

Flexible Manufacturing System for Mass Customization Manufacturing

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Abstract: Mass customization manufacturing (MCM) has been gaining recognition as an industrial revolution in the 21st century. This paper presents innovative approaches in realizing and exercising MCM in theoretical and practical applications. Strategies of generalized production line platform and modularization are explored to support dynamic reconfigurations of MCM. NIST's XML-based Shop Data information integration specification is utilized to derive a data driven reconfigurable MCM modeling methodology. A simulation model of a Boeing aircraft major component assembly line is created and driven by a batch control file, which is generated from the XML-based Shop Data specification.

1 Introduction

Competition in the manufacturing industry over the next decade will be focused on the ability to flexibly and rapidly respond to changing market conditions. With significantly shortened product life cycles, manufacturers have found that they can no longer capture market share and gain higher profits by producing large volumes of a standard product for a mass market. Success in manufacturing requires the adoption of methods in customer-acquisition and order-fulfillment processes that can manage anticipated change with precision while providing a fast and flexible response to unanticipated changes (Fulkerson, 1997). Many companies are confronted with the challenge of changing their strategic orientations to meet demands of the current market place. Mass customization manufacturing (MCM) is a solution to this challenge.

The concept of mass customization was first expounded formally in the book "Future Perfect" by Stanley M. Davis in 1987. In 1993, Joseph Pine (Pine, 1993) gave MCM a clear definition as a strategy that sought to exploit the need to support greater product variety and individualization. Further, the goal of MCM was to produce and deliver customized products rapidly while keeping costs at the mass-production level. Since 1993, advancements to this innovative trend of manufacturing strategy have been drawn from many related knowledge and technology domains (Piller/Stotko, 2002; Kotha, 1996; Tu/Vonderembse/Nathan, 2001; Tait, 2001).

In recent years, advances in computer aided design (CAD), product data management (PDM), and networking technologies have made mass customization no longer a legend, but closer than ever (Ruddy, 2002; Heikkila, 2002). Richard Morley, inventor of the programmable logic controller and co-author of *The Technology Machine: How Manufacturing Will Work in the Year 2020*, forecasted that, "the word 'personal' will take on more applications: personal families, personal food designed to maximize custom diet needs, personal clothing [clothing sized to individual bodies and fabricated to personal climate and skin needs], and personal [customer-designed] cars" (Felton, 2001). Mass customization is about to take center stage. MCM competent manufacturers will enjoy superior market share and greater profit margins, and it is the promise of these economic incentives that will compel other manufacturers to move to MCM sooner than later.

This strategy brings radical changes to methods used to operate traditional manufacturing enterprises. It is changing the way customers make purchases and has a strong impact on how products are made (Smirnov, 1999).

Much of the emerging literature has focused on highlighting the differences between mass-production and mass-customization (Silveira/Borenstein/Fogliatto, 2001). This paper proposes enabling technologies for mass-customization manufacturing systems, and an eXtensible Markup Language (XML) based information integration platform to support MCM.

2 Realizing mass customization manufacturing

Steps taken to realize mass customization can be said to lie in two areas: Product Design For Mass Customization (DFMC) and Mass Customization Manufacturing (MCM) system.

For complex products like aircraft and automobiles, the MCM system faces a challenging role in achieving the critical goals of reduced lead-time and production cost. Since MCM is

characterized by random and unpredictable manufacturing requirements such as customer order arrivals, it is difficult to adapt to the frequent change of manufacturing batch quantities and aggressive delivery times even in efficient Lean Production (LP) systems. As Joseph Pine pointed out, MCM is not an improved extension of LP, continuous improvement, nor the make-to-order factory (Pine/Victor/Boynton, 1993). There remain many problems to be solved and key technologies to be developed for MCM (Svensson/Barfod, 2002).

2.1 Mass customized products and implementation Strategy

Different from the current standardized products or configured products, mass customization manufacturing is developing a different product type, known as Parameterized products. Compare the following concepts:

- **Standardized products:** Standardized products refer to products that have standardized functions, features, geometries, and installation procedures, such as bolts, electrical outlets, videotapes etc. Intense competition occurs at the introduction of the product, when their standards are established. The aim is to minimize product variety, hoping everyone uses the same product.
- **Configured products:** Configured products let customers pick and choose only from among predefined options. For example, manufacturers can ask: “from our 54 options, which one do you like?” The challenge for engineers is to design a framework-and-module mode, instead of one product design. In the game of configured products, manufacturers have to produce and stock different options to guarantee rapid product delivery and maintenance.
- **Parameterized products:** Parameterized products possess a series of attributes called parameters. These parameters allow customers to change the actual design of the product, for example, by creating new sizes, or modifying performance characteristics. Each parameter can be chosen by customers within a certain scope, and the scope itself can also be defined as one of the parameters.

MCM implementation strategies can be divided into three different categories according to the different stages when customization is introduced in the value-chain: (1) form MCM, (2) optional MCM, and (3) core MCM (Alford/Sackett/Nelder, 2000).

Form customization is the simplest MCM implementation strategy, where customization is introduced at the delivery stage. Optional customization allows customization to take place at the manufacturing stage. The essential point of this implementation strategy is to provide a large number of pre-designed, standard options to customers. It produces the configured products. Customers can only select options from a predetermined list and request them to be assembled. Core customization integrates customers with the design process. Accordingly, manufacturing processes and delivery services must be customized too. A typical industry using this strategy is the apparel industry. Fixed design, designed with options, co-designed, or fully customized products can be produced (Lee/Kunz/Fiore/Campbell, 2002). This strategy supports two important ideas that: (1) we cannot accurately predict who our customers will be, and (2) we have the ability to provide the services that these customers demand. Core customization is the final goal and the perfect condition of mass customization manufacturing.

The implementation strategy of MCM may vary for different enterprises, depending on factors such as the type of market, product complexity, and the level of customization that can be offered.

2.2 Product design for mass customization

For MCM product design, the kernel technology is Design For Mass Customization (DFMC). It is based on the concept of Product Family Architecture (PFA) and postponement of product variety.

