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A State-of-the-Art Survey of Methodologies for Representing Manufacturing Process Capabilities

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Abstract

Representations of manufacturing process capabilities are essential for the integration of manufacturing applications as well as the dynamic management of factory data. This survey presents methodologies for describing and using such information within the domain of discrete parts manufacturing. Current practices in industry are identified. Standards and research efforts related to representing manufacturing process capabilities also are described. Finally, a course of action for advancing current practices is presented.

Keywords: computer integrated manufacturing, manufacturing processes, manufacturing resources, modeling methodologies, process capabilities

Introduction

This paper describes the state-of-the-art of methodologies for representing manufacturing process capabilities for discrete parts manufacturing by investigating applicable principles, practices, and procedures. Moreover, this evaluation examines the use of manufacturing process capability representations for the integration of computer-based engineering applications and for the dynamic management of factory data.

A review of the literature revealed various definitions and interpretations of the term *manufacturing process*. For the purposes of this effort, manufacturing process is defined from a manufacturing engineering perspective. That is, a manufacturing process is an action or sequence of actions upon some material to produce a desired part. Therefore, a *manufacturing process capability* is the physical ability of a manufacturing process to perform one or more form-generating operations to some level of accuracy and precision. This ability often is described in terms of attributes related to the manufacturing equipment used to realize a feature of a part. Attributes may include geometry, topology, size, geometric tolerance limits, surface finish limits, common geometry errors, material, equipment control parameters (e.g., feed, speed) and working envelope.

Manufacturing process capability information is necessary for the implementation and application of several key technologies within a rapid response manufacturing environment. As identified by members of the National Center for Manufacturing Sciences (NCMS) Rapid Response Manufacturing (RRM) industry consortium[1], these technologies must support applications within design engineering, manufacturing engineering, and production engineering such as design/manufacturing trade-off studies, automatic process plan generation, and dynamic resource allocation and

1. This survey was performed for the National Institute of Standards and Technology (NIST) Rapid Response Manufacturing Intramural Project under the sponsorship of the U.S. Department of Commerce Advanced Technology Program. This effort was performed by staff of the NIST Factory Automation Systems Division (FASD) in collaboration with the NCMS RRM industry consortium. The mission of FASD is to provide a focus for national research and standards efforts related to information systems for manufacturing.

scheduling. This survey provides background information necessary for developing manufacturing resource and process information models for use within a rapid response manufacturing environment.

This assessment focuses primarily on the domain of discrete parts manufacturing. However, efforts in the electronics industry are cited, since discrete parts as well as continuous processes are used to manufacture electronics components. An objective of this paper is to present a broad perspective of trends in representing manufacturing process capabilities; it is beyond the scope of this paper to analyze any one specific type of discrete manufacturing process (e.g., drilling, casting) in depth.

This paper attempts to answer the following question: How are manufacturing process capabilities represented? For the most part, today's computer-based manufacturing applications use an assortment of models. This paper considers two general types of models: those that enable the integration of manufacturing applications (i.e., information models) and those that improve the understanding of a specific process (i.e., mathematical models). Since the integration of computer-based engineering applications is the impetus for this evaluation, efforts related to information modeling are emphasized. Nonetheless, models specific to manufacturing applications are discussed in a general sense for reasons of clarity. Often, information described in or by a mathematical model must be included in the information model for the successful integration of manufacturing applications.

This assessment describes various efforts related to the use and representation of manufacturing process capability information. Examples from industry which describe the progression of representations are presented. Standards efforts related to information modeling and manufacturing equipment performance evaluation are also discussed. Additionally, recent and current relevant research efforts are identified. Finally, this paper identifies a course of action for moving the current state-of-the-practice for representing manufacturing process capabilities toward the current state-of-the-art.

Current Practice: Examples from Industry

This section examines current trends within industry regarding the use and state of manufacturing process capability information. Whenever possible, representation details are presented. However, this information is not included in all cases due to proprietary constraints. The examples that follow represent current practice among manufacturers and manufacturing software vendors. The determination of process capability from statistical process control data is also discussed.

While some companies rely on manufacturing engineers to look up manufacturing process information in various handbooks, others access this data in stand-alone, computer-based engineering applications. Still other companies use manufacturing process capability information which has been integrated with various applications of design engineering, manufacturing engineering, and production engineering. This section illustrates a progression of manufacturing process capabilities representations in terms of manufacturing resources (e.g., machines, tools, fixtures) from printed media to electronic media.

Information in Printed Media

Despite the advances of computer-integrated manufacturing and information technology, many engineers continue to reference vendor catalogs, generic manufacturing process handbooks [5] [21] [35] [37], and company-specific manufacturing process handbooks for detailed information about the capabilities of manufacturing equipment. These catalogs and handbooks represent a rudimentary attempt to model manufacturing process capabilities. Handbooks, in particular, provide classifications and sub-classifications of manufacturing processes, descriptions of such processes and corresponding manufacturing resources, as well as general rules and constraints related to specific processes. They discuss characteristics of and interactions among relevant factors such as part materials, tool materials, tool geometry, cutting fluids, and power/force requirements. Furthermore, many of them include general discussions of part configuration, types of fixtures, dimensional tolerances, and surface roughness. Much of the information is organized in tabular form to facilitate the determination of process details.

For example, typical use of the *Machining Data Handbook* [35] may involve the following steps given the type of machining operation to be performed and the material to be machined. First, locate the pertinent section and tables in the handbook to obtain the hardness and condition requirements and select the feed, speed, and tool material. Second, refer to the tool geometry charts to determine the tool geometry for the given machining operation. Third, consult the cutting fluid recommendation tables to obtain code numbers and select the appropriate cutting fluid. Lastly, obtain unit power requirements for the material and the given operation from the appropriate table (i.e., for English or metric units) and use the pertinent alignment chart or formulae to calculate power required.

The use of these handbooks and catalogs is not conducive to evolving, integrated manufacturing environments for many reasons. First, these sources do not aid the initial process selection. It is assumed that the types of processes and manufacturing resources have been determined previously. Second, the intent of most handbooks is to make nominal recommendations for process parameters such as speeds and feeds. It is up to the process planner to adjust these recommendations based on the conditions of a particular manufacturing environment or factory. Third, the reasoning by which process decisions are made is not captured. Fourth, the parameters described in these references are not consistent among these sources. Fifth, the information contained in these handbooks is not necessarily current due to the time lag between editions. Hence, they do not contain new developments of and improvements to manufacturing processes and resources. Sixth, extracting information from these handbooks is time-consuming and tedious. While the practice of referring to these handbooks may be suitable for some manufacturers, it can be vastly improved by putting the information in electronic form.

