What is MES (Manufacturing Execution System) in Complex Discrete Manufacturing?
## Contents

Foreword ................................................................................................................................................. 4

1. Defining MES and Complex Discrete Manufacturing ........................................................................ 5
   1.1. What is unique about Complex Discrete Manufacturing? ......................................................... 5
   1.2. What is a Manufacturing Execution System? ............................................................................ 6

2. Requirements for MES in Complex Discrete Manufacturing ................................................................. 8
   2.1. Product and Process Definition ............................................................................................... 9
       2.1.1. Bills of Material (BOMs).................................................................................................... 9
       2.1.2. Process Routings, Work Instructions ............................................................................... 10
       2.1.3. Change and Configuration Management ...................................................................... 10
   2.2. Resources Management ........................................................................................................... 11
       2.2.1. Personnel Qualifications and Certifications .................................................................... 11
       2.2.2. Tooling Calibration ......................................................................................................... 11
   2.3. Production Jobs Dispatch .......................................................................................................... 12
       2.3.1. Daily Jobs Dispatch List .................................................................................................. 12
       2.3.2. Assignment of Resources to Jobs .................................................................................... 13
   2.4. Production Process Execution Management .............................................................................. 13
       2.4.1. Guiding the Technician through Work Steps ..................................................................... 13
       2.4.2. Production Job Progress Tracking .................................................................................... 14
       2.4.3. Events and Alerts ............................................................................................................. 14
       2.4.4. Production Control ........................................................................................................... 15
       2.4.5. Work Order Splits ............................................................................................................ 15
       2.4.6. Online System with High Availability .............................................................................. 15
   2.5. Programmable Equipment and Data Collection ......................................................................... 16
       2.5.1. Running Machine Programs ............................................................................................. 16
       2.5.2. Data Collection ................................................................................................................ 17
       2.5.3. Job Buyoff/Signatures and Status .................................................................................... 19
   2.6. Product and Parts Tracking and Genealogy ............................................................................... 20
       2.6.1. Parts Issue, Kitting ............................................................................................................ 20
       2.6.2. WIP Product Tracking ...................................................................................................... 20
       2.6.3. Parts Installation Records and Product Genealogy ............................................................ 21
       2.6.4. Material Shelf Life and Expiration .................................................................................... 21
   2.7. Production Quality Management ................................................................................................. 21
       2.7.1. Production Inspection Planning and Execution ................................................................. 21
2.7.2. Product Configuration Verification ................................................................. 22
2.7.3. Nonconformance and Defect Management ..................................................... 22
2.8. Production/Plant Performance Analysis ............................................................ 23
   2.8.1. Schedule/Capacity Performance Analysis .................................................. 24
   2.8.2. Cost and Quality Performance Analysis .................................................... 24
2.9. Systems Integration Services ........................................................................... 25
   2.9.2. Business Procurement/Inventory and Financial Systems ............................ 26
   2.9.3. Enterprise Business Intelligence ............................................................... 26
   2.9.4. Enterprise Continuous Improvement Management ................................... 27
3. A Few Other Considerations .............................................................................. 27
What is MES (Manufacturing Execution System) in Complex Discrete Manufacturing?

Foreword

Today’s competitive manufacturing arena demands lower cost, more product variants, shorter product introductions, and better compliance to industry standards and regulations. This has led many manufacturing companies to move beyond the old paper-based processes, and start implementing new streamlined business processes for their shop floors with the use of commercial information systems.

This paper is intended for Operations, Operations Support, Quality Assurance and Information Technology personnel who are evaluating software solutions to improve production management capabilities in complex discrete manufacturing industries. These industries include: aerospace, defense, shipbuilding, nuclear energy, industrial electronics, industrial equipment, and complex medical devices.

Defined are common and unique business process requirements (including verification and documentation requirements) needed to support the effective management of operations in complex discrete manufacturing. Many of the capabilities outlined are not just nice-to-have or best practices for some of these industries, they are required for regulatory compliance by industry and quality management system standards such as ISO9001, AS9100, and ISO13485.

For organizations looking to improve their business processes and implement new information systems, the general requirements provided in this paper can be used as a starting point for creating a requirements list for these initiatives.
1. Defining MES and Complex Discrete Manufacturing

1.1. What is unique about Complex Discrete Manufacturing?

Complex discrete manufacturing industries manufacture complex highly engineered products with longer product cycle times and multiple levels of subassemblies in their bills of material. Many of these companies make and engineer products to order. They also have a need to track manufacturing history down to each “discrete” serialized product unit. In contrast, batch production manufacturers only have to track products by work center, day, batch, or lot.

Complex discrete manufacturers include companies that manufacture products for aircraft, space, military weapons, complex medical devices, robots, and specialized industrial equipment. For many of these products it is necessary to manage complex diverse product configuration, long product life cycle, along with increased market pressure for shorter time to market for new products and stricter regulatory compliance oversight.

Some of the major characteristics that define a complex discrete manufacturing environment are:

- Long cycle times, low volume, make-to-order or engineer-to-order
- Complex product with deep bills of material (BOM)
- Highly skilled labor performing manual assembly and fabrication work including complex NC machines and special materials such as composites
- Complex process routing sequences with decision points and loops
- High flow of engineering changes affecting work-in-process
- Production is not repetitive and mechanics must be alerted to changes
- Data collection during production includes manual data entry, verifications and signatures
- Personnel have qualification requirements and equipment have calibration certification requirements
- Documentation requirements include a complete history for every produced unit, and traceability of the components installed and material used
1.2. What is a Manufacturing Execution System?

Many production environments have historically been serviced by paper-based procedures and homegrown applications. These have not kept up with newer requirements for increased speed, agility, and traceability. The combination of paper and unlinked data silos at the shop floor increases the difficulty to integrate the required plant data into a complete and accurate top-level view of operations. The demand for more efficient practices is motivating plants to modernize and move beyond running the facilities with spreadsheets, paper, and knowledge held by a few key experienced employees that might be nearing retirement. Manufacturers are realizing the need to integrate real-time manufacturing data into their corporate information view.

A Manufacturing Execution System (MES) is an information system that drives effective execution of manufacturing operations. Using current and accurate data an MES triggers, guides, verifies, and reports on plant activities in real time—from order release, to manufacturing, to delivery, to the finished goods inventory. MES systems have been evolving and broadening functionality, to manage internal quality and the supply chain. The term Manufacturing Operations Management (MOM), which came from the batch and process industry, is also used as a synonym to MES. Regardless of the term you prefer, the definition and requirements listed in this paper are the same.