Product Family Architecture is a coherent product framework to be reused and extended by modifying existing product models. Within the product range or family, product similarity exists in order to achieve efficiency in mass production (Tseng, 1997). Postponement of product variety involves delaying activities throughout the supply chain until customer orders are received with the intention of customizing products, as opposed to performing those activities in anticipation of future orders (Van Hoek, 2001).

Basically, DFMC emphasizes a decoupling of the design and manufacturing process to reduce costs. In developing MCM, it is important to take DFMC into consideration in order to reduce the setup time and other volume-related costs drivers. Modification of product shape and size are limited to guarantee that fabrication can be performed on the same production line. Additional information regarding DFMC-related knowledge (Tseng/Lei/Su/Wei, 1997; Helander/Jiao, 2002) is beyond the scope of this paper.

2.3 Mass customization manufacturing system

The design of an MCM system is an extension of the customer-centered concept in fabrication. The design goal is to achieve a balance between product standardization and manufacturing flexibility. Success in mass customization manufacturing is achieved by swiftly reconfiguring operations, processes, and business relationships with respect to customers' individual needs and dynamic manufacturing requirements. It is thus critical to develop a manufacturing system that will achieve this goal.

A competitive manufacturing system is expected to be flexible enough to respond to small batches of customer demand (Bock/Rosenberg, 2000). Because the construction of any new production line is a large investment, current production lines must be able to be reconfigured to keep up with increased frequency of new product designs. In MCM, each unpredictable feature demanded by customers is considered an opportunity, whereas current system capabilities may not be able to support new customer requirements. The key to adjusting the manufacturing capability successfully is to reconfigure the system, developing and integrating new functions when necessary.

3 Breakthrough approach

3.1 Challenges

The revolutionary MCM system is characterized by four challenging characteristics: degrees of flexibility, production capability adjustments, modularization methods, and dynamic network-control system structure.

3.1.1 Degrees of flexibility

The traditional flexible manufacturing system (FMS) is based on numerically controlled machines in addition to other value-added, automatic, material handling facilities. A degree of flexibility within FMS serves to satisfy demands for a relatively diverse range of products with a small to medium batch size production. Compared with FMS, more part varieties are produced in a mass-customized production environment, and manufacturing requirements are often dynamically changed. In addition, customer orders come through more randomly with different delivery dates. Thus, an MCM system must possess sufficient flexibility and rapid response capability to deal with complex manufacturing situations.

Most flexible manufacturing systems today, including the popular Japanese lean production manufacturing system, have not reached the flexibility demanded by an MCM system. Lean production operates as a “pull” system, in which downstream processes call for parts via “Kanbans” (information communication cards) from their predecessor processes when needed (Lu/Gross, 2001). In an environment of high and stable demand level, this is a very efficient organizational method. However, in the event the product mix changes irregularly and drastically, or the product diversification increases, downstream processes require randomly customized parts on flexible schedules to be supplied to their matching predecessor processes on short notice. Hence, extra inventory, equipment, and labor are needed to compensate for product and order variations. In the process, the efficiency gains of the Lean production system are diminished.

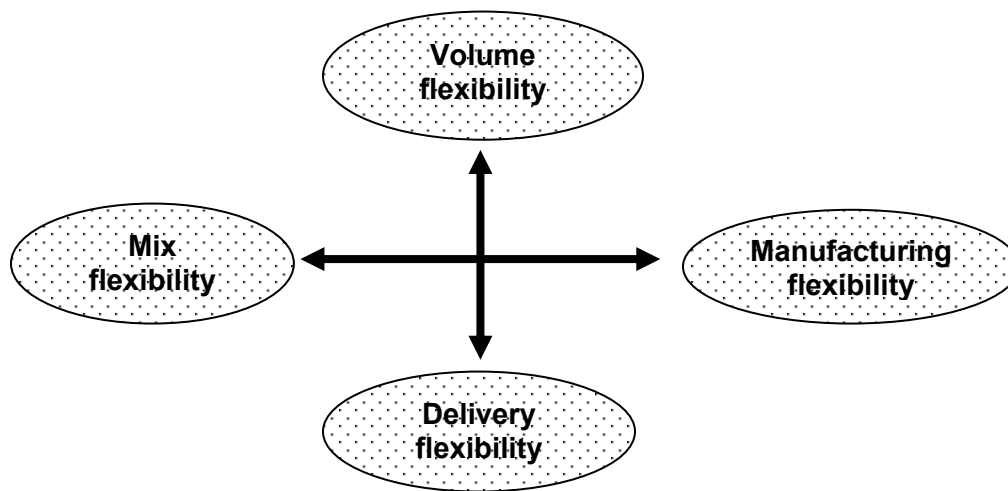


Figure 1: Flexibility in traditional FMS

The concept of flexibility in traditional FMS, which is illustrated in figure 1 above, has four major components: volume flexibility, manufacturing flexibility, mix ratio flexibility, and delivery flexibility (Koste/Malhotra, 1998). The MCM system demands a higher degree of flexibility than traditional FMS. It is highly desirable that each component demonstrates prompt response capability in managing demand changes in a FMS with parallel considerations in product costs, quality and reliability to form the flexibility in an agile MCM system, as shown below in figure 2.

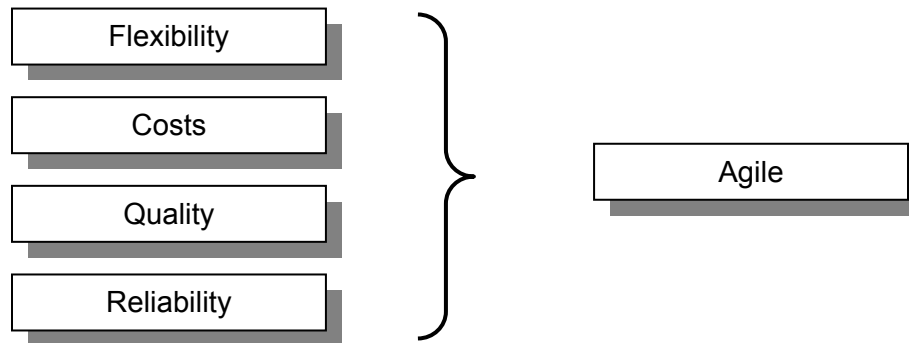


Figure 2: Flexibility for MCM – agile

3.1.2 Production capability adjustments

The expandability of production capability for traditional FMS is limited by the scope of product families during design stages. It is usually a difficult task to renovate a FMS to accommodate new features demanded by market changes.

