ISSUES OF MANUFACTURING ENGINEERING DATA VALIDATION IN CONCURRENT ENGINEERING ENVIRONMENT

C. McLean, S. Leong, and C. Chen
Manufacturing Systems Integration Division
National Institute of Standards and Technology
Gaithersburg, MD 20899, USA
Phone: (301) 975-3511; FAX (301) 258-9749
E-mail: mclean@cme.nist.gov

Abstract

Manufacturing engineering data validation is a critical engineering activity in the product realization process. This paper identifies a set of manufacturing engineering data which is required for production in a machine shop, examines error sources, and proposes a validation methodology for implementation in a computer-integrated concurrent engineering environment. In a sense manufacturing data validation is similar to the practice of inspecting materials and components coming into a shop--the quality of manufacturing engineering data must also be assured before it is released to the shop floor. The ultimate goal of data validation research is to establish techniques that will enable a production facility to produce a product correctly the first time.

Keywords

Engineering information modeling, manufacturing data validation, concurrent engineering, virtual manufacturing.

1 INTRODUCTION

A typical product realization process is divided into three stages: product design, manufacturing engineering, and production. Product design deals with product modeling, functional analysis, and design documentation. Manufacturing engineering specifies the manufacturing procedure and resources required to transform the design into a finished product. Production carries out the engineering plan (product and process design) by coordinating customer orders and resources available to the production system. Among the three, manufacturing engineering has been the most problematic and the least computerized. For the most part, manufacturing engineering still relies on laborious human involvement and is commonly viewed as an art, despite of numerous developments and advances in this area by the CAD/CAM research community in the past decades.

There are few software tools used routinely in industry for automatic generation of manufacturing engineering data. Tools which do automatically generate data typically focus on a narrow portion of the manufacturing engineering problem domain. The main reasons for the lack of tools has been that: 1) there is no effective way of capturing manufacturing knowledge and experience for computer applications, 2) manufacturing inspection package development. Process planning was decomposed into three subtasks: resource selection, plan creation, and plan validation and approval. Tooling package development was decomposed into: tooling strategy development, tooling data generation, tooling package verification, and tooling package release and control. Machining package development was decomposed into: NC strategy development, NC machining package preparation, NC data package verification, and NC package release and control. These tasks were further decomposed into more detailed tasks. For example, resource selection consisted of: facility selection, material selection, equipment selection, tooling selection. On the other hand, process plan creation consisted of: in-process shapes/features/attributes generation, process selection, and operations sequencing.

Another manufacturing engineering activity modeling effort can be found in a recent document prepared by NIST (1995). In the NIST's report, five major manufacturing engineering planning activities were identified as follows: 1) determine manufacturing methods, 2) determine manufacturing sequence, 3) develop tooling packages, 4) develop equipment instructions, and 5) finalize the production package. The tasks identified under manufacturing method determination were stock material selection, process selection, major resources selection, and preliminary cost estimation. Under manufacturing sequence determination were: operation specification, operation sequencing, part routing, and plan validation. Under tooling package development were tool selection, tool design, and tool cost estimation. Under equipment instructions development were: in-process part description, tooling requirement specification, operation instruction generation, machine program generation, and equipment instruction validation. Under production package finalization were: final cost estimation, resource package release, scheduling package release, and plan library update.

Both models are intended to capture manufacturing planning activities in the job shop environment. The NIST model however includes, and highlights the importance of, data validation and cost/performance evaluation activities in the planning process. These validation activities may be viewed as an "in-process" validation function. There are additional needs for data validation. For example, a receiving validation is needed when a manufacturing order is being released to the shop floor or external manufacturing data are received.

The manufacturing planning activities are generally inter-related. An upstream decision frequently becomes a constraint to its subsequent decisions, which may also be fed back to preceding activities for design and process changes. For example, a setup decision is a constraint to NC programming, but difficulties found at NC programming may be sent back to the process planner for process modification.