The diagram in Figure 2 shows eight typical functional areas inside of the scope of MES. This is a slight modification of the MESA (Manufacturing Enterprise Systems Association) collaborative-MES model. The perimeter of the MES boundary shows other enterprise functions and applications that typically integrate with MES. This paper will expound on these eight areas, identifying where unique MES capabilities are required by complex discrete manufacturing.

Ideally, an MES system should provide all the functionality needed by shop floor personnel in one simple user interface—avoiding the need to jump between different applications to get information. One application to learn and one user interface that integrates all the information needed to effectively manage operations.

![Figure 2. An MES provides the functions needed by Manufacturing Management personnel](image)
The requirements for MES have been grouped into eight functional areas, to allow for easy cross reference with the MESA, ISA-95 and ISO-9001 frameworks.

- Process Definition Management
- Resources Management
- Production Jobs Dispatch
- Process Execution Management
- Data Collection and Programmable Equipment
- Products and Parts Tracking and Genealogy
- Production Quality Management
- Production Performance Analysis

The diagram in Figure 3 shows how MES functions map into Level 3 of the ISA-95 model. The ISA-95 reference model is an international standard for systems integration, spanning from enterprise level systems to control systems. Though the ISA-95 model evolved out of the batch, continuous, and repetitive process industries—not complex discrete manufacturing; it is still useful as a general reference framework, providing some consistent terminology to compare MES applications.

The model describes how Level 4 applications (including CAD, PLM, ERP, and APS) pass product definitions, capabilities, and schedule information to Level 3. Enterprise applications at Level 4 need improved integration to Level 3 applications to get up-to-date data from manufacturing—data needed by corporate executive decision makers. The model also describes how plant floor automation applications at Levels 1 and 2 can provide detail measurement and event data to the MES on Level 3.

Figure 3. MES functions are described in Level 3 of the ISA-95 model.
2. Requirements for MES in Complex Discrete Manufacturing

A checkmark or grade on each of the eight functional areas, is not enough to evaluate the fit of an MES to your industry or company’s needs. On the surface, many MES seem to have a similar functional footprint, but some MES cater to specific industries with very specialized functionality. To make an informed assessment, it is necessary to drill down to more specific requirements, to find the solutions that can truly handle your industry and manufacturing needs. Finding the right solution fit can hugely affect the effort, time frame, cost (total cost of ownership), and results of an MES implementation initiative.

Complex discrete manufacturing organizations have unique requirements in their manufacturing and quality management business processes including: (a) Vigilant Resources Certification Management, (b) Complex Product/Process Configuration and Change Management, (c) Detailed Integrated Quality Control Processes, and (d) Detailed Product Unit History and Records Archival.

Vigilant Resources Certification Management

Personnel must be certified as competent on the basis of education, training, skills, and experience. Personnel qualification processes must be standardized and documented. In addition, equipment resources must also be maintained to assure their capabilities, especially measurement equipment used to verify the product. The equipment and tools maintenance and calibration processes must be standardized and documented. An MES can verify calibration status for equipment, and also verify that personnel signing off on a job have the required active certifications.

Complex Product/Process Configuration and Change Management

The manufacturing of a complex product like an aircraft or satellite involves the management of a continuous stream of engineering changes directed at work in process. The integration of the engineering system with MES can create a seamless link between product development, manufacturing planning, and manufacturing execution functions. This link would close the loop on engineering changes, and assure that as-built configurations match as-designed.

Detailed Quality Control Processes

Beyond providing visibility into areas for improvements, the manufacturing information system should provide process control procedures to implement and sustain quality improvements. This includes in-process inspection and verification steps, statistical process control (SPC), alerts to out-of-control conditions, and integrated handling for discrepancies found during production (including defect containment and corrective actions) to eliminate recurrence.

With the high investment that goes into these types of products (for parts and labor), they are rarely scrapped. Instead, these industries require rework, repair, and deviation handling procedures to ensure that deviations are documented, reviewed, and approved by the appropriate personnel. The integration of production and quality systems can ensure that deviation instructions cannot be skipped by the mechanic performing the work. Deviation history is also considered part of each product unit history.

Detailed Product Unit History and Records Archival

MES maintains production history documentation down to the details for each product unit, versus tracking to the batch level. MES documents exactly who, what, when, how, and why—like who completed the job, what equipment was used, which parts were replaced, and who approved the changes.
The following sections define requirements for an MES in the complex discrete manufacturing environment. In addition to the eight functional areas outlined above in Figures 2 and 3, a ninth area is discussed describing the high-level requirements for integration to enterprise systems.

2.1. Product and Process Definition

The MES must manage the documentation package required at the shop floor to execute product manufacturing. This documentation includes design engineering specifications in the form of 2D drawings, 3D models, geometric dimensioning and tolerancing (GD&T) information, and work instructions.

The MES system can either provide its own document management system for production documentation (including illustrations and work instructions), or link to a shared repository with engineering documentation.

The revision level of engineering documentation should be crossed referenced between the engineering system repository, and the MES documents for change management purposes.

Engineering drawings and models for tool fixtures are maintained and crossed referenced with product designs and process plans.

Some parts, aspects of the product, or process design might need to be protected for export control (or intellectual property) purposes. If your organization has these requirements, it is important to assess the capability of the MES to support these types of security controls. These requirements are more than the common user privilege and role administration found in most MES solutions.

2.1.1. Bills of Material (BOMs)

An MES system should allow for multiple BOM management scenarios. The Engineering BOM (eBOM) defines the product structure in terms of part numbers linked to 3D CAD models. They are organized in a hierarchy of subassembly structures that are revision controlled and managed by a Product Data Management (PDM) or Product Lifecycle Management (PLM) system.

The Manufacturing BOM (mBOM) defines the product structure in terms of how the product is going to be built. The mBOM does not necessarily mirror the eBOM, because complex products are often reorganized into temporary kits and subassemblies with the use of phantom and synthetic part numbers. These reflect the different manufacturing stages, and allow improved tracking of the subassemblies as they are completed by different suppliers and manufacturing facilities.

Organizations try to align these BOM structures as much as possible. However, some Engineering departments do not want to change the product definition every time the manufacturing process is changed or reorganized. The MES should support either (a) receiving an mBOM from an external system, or (b) receiving the eBOM and managing the transformation from the eBOM to the mBOM within the MES system. The development of the mBOM is closely tied to the development of the manufacturing process, which is captured in the definition of Process Routings.

An MES must support configuration management in BOMs through effectivities for each component part, with ranges in end units, serial/lot numbers, or dates. Some companies might also use configuration codes on components, to manage variations of the product within a single BOM.
2.1.2. Process Routings, Work Instructions

In complex discrete manufacturing, process routings, and work instructions are usually managed as a single combined document, called process plan. In addition to specifying the planned processing and assembly of the product unit through work centers in the plant (aka. process routing), the process plan details execution sequence rules, work instructions, resources, and data collection requirements for each operation and step.

