C/R) based on due date is a good heuristic for concurrent ETO operations, because it can dynamically reflect the due date of urgency for each deliverable item. To measure criticalness, the C/R heuristic must consider both the total remaining time for the deliverable item and the cumulative remaining processing times, including the processing time for each *upstream* job (that is constrained by the job). The heuristic must be computationally efficient because there are numerous jobs in the system and the critical ratio for each job needs to be recomputed, every time when there is a change to the system. Based on their C/R ranking, jobs are prioritised for resource scheduling. The schedule for each job however, still depends on the availability of its required resource(s). A job with a higher priority may be scheduled for a later time slot when its resource designation is not available. Also a job that requires multiple resources has to wait until all its designated resources are available. On the other hand, in case that multiple resources are feasible for a job at the same time, additional criteria can be used for further differentiation such as cost rate, quality grade, processing speed and utilisation.

4.3 Planning and scheduling integration

Hierarchical planning and incremental scheduling are the two most critical production operation functions. They are integrated in the proposed concurrent ETO operation framework, such that capacity planning and resources scheduling can operate in concurrence, while abiding by finite capacity loading principles to assure schedule feasibility and delivery promise, at each hierarchical operation level. A simplistic version of the proposed integrative planning and incremental scheduling scheme is summarised in the following nine steps.

1 Maintain an accurate inventory of resources availability at varying granularity levels, reflecting resource types and resources organisation in the company over a planning horizon.

2 Verify resources availability over time and reserve (earmark) them accordingly, when a bid is submitted. Dynamically adjust the reservation by a success rate according to the past experience (of the customer and the bid type) as the bid progresses.

3 Convert the reservation into real resource requirement in full and mark them as committed, when a bid is accepted. Release the reservation when a bid is rejected or terminated.

4 Perform iterations of hierarchica/l planning and incremental scheduling after a customer order is released for production.

5 Release new work plans for execution when they are approved.

6 Execute work plans on the shop floor according to the scheduled start time and exercise operation control when necessary.

7 Exercise operation control with proper approval when necessary, to maintain the feasibility of approved work plans.

8 Continue steps 4–7 until every work element in the work plan hierarchy is completed for a deliverable item.

9 Free all unused resources allocation when a deliverable item is completed or aborted.

4.4 Operation control

There are two types of operation control in the proposed concurrent ETO operation framework. One is project control and the other is shop floor control. Project control measures each deliverable item's progress and performance against its work plans that support delivery of the item on time, on budget, and in the form requested by the customer. The primary objective of project control is to ensure product quality and lead time feasibility for each deliverable item, because every item is a back order and tailored to the customer's specific need. Thus, there is no purpose in continuing a production order that does not meet the customer's expectation(s). Therefore, all work plans and schedules must be developed accordingly and project control is to assure the expectation of product quality and delivery promise.

Gray and Larson (2003) outlined a project control process in four steps:

1. setting up a baseline plan
2. measuring progress and performance
3. comparing actual against plan
4. taking action.

They suggested the use of an earned value system to integrate cost and schedule performance for project control. Partial work plans are the baseline for control of concurrent ETO projects. Remedial action must be taken when a significant deviation from a work plan is detected in the execution process. A control action for a project usually involves making a tradeoff decision between quality, cost and lead time. While each project manager may have a different priority ranking of quality, lead time and cost for each contract, quality is always a constraint to comply with. On time delivery is a promise to keep. Cost is therefore an objective to be optimised. To meet product quality and delivery expectation, a remedial action for project control involves:

1. negotiating with other production orders for alternative resources and/or timing
2. resolving in-compatibility in quality, cost and/or lead time between sibling work elements or between child-parent work plans within a deliverable item
3. getting the customer's approval for changing a technical solution approach and/or a delivery lead time.

For in-compatibility, project control usually relies on distribution or redistribution of available resources, lead time, and quality responsibility within a manager's own control limit. Contingency funds may be used, if available.

The need for operation control usually arises from an event of budget overrun, lead time overrun, or quality problems during execution on the shop floor. A project control problem may be elevated from a lower tiered work manager, through the hierarchy of work managers, to the contract manager at its top, who communicates with the customer in case a major technical change or new delivery date is required.

