A Roadmap to Concurrent Engineering 2.0

Transitioning from Part-Centric to Process-Centric Change Management in Complex Discrete Manufacturing

Scope

This paper contains a roadmap to Concurrent Engineering 2.0 which is best described as a system of practices that enable an advanced level of concurrency between Engineering and Production. The best practices are organized into a systematic methodology that integrates and streamlines business processes, information flow, and change management between Engineering and Production departments. The software solutions that carry out these methodologies include Product Lifecycle Management (PLM), Operations Process Management (OPM), Manufacturing Execution Systems (MES), and Quality Assurance (QA).

The successful first wave of Concurrent Engineering efforts from the early 1990s has been classified as Concurrent Engineering 1.0 and is contrasted with the current wave of improvements in concurrency enabled by the latest breed of technology and software tools.

This paper is presented as a how-to guide and is targeted for Product Design Engineers, Manufacturing Engineers, Industrial Engineers, Quality Engineers, and Operations Managers who are interested in streamlining complex engineering change practices in industries such as aerospace, defense, shipbuilding, nuclear energy, industrial electronics, and complex medical devices.

Key Points

- The most significant improvements in Concurrent Engineering 2.0 methodologies stem from elevating the importance of manufacturing process design to the level of product design.
- Digital process validation and optimization techniques, including simulation and line balancing analysis, should be incorporated into the regular approval process and used throughout the program lifecycle.
- Technologies like Services Oriented Architecture (SOA) and Access Rights Management have emerged to facilitate the integration of Engineering and Manufacturing software.
- Companies with a global supply chain will benefit by applying Concurrent Engineering methodologies to assemblies and complex components in the second and third tiers of partners and suppliers. A competitive advantage can be achieved by better understanding how product design changes impact manufacturing for multiple downstream suppliers, which eventually impact final product cost and schedules.
Introduction

For many years, a wall existed between product Engineering and Manufacturing Engineering practices. Product Engineers would complete an initial design in a relatively short time and throw it over the wall to Manufacturing Engineers who had to figure out how to build something close to what the Product Engineers specified. Product design would be adjusted many times before the first stable processes and prototype units were approved.

In the 1990s, market pressures pushed companies to go straight into full production, skipping the prototyping phase in order to get products to market faster. Companies implemented concurrent engineering concepts that promoted the integration and concurrent development of design and production activities. This initial integration, Concurrent Engineering 1.0, reduced cycle time between traditional design and production phases and reduced the number of engineering changes on new programs. Tools like 3D product and process modeling emerged to allow manufacturers to test and validate product and process designs in a virtual environment before committing to actual production.

Figure 1. Concurrent Engineering 1.0 moved Manufacturing Engineering in parallel with Product Engineering. Concurrent Engineering 2.0 also moves Quality Planning and Production Planning in parallel. This shortens time to production and response time to issues requiring engineering changes.
Great results have been achieved thanks to Concurrent Engineering 1.0, but there is still much work to do and much opportunity to increase productivity by further integrating tools, processes, and workflows. A roadmap and an overview of the techniques that will enable the next wave of Concurrent Engineering 2.0 initiatives follows.

Concurrent Engineering 2.0 is expected to yield the following improvements:

- Leveraging of investment in 3D models throughout the product lifecycle
- Improved visibility to engineers to work in-process and shop floor operations
- Shortened cycle time for getting new or improved product to market
- Improved change implementation across the supply chain
- Quicker turnaround time for quality issues that require product or process engineering design changes
- Reduced number of product and process changes
- Reduction of the training learning curve for new employees and production of new or improved products
- Systematic reconciliation of as-designed, as-planned, and as-built product configuration

“Linking product and process design activities ensures that any changes are visible to both the design and manufacturing communities. In an ideal world, these two arenas have shared visibility and are synchronized. As Maruti Suzuki would testify, there are large benefits to be reaped for new product introduction (NPI) and ramp-to-volume processes, as well as for continuous process and product design improvement.”

AMR Research, “Linking MES Into PLM Is the Final Frontier”
Current Engineering Change Management Best Practices

The Aberdeen Group published a survey in September 2007 titled “Engineering Change Management 2.0,” which contrasted engineering change practices among manufacturing companies and highlighted significantly higher performance for companies with best-in-class practices. Survey results show that the average company has much to gain by improving engineering change practices.

The report included the following current best practices as recommendations for Engineering Change Management:

- Improve coordination of change between engineering and manufacturing groups.
- Improve coordination of change across the supply chain.
- Perform formal change impact analyses.
- Use a formal change implementation plan and audit procedure.
- Use root-cause analysis as part of the Corrective Action process.
- Centralize access to change status, approval routing, and change history.
- Implement engineering and manufacturing systems that improve workflow, 3D visualization, configuration control, and change management.