Work Instructions include text narratives and illustrations, which guide the technician through the appropriate process sequence. The instructions show how to set up tools, position parts, run machines, and how to perform required measurements and verifications along the way.

Many manufacturing shops are still working off work instructions printed on paper, but most MES support delivery of online work instructions on big screens mounted at the work benches.

Illustrated work instructions are usually easier to follow, learn, and preferred by mechanics and technicians. However, creating and maintaining illustrations for work instructions can be labor intensive. These have been traditionally reserved to clarify the more complex work steps, where costly mistakes must be avoided (or where words are not enough) to appropriately explain the work sequence.

Illustrations and animations can also be created directly from 3D models, and delivered via 3D model viewers. The latest generation of software tools from CAD vendors are making it easier to create these illustrations. They leverage the product design 3D CAD models by automatically converting them to lighter file formats with lower bandwidth requirements. The lighter formats lower the graphics quality a bit while maintaining enough definition for work instructions. These 3D based illustrations are quickly replacing illustrations based on pictures and manual sketches. The MES or CAD illustration tool might also provide a way to annotate the 3D based illustrations with a few pointers.

2.1.3. Change and Configuration Management

Engineering changes affecting in-process units are not exceptions, but part of normal every day processes. This is due to the complexity of the products, and the industry push to quickly incorporate the latest leading edge technology. The integration of engineering systems and MES is essential to close the loop on engineering changes, and assure that as-built configurations match as-designed.

For some companies, the MES must support the management of product revisions that cut in at specific dates or serial numbers. In addition, they support configuration codes and effectivities on BOM components for different models (or different ranges) of end-units, serial numbers, or lot numbers.

Process plans must be under revision control with cross references to the revision level of referenced BOMs, illustrations, and procedures.

When illustrations are based and crossed referenced directly to the original eBOM and 3D CAD models, the revision process in MES can be aided with impact assessment tools. These tools guide the users through the revision of process plans and work orders based on where-used queries.
The standardization of work practices and authoring of work instructions into process plans can be aided by the use of a library of standard operations and standard instructions text. These libraries of reusable instructions can further improve efficiencies. They need to provide ways to do mass updates of work plans and work orders, while preserving cross references and revision control between the library entries and the documents that reference them. The MES may also provide document control capabilities for attached documents that are not already under revision control in externally linked systems.

2.2. Resources Management

Process routings are extracted from the process plan structures and exported to the Enterprise Resource Planning (ERP) system. This needs to be done to the level of detail required by that system to perform production capacity planning, and material and labor cost tracking functions. Usually this is done at the operation and work center levels, keeping step level details within the MES.

The MES lists the resource requirements for each manufacturing job as part of the definition of the process routing. This is then passed to the ERP or scheduling system. Verification of resource capabilities and certification is one of the critical functions handled by MES, including personnel qualifications and tooling calibration records.

2.2.1. Personnel Qualifications and Certifications

Regulated industries (such as Aerospace) require that qualified, trained, and certified personnel are performing the work. Personnel must be certified competent on the basis of education, training, skills, and experience. An MES can maintain certification records for employees and verify that the personnel signing on to a job have the correct active certifications.

The MES can house the certification data in one main repository for the organization, or it can be integrated into a Human Resources system to access this information. Each work center manager can periodically review which employees require training to keep certifications valid.

The MES can also maintain records on each employee’s experience with different types of jobs. This information can be used to help assign personnel to jobs. For some types of certifications, the MES can automatically recertify personnel based on job experience instead of requiring the employee to re-attend a training course periodically.

2.2.2. Tooling Calibration

Gauge and tool management can be done in a separate system but there are several advantages to having it within the MES system:

(a) The MES system maintains usage information for each tool. Calibration can be triggered based on actual usage frequency instead of (or in addition to) the traditional date driven rules.

(b) MES traces measurements to the tools used, and can enforce that tools be in good calibration status before data measurements are accepted.
Tooling and gauge calibration management features include:

- Gauge and tool crib management (including check-in/out of tools to crib, and to production work centers)
- Calibration scheduling based on dates or tool usage.
- Calibration due reports for using work centers. Email or dispatch notification when Tools/Gauges are due for calibration.
- Calibration instructions and standard templates
- Recording of calibration results
- Optimization of calibration intervals (based on history) for each tool

By requiring tool identification during measurement data collection, the MES can narrow down recalls, in the event that a malfunction is discovered at a later time in a measurement device.

2.3. Production Jobs Dispatch

The ERP system performs capacity planning at the work center level (based on the resource requirements provided by the MES), and adjusts production schedules weekly or daily. Production Work Orders are usually released by the ERP to the MES when they are ready to be worked by Production; this is usually a two or four week time horizon.

Some organizations might develop rough planned dates for work orders in ERP. Then for more detailed schedule dates, use a scheduling system that considers resource availability in more detail using a shorter time horizon. Detailed scheduling is typically done at the operation level, taking in consideration machines, tool fixtures, and personnel skills as resources.

2.3.1. Daily Jobs Dispatch List

Dispatch of jobs to the production shop floor should be done in accordance with the work sequence defined in the process plans. However, with appropriate approval, the MES must be able to deviate from planned sequence. The ability to postpone jobs (or partial jobs) to a different sequence (or alternate work center) to work around unplanned issues, such as part shortages or machine downtime, is imperative.

A jobs dispatch list should clearly indicate any issues that would delay completion of the job. This will prevent job starts on jobs that are not ready to be fully completed. Delays and hold conditions that should be recorded and displayed include: machine downtime, part shortages, and waiting for engineering disposition on issues found during production.

A graphical display of actual dates versus schedule dates, for each job in a Gantt chart makes it easy to assess performance to schedule visually. This can highlight jobs that are falling behind, and might need to be prioritized or expedited.
2.3.2. Assignment of Resources to Jobs

The dispatch function in MES should facilitate assignment of resources to production jobs. Histogram views can help assess resource utilization, and assist with job assignments. To help supervisors assign personnel to each job, it is helpful to display personnel skills, qualifications, and recent experience with similar types of jobs.

A Time and Attendance (T&A) or workforce management system can be integrated to MES to display daily attendance records to supervisors to help assign available resources to jobs. In addition, the integration can go further, helping to reconcile labor hours with attendance hours.