MCM requires rapid adjustment of production capability based on customer demands. To accommodate ever-changing manufacturing requirements, an MCM system needs to be equipped with rapid, production-plan-configuration and resource-allocation capabilities. Since one of the MCM philosophies is to face a certain level of unknown customized demands, a key objective for the development of an MCM system is continuous satisfaction of customer demand.

3.1.3 Modularization methods

Modularization methods in traditional manufacturing systems are often product-oriented, where modules are grouped in teams with intercross functions. It is difficult for such a system to change structures when products need to be changed and production capability needs to be adjusted. In addition, the old modularization method is likely to cause inner frictions when adjustments are performed. In an MCM system, it is more desirable to categorize modules based on their functionalities: the greater the diversity of module classifications, the better the system's potential to satisfy different customized demands.

3.1.4 Dynamic-network-control system structure

Control system structures in FMS are often constructed in a hierarchical mode. Modules assigned at various closely interactive layers result in the limitation of the capability for system reconfiguration, reliability, and system expandability. Moreover, the complexity of this type of system structure will increase as the scope of the system increases. Stand-alone technologies may not be sufficient to satisfy the operation of a highly complex MCM system. Dynamic network control is needed to maximize the optimal potential benefit.

Because of the complexity in ever-changing manufacturing requirements and flexible process routing, fixed and centralized control is almost impossible in a MCM system. Dynamic and flexible network utilizations in MCM functional modules can maximize the strength of each empowered resource, and hence, the overall risk and costs are reduced. The dynamic network connections among functional modules are characterized as:

- Instantaneous: Accessing valid resources and reconfiguring functional modules should be instantaneous.
- Low cost: Besides the initial capital investment, it is better to reduce the recurring system costs.
- Seamless: A set of system mechanisms needs to be established to ensure seamless data exchange among customized orders, suppliers, services, and production controls.
- Frictionless: There should be no resource conflicts when a new network is created. Success in this feature promotes better cost controls and dynamic network operations.

3.2 Breakthrough approach

New mechanisms are demanded to solve the above-mentioned challenges in manufacturing systems (Qiao/Lu/Riddick, 2003; Qiao/McLean/Riddick, 2002; Xiao/Qiao/Dong, 2001). Working with an aircraft case study, three breakthrough approaches for the mass customization manufacturing system have been developed and are described below.

3.2.1 Generalized production line platform to support reconfiguration

The first strategy is to develop a generalized production line platform to support reconfiguration for an MCM system. The generalized production line platform includes movable and re-configurable workbenches, as well as flexible transportation equipment.

Production lines are usually considered to be relatively rigid and unable to keep up with changes in product design, and this strategy is devoted to change this situation. A generalized production line platform is to make the reconfiguration possible from the physical standpoint. There are already some successful attempts by manufacturing enterprises to move in this direction. The production line of Motorola pagers has successfully developed this type of generalized platform. Basic workbenches on the production line are standardized, with different fixtures, manipulators, and their control codes. Hence, when Motorola needs to produce a new product, the original line can be taken apart and reconfigured to support a new production run easily and promptly. The line conversion requires only a small amount of positional modifications to the basic workbenches, which greatly saves time and costs in the new production line construction. In addition, General Motor's Michigan Electronic Vehicle assembly factory has been equipped with movable workbenches that can be adjusted efficiently according to manufacturing requirements. This factory can change swiftly to meet new demands; its expandable throughput ranges from 2000 to 100000 per year.

In the case study of the section 5 below of a Boeing Commercial Airplanes (BCA) factory, this MCM practice is planned conceptually for one of the wing assembly lines. Reconfigurable workbench modules with mobile capability serve as part of a manufacturing platform. This platform consists of multiple such modules in one or more assembly lines. Feeder lines provide customized or standard subcomponents to each work piece at their point of use while the work piece is on a workbench module that advances through the customizable assembly line according to the system takt time. (TAKT is a German word for pace. TAKT time is the rate at which your customer requires the product.

TAKT time defines the manufacturing line speed and the cycle times for all manufacturing operations).

A clearly defined division between fixed and customized elements on the common workbench has been somewhat of a challenge with regard to achieving a customized mass-production state. Most of the BCA wings share a sizable number of similarities. However, there are a number of unique parameters, such as various specific wing sizes, different engine mount configurations, individualized paint schemes, wingtips or winglets, that may lead to different configurations of the end product. Contributions from several commonly configured workbenches to the overall platform performance are evident when modulated workbenches are capable of handling the majority of similar jobs and all customized jobs are not creating any bottlenecks in the system.

3.2.2 Production line modularization

The second MCM strategy is to develop the production line modularization. The strategy of production line modularization is to group the production line into functional modules. Each functional module stands for a typical manufacturing capability. They can be combined or reconfigured to form a new manufacturing alignment according to customized demands.

A system overview of a type of modulated MCM modeling is demonstrated below in figure 3. From the hardware point of view on the factory floors, the seed module can be a reconfigurable workbench. Different scenarios yield different products and/or production rates that take place around the workbench. Multiple workbenches can exist in this system simultaneously for different part configurations throughout part manufacturing processes.