Information in Electronic Media

Realizing the value of the data in handbooks and seeing the potential of computer-based engineering systems, manufacturers and manufacturing software vendors alike have moved the information provided in these handbooks to electronic formats. Sometimes the information was simply entered into a word processor. In other cases, the information was organized in a data base to be accessed by one or more computer-based manufacturing applications.

As an example of a data base, the Institute of Advanced Manufacturing Sciences, Inc. (IAMS) produces CUTDATA which it advertises as a computer-based version of IAM's *Machining Data Handbook*. This product is intended to support the following activities: planning machining processes for a part, determining machine-tool requirements, and estimating production time. This software claims to provide a manufacturer with the ability to capture, store, and share in-house machining experience by customizing and expanding the data base. IAMS advertises that CUTDATA supports more than 84000 machining recommendations regarding depth of cut, number of passes, cutting speeds, feed rates, tool materials, tool geometries, and cutting fluids for approximately 1500 materials. In order to minimize machining time and maximize machining efficiency, it calculates cutting time per pass and material removal rates. It claims to calculate horsepower requirements for each cut to prevent machine overload. It also supports other data bases to provide organization and control of manufacturing resources.

Manufacturers developed similar data bases in-house for managing manufacturing resource information such as cutting tools, machine tools, holders/adapters, and gages. These data bases often were developed exclusively for a single application, with little or no consideration given to sharing information with other related applications. Efforts are now underway within several companies to coordinate the information required by various engineering applications for the express purpose of integrating those applications. This coordination activity requires the development of manufacturing resource models which are not specific to any one application.

Building upon its previous experience with stand-alone data bases, Texas Instruments (TI) is consolidating data systems in order to integrate manufacturing engineering applications. Currently, TI uses Oracle data bases to maintain information on cutting tools, holders/adaptors, and machine tools. At the present, these three data bases are accessed by applications for tool management, direct numerical control, feeds and speeds calculation, cutter assembly development, and machine tool maintenance and diagnostics.

In order to leverage existing technologies, TI, Ford, General Motors, United Technologies, and Oak Ridge National Laboratory are working together to develop a manufacturing resource model and resource library. This consortium, which is under the auspices of the National Center for Manufacturing Sciences (NCMS) Rapid Response Manufacturing (RRM) Program, will use the resource model and library in the RRM Integrated Product/Process Model (IPPM). The IPPM is a conceptual schema which includes design and manufacturing information that is required to support product development from conception through production. While the IPPM team must develop models for manufacturing information, for product data it will augment the Standard for the Exchange of Product Model Data (STEP) [24] which is under development within the International Organization for Standardization (ISO).

In a similar effort and as part of the DARPA[2] Initiative in Concurrent Engineering (DICE) Manufacturing Optimization Project [34], Raytheon developed a "virtual process team" concept for concurrent engineering. This concept is a refinement of the

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2. The Defense Advanced Research Projects Agency, recently renamed the Advanced Research Projects Agency (ARPA).

DICE model based on human “tiger teams” in which various geographically dispersed specialists contribute to the development of complex product designs. Figure 1 illustrates Raytheon’s two-level approach in which the bottom level “specialized” process team provides information to the top level product virtual team with a global perspective. This approach allows for a comprehensive representation from each specialized process area for the formulation of the final manufacturing recommendations. The Manufacturing Optimization (MO) System is an implementation of these concepts.

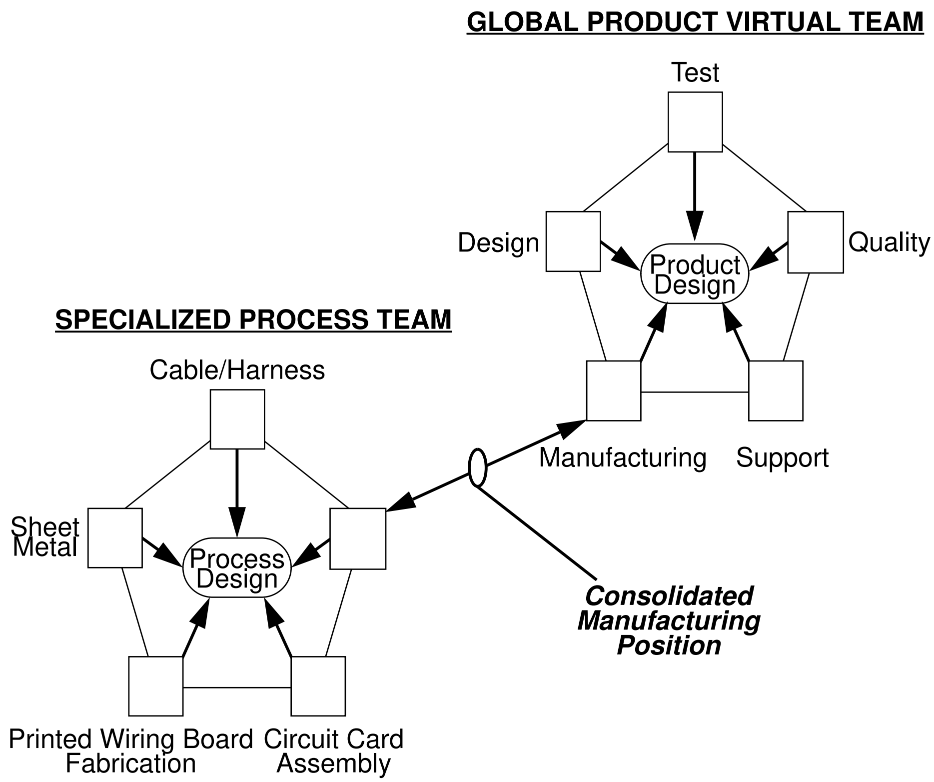

Figure 1 **DICE MO Project’s Two-Level Team Concept†**

†. Lapointe, Linda J., et al., *System Description Document for the Manufacturing Optimization (MO) System*, Defense Advanced Research Projects Agency, Washington D.C., 1993, p. 2.