For work centers where multiple machines can perform similar tasks it is necessary to specify which machine is performing each job. This way if a problem is found later with a specific machine and it is necessary to identify which product units might have been affected, the information is documented. An added benefit of specifying the machine being used for each job is knowing which machines are busy. In addition, the MES should also be able to record when a machines are down for maintenance or repairs. Supervisors will then have advance warning of resource constraints, allowing them to reorganize jobs and assignments.

The MES should help select the appropriate tool or gauge to use for each measurement based on: the tools assigned to the work center, the tolerance requirements for the data collection, and the accuracy and calibration state of the tool. Each work center should also have a proactive warning list of tools and gauges checked out but requiring calibration in the near future. This way corrective action can be taken before the tool condition becomes a constraint.

2.4. Production Process Execution Management

This is an essential group of MES functionality, which streamlines production execution. It includes recording the execution of the work order operations. Technicians are guided through the work steps assuring all work is done in the prescribed sequence and no steps are missed.

In addition, alert messages can be set to inform the technician and supervisor (in real-time) of issues that arise during production. Risk mitigation on scheduled dates could require expedited action from support personnel or immediate workaround action from Production Control or the supervisor (to reschedule the assigned jobs at the work center), minimizing the impact of idle time while the issue is being resolved.

2.4.1. Guiding the Technician through Work Steps

The MES can go beyond simply displaying an online document to the technician. The MES can guide the technician through the various steps from selecting a job on a dispatch list, signing on to the job to start the clock, collecting data for measurements and parts, through recording the completion of the job. This functionality can range from nice-to-have, to an absolute necessity for work that is sensitive to the sequence of detailed steps.

The mechanic should only be able to view the latest appropriate documentation and illustrations for each job. To remove human error, it is important that the MES tracks and automatically displays the appropriate version and revision of work instruction, versus having the technician look them up in another system. The MES can require additional acknowledgement if this is the first time the technician has seen the specific revision of the work instructions. This ensures that the technician has reviewed the new work instructions, and does not miss an important change that would lead to product defects.
Work instructions should include warnings about safety precautions, and wearing the appropriate safety gear. In some cases, an acknowledgement might be required from the technician about safety precautions before allowing the technician to proceed with the work. The MES can cross-check the required qualifications for the job against the technician’s qualifications, and alert the technician if more than one skill (or person) is required for the job. When jobs span multiple shifts, it is important for one shift to be able to leave an online note attached to partially completed jobs for the next shift.

### 2.4.2. Production Job Progress Tracking

The job progress tracking function includes tracking the completion of each manufacturing order, each operation, each product unit, the resources used, and the bills of material and parts used. This also allows production planners to identify where each product unit (or lot) is within the manufacturing cycle, and what materials are needed and when during the production. This visibility can help manage inventory, including notifying production control when kitting is needed for the next jobs in the queue. This level of visibility also allows organizations to properly inform customers on when to expect their products delivered.

Part of tracking progress is the ability to track labor costs for each job. This is usually done by requiring personnel to clock-on and off jobs. The first clock-on also indicates the start-time for the job. At clock-off, the technician might be indicating the number of units completed. The last clock-off is used for job completion time. Clock on/off times might be passed to a labor costing system, which is configured to distribute labor and allocate people’s time on parallel tasks to each job (and production unit) according to configured allocation rules. It should be able to take into consideration the time clocked on, versus the labor standards for each job.

It is typical for complex discrete industries to consider each operation in the work order as a separate production job, which is often designed to be completed within an eight hour shift. However, an MES should be able to handle different people clocking on and off jobs multiple times, on different shifts, while recording the partial completions (quantity or percentage) of the job.

When working units one at a time, it is usually preferred to show progress as a percent complete for each job. However, when work centers are producing bigger quantities per job, an online Andon Board might be preferred. An Andon Board is a visual schedule progress display that uses green, yellow, and red status indicators (along with planned and completed quantities) to highlight when a work center is under the expected production level for the day.

### 2.4.3. Events and Alerts

Automated event tracking is an important task for the MES. Regular events (such as the completion of a job by a machine) can be displayed to the respective operator to trigger the next step without delays. Other types of events might be exception or alert events that require a special action such as triggering an alert to the appropriate supervisor or support personnel. These alerts might be redundantly broadcasted via email to supervisors or support personnel in the organization.

However, most alerts are displayed by the MES at the work station, to get the immediate attention of the operator or technician.

Alert event examples include warnings for out of spec (or out of control) conditions, warnings for tools out of calibration, personnel with expired certifications, and line stops.

The physical idea of a red Andon Light alert on a post at each work station indicating a line stoppage, can be translated into a digital version. Providing a color-coded display for the work center status, where red indicates any current stop condition. An advantage of providing these types of indicators
What is MES in Complex Discrete Manufacturing

via an MES is that the system can provide an online view of the entire plant – quickly highlight where issues are happening in real-time, who is assigned to follow up, and how long the work center has been impacted.

Some MES can also broadcast alerts to supervisors and managers, escalating issues based on the urgency and time the issue (or hold condition) has been open without action or resolution.

2.4.4. Production Control

Production Control features include: (a) the ability to expedite the resolution of issues that are holding up production, such as part shortages or machine failures, (b) coordination and approval of work-around deviations from planned work sequences, and (c) incorporation of urgent engineering changes that impact production schedule. The MES should provide screens and reports that help analyze impacted areas, and help move schedule times and assignments to work around these situations. Some MES provide both planned and revised schedule dates, to keep track of the original plan and the new work around dates.

Production Control personnel might also be involved in confirming the impact of engineering changes to units in-process. They help determine the best place in the production schedule to make changes effective. This interaction can be supported in the MES via screens that query where the specific drawings or models are used and display the related work in-process. Integration interfaces can also be used to transmit ECN effectivity requests and confirmations between the PLM and MES systems.

Production Control (or Industrial Engineering) personnel can take responsibility for periodically reviewing actual production job times against time estimates, and requesting changes to time standards and schedules. This ensures that schedules reflect realistic attainable goals. The MES should facilitate this function by providing reports that compare estimates to actuals and highlight areas that might need re-assessment.

2.4.5. Work Order Splits

Sometimes production issues may require that a production lot be split into sub-lots, so that a subset of the product units can be moved ahead of the rest (or be moved through a special rework sequence). Work Order splits are usually much easier to handle in the MES system than in the ERP system. MES integration interfaces can handle the coordination with the ERP system in the background. This makes sure the accounting side is handled correctly without losing important traceability information for the work performed against each sub-lot, and the component genealogy information for each sub-lot.