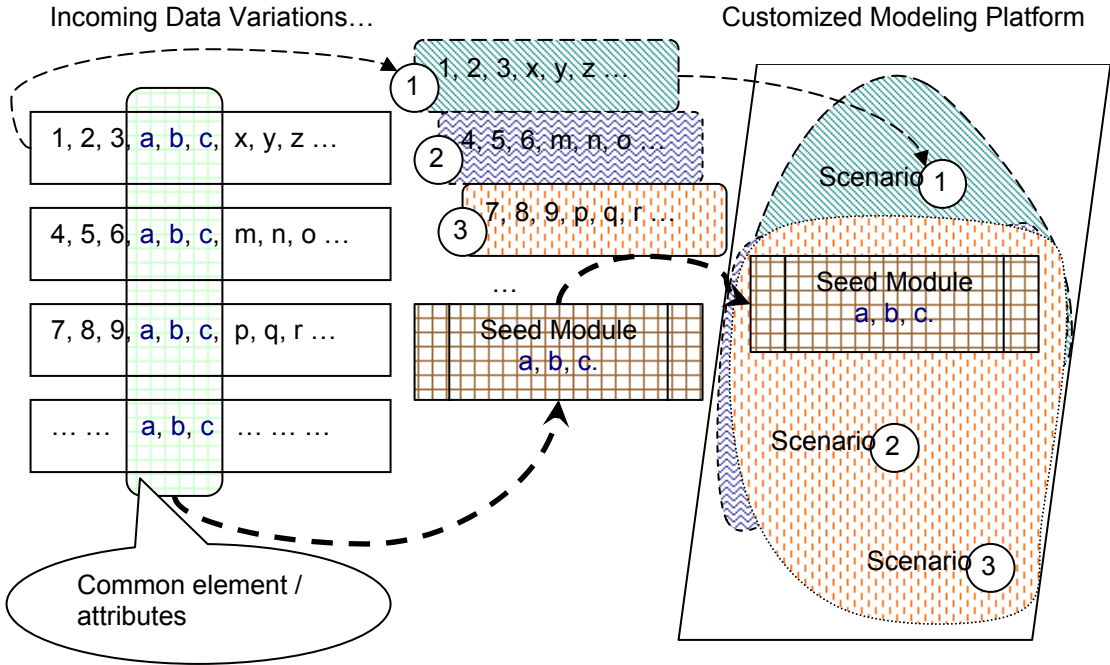


Figure 3: Modulated MCM modeling

Simulation modeling of the same modulated MCM shares similar concepts. The seed module can be a seed file that reflects the overall skeleton structure of the MCM

environment. Entities in each scenario may not be totally different from entities in the seed file. Nevertheless, entity attributes in each scenario most likely will be different. The ability to entertain entity attribute changes from different scenarios is necessary in all seed files. Coding of each seed file can be performed either by individually programmed batch control files, or generated from a set of common simulation specifications. In certain business environments, talented resources capable of generating the whole MCM simulation model could be scarce. The approach depicted in figure 3 requires only one of a few of the simulation modeling gurus to generate a seed file per project, given that the overall system structure already can produce scenario files. Other project team members may then exercise their individual scenario files in seeking different MCM options. Hence, not only those on the shop floor exercise the methods of MCM, but simulation modeling practitioners can operate under the same flexible principles as well.

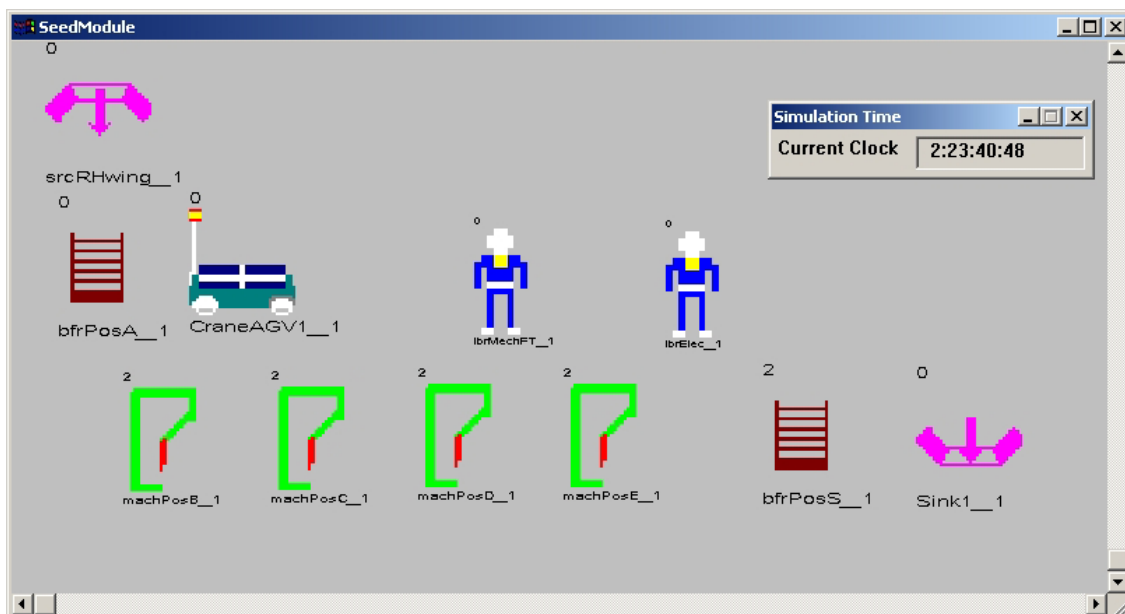


Figure 4: Modulated MCM simulation example

An example of a simulation seed file is shown above in figure 4. As the production rate changes, the number of machine and labor resources can vary based on, preferably, external scenario files. Criteria regarding what to customize, in external scenario files, and what to include in the seed model file in MCM modeling really depends on the nature of each particular project.

3.2.3 XML based information integration for MCM data driven and reconfiguration

An information-integrated methodology is critical in an MCM system. Until now, no integration methodology has offered all the flexibility required in such an environment. There are three reasons for the urgent necessity of an integrated information methodology.

- A mechanism is needed to provide the “effortless” integration between a set of ‘soft-wired’ business process modules, such as linking sales order processing with design engineering (for quickly reviewing customization requests and advising on

price) and with production (for determining lead time and releasing orders directly to manufacturing schedules) in "near real time" (Ross, 1997). The information needed is often scattered in various sources such as databases, PDM systems, hand-or computer-generated drawings, and flat files and spreadsheets. Commercial off-the-shelf (COTS) and homegrown applications may be used to create and maintain this information, leading to situations where the needed information may be incomplete, and different incompatible formats for similar information may have been used.