The purpose of the MO system is to enable all manufacturing specialists to participate in the product/process development activity concurrently. The system provides a set of tools to model the manufacturing processes and to centralize the various process trade-offs. The individual manufacturing participants recommend, compare, and negotiate options among each other. After the manufacturing team has reached consensus, it passes the results to the cross functional (top level) team for their negotiation.

In addition to a Manufacturing Analyzer and a Manufacturing Advisor, the MO System provides a Process Modeler which enables a user to model processes and resources required to manufacture a part. Using an object-oriented methodology, the MO project implemented its Process Model using the EXPRESS and EXPRESS-G languages [16]. A part of STEP, EXPRESS is the official language for specifying aspects of product data. EXPRESS-G is the graphical form of EXPRESS. Figure 2 contains the EXPRESS-G model of the MO process model schema. The process model contains a hierarchical tree structure of a manufacturing activity which consists of reasoning logic, manufacturing data, resources, and ordering information. The reasoning logic describes rules which tie the product to the processes. Types of manufacturing data include processes, operations, and steps. A process is an organized group of manufacturing operations sharing characteristics. An operation is a unit of work performed on the part. Scrap rates, rework rates, and required resources are associated with each operation. A step is an elemental unit of work within an operation. A resource is any facility, person, equipment, or consumable material used in the manufacturing process. They are associated with each process, operation, or step. Finally, sequential or concurrent ordering of children associated with a manufacturing activity is specified.

The RRM IPPM effort and the DICE MO project demonstrate that industry needs and uses manufacturing process capability information to integrate manufacturing applications. Furthermore, these particular efforts provide examples for leveraging existing information technologies and related standards, most notably STEP.

From a production perspective, an increasing number of manufacturers conduct process capability studies using statistical process control data. These studies typically focus on determining the capability of a single process operation, as related to an individual quality characteristic (i.e., variable or attribute data) of a part [22]. From this viewpoint, *process capability* is defined as the "quality performance capability of the process with given factors and under normal, in-control conditions."[3] This definition assumes that the process is described by measurable factors and that the measurements of these process factors are normally distributed and in a state of statistical control. As such, a process is capable "when the process average plus and minus the 3-sigma spread of the distribution of individuals [i.e., single measurements of a characteristic]... is contained within the specification tolerance (variables data), or when at least 99.73% of individuals are within the specification (attributes data),...."[4] Process capability is often referred to by the capability index C_{pk} which is the number of standard deviation units from the process average to the nearest specification limit, with the difference divided by three.

Relevant Standards

This section discusses two classes of emerging and existing standards which are relevant to representing manufacturing process capabilities. First, information standards are discussed because they facilitate the integration of manufacturing applications. Second, standards related to the performance of manufacturing resources are covered, since relationships can be drawn between manufacturing resource performance and manufacturing process capability.

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3. Feigenbaum, Armand V., *Total Quality Control*, 3rd ed., McGraw-Hill, New York, 1983, p. 779.

4. Ford Motor Company, *Continuing Process Control and Process Capability Improvement*,1987, p. 55.

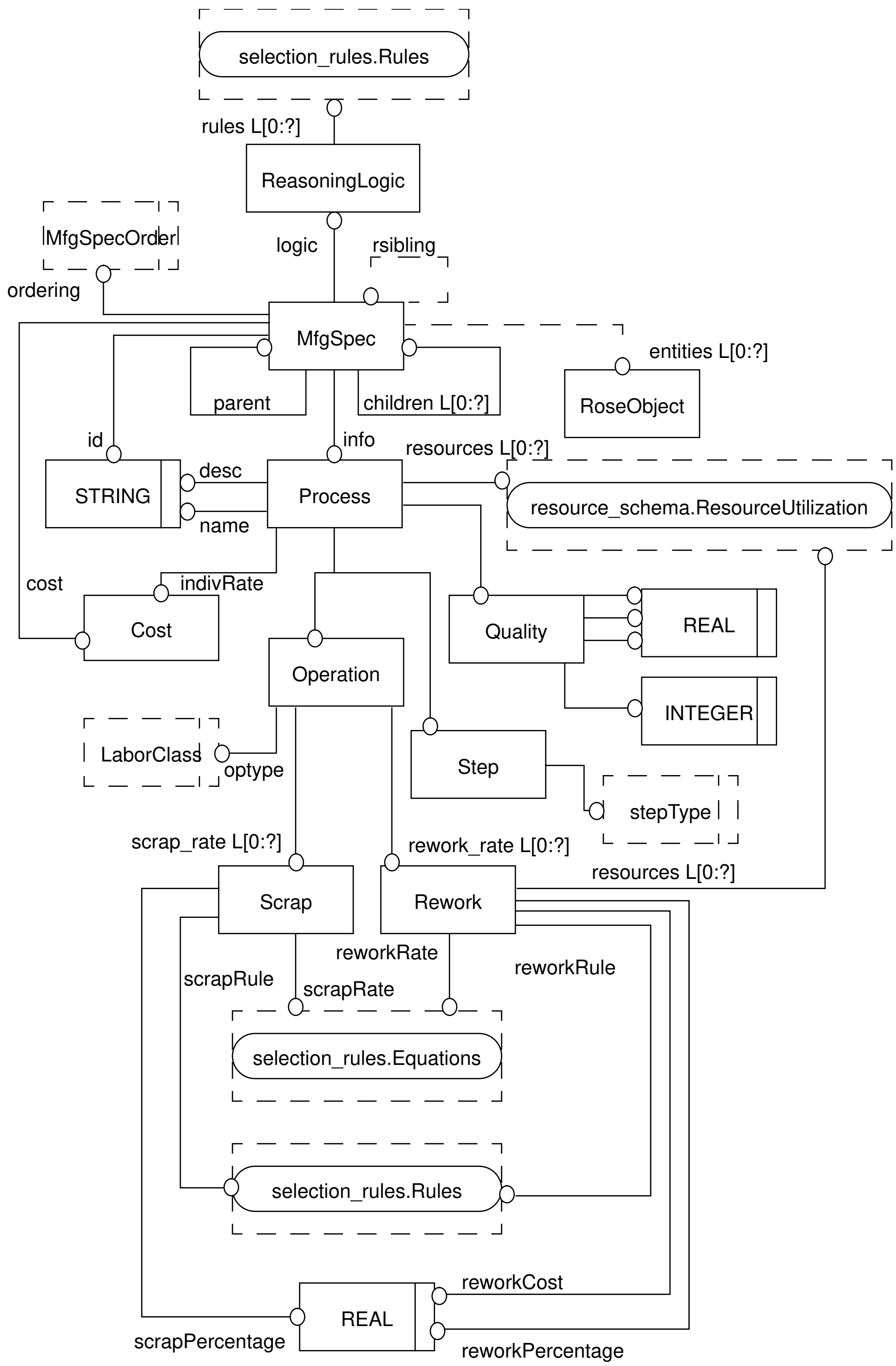

Figure 2 **DICE MO Project's EXPRESS-G Model of Process Model Schema†**

†. Ibid., p. 109.