2.4.6. Online System with High Availability

A paperless online execution system requires high availability, since many plants run three shifts around the clock. That means 24x7 availability, fault tolerance, and system backup are very important to these environments, and need to be part of the MES deployment considerations. The MES should be designed to support high availability, and not require periodic significant down time for performance tuning or backup.
2.5. Programmable Equipment and Data Collection

It is difficult to separate topics in this section (such as running programs and performing data collections) from some of the production execution topics listed above. However, for the purposes of this paper we have maintained the separation to stay aligned with the MESA and ISA MES/MOM models referenced. Each of these functional areas must have proper individual evaluation, but the organization should also consider how closely these functions work seamlessly together within the MES solution. Optimally the user should not feel they are going into different systems (or screens in the MES) to perform each separate function. The user should feel they are performing a job online, and that the data collection is part of one seamlessly fluid integrated process.

2.5.1. Running Machine Programs

Current market conditions demand faster new product introduction, more product variants, shorter runs of small batches, and more flexible programmable machines. As a result, most shop floors have to manage continuing change. To meet new manufacturing demands, existing machines are upgraded, reconfigured, and adjusted to improve efficiency and enhance flexibility. New machines are acquired to increase capabilities. Manufacturing processes, tooling, and materials also continue to evolve to improve productivity. An MES must be able to help manage this changing environment while making sure the machine programs executed are the correct versions for the specific equipment, operation, and part number.

A process plan in an MES can include work instructions to run a machine. These instructions can range from simple setup sheets, to execution of complex programs—such as NC (Numerical Control) or CMM (Coordinate Measurement Machine) programs—to performing a manufacturing process step or inspection on a specific part. An MES should be able to store these programs, maintaining a cross reference between the latest work instructions and the latest program for the specific operation and part specifications.

Machine programs are revised constantly to accommodate machine, part design and tooling changes. There might be a separate document management system for NC programs, but it must be carefully cross referenced to the process plans. This will ensure that the operator is selecting the correct version of the program for the current part and operation. The task of pulling all documents required by production together is not a trivial indexing task. Sometimes costly mistakes are made when we depend on manual systems of reference. The task becomes more complicated if programs are not in the same system as tool setup sheets and drawings. It is very helpful having the change management processes of product design, process design, and the actual production equipment closely tied together with workflow processes that trigger other impacted groups. Then the changes can be evaluated to make sure related downstream process instructions and tooling are updated accordingly.

There are many suppliers and types of machining and inspection devices, and many ways of integrating them to MES. However, more suppliers are offering IP connectivity for their machine tool devices and pre-developed logic instructions. Integration standards like OPC-UA (PLCopen) between machine controllers and MES, and Profinet, Powerlink and EtherCAT between machine controllers and sensors are also helping create toolkits for quicker integration between machines and MES.
In addition to maintaining a centralized library for NC and CMM programs, an MES should be able to help with the following tasks:

- Upload and administer machine parameters
- Connect to all types of controllers and tool pre-setters via serial (or Ethernet) interface
- Download programs to machines and controllers
- Upload data from machines (via integration interfaces) as data collection for operations including machine states, error codes, and parts counts
- Display data collected from machine interfaces back to MES operator user interface

2.5.2. Data Collection

Product quality is verified during production, via checklists and recorded measurements. These measurements may have statistical process controls (SPC) parameters set on them to trigger alerts, based on out of control conditions and rules configured in the MES. In-process quality verifications allow detection of issues as early as possible during the manufacturing process. Different types of in-process data collections include:

- Manufacturing job status and quantities completed
- Checklist verifications during setup or inspection step
- Actual dimension (or weight measurements) to be compared with specifications
- Environment (or equipment) configuration variables
- Tooling (or machine) setup information
- Resources identification
- Material Expiration
- Personnel signatures

The MES must be able to allow manual typing for inputted information. However, the less typing required the better to improve speed and reduce the chance of human error. The good news is that interfacing devices for data collection is easier than ever. Besides workstation keyboards and touch screens, devices for data collection include barcode, RFID, gauge interfaces, and handheld devices like PDAs. Usage of these devices improves productivity, reduces manufacturing cycle time, and reduces errors.
Many scanners and measurement devices connect via USB and send data to the application acting as a keyboard. For this type of *keyboard wedge* interface, no special additional programming is required.

Sometimes it helps to program special preamble characters on scanners with a keyboard wedge type of interface. This allows the MES to distinguish a barcode scan from manual typing, and trigger special commands (or parsing) of a more complex 2D barcode. Most barcodes found on parts (or travelers) are 1D barcodes (UPC, Code 128, Code 39, etc.). 1D barcodes contain a single text string (such as a part number or a serial number) that needs to be read into a single field value in an MES input screen. 2D barcodes contain a paired list of field names and field values. 2D barcodes usually need to be parsed into multiple data fields.

Data collection processes should be as close to real time as possible. After the fact data collection is never as accurate. For example, filling out a time sheet at the end of the day (or end of the week) will not reflect labor costs as well as sign on/off jobs during the manufacturing day.

Data collection can be performed directly or indirectly. Indirect data collection happens when the system records several types of data or transactions based on a single direct action by the user. For example, timesheet records can be automatically recorded based on users signing on and off jobs. Timesheet records can still be adjusted, but this type of automation is an enormous improvement on labor accuracy. Another example, is recording product movement based on operations starting in different work centers, and tracking work in-process inventory levels based on parts issued from inventory and consumed into higher level assemblies. Instead of having additional data entry transactions for material movement, we can track movement as a side effect of other actions. This lowers the amount of direct data entry by the user, while increasing the information available about work in-process at the shop floor.

The MES also sends data to other systems to avoid redundant data entry. For example, labor job clock on/off transactions are transmitted to ERP (or labor tracking system) in the background. In many cases, there is no need to have redundant labor clock devices, the MES user interface can act as a labor clock device to the labor system.

We discussed interfacing to machines in the prior section (in relation to running machine programs), but an MES might also interface to machines for data collection. Integration for direct import of data from machines can help us minimize the operator bias we might find in manually entered data. However, be careful not to get carried away with automation. The cost for each interface should be evaluated versus the benefit of speed and accuracy. In some cases it is just as easy to read a counter on the machine and type it into MES, rather than set up an interface to read the part count directly from the machine. In other cases, this type of interface might be justified based on volume, and the importance of accuracy for this particular type of data and manufacturing.

The MES should be able to upload data from machines (via integration interfaces) as a data collection for operation. This includes machine states, measurements, error codes, and parts counts. The MES must also be able to display data collected (via machine interfaces) back to the operator on the MES user interface.