- Data-driven manufacturing system enabled with reconfiguration technology. One way to realize MCM is to construct the manufacturing system with functional modules. The establishment of a kind of dynamic network among these functional modules is important to reconfigure the system to adjust manufacturing capability. The reconfigured system elements could be immediately, inexpensively, seamlessly, and cohesively connected. The aim is to quickly identify changes and use the changed data to drive system reconfigurations, which is important for flexible manufacturing capability adjustment.
- Better methods need to be developed for efficiently reusing existing simulation model data (Nicholson, 1999). Developing simulation models is time-consuming work that often must be repeated to undertake different simulation studies. Simulation models contain several kinds of information including information about the manufacturing system layout, processing logic, routing logic, and stochastic information about the manufacturing processes. Finding an efficient way to use existing information to the utmost extent is urgently needed for manufacturing applications.

To address the information integration issues, NIST is developing an information model and an XML-based exchange file format that facilitates the exchange of manufacturing information between simulation applications, other manufacturing applications, and data sources (McLean/Jones/Lee/Riddick, 2002). XML was chosen as the encoding mechanism for the exchange file format, hereafter referred to as the Shop Data File (SDF).

A Shop Data Information Model describes the content of a Shop Data File. It contains descriptions of the important elements of manufacturing operations, the attributes of those elements, and the relationships among the elements. Two equivalent methods are being used to create the Shop Data Information Model. Both Unified Modeling Language (UML) static structure diagrams and XML schemas are being used. The static structure diagrams (Carlson, 2001) provide a graphical description of the model, while XML schemas provide a textual description of the model that facilitates the creation of the XML instance documents, i.e. the Shop Data Files. For validity checking, the XML schema for the Shop Data Information Model can be stored within and exchanged with a Shop Data File. It can also be stored on a web server for reference over the Internet.

XML documents possess some advantages (Standefer, 2001), which make them suitable for the information integration necessary for MCM data driven reconfiguration. In addition, other applications can be developed based on XML text file documents. Documents can also be exchanged easily between applications using basic communication mechanisms. XML allows for the definition of documents that are both human and machine interpretable.

In the case study at The Boeing Company, data describing potential manufacturing system layout and process designs were extracted from the existing applications and encoded in a

Shop Data File. Functional groups can be managed and written in XML description according to the Shop Data Information Model format. The Shop Data File was used to generate Batch Control Language (BCL) and Simulation Control Language (SCL) files. These BCL/SCL files can be executed directly by the DELMIA QUEST simulation software. By enabling data-driven simulation in this way, layout models for analysis with simulation can be built quickly, and functional groups can be combined or reconfigured by applications to form new manufacturing capabilities according to the requirements.

4 Integrated design and simulation system to enable MCM

Based on the methodology presented above, an integrated design and simulation system is developed to support an MCM system as depicted below in figure 5. This system consists of three subsystems including a system controller, a conceptual workshop and simulation, and a Shop Data Information Model. The intent of this system is to rapidly create and modify system designs based on changing manufacturing requirements. It also enables verification of those designs to meet new requirements through simulation.

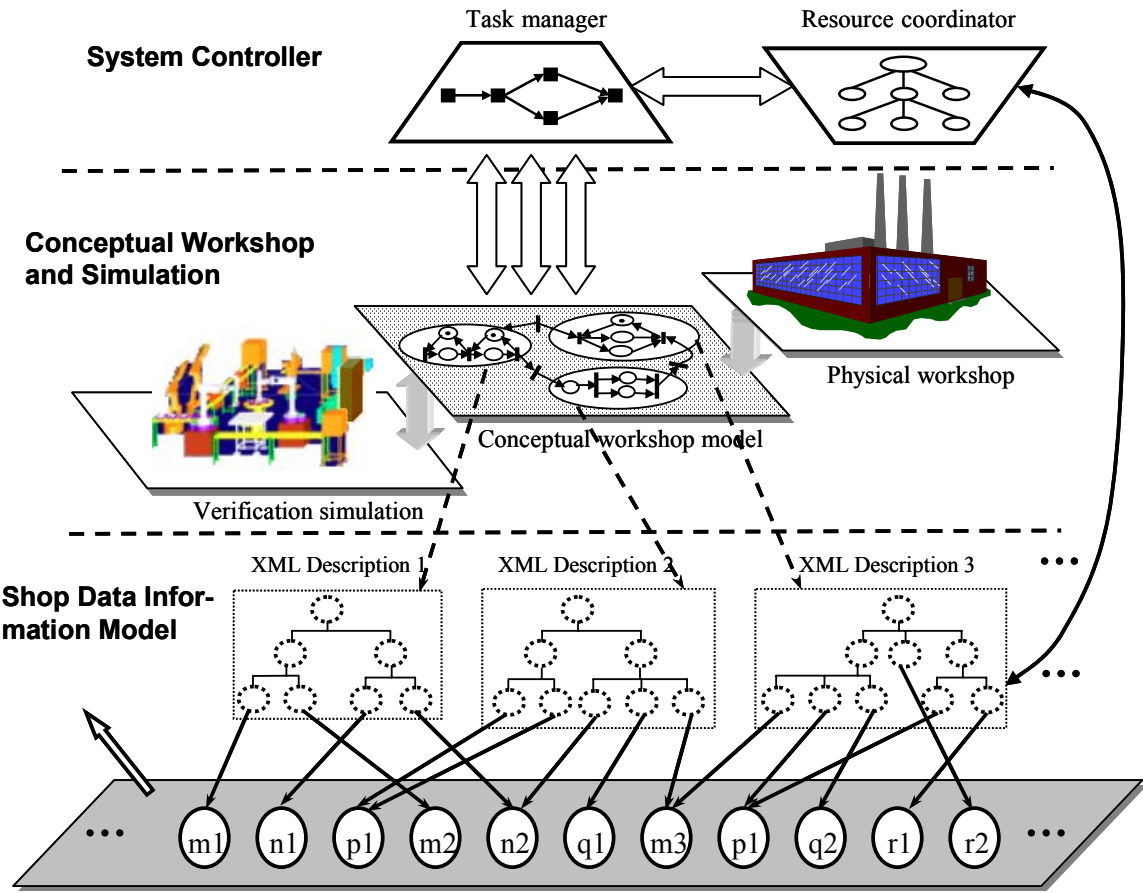


Figure 5: Integrated design and simulation system to enable MCM

The system controller subsystem consists of a task manager and a resource coordinator. The task manager decides mixed part selections, mixture ratios of parallel operation preparations, different part type workflows for events such as buffer input and output

sequencings, and the assignment of tasks and resources to machines and workstations. The task manager sends resource requirements to the resource coordinator. The resource coordinator decides the available resources. A resource scheme will then be released to the task manager.