Although no part of STEP explicitly addresses the representation of manufacturing process capabilities, there are several activities within STEP that are relevant. These activities include the development of the following standards: *Product Data Representation and Exchange - Part 49: Integrated Generic Resources: Process Structure and Properties* [26]; *Product Data Representation and Exchange - Part 207: Application Protocol: Sheet Metal Die Planning and Design* [27]; and *Product Data Representation and Exchange - Part 213: Application Protocol: Numerical Control (NC) Process Plans for Machined Parts* [28].

Part 49 specifies the resource constructs for elements of a process plan (i.e., a specification of instructions for a task). This specification defines the elements necessary for the exchange of process information. It defines schemata for process method definitions, process properties, and process property representations. The process method definition schema "represents the data in a process plan, but not the process and data that are required to develop the process plan."[5] The process property schema defines the properties of the three primary components of a process. First, the schema provides for the specification of the properties of the actions of a process. Second, the properties of the resources to be used in the execution of the process method are defined. Third, the schema defines the properties of the product that will result from the execution of the process method. The process property representation schema defines the representation of the properties required by a resource or an action.

The STEP Application Protocols are the specifications which manufacturing applications implement to provide conforming data exchange capabilities. The development of Part 207 required the definition of machine characteristics for sheet metal part presses and stamping machines. The working draft of Part 213 on NC process plans for machined parts includes a generic structure which allows the modeling of production equipment including the grouping of equipment into work cells.

Another ISO effort which is relevant to representations of manufacturing process capabilities is the Resource Usage Management project within Technical Committee 184 Subcommittee 4 Working Group 8 entitled Manufacturing Management Data (MANDATE). This project's scope is "to develop generic and application oriented standards that enable enterprises to document resources and entire manufacturing processes,... communicate internally and externally about them and... optimize their Resource Usage Management."[6] Furthermore, the Resource Usage Management project plans to develop "a representation of Resource Usage Management data and functions and a formal method for the representation of resources. The project collaborates with other standardization efforts to develop application oriented representations of Resource Usage Management data and functions."[7] This effort plans to account for the description of resources such as capabilities, schedules, capacities, strategies of technological resource binding and configurations of resources.

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5. ISO CD 10303-49, *Product Data Representation and Exchange - Part 49: Integrated Generic Resources: Process Structure and Properties*, ISO, September 21, 1993, p. 5.

6. ISO TC184/SC4/WG8, *Scope ISO TC184/SC4/WG8 - Project 2: Resource Usage Management*, ISO TC184/SC4/WG8 Document N13 (draft), July 14, 1992, p. 5.

7. Ibid., p. 5.

While some standards attempt to codify aspects of manufacturing process capability data for the exchange of information between manufacturing applications, other standards attempt to codify aspects for performance assessment. In addition to ISO, national standards organizations such as the American National Standards Institute (ANSI), the British Standards Institute (BSI), the Deutsches Institut für Normung (DIN), and Japanese Industrial Standards (JIS) Committee provide standards for evaluating the performance of manufacturing equipment. For example, under the auspices of ANSI, the American Society of Mechanical Engineers (ASME) produced ANSI/ASME B5.54 *Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers* [2] which "establishes requirements and methods for specifying and testing the performance of [computer numerically controlled] CNC machining centers."[8] This standard seeks to clarify the performance evaluation of machining centers and facilitate performance comparisons between machines by unifying terminology, general machining classification, and the treatment of environmental effects.

ANSI/ASME B5.54 defines common terms, machine types, machining ranges (work zone), position resolution, and operating modes. It also addresses machine environmental requirements and responses. This standard provides tests for evaluating machine accuracy performance as a machine tool, the machine as a measuring machine with probes in the spindle, machine cutting performance and, optionally, the machining of test parts for the assessment of point-to-point machining capability and contouring capability.

By providing tests for assessing the performance of machine tool equipment (i.e., a manufacturing resource), B5.54 identifies various performance characteristics to be measured during performance testing. The values of these characteristics provide information about the capability of a given machine tool and, therefore, the manufacturing process which uses that machine tool. This standard provides tests to evaluate characteristics such as repeatability, linear displacement accuracy, angular displacement accuracy, geometric accuracy, and volumetric performance.

This standard does not currently provide for the assessment of all parameters relevant to machine tool performance. In particular, it excludes software verification, dynamic analysis (modal analysis), and exhaustive machining tests. Furthermore, B5.54 does not address methods to specify and evaluate productivity of machining centers such as horse power and maximum spindle speed.

Similar standards have also been developed by specific industries. For example, the National Aerospace Standard (NAS) 979 [39] provides "for the selection of cutting tests required to evaluate the performance of conventional and numerically controlled machine tools..., excluding drilling and turning machines, and to provide a standard format for recording and reporting actual performance results."[9] This standard establishes another machine classification system. It defines cutting tests to assess

8. ANSI/ASME B5.54, *Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers*, American National Standards Institute, New York, 1993, p. 1.

9. NAS 979, *Uniform Cutting Tests - NAS Series: Metal Cutting Equipment Specifications,* National Standards Association, Washington, D.C., 1969, p. 1.

characteristics such as maximum torque, maximum rated horsepower, maximum feed rate, overshoot/undershoot, accuracy of motion, transverse tilt, longitudinal tilt, profile, and spindle precision, spindle accuracy, dimensional accuracy, repeatability, and flatness.

Manufacturing Process Capability Representations: Related Research

This section examines research efforts related to representations of manufacturing process capabilities. As in the previous sections, the focus is on models for exchanging process capability information among manufacturing applications; however, mathematical process and process flow models which may be used in a specific manufacturing application for assessing capability are discussed briefly.