Voice technology has come of age. We can have: (a) voice directed commands, and (b) speech recognition that can translate dictated words and numbers into text strings for data input.
For companies manufacturing products for the Department of Defense (DoD), an MES must also support a special type of barcoded tag, the UID tag. UID is a unique identification across the DoD enterprise for uniquely identifying entities, including things, real property, organizations, and people. Unique Item Identifier (UII) represents the set of data elements marked on an item that is globally unique and unambiguous.

The UID mark (a data matrix barcode symbol) is a high density 2-D (ECC 200) matrix style barcode. The UID data contained within the data matrix is formed by combining the manufacturer's (or enterprise's) identification with a part number, and/or a serial number which is unique to that one item. The quality standard for acceptance of the machine-readable coding must meet the specifics of MIL-STD-130, ISO15415, AS9132, or AIM DPM-1-2006.

The MES must be able to interface with UID databases (such as iGUIDES), which help maintain UID information for the DoD. The MES must support a flexible UID construction and deconstruction methodology to support the multitude construct requirements in MIL-STD-130. Both 1D and 2D formats are used as part of UID tags.

There are also radio-frequency identification (RFID) tags. Both active and passive RFID tags are widely used in packaging, transportation, and warehousing scenarios. RFID tags can also be used to facilitate the tracking of material movement in the plant. Material issued to the shop floor can be identified to RFID tagged bins, and tracked as it moves around the plant. Product units can also be placed on bins (or carts) with RFID tags, and tracked as it moves from one work center to the next. This type of tracking provides more accuracy for how long material is sitting in staging areas, and can help identify bottleneck areas in the flow through the plant.

2.5.3. Job Buyoff/Signatures and Status

As mechanics and technicians complete jobs they also perform buyoff signatures indicating that the job has been completed according to work instructions and specifications. Online buyoff verifications eliminate many of the redundant verifications required in paper-based procedures. Inspectors also “stamp” buyoff signatures online on inspection steps. Signatures can automatically complete manufacturing jobs, and status is automatically transmitted to ERP system in the background.

There are several federal guidelines that may apply to different industries for electronic signatures and authentication. They include 21-CFR-Part-11, and standards published by NIST (National Institute of Standards and Technology) on electronic authentication and digital signatures.
2.6. Product and Parts Tracking and Genealogy

Efficient production operations and just-in-time (JIT) practices are dependent upon availability of the proper parts, at the proper time, and at the proper location. The mismanagement of materials is a potential source of configuration errors, kitting errors, and uncontrolled inventory. Many of these issues can be avoided with proper integration between the inventory system and the MES.

2.6.1. Parts Issue, Kitting

Real-time visibility and accurate accounting of Work-in-Process (WIP) inventory requires the tracking of parts from the time they are issued out of stock, as they are moved through shop floor storage areas, until they are installed (or used) by a production operation. The location of component parts can be identified to a storage bin, cart, or shelf. They should be labeled for the target work center, work order, and operation.

The MES should be able to support different types of parts picking (or issuing) scenarios for different types of work centers:

- MES can generate a parts pick list for each operation that is either sent to the inventory system via interface, or carried manually to the stockroom by the mechanic.
- Pick list can be generated by the inventory system. Transactions for parts issued out of the stock room to production can be sent directly from the inventory system to MES via an integration interface.
- Stockroom (or material handling) personnel might do parts kitting for each work order (or operation) before a job is dispatched to the manufacturing personnel. Kits are then placed in the staging area for each production work center.

Kitting component parts onto bins (or carts) prior to a job starting, is a proven method for detecting part shortages early. This also prevents jobs from stopping midway due to part shortages. Accurate kitting can avoid losses, damage, and miscounting of in-process parts floating around the shop floor.

WIP inventory levels for parts issued to jobs but not installed are also tracked in the MES. Then once installed during production they are automatically reduced and recorded. The MES might also be transmitting backflushing signals to the inventory system to record parts issued based on completed product quantities.

2.6.2. WIP Product Tracking

Barcoding of storage areas, storage bins, and parts issued can facilitate tracking the movement of material, and products on the shop floor.

Product units are tracked by either serial number, lot number or work order number. The physical location of the product can be derived in the MES by the work order routing. This will show the movement of the product units from one work center to the next as the operations are completed.

Mayor subassemblies and components manufactured may also be tagged (or pegged) to a specific end-unit-number, such as an aircraft tail number (or ship number).

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2.6.3. Parts Installation Records and Product Genealogy

The product history and audit trail maintained by MES includes a complete genealogy of materials and component parts used in the assembly. This includes part number (and revision), serial number, lot number, spool number, and vendor CAGE code.

The MES should provide the ability to verify the as-built BOM against the as-designed (or as-planned) BOM for the respective engineering change level. This report also verifies that production was performed according to the applied engineering change notices (ECNs) listed for each product unit.

Manufacturers can identify quality concerns originating downstream in the supply chain. The parts genealogy data provides forward and backward traceability that is critical for recovering quality costs, narrowing down the scope in the event of a product recall, and limiting exposure to additional risk associated with low quality suppliers (or suppliers that do not correct issues promptly).

2.6.4. Material Shelf Life and Expiration

An MES should be able to flag certain material as having an expiration date. The user would then be required to record and confirm the expiration date before using the material.

A number of manufacturers make products that contain composite materials. Some of the premade composite materials, and chemicals are temperature-sensitive material that must be stored at a specific minimum refrigeration temperature to prolong their shelf life. Often materials can sustain only a limited amount of “out time”—that is, time spent outside cold storage. The MES (or inventory system) must reduce the shelf life of the material anytime it is taken out of the cooling environment. Cumulative out-time has to be calculated each time the product is removed from the refrigerator.

2.7. Production Quality Management

Most MES provide built-in quality control procedures for in-process inspection and verification steps, statistical process control (SPC) procedures, alerts to out-of-control conditions, and integrated handling for discrepancies found during production. This includes correction, defect containment, and corrective actions to eliminate issue recurrence.

The cost of parts and labor can accumulate fast in complex products. If the investment in production is high, products are usually reworked instead of scrapped. The MES must provide rework, repair, and deviation handling procedures. This ensures that deviations are documented, reviewed, and approved by the appropriate personnel. Deviation history is also considered part of each product unit’s history.

2.7.1. Production Inspection Planning and Execution

Inspection planning defines product inspection, test, and verification requirements. Engineering quality into the production process means doing more in-process verification and less final inspection. In addition, there should be more sampling inspections, instead of 100% inspection. Modern practices also encourage that the production mechanic take more ownership of product quality. This means performing more inspection without the need of an additional inspector. To achieve these goals, quality must be integrated into the production process, and therefore into the MES. The MES can enforce completion of in-process inspection steps and signatures before the next operation is allowed to start.
Product critical and key characteristics flow down from the engineering specifications into the inspection requirements. It is important to maintain a cross reference of each inspection requirement, to the respective revision of the engineering models and characteristics facilitate change management.