The conceptual workshop and simulation subsystem is composed of three levels. The physical workshop is the collection and layout of physical resources located in the workshop. Resources in the workshop are grouped into functional modules. Each functional module in the physical workshop has an equivalent representation in the conceptual workshop model. Functional modules can be reconfigured and dynamically controlled by the task manager to create efficient logical grouping of processors in order to allow high levels of efficiency and flexibility to reach the level of agility required.

The Shop Data Information subsystem contains all of the resources of the manufacturing system and their related information. This subsystem can be managed via the resource coordinator. The Extensible Markup Language (XML) is applied here to define a Shop Data File, which is based on the Shop Data Information Model format developed at NIST.

4.1 Design of flexible layout and process plan to support MCM

To reach a high level of productivity and efficiency while designing a mass customizing manufacturing system, a key issue is the routing flexibility offered by the layout. Usually, relatively static layouts are designed based on a deterministic demand, thus cells or lines can be created and the relationships (flows) between these cells or lines can be determined at the design stage and used for layout optimization. In a mass customization environment, such relationships change regularly as needed (Olivier/Marcotte/Montreuil/Lefrancois, 1996). The layout design methodology will influence both the flexibility and dynamic adjustability of a manufacturing line, so it is important to create an adaptable layout.

In this paper, DELMIA QUEST is utilized as the discrete event simulation tool for assembly simulation. A data driven simulation approach based on XML Shop Data File is presented as described in figure 6 below. In such an illustrated system, a Shop Data File contains the

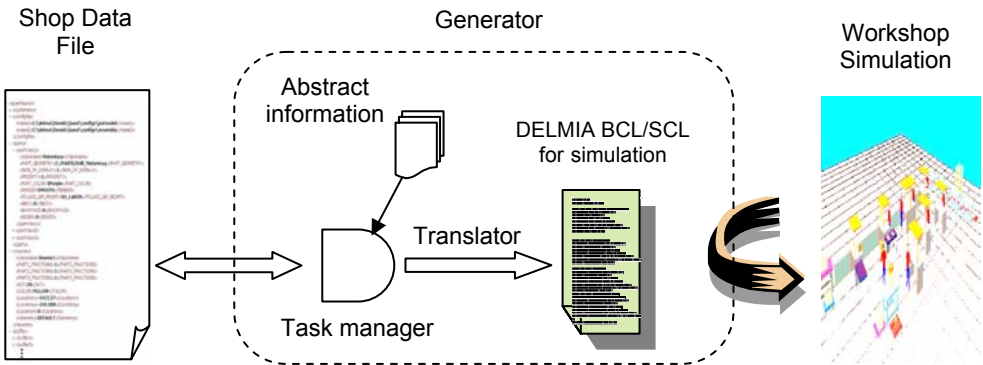


Figure 6: Data driven simulation approach based on XML SDF

resource, layout, and process information of an assembly line, which can be created from the available manufacturing data sources. This is the input of the Generator, which uses the information to generate BCL and SCL files, two languages associated with the QUEST

software of the DELMIA Corporation. A translator is embedded in the generator to translate the shop data information into a BCL/SCL file. Abstract information used specifically for simulation, such as part display parameters is added to the translator, which is a part of the generator. Utilizing this approach, simulation can be driven by an XML-based text file, and the manufacturing system modification and configuration can be performed by modifying this text file. For example, in the Boeing case study, layout and process information were drawn from the Shop Data File, and transformed into a BCL simulation executable file. Further details of the Boeing case study will be described below in section 5.

This data-driven manufacturing system design and simulation methodology is flexible and can reuse the existing data to rapidly build simulation models, which mean the great profit in industrial application. It is important to keep in mind that this is a generalized way of utilizing the Shop Data File, and the generator will vary between different simulation tools.

4.2 Data driven simulation and analysis of layout scenarios

Because a production layout can be automatically created in a QUEST model by means of translating layout information from the Shop Data File, more layout design scenarios can be examined rapidly than traditional ways. Moreover, modifying scenarios of the model file can be easily accomplished by changing element attributes of the source XML file according to the simulation and analysis results. Characteristics of layout scenarios, which can be analyzed by simulation, include:

- Physical layout
- Product mix
- Process routing for each product
- Required inputs and generated outputs at each process for each product
- Processing capabilities of each processor
- Availability and reliability of each processor
- Coordinator's preferences on the assignment of tasks to processors such as load uniformity or minimum level of utilization
- Daily product demand patterns.

5 An example of an aircraft major component assembly line

Every Boeing commercial airplane is customized for a specific customer. Manufacturing processes of some major components are desirable to follow the FMS concepts in a customized manufacturing environment. In the case study that follows, a wing assembly process is examined by means of discrete simulation modeling.

There are more than thirty complex processes applied to more than fifteen machine classes in this example. Most processes require a different number of labor entities from various labor classes. The overall pace of the whole system (i.e., the system takt time) is desired to be a variable that impacts the process time of all related processes, as well as the number of assigned laborers. As described in section 3 earlier, the modular approach to MCM system design not only benefits the overall performance of a flexible MCM system, but also enhances simulation-modeling exercises.

Discrete event simulation technology in this study employs the same platform concept as in modeling highly flexible and rapid reconfigurable production lines. Such modeling methods reflect manufacturing processes according to the ever-changing customized demands. Many fundamental manufacturing process parameters, such as layout reconfigurations, and resource re-allocations, can be derived ahead of time from the simulation models.

A high-level process flow of this simulation model is shown below in figure 7, where source 1 generates incoming parts according to the system takt time with optional statistical distributions. Buffer S receives incoming parts via the only crane resource in the system. The part will then be lifted by the crane to the machine B where multiple processes will be performed by multiple resources. The part then continues to move from the machine B to the machine P, the end of the process line. Multiple processes are assigned throughout this line on each machine. An additional process is needed in the middle of the line where the part will be transferred to the buffer A followed by a couple of external processes. Afterwards, buffer A receives the part and calls for the overhead crane to transfer the part back to buffer T where the part will continue through the rest of the process. At the end of the line, the part goes from the machine P to the buffer A then to the sink, which is the final destination of all parts in the simulation model.