This report recommended the following best practices:

- Make Engineering and Manufacturing Bills of Material development concurrent.
- Make facility, line, and workcell design concurrent.
- Make work instructions and 3D design concurrent.
- Make robotic design part of the concurrent process.
- Integrate Engineering and Production systems to automate engineering configuration change management

**Concurrent Engineering 2.0**

Concurrent Engineering 2.0 expands on the achievements of best practices as recommended by the Aberdeen Group. It places Process Engineering at center stage, and puts additional emphasis on change management for the manufacturing process itself. Concurrent Engineering 2.0 recognizes that competitive innovation is not just about having the best product design, but also about codesigning a manufacturing process that will bring a quality product to market quickly at a reasonable cost. Process-centric change management becomes as important as product-centric change management. Under Concurrent Engineering 2.0, all work orders specify a revision level for the process as well as one for the product.

Industry leaders have been integrating product and process change practices thanks to the enhanced integration capabilities of software tools that fall under the Computer-Aided Design (CAD) and Product Lifecycle Management (PLM) umbrella. Companies with a design-for-manufacturing philosophy have achieved great results for their latest programs. In parallel, market leaders in complex manufacturing have also achieved great benefits from the integration of Process Planning, Quality Management, and Process Execution thanks to the integrated solutions offered by Operations Process Management (OPM) and Manufacturing Execution Systems (MES).

The next wave of process improvements will be achieved by integrating engineering and shop floor systems into a streamlined collaboration that includes Product Design, Manufacturing Engineering, Industrial Engineering, Process Planning, Quality Engineering and Supplier Management. The business improvements are enabled by the latest generation of software tools and technologies like Service Oriented Architecture (SOA) and Business Process Management (BPM) that facilitate data exchange and workflows across Engineering and Manufacturing disciplines and across the global supply chain.

The essential ingredients for Concurrent Engineering 2.0 are these:

1. Integrated concurrent Engineering tools
2. Integrated Product and Process Change Management
3. Collaborative Concurrent Culture

The following sections describe each ingredient in more detail.
Integrated Concurrent Engineering Tools

Until recently, the tools for process Engineering and Process Planning had not been integrated. Manufacturing Engineering purchased 3D simulation and Computer Aided Process Planning (CAPP) tools; Industrial Engineering purchased process optimization and balancing tools; Quality Assurance purchased tools to track defects and Corrective Action efforts; and Supplier Management purchased tools to track and manage suppliers. In many instances, engineers had to rely on home-grown sophisticated spreadsheets and load balancing exercises using project management tools or a whiteboard to analyze options for production. Desktop applications are still widely used for many of these activities and are not considered part of the mainstream change management process.

All these activities might be happening concurrently with different tools, systems, semantics, and repositories. To date, there has not been a holistic systematic change process that encompasses all disciplines/departments and reduces the amount of reconciliation needed to ensure that engineering changes have been incorporated and properly validated throughout the change process. A critical missing link for most companies is the vital cross-reference between the process model revision and the product revision level.

As we delve deeper we find that in typical current practices, product design revisions trigger many informal procedures in different departments. Changes to routing, bills of material, illustrations, and work instructions are tracked to the product change level and only rarely tracked to the process change level. Simulations and line balancing analysis are often not revisited for major product design revisions.
On the shop floor, it is necessary to validate and manually verify that all referenced documentation reflects the same engineering revision level and correct configuration effectivity. It is not trivial to provide assurance that all pieces reflect the correct change level because many revisions are done in parallel by multiple departments.

The development of the Manufacturing Bill of Material (MBOM) based on the Engineering Bill of Material (EBOM) is intimately related to the development of the manufacturing process plan, but often the MBOM and process plan are developed in different systems by different groups. This creates coordination inefficiencies and opportunities for error.

Product Data Management (PDM) systems are often integrated directly with Enterprise Resource Planning (ERP) systems, and in parallel with Manufacturing Execution Systems (MES). These practices reflect the ideology that it is necessary to manage only product design, and to synchronize the rest of the enterprise system to product revisions. In contrast, Concurrent Engineering 2.0 puts the management of process plans at center stage. All other enterprise systems for manufacturing are then synchronized to process plan revisions. The MBOM and Process Routing become byproducts of developing process plans. This paradigm reduces the number of systems that must be reconciled because it is necessary only to reconcile the product design revisions to the process plan revisions.

Some of the hurdles that prevented earlier progress in this area included mixture of immature commercial software tools, assortment of configuration management practices, manual change traceability procedures, differences in software and department semantics, and a lack of integration standards.