Some measurements require special gauges. Inspection instructions can call out specific gauge types (or measurement equipment), and can also require calibration verification. It is important to record which tools were used for each measurement, in case an issue is found later with a specific gauge.

Some measurements may be flagged as requiring statistical process control (SPC) oversight. The MES collects actual measurements across different work orders, and displays SPC control charts during production. In addition to alerting for out-of-spec conditions, the MES should be able to use rules, such as the Western Electric rules, to alert for SPC out-of-control conditions.

Major product or process changes should trigger additional inspections validating that the manufacturing process still produces the expected results according to the engineering specifications. This process is also called First Article Inspection (FAI) (or Product Process Verification (PPV)) in the Aerospace industry, and is required by AS9100 standards.

As inspection and test steps are reached in the job sequence, the MES should dispatch these tasks to the respective inspectors via online “callboards” (or inspector dispatch lists). The MES can track and report if some areas are experiencing delays due to a lack of inspectors.

Inspection, test, and final inspection results are stored, along with production data for each product unit (or lot), and are available online. Some inspection and test results might be required to be delivered with the final product to the customer, or uploaded to the supplier portal in PDF or XML format.

### 2.7.2. Product Configuration Verification

A very important role of the manufacturing system is to ensure that the product is built to the correct engineering specifications. From a quality management point of view, it is necessary to validate that the product was indeed manufactured to specifications. Some of the tools used for this function include:

- Reconciliation of as-built to as-designed configuration, with deviation approvals where necessary.
- The Device History Record (DHR aka. As-Built Report), includes a list of Engineering Change Notices (ECNs) incorporated into each product unit.

This type of product documentation might need to be delivered to the customer along with each product unit.

### 2.7.3. Nonconformance and Defect Management

In complex discrete manufacturing, the management of nonconformance conditions that are found during production go beyond counting defects, scrapped material, and calculating yields. The MES must provide for the disposition and management of nonconformance findings (aka. discrepancies). And it must incorporate the deviation approvals along with the execution of the planned manufacturing process.

Defect containment actions may include corrective action requests sent to suppliers, orders for assessment of products and materials in inventory, alerts to potentially affected production orders in process, and product recalls (or warnings) issued to customers.
When a nonconformance to engineering specifications is detected during inspection, it must be documented and routed through a disposition and approval process. This will determine if product (or component) must be scrapped, returned to vendor, requires rework or repair, or can be used as-is. The integration of production and quality management can ensure that deviation instructions for rework or repair cannot be skipped by the mechanic, before continuing with the production process.

Work flow processes need to support different types of discrepancy disposition and approval routings for the different types (and severity) of issues found during production. Some issues might require escalation to product engineering for approval. While others might just need approval by the local quality assurance personnel.

Defects and nonconformance incidents are classified by defect type, cause type, and responsible department (or work-center). Providing this data can help identify areas for improvement. Corrective actions can be initiated from MES to permanently resolve repeating issues documented in discrepancies. Corrective Actions should be linked to the related discrepancies to track improvements of designs, processes and suppliers.

2.8. Production/Plant Performance Analysis

Making informed management decisions requires good performance metrics for the organization. Several studies have revealed that a manufacturer’s success is largely correlated with how effectively the organization measures operational performance. At the same time, studies reveal that only a fraction of manufacturers have effective procedures in place for capturing and measuring performance. MES provides up-to-the-minute reporting of actual manufacturing costs and results, along with the comparison to past history and expected business results.

An MES provides a platform for consistently collecting reliable real-time data from day-to-day operations. Then it automatically rolls this data into reliable departmental and enterprise level performance metrics, and Key Performance Indicators (KPIs). The MES is already compiling data for process control and regulatory compliance purposes. As a result, there is minimum redundant data collection solely for the purposes of metrics. The performance analysis may be prepared as a daily or weekly report, or presented on-line on demand.

Questions on the mind of the management team might change periodically depending on the business climate, but usually include questions such as the following:

- Do we have the resources to deliver what is due?
- What constraints are holding us back?
- Are we overrunning planned costs?
- Where should we invest for improvement?
- How much do we invest in quality?
- How much are errors and rework costing us?
- What percent of poor quality is due to supplier versus internal?
- How quickly do we respond to unplanned issues?
- Are process improvements effective? Are we really improving?
- Can I demonstrate compliance? Am I ready for regulatory audits?
2.8.1. Schedule/Capacity Performance Analysis

Understanding the real potential capacity of a manufacturing facility (or system) can be a challenge. The actual capacity can be masked by many factors, such as inadequate buffer inventory, labor issues, equipment downtime, part shortages, or poor quality. Metrics can help identify areas of poor performance, and provide the ability to drill down to dimensions that help identify where constraints in the plant are affecting capacity and schedule.

Schedule and capacity metrics may include the following:

- Throughput Rate = Units produced per calendar day
- Personnel Productivity = Units produced per labor hour
- Performance to Standards = (Operating Time/Total Pieces)/(Ideal Standard Time per Piece)
- Labor Performance = Standard Labor Hours/Actual Labor Hours
- Late Days to Schedule Date
- Cycle Time Efficiency = Value Added Cycle Time/ Total Cycle Time

Lean manufacturing principles include the ability to provide easy visibility to production personnel, and to issues at the shop floor. Andon dashboards can provide visibility to each work center on how the daily production rate is comparing to the scheduled goal.

2.8.2. Cost and Quality Performance Analysis

Six Sigma practitioners use the DMAIC (Define, Measure, Analyze, Improve, and Control) process to systematically determine the best areas for improvement, and the variability for reduction in a manufacturing process. Lean practitioners refer to the Toyota problem solving methodology, and to kaizen events. Any of these methodologies can be supported with metrics derived from manufacturing data.

MES can provide performance analysis reports based on data collected during manufacturing and defect reporting. This information can help identify probable causes behind poor performance, by correlating different product lines, components, resources, or processes. Pareto charts are effective tools for this type of analysis.

Good metrics can also help understand the organization’s cost of quality. This includes both the cost of proactive measures, and the cost based on the consequences of poor quality. Measures of cost and quality can include the following:

- Yield = Good Pieces / Total Pieces
- Labor Loss Rate to Poor Quality = 1 - (Rework Labor Hours)/Total Labor Hours
- Component Defect Rate
- Customer Rejects/Return Material Authorizations
- Number of Safety Incidents per Year
- Number of Significant Findings in Audits per Year

Continuous monitoring and analysis of KPIs provides a base for production improvement. The performance indicators can be evaluated in different breakdowns (by work center, product group, process type, or supplier), analyzed, and used to identify areas for improvement or corrective action.
2.9. Systems Integration Services

Integration of plant floor systems with engineering and business systems, allows a streamlining of business processes that span across the organization. This includes product and process change management procedures. The discipline and agility acquired through enterprise systems integration can provide significant competitive advantage to an organization.