Two different part-carrying platforms are involved in the system. The “high speed” dolly transfers parts to and from buffer A. The “low speed” dolly carries one part at a time from machine B all the way to machine P. Additional components are introduced to the system from source 2 and 3 at different stages of this process line.

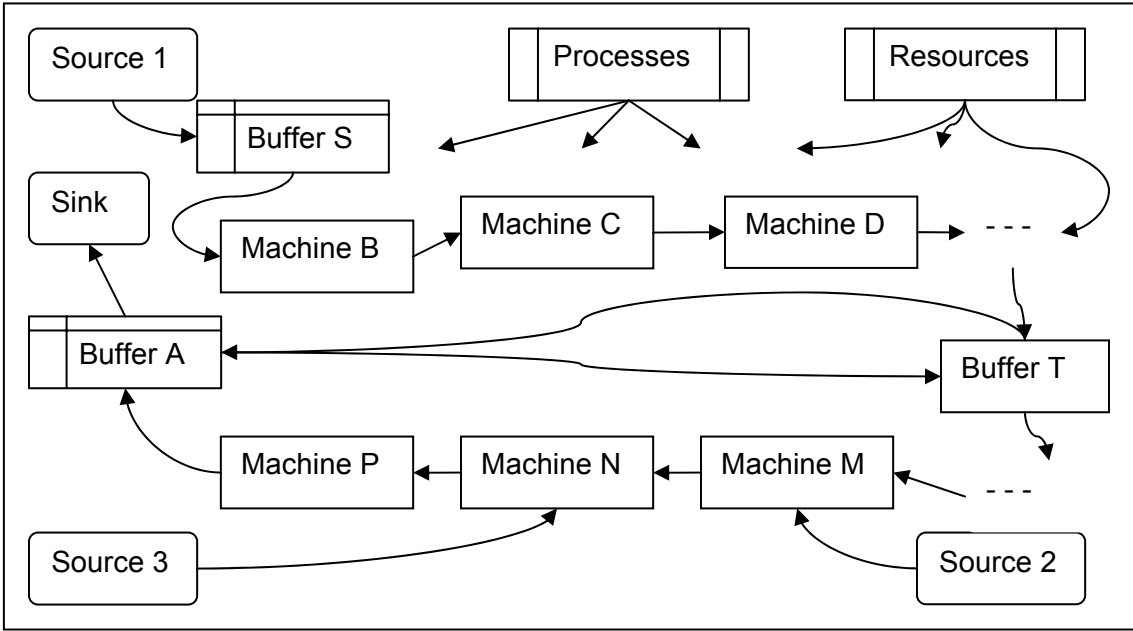


Figure 7: The simulation model process sequence

Resource class types in this model consist of labor, machine, and Automatic Guided Vehicle (AGV) elements. The machine class stands alone for each machine, while the labor and AGV classes are managed by their respective controllers. Those thirty plus processes that are stand-alone objects can be assigned to multiple machines. Thus, each

machine has from two to six assigned processes. Processes run at all times in an endless do-loop as part of the nature of this modeling environment. As soon as a condition is met for a process, it will execute its logic and its assigned time duration on the machine where it resides. After the last process sequence of the last machine class has been executed, the part is transferred to the sink class where it will be logically destroyed and removed from the modeling system.

A Shop Data File containing resource, layout, and process information of an assembly line is used to generate Batch Control Language (BCL) file, according to the process discussed in section 4. This BCL file can then be directly executed in QUEST. The aircraft major component assembly line simulation model is created and driven by this BCL file. A screen copy of this model is shown below in figure 8.

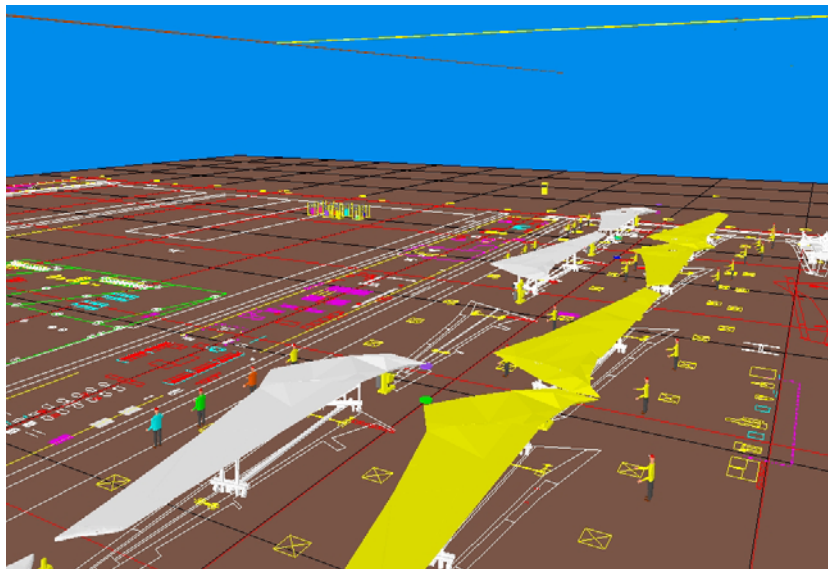


Figure 8: An aircraft major component assembly line simulation model

An example XML Shop Data File of this seed module modeling approach is partially listed below:

```
<?xml version="1.0" encoding="UTF-8"?>
<shop-data type="BCA" identifier="737800" number="wing" xmlns:xsi="http://www.w3.org/2001/XMLSchema-
instance" xsi:noNamespaceSchemaLocation="C:\NIST\XML\shop_data.xsd">
...
  <part type="wing" identifier="rh1" number="1">
    <name>Part737RHwing</name>
    <description>WingMajor/737-800wingRHatZero</description>
    <reference-keys/>
    <revisions/>
    ...
    <group-technology-code>
      ...
      <color-code>YELLOW</color-code>
      ...
    </group-technology-code>
    ...
  </part>
```

```

<part type="wing" identifier="lh1" number="1">
  <name>Part737LHwing</name>
  <description>WingMajor/737-800wingLHatZero</description>
  <reference-keys/>
  <revisions/>
  ...
  <group-technology-code>
    ...
    <color-code>YELLOW</color-code>
    ...
  </group-technology-code>
  ...
</part>
...
</shop-data>