The assortment of complex configuration management practices lead to lack of standardization across software programs. It was difficult to find software products with similar semantics, and compatible configuration and change management capabilities. The demands for more collaborative engineering tools have created much more consistency across the software spectrum. Language like “process models”, “operations”, “work plans”, and “engineering requirements” is becoming more consistent across different software programs. Technologies like SOA and Access Rights Management have emerged to further facilitate the integration of engineering and manufacturing software.

The maturity and consolidation of software tools in the PLM and OPM arenas has brought about centralized databases and integrated work flows that enable departments to work in a collaborative environment with shared communications and change control mechanisms.
Enhanced Engineering, Planning and Execution Collaboration

Software elements that require integration with the centralized process models and process change control include the following:

- 3D visualization and producibility analysis for assembly, human factors, robotics, and machine tools
- Work process optimization including line balancing, and simulation
- Resource utilization planning
- Work order change management
- Work instructions
- Inspection plans for internally and externally built parts
- Discrepancies and corrective action

Figure 5. Integrated and streamlined software tools for Process Engineering and Planning.
Several traditional steps have been eliminated in the streamlined procedures for Concurrent Engineering 2.0. For example, there is no need to maintain a separate MBOM. The MBOM can be derived from the process Work Plans and the process sequence diagram. Before Concurrent Engineering 2.0, it was necessary to reconcile the MBOM to the EBOM and to reconcile the consumption of component parts into process operations. The new procedure creates the high-level process flow and MBOM in a single step. Since the MBOM is derived from the process sequence, the reconciliation of MBOM and EBOM is also proof that the Work Plans must have mapped all EBOM part and effectivities correctly.

**Figure 6.** The MBOM can be automatically generated from work plans, assigned parts and precedence.

Why do we need an MBOM? It is common for the EBOM to require some transformation to better represent how the product will be manufactured. One reason is that downstream systems require part number centric demand and lead times to trigger purchasing of parts. This forces the use of synthetic part numbers to represent sub-assemblies in the manufacturing view of the product structure, the MBOM.

A second eliminated step is the independent development of a separate process routing. As 3D Work Plans are developed, process routings are also developed and will be passed to other enterprise systems for capacity planning and scheduling.

A third eliminated step is the development of a separate Inspection Plan. Engineering Requirements and Product Characteristics flow from the 3D model into a Product Characteristics database and can be mapped to an Inspection Plan developed directly from the Execution Work Plan. Inspection data maintains a link to the original source, which can be leveraged in automated change incorporation procedures.
Integrated Product and Process Change Management

The traditional slow turnaround of Engineering changes has lead to shop floor practices that work around Engineering, implementing revisions in anticipation of the formal change process. Changes have often been implemented in production first and only later pushed through the formal process. These risky practices cause difficulties in reconciling as-designed and as-built records and frequently cause rework.

Concurrent Engineering 2.0 procedures leverage the ability to quickly incorporate product design changes into manufacturing process plans. Manufacturing Engineers should be able assess the impact of a product or process change using 3D animation and simulation. Integrated product and process procedures allow Manufacturing Engineers to change the formal process on the shop floor with live online collaboration among Engineers in other disciplines.

At center stage in Concurrent Engineering 2.0 procedures is a change of focus from product revision to process revision. In the process-centric business flow, all downstream systems are aware of the process Work Plan revision, not just the product design revision.

Following is a list of steps between Engineering and Production in the business process flow. Many steps must be completed before the next step, but steps should be worked concurrently whenever possible.

1. **Author Product 3D Models.**
   Product Design Engineers author the product structure parts tree, which is called the EBOM. 3D model geometry is authored for each part and associated hierarchically with the complete product structure.

2. **Author Work Plans, Operations; Assign Parts, Tools.**
   Manufacturing Engineers receive notice of change actions from Product Engineers. All changes made on process models are under change authority and are internally cross-referenced to the product model object. Resources definition includes subassemblies and tooling. From this point on, the process revision becomes the change control agent for downstream changes, but is also referenced upstream to product design revisions.

3. **Author Work Plan Sequence and Precedence.**
   The process Work Plan precedence is used to generate the MBOM and to autogenerate any phantom part numbers required to accommodate scheduling and management for intermediate assembly states across locations or suppliers. Manufacturing Planners are still autonomously creating and managing manufacturing subassemblies through the Work Plans. The Work Plan precedence diagram is also used in manufacturing optimization and simulation analysis.

4. **Analyze and Validate Process in 3D.**
   It is very easy to overlook the effects of product design changes on process and tooling. The manufacturing process and tooling can be validated in a virtual 3D environment and many oversights can be caught without ever impacting actual production.
5. **Optimize and Balance Process Flow through the Plant.**
Optimization exercises are usually done at the beginning of new programs; however, it is just as important to revisit simulation models after significant changes are made to the manufacturing process or facility. Change impact analysis should be done for any significant changes.