The input data required for these activities include product design, production data, and manufacturing resources. Product design specifies part geometry, form features, material, and tolerances. These product data help the planner narrow the scope of feasible manufacturing processes. Production data allow the planner set a target production quantity and lead time for the process plan. Also it further limits available manufacturing options. Manufacturing resource data such as machines, tools, fixtures, raw materials, and process knowledge are critical to the process decision. The knowledge of resource availability and capability not only enables the planner to make feasible engineering data and their representations are not well defined, and 3) manufacturing practices differ significantly among companies. Even fewer computer tools are available for manufacturing data validation. No effective modeling tools exist for capturing engineering and manufacturing resource functionality for data validation. Thus, manufacturing engineering data are often inaccurate and incomplete. Errors sometimes remain undetected until the data is first used on the shop floor, ultimately resulting in data rework, delays in production and product delivery, and higher manufacturing costs. This problem can be critical in production environments where there are long engineering lead times, where engineering data are frequently changed, or where data are shared by a number of engineers involved in product and process development. An automatic data validation tool kit is thus highly desirable, especially when manufacturing engineering data are generated by external resources and the efficiency of a receiving inspection of these external data is a major concern.

The goal of this research effort is development of a manufacturing data validation methodology which, upon its completion, will be able to ensure that the data are complete, correct, and up to date such that the product can be made correctly, as planned at the first time The problem is further complicated in environments where product design and resource availability may evolve constantly, subsequently affecting the validity of downstream manufacturing engineering decisions.

This paper is focused on the modeling and validation of manufacturing process data. The problem domain is limited to the machining job shop environment in which there exist no production lines and no major changes to the production system layout are expected. To outline the manufacturing engineering process in a typical job shop environment and set the scope for further discussion, a brief overview of major manufacturing planning activities is presented in the next section. Section 3 highlights various types of manufacturing engineering data and presents an integrated manufacturing information model. The types of data errors and validation needs are identified in Section 4, followed by a presentation of a data validation methodology in Section 5. A description of the implementation currently under way at NIST is presented in Smith (1995) and is summarized at the end of this paper with concluding remarks.

2 MANUFACTURING ENGINEERING ACTIVITIES

There are three basic functions of manufacturing engineering in a typical manufacturing firm. They are manufacturing administration, manufacturing planning, and process engineering. Process engineering includes design of tooling and production line setups. This paper is focused on the manufacturing planning function and to a lesser degree, the administration function, because they directly contribute to manufacturing data generation and validation.

The modeling of manufacturing engineering activities has been frequently reported in the literature in recent years. Most of these activity models are presented in IDEF0, which organizes activities in a hierarchical structure. For example, in Parker (1994), manufacturing engineering activities were organized into four major tasks: process planning, tooling package development, machining package development, and decisions but also improves the decision efficiency by further limiting the scope of feasible solution space; for all planning decisions are made based on available resources, whether they are internal and/or external. However, all the input data are subject to change, which may make a feasible process plan invalid at the time of use. To ensure the validity, some control mechanism needed to monitor and broadcast changes to affected engineering data entities.

Most manufacturing engineering data are still manually generated, even though computer tools are available for assistance. For example, typical process planning systems used in industry still rely on user input for decisions such as feature recognition, process selection, and setup configuration. The planning systems provide a mere working environment for facilitating supplemental planning activities such as plan formatting, plan storage, and data retrieval. For NC programming, APT-based programming systems are typically used to assist in geometry definition, features identification, and tool path generation. Again, in most cases, the user still has to specify part geometry, tool path boundary, and machining parameters. The manufacturing data generated by these planning activities are commonly called routings, operation sheets, material lists, tool lists, fixture lists, machine setups, workpiece setups, tool designs, in-process inspection plans, operator instructions, and NC programs.