Many leading manufacturers are integrating their manufacturing system to the Enterprise Resource Planning (ERP), and Product Lifecycle Management (PLM) systems. PLM handles the product definition (including specifications and geometry), ERP handles market facing activities (including planning demand fulfillment, purchasing, and inventory control), and MES handles product realization activities (including work execution, work-in-process tracking, and quality management). The tight integration of these systems can compress time-to-market for both new product and major product upgrades.

To facilitate integration across enterprise systems, an MES should provide integration interfaces that support integration via XML, and services conforming to guidelines published by standards groups. These include ISA (International Society of Automation), OAGi (Open Applications Group), and OPC Foundation.

![Diagram of integration interfaces between PDM, ERP, and MES systems](image)

2.9.1. Engineering Product and Process Design Systems

The integration of engineering systems (including CAD and PLM systems), to the manufacturing system can assure that engineering design changes are correctly incorporated into the manufacturing process definition. The integration also ensures that products in-process are properly updated with the latest engineering revision level, assuring that the “as built” configuration matches the “as designed” configuration.

Engineering system integration should include the following interfaces:

- Part/Material Number and Attributes
- Design Documents including Drawings, 3D Models, and Process Specifications
- Bills of Material (BOM)
- Engineering Change Notices (ECN)
2.9.2. Business Procurement/Inventory and Financial Systems

Integration between the manufacturing system and Enterprise Resource Planning (ERP) software should include the following integration interfaces:

- Departments, Work Centers
- Personnel, Skills and Certifications
- Part Substitutes and Procurement Data including Suppliers
- Work Order Routings
- Work Order Release to Production
- Work Order Operation Schedule Updates
- Work Order Operation Status
- Work Order Splits
- Parts/Material Issues to Work Order or Operation
- Job clock on/off transactions

The integration between ERP and MES can enable more efficient practices. For example, scheduling and status can be performed at an operation level to allow parts issued at the operation level, instead of the work order level. Job clock-on/off can be transmitted to ERP (or labor tracking system) from MES to allow redundant labor clocks to be eliminated.

2.9.3. Enterprise Business Intelligence

Many organizations want to benchmark performance using Key Performance Indicators (KPIs) at an enterprise level. Many KPIs are composite indexes that look across different aspects of the organization including sales, inventory, cost, suppliers, and customer managing systems and metrics. To consolidate these different data sources into one enterprise data warehouse, there are two primary alternate approaches: federation and integration.

Integration involves physical consolidation of the data. This means the data may be transformed, converted, and/or enhanced to maintain the interrelationship. Federation typically implies a more temporary integration of the data. For example, a query is executed that requires data to be accessed (and perhaps joined), from multiple heterogeneous environments. After the queries are done, the original data still resides within the original source environments. In federation, the joined results are not duplicated in permanent data storage.

The MES datamart should facilitate the roll up of data into an enterprise data warehouse. If the MES datamart provides clean data with proper dimensions, it helps in creating a federated scheme for the enterprise.

KPIs that require data from both ERP and MES data sources include:

- Perfect Order – Considers work order accuracy (quantity, model, revision); component issue accuracy (part number, revision, quantity); on-time delivered product; defect free delivered product (no warranties claims); and invoice and product documentation accuracy rate.
- Inventory Turnover (aka Inventory Turns) – Considers Cost of Goods Sold from stock sales during the past 12 months.
- Supplier Rating – Considers price, schedule, and quality history then compares with supplier choices for future purchases.
2.9.4. Enterprise Continuous Improvement Management

A formal methodology for implementing and tracking continuous improvement is an important part of the overall enterprise quality management system. Continuous improvement tracking is done via a corrective and preventive action (CAPA) process.

The MES provides data that is used to determine areas for improvement. Corrective actions can be initiated to address (a) recurring nonconformance issues, (b) supplier issues, (c) issues found during procedural audits, and (d) poor performance areas. It is important to be able to tie corrective actions back to the original issues within an order, to verify effectiveness of the implemented actions. Warnings and containment actions within MES may be tied to the completion of specific corrective actions.

Investigations performed for root-cause analysis and procedural audits require access to production history information. This information includes details about who did what, when, and how it was done. In addition, it shows information about deviations from the standard configuration and processes.

3. A Few Other Considerations

This document identifies functional requirements for MES in complex discrete manufacturing. These requirements form a foundation for software selection, but there are a few other dimensions to evaluating a software solution and a vendor to support the organization. The questions below are examples of other important considerations when evaluating software technology and vendor capabilities:

- Is the complete MES functionality provided in a single tightly integrated system?
- Does the MES provide configuration capabilities for roles, workflow, additional fields, reports, alerts and dispatch lists?
- Does the MES provide an integration platform and the required interfaces for integration to enterprise systems including ERP, HR, and PLM systems?
- Does the MES vendor have expertise working with similar manufacturing companies in your specific industry?
- Can the MES software be supported after implementation with the skills available in your information technology team?
- Does the MES vendor have an annual forum or conference where your organization can exchange best practices with other users of the product in your industry?

The functionality requirements provided in this document provide a basis for an evaluation of commercial MES software solutions in the market. These requirements can be merged with additional specific requirements from your organization and shared with a vendor as part of a qualification process to down select MES software. This process is often formally done by sending a Request for Information (RFI) document to several candidate software vendors.

Selecting a software solution with a good fit to the organization’s business processes is a very critical factor to success in an MES implementation project. Just as important will be the organization’s commitment of resources to the project, and the management of risk during implementation to keep the project focused to the original project goals.
About Author

Conrad Leiva is currently VP Product Marketing and Alliances at iBASEt. His career has included consulting with many Aerospace & Defense companies on how to streamline the paperwork and information flow among Engineering, Quality, Production and Supply Chain disciplines. Recently, Conrad has focused his work on Manufacturing Intelligence and the integration between PLM, ERP and manufacturing systems working with PLM and ERP partners.

Conrad is a graduate of M.S. Industrial Engineering from Georgia Tech and holds certifications in MES/MOM Manufacturing Operations Management Methodologies, Product Marketing, and is a Certified Quality Auditor. Conrad is also a board member at MESA (Manufacturing Enterprise Systems Association) and a frequent contributor to MESA publications.

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