6. **Author 3D Visualization for Work Instructions.**
If a picture is worth a thousand words, a 3D process animation is worth ten thousand. 3D process models leverage the investment in 3D product models, and 3D visualizations for work instructions leverage the investment in 3D process models. 3D visualizations are internally cross-referenced to objects in the product model, and also associated with process operations that are passed to the execution system. 3D animations reduce the training learning curve for new employees and new products.

7. **Reconcile derived MBOM and Work Plans to EBOM.**
When the MBOM is derived from the Work Plan Precedence Diagram, the reconciliation of the derived MBOM to EBOM also guarantees that the EBOM was correctly mapped to Work Plan operations.

8. **Author Detail Instructions and Inspection Plan.**
The Process Planner completes the development of the information display for the mechanic on the shop floor. The Process Planner can package all the information including bookmarked passages from standard procedures and can further add pictures and video to work instructions.

Engineering requirements flow from 3D product models into the product characteristics database. Product characteristics and their specification limits become part of the Inspection Plans that add process-centric control limits, sampling rules, and flags for First Article Inspection requirements. Sampling plans may also include additional process data collection and material tracking requirements.

9. **Execute Production with online Visuals, Data Collection and Status.**
Work Orders executed with online work instructions ensure that the mechanic is always accessing specifications for the correct configuration and engineering change level. The use of model- and multimedia-based work instructions greatly reduces the learning curve and the need to translate a lot of instruction text for global operations.

The paperless online execution system provides real-time visibility of shop floor data to engineers and integration with the Enterprise Resource Planning (ERP) system ensures that scheduling, inventory, and financial process are synchronized to the shop floor.

For parts produced by suppliers, the system creates Inspection Orders instead of Work Orders. A supplier portal can provide direct access to authorized suppliers. Inspection Orders contain inspection requirements for each Purchase Order line item based on the engineering requirements and inspection plans.
10. **Document Production Discrepancies and Corrective Action.**
   When inspectors or mechanics discover a discrepancy, they document it and route it to Engineering for disposition. The engineer needs visibility and capability to place work on hold on the shop floor and supersede work instructions with corrected specifications or rework instructions. Historical data is accessed online for root-cause analysis. Integrated disposition and online routing for approvals allows quick resolution turnaround.

11. **Manage In-Process Production Changes.**
    Work Order instruction changes are required to handle in-process engineering changes, repairs or workarounds for part shortages on specific production units. Tightly integrated change control procedures and configuration management eliminate the need for extensive reconciliation procedures at the end of the manufacturing process.

    The integration of engineering and shop floor processes is especially important during the production of the first batch of a new product, when unforeseen problems are most likely to arise.

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**Concurrent and Collaborative Culture**

Are Product Engineers spending time on the shop floor? Are they working in collaboration with Production and Manufacturing Engineers?

A collaborative culture is critical to the success of concurrent engineering. New software tools are an invaluable resource, but the company culture must also change to achieve the desired results. The importance of the manufacturing process needs to be elevated, and thus the importance of Manufacturing Engineering, Industrial Engineering, and Quality Engineering departments in the organization. Product Engineers must be encouraged to spend more time on the shop floor evaluating the efficacy of their designs.

Good metrics also contribute to a good culture. It is important to measure actual results in order to ensure ongoing support from management. Success of concurrent engineering initiatives can be measured by charting the number of engineering changes for each new product launch and the cycle time for implementing engineering changes from ECOs to Work Orders. It is important to emphasize reduction of the number of changes versus pumping out more changes more quickly. Everyone in the value stream should be accountable to these goals.

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"Today, the number of companies that are basing their design/build/operate processes on PLM solution sets has grown significantly. Closing the loop between the as-built records and the as-designed product to validate production processes is becoming an important aspect in optimizing manufacturing operations."

Summary

Industry analysts from groups including AMR Research, ARC Advisory Group, and the Aberdeen Group agree that streamlining business processes between Engineering, the global supply chain, and the shop floor is one of the biggest opportunities for improvement in manufacturing operations.

Concurrent Engineering 2.0 can achieve this streamlining through the described practices with the following benefits:

- Leveraging of investment in 3D models throughout the product lifecycle
- Improved visibility to engineers to work in-process and shop floor operations
- Shortened cycle time for getting new or improved product to market
- Quicker turnaround time for quality issues that require product or process engineering design changes
- Reduced number of product and process changes
- Reduction of the training learning curve for new employees and production of new or improved products
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References


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