3 MANUFACTURING ENGINEERING DATA

Manufacturing engineering data can be broadly classified into two types: product data and process data. Product design data may be documented in CAD models (or data files) and are often translated into engineering drawings for the shop floor. Engineering change orders which record changes to an engineering design may also be included. Primary manufacturing process data are identified as the following nine types:

1. route sheet,
2. stock material specification,
3. intermediate stock shape and geometry,
4. operation sheet,
5. machine setup sheet,
6. workpiece setup sheet,
7. tool list,
8. fixture list, and
9. NC program.

A route sheet specifies a sequence of workstations which each workpiece must visit. It may include both processing stations and queue stations. It may also include scheduling data such as expected arrival time and duration of stay at each station. A stock material specification denotes the initial size and shape of the selected stock material. The selection is done according to the material type and its AISI code specified in the product design. An intermediate stock shape and geometry records the resulting form features and geometry created on the workpiece at each processing step.

Intermediate shape data are critical to workpiece setup and NC programming. To define intermediate shape information for manufacturing, form features are commonly considered as an effective means. An operation sheet contains a set of sequenced machining operations to be performed on the machine with a given workpiece setup. Thus each operation sheet is usually supplemented with a machine setup sheet and a workpiece setup sheet.

A machine setup sheet contains instructions for setting up the machine for the operations specified in the operation sheet. It may include the assignment of cutting tools to specific locations in the tool magazine on the designated machine. If multiple tools are specified in the setup, a tool list needs to be created to list all tools required in this setup. A workpiece setup sheet specifies how the workpiece will be set up on the machine. It may be accompanied by a sketch of the fixturing configuration. If fixture components are used, a fixture list is then required to list the fixture elements to be used for the setup. An NC program is a set of machine instructions prepared for a machining activity. It is machine controller-specific. An NC program is typically prepared for a workpiece setup.

In practice, some of these manufacturing data such as setup instructions and fixture lists may not be made explicitly available and are not formally defined in the manufacturing engineering data packet for the shop floor because they may appear to be trivial and/or tedious. Furthermore, manufacturing process data and formats used in different company may vary considerably. These variations makes manufacturing data exchange and validation extremely difficult. Thus the modeling and standardization of manufacturing data has become a recent research focus in the CIM community. A generic process model called ALPS is presented in Ray (1992). Its application includes modeling of process plans for machining parts. A process plan model specifically developed for NC machined parts can be found in Parker (1994). It attempts to capture all related data entities. By simplifying the above modeling concepts, an object-oriented process data representation schema was proposed and implemented in Sanchez (1994). In the implementation, many data types such as manufacturing features and manufacturing resources were populated and evaluated for their compatibility.

A manufacturing information model has been developed based on the work reported in Parker (1994) and Sanchez (1994) with an emphasis on its compatibility with commercial CAD/CAM packages and current industry practice. Due to limited space, the information model can not be shown here. For the full information model, see Chen (1995). The information model shows that a process plan may have a number of subprocesses, of which each specifies a workstation, a process activity, and a material removal volume (MRV) subset. Each workstation identifies a machine selected to carry out a processing activity. Each processing activity includes a workpiece setup, a machine setup, and the processing task, which is often termed as a material removal activity in the machine shop environment. Each workpiece setup links to a fixture list, while each machine setup points to a tool list, if multiple tools are used. A material removal activity is accompanied by an NC program and a number of operation clusters. An operation cluster denotes a sequence of operations which collectively create a manufacturing form feature (MRV). In other words, an operation removes only a portion of a manufacturing feature (a part of an MRV and called elemental MRV in the figure). Furthermore, each MRV may be constrained by one or many islands, which are converted from protrusions defined in the product model and are treated as physical constraints to the material removal activity. Similarly an elemental MRV may have elemental islands as its constraints. Among the nine manufacturing process data, only route sheets are not explicitly captured in the proposed representation scheme. However, the data required for creating a route sheet such as operations sequence and workstations are available in the model.