```

Its matching stylesheet file is partially shown below:

```

<?xml version="1.0" encoding="UTF-8"?>
<xsl:stylesheet version="1.0" xmlns:xsl="http://www.w3.org/1999/XSL/Transform">
  <xsl:output method="html" version="1.0" encoding="UTF-8" indent="yes"/>

  <xsl:template match="shop-data/parts/part">
    <br>CREATE PART CLASS '<xsl:value-of select="name"/>'</br>
    <xsl:if test="description[. != '']">
      <br>DISPLAY 'C:/NIST/PARTS/<xsl:value-of select="description"/>'</br>
    </xsl:if>
    <br>SET PART_CLASS '<xsl:value-of select="name"/>' NUM OF DISPLAY TO <xsl:value-of
      select="@number"/></br>
    <br>SET PCLASS '<xsl:value-of select="name"/>' PRIORITY TO 1</br>
    <br>SET PART_CLASS '<xsl:value-of select="name"/>' color TO $<xsl:value-of select="group-
      technology-code/color-code"/></br>
    <br>SET PART_CLASS '<xsl:value-of select="name"/>' RENDER TO $SMOOTH</br>
    <br>SET PCLASS '<xsl:value-of select="name"/>' BBOX TO OFF FOR DISPLAY INDEX 1</br>
    <br>SET PART_CLASS '<xsl:value-of select="name"/>' BACKFACE TO 0 FOR DISPLAY INDEX 1</br>

    <br>SET PCLASS '<xsl:value-of select="name"/>' EDGES TO OFF</br>
  <p/>
</xsl:template>

  <xsl:template match="shop-data/parts">
    <xsl:apply-templates select="part"/>
  </xsl:template>
</xsl:stylesheet>

```

Example BCL codes generated by the above XML stylesheet are:

```

...
CREATE PART CLASS 'Part737RHwing'
DISPLAY 'C:/NIST/PARTS/WingMajor/737-800wingRHatZero'
SET PART_CLASS 'Part737RHwing' NUM OF DISPLAY TO 1
SET PCLASS 'Part737RHwing' PRIORITY TO 1
SET PART_CLASS 'Part737RHwing' color TO $YELLOW
SET PART_CLASS 'Part737RHwing' RENDER TO $SMOOTH
SET PCLASS 'Part737RHwing' BBOX TO OFF FOR DISPLAY INDEX 1
SET PART_CLASS 'Part737RHwing' BACKFACE TO 0 FOR DISPLAY INDEX 1
SET PCLASS 'Part737RHwing' EDGES TO OFF

CREATE PART CLASS 'Part737LHwing'
DISPLAY 'C:/NIST/PARTS/WingMajor/737-800wingLHatZero'
SET PART_CLASS 'Part737LHwing' NUM OF DISPLAY TO 1

```



```
SET PCLASS 'Part737LHwing' PRIORITY TO 1
SET PART_CLASS 'Part737LHwing' color TO $YELLOW
SET PART_CLASS 'Part737LHwing' RENDER TO $SMOOTH
SET PCLASS 'Part737LHwing' BBOX TO OFF FOR DISPLAY INDEX 1
SET PART_CLASS 'Part737LHwing' BACKFACE TO 0 FOR DISPLAY INDEX 1
SET PCLASS 'Part737LHwing' EDGES TO OFF
```

...

Because this example model is created from an XML-based Shop Data File, modifying scenarios of the model file can be easily accomplished by changing element attributes of the source XML file. As in the example shown above, the BCL specific commands, such as CREATE PART CLASS, are managed in the XML stylesheet. Simulation model object related information, such as the part color and name of the part class: 'Part737RHwing' are originated from the Shop Data File. A complete new BCL file is generated per flexible manufacturing scenario. This BCL file then executes and generates a customized QUEST simulation model for its matching conceptual FMS environment.

The approach of this simulation modeling successfully manages a flexible customized manufacturing system in a flexibly modulated and customized fashion. For each complicated customized scenario, it is comprehensible that traditional manual modeling modification will take much longer effort than this technique. As compared to alternative approaches to this MCM application, benefit of this innovative methodology is evident in the following points:

- Customizable
- Ease of deployment
- Portability of the XML-based Shop Data File
- Popularity of the XML language
- Scaleable
- Reusable of the modulated seed model file

Additional detailed verification between simulation models and flexible MCM exercises on the shop floor remain to be fully performed once this conceptual process development turns into reality. Nevertheless, approaches and methodologies presented in this work illustrate unparalleled advantages in operating flexible and customized manufacturing systems.

6 Conclusion

Much of the emerging MCM literature has focused on highlighting the differences between mass-production and mass-customization. This paper touches both the theory and the practical application of the Mass Customization Manufacturing system. A generalized mobile production modularization platform that supports customized reconfiguration has been explored. Combining this with an XML-based data driven simulation modeling of the system further demonstrates the powerful nature of the MCM theory. Further, MCM theories have been employed in modeling a flexible airplane component manufacturing line.

A method also has been discussed to solidify foundations that enable possibilities in MCM dynamic networking. Because XML uses a commonly accepted text based data structure,

it is becoming near universal among data exchange software and computing systems. Thus, the application of the XML in an MCM fashion can enable effective data exchange across various hierarchies in a system. Modifying scenarios of the model file can be easily accomplished by changing the element attributes of the source XML file. Moreover, the mechanism of the Shop Data File enables effective data exchanges among MCM systems. This is valuable to The Boeing Company, since almost all commercial airplanes are custom ordered with some unique features and the manufacturing processes are very complicated.

More applications can be derived from the same customized portable modulated platform hardware and XML-based modeling approaches as discussed in this paper. The full potential from exercising MCM on both the manufacturing shop floor and in the simulation modeling has yet to be fully discovered.

Product Disclaimer

Commercial software products are identified in this paper. These products were used for demonstrations purposes only. This does not imply approval or endorsement by NIST nor that these products are necessarily the best available for the purpose.

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