Representing Information: Conceptual Models, Implementation Models, and Data Bases

Many research efforts concerned with the integration of manufacturing applications include the development of conceptual models, implementation models, and data bases for defining and providing process capability information. A conceptual model is a high-level representation which is independent of any given implementation. An implementation model translates the conceptual model into a form required by a specific data base implementation. Finally, the data base is populated with data. Most efforts involve the modeling of manufacturing resources (e.g., machine tools, adaptors). These models are then coupled with expert systems and knowledge bases for integrating manufacturing applications.

For the development of these models and data bases, researchers usually employ object-oriented, relational, or a combination of object-oriented and relational methodologies. In other cases, no formal methodology appears to have been used to represent the information. A description of various research activities related to the representations of manufacturing process capability information follows.

While proposing an architecture for a modular process planning system, Ray [43] identifies several process representation issues. Specifically, he calls for standard representation of processes and processes plans, as well as standard information models to support these plans. This general purpose architecture for a process planning system includes three models for manufacturing resources, plan formulation, and process specification. The Manufacturing Resource Model, which would maintain the specifications and status of all resources, would support resources such as material, equipment, human, and information. Preliminary work was done to organize equipment into several hundred classes. The Plan Formulation Model would enable the sharing of partial planning solutions. The model based on ALPS, an acronym for A Language for Process Specification [9], would serve as a repository for process plans in a form usable by other systems in a manufacturing environment.

Within the ESPRIT[10] project for Integrated Modeling of Products and Processes Using Advanced Computer Technologies (IMPPACT), Eversheim [13] developed functional and information models in order to integrate computer aided design (CAD), computer aided process planning (CAPP), and numerically controlled (NC) systems. The reference and implementation models for functions and their information flows use IDEF-0[11] [16]. The conceptual level of the information model uses the object-oriented Nijssens Information Analysis Method (NIAM) [41], while the implementation of the information model uses EXPRESS. The information model for production process modeling contains a product model, a production process model, and a factory model. The information shared by these three sub-models is combined by a feature modeler. The production process acts as a link between the product model and the factory model. A manufacturing resource entity represents all the manufacturing facilities on the shop floor. A production activity entity represents a process group, a process, an operation, or a pass. Relationships between the manufacturing resource (e.g., machine tool) and the production activity (e.g., process) entities can be specified. Part data and the generated planning results were stored in IBASE, the IMPPACT data base. Machine tool, cutting tool, and fixture data were stored in an Oracle data base.

For the development of a process selection rule base for hole-making, Khoshnevis [32] represented various hole-making processes in taxonomies. Table 1a and Table 1b present process capability matrices for specific hole-making processes. This information served as input for defining schemata using Knowledge Craft, an object-oriented language for representing manufacturing knowledge and facts. Figure 1 through Figure 3 present the representations of the hole-making category, a specific type of hole-making process (i.e., grinding), and an instance of a hole.

Using a relational methodology, Butala and Peklenik [8] describe the step-by-step development of a tool system data base, from requirements specifications to data base implementation. The development of the data base includes four steps: functional modeling, conceptual modeling of the data, derivation of implementation schemata, and implementation of the data base in a data base management system (DBMS). The functional model identifies the subsystems within a production system that are related to the tool system. The conceptual model, which is independent of any specific implementation, was developed with the Entity-Relational (E/R) Methodology [10]. The result of this activity is a schema which is represented by E/R diagrams. These diagrams identify objects (entities), describe relations between objects, and specify properties of objects and relations. A high-level conceptual schema illustrates the data interrelationships among the tool system, a computer-aided process planning system, and a production planning and control system. This schema logically decomposes into the tooling data model and the tool logistics data model. The tooling data model supports manufacturing engineering activities, and the tool logistics data model supports production engineering activities. The tooling data model consists of tool elements which are further specified as a type of tool (e.g., drill, mill) with different sets of attributes. The second step of the data base development involves the transformation of the conceptual model into a canonical form using a relational model. This relational schema presents the data and its interrelationships in a two-dimensional table and aids in the elimination of redundant data elements. The relational model leads to the final

10. The European Strategic Program for Research and Development in Information Technologies

11. The U.S. Air Force Program for Integrated Computer Aided Manufacturing (ICAM) developed several IDEF (ICAM Definition) modeling methodologies to graphically characterize manufacturing systems. IDEF0 is the ICAM methodology for producing functional models.

Parameter†	Twist Drilling	Spade Drilling	End Drilling	Gun Drilling	Counter Boring
Smallest T.D.	0.0059	1.0000	0.1250	0.0750	0.2500
Largest T.D.	3.5000	6.0000	1.0000	2.0000	3.0000
Negative Tol.	0.007xD$^{0.5}$	0.004xD$^{0.5}$+0.0025	0.0010	0.0010	0.004xD$^{0.5}$+0.0025
Positive Tol.	0.007xD$^{0.5}$+0.003	0.005xD$^{0.5}$+0.003	0.0010	0.0010	0.005xD$^{0.5}$+0.003
Straightness	0.005x(l/D)^{3}+0.002	0.0003x(l/D)^{3}+0.002	0.0025	0.0003x(l/D)^{3}+0.001	0.01
Roundness	0.004	0.004	0.004	0.002	0.003
Parallelism	0.001x(l/D)^{3}+0.003	0.006x(l/D)^{3}+0.003	0.0035	0.001x(l/D)^{3}+0.003	0.006x(l/D)^{3}+0.003
Depth Limit	12D	10D (vertical) 12D (horizontal)	2D	125D or more	20D
True Position	0.002 ~ 0.009 (depending on diameter)	0.008	0.008	0.001	0.0001
Surface Finish	100	100	63	30 ~ 80	50

Table 1a **Process Capability Matrix for Hole-Making Processes†**

Parameter†	Precision Boring	Reaming	Boring	Grinding	Honing	Tapping	Small Hole Drilling
Smallest T.D.	0.3750	0.0625	0.375	-	-	0.1250	0.0075
Largest T.D.	10.000	4.0000	10.000	-	-	4.0000	0.0587
Negative Tol.	0.0001 ~ 0.0004	0.0004	0.0003	0.0001	0.0001	0.004xD$^{0.5}$+0.0025	0.007xD$^{0.5}$
Positive Tol.	0.0001 ~ 0.0004	0.0004	0.0003	0.0001	0.0001	0.005xD$^{0.5}$+0.0003	0.007xD$^{0.5}$+0.003
Straightness	0.0001	0.0001	0.0005	-	-	-	-
Roundness	0.0001	0.0005	0.0005	-	-	0.003	0.004
Parallelism	0.0035	0.01	0.0010	-	-	-	-
Depth Limit	-	16D	-	-	-	20D	7D
True Position	0.0002	0.01	0.0001	-	-	-	0.001
Surface Finish	6 (nonferrous material) 25 (cast iron or steel)	16	8	3	2	75	50

Table 1b **Process Capability Matrix for Hole-Making Processes††**

†. Surface finish units are in microinches. All other units are in inches.