Shop floor control in a typical job shop engages in: (1) assigning a priority to each job which sets the sequence for job execution at work centres and (2) issuing dispatching lists to each work centre that inform shop floor supervisors of which jobs are to be produced at a work centre, their priorities and when each job should be completed. Gantt charts are often used to visually display the workloads at each work centre (Gaither and Frazier, 2002). A shop floor in a concurrent ETO operation environment can be a machine shop, an assembly floor or an engineering design office. The proposed ETO operation framework applies the finite loading approach to the shop floor that allocates the work centre's capacity to jobs hour by hour by varying the start and completion times of each job. It assures that no more work is scheduled to a work centre during any hour other than the capacity of the work centre. Therefore, the major remaining objective is to evaluate the events on the shop floor that have an impact on the feasibility of a delivery commitment, and to develop a remedy before the problem deteriorates. This is especially important when an impact has a domino effect on subsequent operations in the work plan (hierarchy) and/or on other production orders that share the same resources. An event that does not affect a critical job does not have a real impact, as it does not compromise any delivery promise.

In the proposed concurrent ETO operation environment, jobs may be assigned to an organisational unit without specifying a particular resource (instance). In that case, it could be up to the unit leader to decide which jobs to work on and by whom, when a feasible resource becomes available. Alternatively, all operations may be left open to all qualified resources in the unit to promote participative management, maximise resource utilisation, and reduce the unit leader's control load. Typical shop floor control problems in a concurrent ETO operation environment are schedule deviations caused by unscheduled events of rework, resource breakdown, delay in material arrival, or delay in a scheduled start or completion time for a job. Deterministic computer simulation is an effective tool for evaluation of its impact and domino effects. Computer simulation also enables the user to evaluate what-if questions in order to appraise remedial alternatives. When resource availability becomes highly limited, deterministic computer simulation is an effective enumeration tool for work planning and scheduling.

5 Conclusion

This paper presented the concept of concurrent Engineer-To-Order (ETO) operation. It detailed the concurrent ETO concept and discussed its relevance to other contemporary manufacturing operation concepts. A concurrent ETO operation framework was proposed to explain interactions among the sales, engineering, material acquisition, and manufacturing processes with a focus on concurrent operation planning, scheduling and control. This paper is intended for laying a foundation for design and development of an effective concurrent ETO operation system.

Concurrent ETO is a make-to-order operation that starts with a product specification and finishes with delivery of a customised product. It focuses on an integrative operation of the sales, engineering, manufacturing and test activities in order to economically minimise product development lead time and assure delivery commitment, by applying the concepts of concurrent engineering, mass customisation and lean manufacturing. It is different from a conventional ETO operation in its concurrence in carrying out engineering and manufacturing processes and treating them both as a production activity. It differs from an MTS operation in that it does not have an existing BOM and process plans to drive material and capacity requirement planning. The function of material requirement planning in concurrent ETO operations reduces to a series of materials requests and acquisitions for each production order. Master production scheduling is closely related to the sales operation in the proposed framework, because ETO is a make-to-order only operation and in principal, it commits resources for each active bid item in the bidding process, in light of its acceptance.

It is of interest to concurrent ETO operations to consider an effective means for scheduling both machine and labour resources for an operation, especially when resources utilisation is high. It is also of interest to look into dynamically grouping workers for assembly operations of which each require a certain number of concurrent workers to collaborate. Dynamically bundling operations of the same type into batches under due date constraint is a relevant research issue for a concurrent ETO operation to minimise resources consumption. Similarly, each release of an incremental BOM is a request for material and thus triggers an acquisition (purchase) process in a concurrent ETO operation. How to strike a balance between the total acquisition cost and the development lead time is an interesting research issue as well.

ETO products are mostly one of a kind. Product repair and maintenance are usually unique and often performed by the original service contractor. Product data management therefore, is an important ETO function that maintains product life cycle data and supports for all lifecycle activities from bidding to engineering analysis, specification, contracting, design, manufacturing, operation, service/modification and disposal. The operational efficiency of managing life cycle data and workflows is critical to every concurrent ETO operation, considering the need for frequent design/process changes, hierarchical planning, incremental scheduling, and above all, numerous resources allocation and reallocation during execution. As supply chain and collaborative development concepts turn into an operation reality, the study of ontology becomes imperative for the engineering manufacturing contracting industries, beginning from the definition of products, components, processes, work elements, operations, object states, control events and material types. Quality assurance is an emerging interest for the MEC industries. It requires not only a quick manufacturability evaluation but also an analytical evaluation, in detail, of the processing technology proposed for the technical solution to each bid item, and to ensure reliability of the product quality at the bidding process.

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