4 TYPES OF MANUFACTURING PROCESS DATA VALIDATION

The validity of manufacturing data largely depends on the time-phased cogency of: 1) product design, 2) resource data, and 3) the applied manufacturing engineering knowledge. Because these input data are likely to change over time after decisions are made, the manufacturing engineering data may later become suboptimal or invalid. Thus validation is needed not only at the time of data generation but also at the time of applying these data. Five types of potential data errors and validation needs are identified as follows:

- data integrity,
- resource availability,
- resource capability,
- process validity, and
- cost/performance metrics.

Data integrity deals with the issues of data availability, version control, and data structure (syntax). Data availability checks the existence of each required manufacturing engineering data. Version control ensures that the latest or a correct version of input data is used for generation of manufacturing engineering data. Data structure or syntax ensures checks that data is correctly formatted. A typical data integrity problem is caused by using a wrong version of product and/or process design. For example, an old process plan version may be used to generate NC programs because the NC programming department was not aware of the update.

Resource availability verifies that manufacturing resources specified in the process plan are available. After planning, a selected resource may become unavailable due to reasons such as obsolescence, maintenance, or schedule conflicts. Hence manufacturing data must be re-checked for resource availability before they are released to the shop floor. Process capability is concerned about whether the selected resource has the capability to reliably perform the specified task. Two primary sources of process capability problems are: 1) the resource capability was mis-represented, or 2) the resource's capability has been down-graded (updated) after planning was completed. For example, a machine's repeatability and accuracy may have deteriorated after a period of service.

Process validity is concerned about whether process data such as operation sheets and machine control instructions will perform the task as planned. Typical process validity problems include: 1) inappropriate operation sequence, 2) insufficient setup/teardown instructions, 3) fixturing damage to the workpiece, 4) inappropriate selection of tools, machining parameters, and reference points, 5) collision of a tool holder into the machine tool, fixtures, and/or a workpiece setup, 6) gouging and undercut, 7) workpiece deformation, and 8) thin-wall effects on adjacent form features.

The validation of manufacturing data for cost and performance concerns is different from the other four types of validation. It does not attempt to evaluate the feasibility of the manufacturing engineering data. Instead it is concerned about the optimality of the manufacturing planning decision. It may identify expensive operations, excessive load and unload time, and bottleneck stations. It may also search for less expensive stations.

5 VALIDATION METHODOLOGY

For development of a generic validation methodology, a standard manufacturing engineering data representation is critical. It is a certain requirement for implementation of a computer integrated validation system. In today's manufacturing practice, most data validation is done by the planner who generates the data, and verified (approved) by a supervisor or another planner. Common validation methods are visual inspection, computer graphic simulation, and try-out on a real machine. Although manual inspection and machine try-out are the most common approaches to data validation, significant progress has been made toward development of computer-based data verification techniques.

The development of data validation tools has been largely limited to NC program simulation. Most computer-aided NC programming packages today have some graphic simulation capability for tool path verification. There also exist stand-alone packages for NC program verification, aiming at manually- or externally-generated NC programs. In either case, however, the user still must observe the graphic display and determine whether or not the program is correct, or whether collisions occur. Automatic collision detection capabilities have become available recently in some graphic simulation modeling packages such as Deneb's VNC (1995). Limited capability of operations sequence verification can also be found in recent versions of process planning systems such as ICEM/PART (1994). This is done by checking whether or not the specified removal sequence of manufacturing features violates any physical constraint on the workpiece.

Based on the manufacturing data types and potential errors presented in Sections 3 and 4, the needs for data validation are identified in Table 1. As shown in the table, four manufacturing data types need to be validated for each of the five potential data errors. They are: route sheet, operation sheet, tool list, and fixture list. Machine setup, workpiece setup, and NC program require validation for data integrity, process validity, and cost/performance metrics. Stock material specification needs to be evaluated for data integrity, resource availability, and cost and performance. The only concern with respect to intermediate shape and geometry data is data integrity.

From a data validation point of view, data integrity checks are required for all data types. A resource availability check needs to be applied to those data types which require manufacturing resources. The need for resource capability validation is similar to those for resource availability, except stock material specification. The check for process validity is required for all but stock material specification and intermediate shape data. A cost and performance evaluation can be applied to all the manufacturing data types.