††. Khoshnevis, Behrokh, et al., *A Process Selection Rule Base for Hole-Making*, Available from the Factory Automation Systems Division, NIST, Gaithersburg, MD, February 1993, p 20.

```
(defschema hole-making
    :parallel
    (is-a cutting)
    (ToolAxis)
    (smallest-tool-diameter)
    (largest-tool-diameter)
    (negative-tol)
    (positive-tol)
    (straightness)
    (roundness)
    (parallelism)
    (depth-limit)
    (true-position)
    (surface-finish)
    (check-capacity check-hm-capaciity)
)
```

Figure 1 **Representation of Hole-Making Category†**

```
(defschema grinding
    :parallel
    (is-a hole-improving)
    (Input-Length 1/8)
    (Make-Process-Time Make-Grinding-Time
    (negative-tol 0.0001)
    (positive-tol 0.0001)
    (surface-finish 4)
    (check-capacity check-finish-increment)
)
```

Figure 2 **Representation of Grinding Process†**

```
(defschema /CH1 2 1 18 0 0/        ;;;hole identifier
    (negative-tol 0.08)
    (positive-tol 0.0002)
    (roundness 0.002)
    (parallelism 0.02)
    (true position 0.02)
    (surface-finish 5)
    (straightness 0.02)
)
```

Figure 3 **Representation of Hole Instance†**

†. Ibid., pp. 29-30.

step of the data base development -- implementation of the data base using Oracle, a relational data base management system.

Some researchers have proposed alternatives to the object-oriented or relational techniques for modeling processes. For example, Felser and Mueller [15] propose an extension to EXPRESS called EXPRESS-P in order to couple part and process information. EXPRESS currently does not adequately support the description of behavioral information. The proposed language is based on the concept of a system as a network of communicating concurrent agents or entities and deviates from the object-oriented approach currently used in the development of STEP.

As part of an effort to develop a prototype generative process planning system for machined components, Gindy and Ratchev [19] [20] developed a logical model and corresponding language to represent machine tool capabilities. In this model, a set of resource elements represents a machine tool's capability. Each resource element is a set of form generating schemata that describe the operations of which a machine is capable. These operations are defined by analyzing the machine tool's elementary form generating schema which are derived from the machine tool's structural configuration. The structural configuration includes a description of the kinematic chains of elementary motions (translations and rotations) and the rules for grouping these motions. The machine capability language L_m provides for the specification of legal combinations of cutting tools and machine motions. The language syntax is based on a grammar with four elements. The first element is a set of symbols which represent the machine tool motions and cutting tool attributes. The second element is a set of symbols which depict the functional patterns that represent the different aspects of machining capability. The third element is a set of production rules which determine the legal chains of formative motions and tools. The last element of the grammar is a start symbol.

In another effort related to the selection of hole-making processes, Halevi and Weill [23] developed a Tool Capability Table to support an algorithmic approach to generative process planning. He discusses the information that is stored in the table and the form of the information in the table (i.e., constants, equations, and tables). However, no formal methodology for representing the information was discussed.

In the area of semiconductor manufacturing, Boning [7] presents a general process modeling framework which consists of a modeling methodology for describing any manufacturing process using state and state transformation information as well as a conceptual model that distinguishes between and defines terms for the state information and state transformations specific to the fabrication of integrated circuits. The terminology and diagramming method for the general modeling methodology are discussed. The application of this methodology yields a conceptual model which consists of process state descriptions, process model descriptions, fundamental component models, and abstract component models. Process state descriptions identify and partition the semiconductor process state information. Process model descriptions include the comprehensive model and state evolution models. Fundamental component models are derived from the comprehensive model and are used in the construction of process step graphs. They incrementally describe the effects of one state on another state. Abstract component models allow for the description of process steps without the use of fundamental state or transformation components by ignoring or hiding the details of intermediate states and models.

With respect to representing process capability, a special case of this comprehensive process model, called the two-stage semiconductor process step model [36], is of interest. It establishes the relationships among the part (i.e., wafer), the process, and the equipment (i.e., manufacturing resource). This two-stage process model (Figure 3) focuses on the transformations that a wafer undergoes during the processing operation. The two-stage model of this transformation includes an equipment model and a process model. The equipment model is wafer-independent, while the process model is equipment-independent. The two-stage model also defines three categories of information about a processing operation: settings, treatment, and change-in-wafer-state. Setting information includes the control parameters of the equipment used in processing. They are often considered as events that take place at the machine which are initiated by an operator or a program. Treatment information describes the physical environment around the wafer. Examples include gas ambient and temperature or fluxes

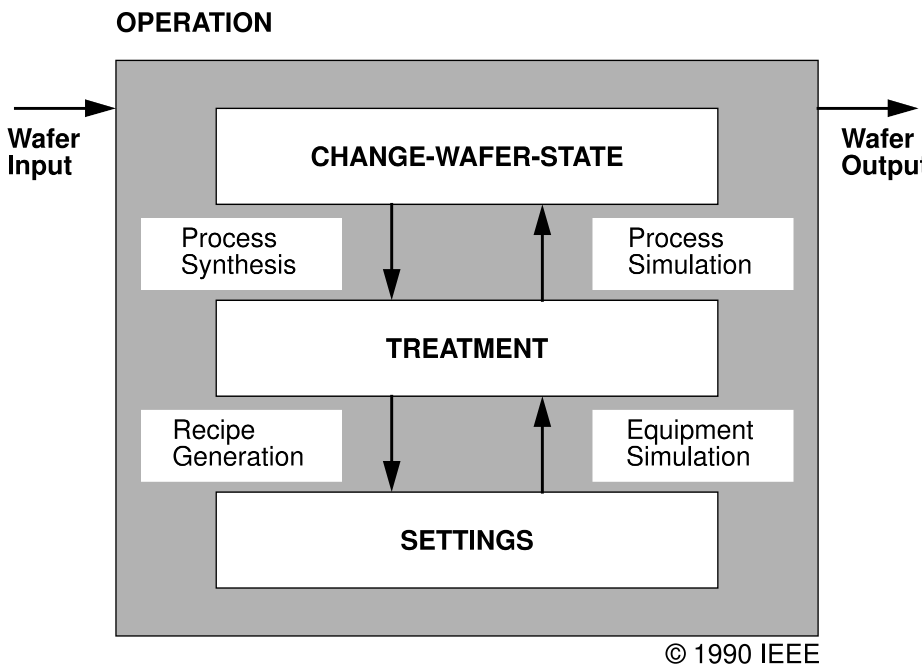

Figure 3 **Two-Stage Process Model†**

†. McIlrath, Michael B. and Boning, Duane S., "Integrating Semiconductor Process Design and Manufacture Using a Unified Process Flow Representation," *Proceedings of Rensselaer's Second International Conference on Computer Integrated Manufacturing*, Troy, New York, May 1990, pp. 227.

of materials impinging on the surface of the wafer. As the name of the final information category indicates, change-in-wafer-state describes the change that the step induces on the wafer.

The equipment model of the two-stage process model describes the interaction between the settings and the treatment. Equipment models may be as simple as a calibration table or as complex as a predictive model based on the physics imposed by the machine. The process models describes how a specific treatment produces changes in the wafer. The two-stage model has been used to clarify and support the use of process information in numerous activities including process representation, simulation, synthesis, and control [7].

In summary, researchers employ a variety of methodologies for representing manufacturing process capabilities information. Information about manufacturing resources is often modeled with object-oriented or relational methods and stored in data bases. Information about process behavior is usually obtained from manufacturing engineers, represented as rules, and stored in knowledge bases. Some research efforts follow information modeling principles of functional models, conceptual models, and implementation models. Languages have been proposed for describing process capabilities.

Other Types of Models

Thus far, the emphasis of this assessment has been information models. The focus now turns to other types of models: those used for determining the capability of a manufacturing process. Due to the complexity of this topic, a complete review of these models is beyond the scope of this paper. However, a discussion is warranted since these models logically impact the development of information models for manufacturing process capabilities.

The literature contains several references which discuss general methodologies [3] [12] and application-specific examples [6] [11] [30] [50] for modeling and analyzing manufacturing systems from a production management perspective. In contrast, no general methodology for modeling and analyzing manufacturing systems from a manufacturing engineering perspective (i.e., specific processes and manufacturing resources) was found. However, the literature contains numerous examples of research efforts concerned with evaluating various aspects of specific manufacturing processes. Several recent examples are presented following a discussion of the general modeling methodologies for production management applications. Most of these general concepts may apply to the modeling and analysis of processes from a manufacturing engineering viewpoint.

Askin and Standridge [3] define a model in terms of a system. That is, a model is "a representation of a real system in another medium, usually in a simplified form."[12] Models are then classified as either physical or mathematical abstractions of reality. Blueprints, facility drawings, CAD solid models, and the like are listed as examples of physical models. Alternatively, mathematical models describe a real system using a set of mathematical equations or logical relationships. They use controllable decision variables which are relevant to the intended use of the model. Askin and Standridge present two perspectives for categorizing mathematical models. The first category is described by the output of the model, while the second category is based on the computational form of the model. The output-based category includes descriptive and prescriptive models. A descriptive model is one which produces an estimate of system

12. Askin, Ronald G. and Standridge, Charles R., *Modeling and Analysis of Manufacturing Systems*, John Wiley & Sons, Inc., New York, 1993, p. 18.

performance given a set of values for the decision variables. Simulation models fall into this category. A prescriptive model is one which recommends how to set the decision variables. For example, this type of model is often used for the selection of production process parameters which are determined by statistically designed experiments such as those advocated by Taguchi [49]. With respect to the second category of mathematical models, computational form-based models can be described as analytical or experimental. Analytical models represent an abstraction of the real system using a set of equations that summarizes the aggregate performance of the system while ignoring the detailed events that occur. Conversely, experimental models imitate the events of the real system and allow for experimentation with operating parameters or control logic. The following uses of such models are identified: optimization, performance prediction, control, insight, and justification.

In a similar vein, El Maraghy and Ravi [12] discuss the design, modeling, and evaluation of flexible manufacturing systems. The following categories of models are identified: physical, analytical, discrete simulation, and knowledge-base simulation. In addition to citing examples, the authors examine the strengths, weaknesses, and potential for each type of model relative to flexible manufacturing systems.

The methodologies described by Askin and El Maraghy may serve as an initial template for developing a general methodology for modeling and analyzing specific aspects of manufacturing process capabilities. At the present, there appears to be no widely accepted methodology for modeling and analyzing manufacturing process capabilities. However, a cursory literature search identified numerous papers which describe research efforts to optimize, simulate, and predict the performance of manufacturing processes or elements of manufacturing processes (e.g., tools, fixtures). The following examples illustrate a few approaches used to gain insight into grinding, fixturing, and cutting.

Konig and Knop [33] compare two methods for predicting the behavior of grinding processes. The first method, process simulation, is a tool for determining significant process variables independent of the process. This method relies on knowledge of physical laws and quantification of relevant parameters. In theory, if the model contains all physical phenomena related to cutting edge contact, then all parameters are known. Hence, all process variables are readily determined. However, in practice, many physical relationships within grinding processes are not well understood, and regression analysis is necessary to estimate the effects of these relationships. Additionally, the data required to describe and evaluate grinding wheel topography is vast and requires powerful computing resources. Therefore, practical use of this method is not feasible. The second method uses an empirical process model to predict the behavior of grinding processes under practical conditions. Although no causal relationship is established between the model's equations and the physics of the grinding process in this method, it is more readily implemented. Structural relationships for grinding can be determined using statistical analysis. Values can be obtained for grinding parameters from measurements taken during production, and numerical solutions can be calculated on portable computers.

Mittal [38] presents a methodology for the dynamic modeling and simulation of a fixture-workpiece system. A simulation of an end milling operation to analyze the effects of various factors, particularly those related to locating and clamping, on workpiece accuracy is described. The Dynamic Analysis and Design System (DADS) is used to build a model that incorporates the overall interaction of the fixture and the workpiece by accounting for clamping forces, machine forces, torques, and elastic deformations where the fixture's locator or clamp contacts the workpiece surface.