Table 1: Needs for Manufacturing Engineering Data Validation

Data Type	Data Integrity	Resource Availability	Resource Capability	Process Validity	Cost/PerformMetrics
Route sheets	x	x	x	x	x
Op. sheets	x	x	x	x	x
Stock specs.	x	x			x
Inter. shapes	x				x
Tool lists	x	x	x	x	x
Fixture lists	x	x	x	x	x
M/T setups	x			x	x
Work setups	x			x	x
NCprograms	x			x	x

It is possible to develop a validation method for each validation need as identified in the table. For example, a validation technique may be desired for checking the availability of resources identified in an operation sheet. One drawback is that there will be many validation packages. It is advantageous to develop a validation tool for each data type for checking all its potential data errors. Such a tool could be easily incorporated into a manufacturing data generation package for an "in-process" data validation. On the other hand, it is also desirable to develop a validation tool for each error type. For example, a validation method could be developed to check only data integrity but for all data types. If so, a logical validation procedure should be to check for: 1) data integrity, 2) resource availability, 3) resource capability, 4) process validity, and then 5) cost/performance.

Data integrity needs to be checked first, to make sure that all required manufacturing data are available and complete; and they are prepared based on the most up-to-date or correct version of input data. Resource availability should be the second step in the validation process. It identifies resources specified in the data and checks if selected resources are available at this time. If they are, a check for resource capability should then be ordered. Otherwise, the problem should be reported and no need to continue for further validation. Resource capability verifies whether each resource can properly perform its intended task. It can be done by checking against its static capability as recorded in the database and may be done independently for each selected resource. An example might be checking to see if each tool in the tool list can properly cut the selected stock material.

Data validity checking is required to ensure that each manufacturing data entity is valid and complete. All manufacturing data may be required for this validation. For example, if a hole is to be drilled on a machine, the validation has to make sure that the hole can be created and precisely located on the workpiece, with the given machine, tools, setup instructions, and fixturing configuration. If an operation sheet is to be evaluated for its process validity, machine setup and workpiece setup need to be first examined, which in turn may retrieve and examine the intermediate stock shape and geometry. In our view, process data validity is the most complicated and challenging validation task. After passing the above four validation tests, the manufacturing process data are considered as valid. The last data evaluation of cost and performance is an attempt to improve its optimality.

For validation of data integrity, a simple data inventory list may be sufficient for checking the existence of each data entity required; on the other hand, an engineering business model may be sufficient for information flow management and version control. For validation of resource availability and capability, a search algorithm will be developed to identify the resources specified in the manufacturing data and verify their existence and capability against the records in the database. For this purpose, a standard manufacturing data representation and a database system will be required. For validation of process validity, computer-based graphic simulation techniques have been widely applied. However, in addition to material flow simulation, various functional models of manufacturing resources and systems need to be created for each application. A computer-based technique for automatic generation of functional models for manufacturing resources such as machine tools and fixturing configurations will certainly improve the validation efficiency and effectiveness. Current simulation capability is still largely limited to statistical data collection and graphic display with only very limited capability of collision detection for NC program verification. Additional capabilities such as material deformation, think wall effects, and tolerance analysis have to be included. Emerging virtual reality techniques could be helpful in construction of virtual machines and manufacturing systems for the proposed data validation.

6 IMPLEMENTATION

Significant progress has been made at NIST toward development of a manufacturing engineering data validation tool kit. Due to the fact that manufacturing data may come from various sources, the need for standard resource and process data models has been recognized. The development of a generic information model is under way. A system architecture and a database management system are being defined to support various engineering activities on different computer platforms and to maintain the vast amount of product, process and resources data. The implementation of the proposed validation methodology is intended to validate manufacturing data at the time when each data entity is created and re-check the data when a manufacturing data packet is being prepared for a manufacturing order.