While the previous two examples focus on single elements of a manufacturing process, Schulz and Bimchas [46] describe a preventive simulation method to examine the interactions among machine tool, workpiece, tool, clamping device, cutting technology, and sequence of operation. The implementation of this method, which permits the optimization of the cutting process environment during planning, uses three models. First, the machine model describes all variables which influence the spatial dislocation of the cutting edge such as the tool, clamping, and spindle. Second, the workpiece model describes workpiece/fixture characteristics which are represented by the Finite Element Method. Last, a technological model describes the dynamics at the effective cutting area of the workpiece.

Recommendations: Advancing the State-of-the-Practice and the State-of-the-Art

The state-of-the-practice refers to those technologies which are currently commonplace throughout an industry. On the other hand, the state-of-the-art refers to new technologies that are not widely available or used. Moreover, these technologies, if available, would significantly advance industrial practices.

The industrial examples which were presented previously characterize the state-of-the -practice. That is, in production environments, representations of manufacturing process capabilities appear to be gradually migrating from printed media to electronic media. In many companies, handbooks are still the reference of choice for many process planners. In others, some information contained in handbooks has been entered into data bases for access by stand-alone manufacturing applications.

Few companies use state-of-the-art methodologies for representing manufacturing process capability information. Those who do are just beginning to characterize their processes. In order to integrate their manufacturing systems, particularly for process selection, these companies, individually or collectively through consortia, have developed or are developing conceptual and implementation models of process capability information. In several process selection systems, data bases contain information about a company's manufacturing resource data (e.g., machine tools, fixtures, tools), while expert systems contain knowledge provided by manufacturing engineers.

Significant challenges for advancing both the state-of-the-practice and the state-of-the-art exist. The results of most industrial efforts often are not publicly documented, making it difficult for others to leverage the results of those efforts. A major obstacle is that many manufacturers, especially small manufacturers, do not have the resources or know-how to develop and implement representations of manufacturing process capabilities. Continuing on the current course would, at best, promote parochial integration within those companies that can afford to model their processes. The consequences of maintaining the status quo must be viewed in terms of long-term costs. Just as those manufacturers found that data bases developed for stand-alone systems impeded the integration of their current manufacturing applications, conflicting representations may impede the integration of advanced manufacturing applications in the future. In order for these applications to exchange process related information, countless translators would have to be written.

A generic framework for describing all necessary aspects of discrete parts manufacturing processes (including capabilities) would advance the state-of-the-practice and the state-of-the-art. First, such a framework would eliminate a major obstacle to manufacturers by providing the methodology and schemata for representing process information. Manufacturers and equipment vendors would then provide the data to populate the process data base. Second, adopting such a framework would ensure the future integration of new or improved manufacturing applications.

This framework would marry the technical domains of manufacturing processes and software engineering. Like Boning's framework for semiconductor processes, a general framework would provide a methodology for modeling process related information. Candidate methodologies include object-oriented approaches described by Rumbaugh [45] and others or the Structured Analysis/Structured Design approaches presented by Yourdon [51] and others. At a minimum, such a methodology must provide three types of descriptions. The first is a description of objects or entities within a manufacturing process such as manufacturing resources. This description includes identifiers, attributes, associations with other objects, and operations. The second is a description of aspects of the process concerned with time and changes (i.e., an activity or dynamic model). The third is a description of process aspects such as functions, mappings, and constraints which transform values (i.e., the functional model).

For the long term, a standardization effort akin to STEP could be used to develop and implement a generic framework. ISO TC184/SC4/WG8 is charged with a closely related task. However, this effort has not moved beyond the initial stage of developing a statement of work. It would benefit from pre-standardization work to remove existing technical obstacles and build an infrastructure for such a standards development process.

As a first step, a foundation of common terminology must be laid. Within the domain of manufacturing, there exist varying interpretations of many terms such as *manufacturing process*, *process capability*, *model*, and *manufacturing resource.* Precisely defined terms are required for the development and implementation of a generic framework.

Taxonomies of manufacturing processes and resources must be developed or adopted. These classifications can be derived from handbooks and standards such as ASME/ANSI B5.54. The taxonomies presented in most handbooks are based on manufacturing processes with manufacturing resources associated with each process. However, manufacturing engineering decisions are constrained by available manufacturing resources. Therefore, a taxonomy of manufacturing resources is necessary. This classification would allow processes to be associated with each type of manufacturing resource, such as milling, drilling, and boring with a 3-axes machining center [1].

Generic manufacturing resource models are a critical element of this framework. The attributes of manufacturing resources must be described consistently. As is evident by a review of vendor catalogs of like manufacturing resources, there is presently considerable variation among the attributes used to describe those resources. These differences make comparisons of resource capabilities very difficult. A detailed evaluation for each type of manufacturing resource is required to develop the resource model. In addition to vendor catalogs, this information can be obtained from generic and company-specific handbooks and data bases.

Generic manufacturing process models which describe process behavior must be developed. This type of model should describe the relevant changes that occur during the process. It should support the mathematical models which describe the physical phenomena of the process (e.g., dynamics, kinematics). These rigorous models will improve existing expert process selection systems which are based on process planner experience. While experience is an important source of information, it is often biased by factors that may no longer be relevant. A separate evaluation for each type of process is necessary.

While even these pre-standardization activities are too much for any one organization to accomplish within a reasonable amount of time, a smaller effort should be undertaken to determine the feasibility of such an approach. With a focus on one or two types of processes and corresponding manufacturing resources, the models and data produced by this effort should be available to manufacturers at large for validation. The experience gained from these activities would serve as a catalyst for developing standards.

Conclusions

The need for manufacturing process capability information is pervasive throughout the product realization process [4] [40]. To integrate various design, manufacturing, and production management applications, it is important to know and understand the information required by those applications as well as the objectives of the applications. A knowledge-base of manufacturing process capabilities would facilitate the integration of engineering activities required for rapid response manufacturing. For example, this information would serve to integrate design trade-off studies to resolve potentially conflicting objectives of the part designer and the process planner, among others. Manufacturing process capability data also would enable the activities such as dynamic resource allocation and scheduling.

This paper has examined the state-of-the-art regarding methodologies for representing manufacturing process capabilities. This survey presented methodologies for describing and using such information. Current practices in industry have been identified. Standards and research efforts related to representing manufacturing process capabilities were also described. Finally, a course of action for advancing current practices was presented.

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