In addition to the development of a distributed system architecture and manufacturing resource and process data repositories, the implementation effort also includes development of computer-based validation tools for checking data integrity, resource availability, resource capability, and data validity. Development of cost and performance validation tools are also being considered. The system environment is expected to support sharing of various data generated by commercially-available, heterogeneous CAD/CAM systems. The standard information model under development will be used to capture commonly needed manufacturing resources and process data, which will be stored in a distributed database management system and be concurrently accessible by multiple application systems. A number of commercial CAD/CAM systems including Matrix (1994), Pro-Engineer, ICEM/PART (1994), and Deneb's I-GRIP, Deneb VNC (1995b), and Quest (1995a) are currently being integrated to create the concurrent engineering environment.

Matrix is a product data management (PDM) system. It is used to implement an engineering business model for data integrity validation and information flow control. Pro-Engineer is a CAD system used to create test product designs. ICEM/PART is used to interpret a Pro-Engineer model and generate a process plan (operation sheet) for prismatic parts. It will be integrated with other applications to share resource data and store process plans in the database. A validation module will be implemented for checking availability and capability of resources as recorded in the database. Deneb's software packages are initially used to manually create functional models of selected manufacturing systems and resources for process data validation. Automatic modeling of these functional models based on a script will be the next step toward the tool kit development.

7 CONCLUDING REMARKS

Manufacturing engineering data validation is an integrated part of the manufacturing planning process. It is, in our view, the most problematic and the least computerized engineering activity in the product realization process. The main reasons have been: 1) there is no effective way of capturing manufacturing knowledge and experience for computer application, 2) manufacturing engineering data and their representation are not well defined, and 3) manufacturing practices differ significantly among companies. An additional obstacle to validation tool development is that there are no effective tools for creating functional models of manufacturing resources with enough functionality for data validation. Thus, manufacturing engineering data are often inaccurate and incomplete; and errors are sometimes undetected until the data is first used on the shop floor. If only validated data reach the shop floor, many production and delivery delays may be eliminated and higher manufacturing costs may be avoided.

The research effort reported in this paper is aimed at development of a methodology for manufacturing engineering data validation. To this end, nine major manufacturing engineering data types are identified: route sheet, operation sheet, stock material specification, intermediate stock shape and geometry, machine setup, fixture setup, tool list, fixture list, and NC program. Various error sources have been studied and the needs for validation are identified in five categories: data integrity, resource availability, resource capability, process validity, and cost/performance. Validation for data integrity and cost/performance metrics are required for all data types. Resource availability and capability checking should be applied to those data specifying resource usage such as route sheets, operation sheets, tool lists, fixture lists, and stock material specifications. Process validity is the most difficult validation because functional models of manufacturing resources and systems are required to simulate the physical manufacturing process.

The implementation of an engineering data validation system is currently under way at NIST. A number of commercially-available CAD/CAM systems have been assembled and integrated for implementation of a manufacturing engineering data validation tool kit. Among them, Matrix is used for information flow and data integrity control. Deneb's VNC is used to create a functional model of resources for process validation. Quest is used to model material and resource flows on the shop floor. Additional validation tools are being developed for resource availability and capability validation.

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9 BIOGRAPHIES

C. McLean: Group Leader of Manufacturing Systems Engineering, NIST Manufacturing Systems Integration Division. Managed research programs in manufacturing automation at NIST since 1982. Established research program in Computer-Aided Manufacturing Engineering with emphasis on engineering tool integration, manufacturing data validation, production systems engineering, manufacturing simulation, production scheduling.

S. Leong: Joined NIST in 1994, after sixteen years in the manufacturing industry. Established experience at Ford Motor Company, John Deere, and IBM in design, development and implementation of factory automation systems. Spent the last eight years in providing manufacturing consulting services to manufacturers for design and implementation of manufacturing execution and shop floor control systems.

C. Chen: Professor of Florida International University working on IPA as an Industrial Engineer of the Manufacturing Systems Engineering Group in NIST Manufacturing Systems Integration Division. Research interests include engineering information modeling, CAD/CAM systems integration, and production planning and scheduling