Preface

The Computer-Aided Manufacturing Engineering (CAME) program is developing tool kits and specifications for integrating design, manufacturing engineering, and production operations [MCL 94]. One of these toolkits is the Manufacturing Engineering Tool Kit (METK) [IUL 96]. The goals of the METK project are 1) to develop generic interface specifications, data structures, information models, and data validation methodology for manufacturing engineering software; and, 2) to demonstrate an integrated toolkit using commercial, off-the-shelf software applications. The benefit will be an increase in the productivity of manufacturing engineers, and a reduction in the time required to get error-free, engineering data to the shop floor. The U.S. Navy Manufacturing Technology Program and the Systems Integration of Manufacturing Applications (SIMA) Program [BAR 95] at the National Institute of Standards and Technology (NIST) sponsor many integration activities such as the METK.

The primary output of the METK project will be a collection of specifications called Initial Manufacturing Exchange Specifications (IMES) [KEM 97]. IMESs provide a means to meet the needs of the U.S. industry in the area of standards and testing methods by providing a structured approach to project activities in this arena. They fill an important void in the manufacturing systems integration standards process as it exists today. Each IMES will be developed through an industry review and consensus process. It is expected that the manufacturing community will accept them as an authoritative specification.

Three types of IMESs have been identified: an interface specification between a human being and a software application; an interface specification between two or more software applications; and a reference information repository specification. Each IMES involves components that define the integration aspect, specify a definitive solution to the integration problem, and demonstrate the validity of the proposed solution. It must contain a clear description of WHAT information the interface or repository MUST convey, and HOW it is conveyed. The content is usually specified by an information model of all the objects and related information attributes that are covered by the specification.

To support the scope and domain specifications, the IMES shall address a particular "example scenario," identifying an actual interface/information requirement derived from a real industrial problem. The proof of the value of the IMES to industry will be the ability to build a prototype of the IMES, using the software applications actually used by the industrial practitioners, and solving the cited problem. To support the development of an IMES, projects will have seven phases: identify/define the industry need, conduct requirements analysis, develop proposed solution, validate proposed solution, build consensus, transfer technology, and initiate standardization. Each of these phases has a well-defined set of deliverables.

The industry need for the METK was described in [SMI 95, SMI 96]. An initial prototype for the METK was developed [IUL 96] in order to conduct the requirements analysis phase of the IMES process (Phase 2). That prototype contained software applications to implement the following functions: product data management, workflow management, computer-aided design, generative process planning, and Numerical Control (NC) validation. The concept of a process plan was used to integrate the process planning and NC validation applications. This document describes the results of the requirements analysis for the process plan specification. It provides a description of the scope and domain for the specification, a review of the related literature and standards, a list of the units of functionality, and the definition of required application objects.

1.0 Introduction

Hundreds of manufacturing engineering software applications have become available over the past decade. These applications can help manufacturing engineers perform the various tasks necessary to create and validate manufacturing instructions from a product design. Industry forums hosted by NIST in Gaithersburg, MD, in 1995 [SMI 95, SMI 96] identified integration of these engineering applications as a major unsolved problem. They indicated that a solution to this problem would result in a significant reduction in time, cost, and rework.

The Manufacturing Engineering Toolkit (METK) Project was conceived to address both integration and validation problems [IUL 96]. Its major goals are 1) the identification of integration standards for implementing plug-compatible systems for manufacturing engineering functions and 2) the automatic validation of the information generated and used by those functions. The METK Project is part of the Computer-Aided Manufacturing Engineering (CAME) Program [MCL 94] in the Manufacturing Systems Integration Division (MSID) of Manufacturing Engineering Laboratory at NIST.

A prototype toolkit has been developed [IUL 96], which contains software applications to implement the following functions: product data management, computer-aided design, generative process planning, and NC validation (see Figure 1). Those applications include Matrix™ from Adra Systems, Pro-Engineer™ from Parametric Technology Corporation, ICEM™ Part from Control Data, VNC™ from Deneb Robotics[1]. A major focus of the initial prototype was the integration of ICEM™ Part and VNC™. This integration was achieved using the concept of a process plan [MCL 87, IUL 95]. An example of such a plan is given below in Figure 2 (Note, Step 1 in the Procedure section in Figure 2 is not needed to implement the process plan on real equipment.).

Matrix™ implements both the data management and workflow management functions. It manages an object-oriented database of distributed information including documents, the applications that create the documents, and the processes that govern their life cycles. Document check-in and check-out are achieved using the protocols defined in [MFG 98]. We have defined a collection of objects relevant to the METK project, determined the states in each object's life, and notification triggers that govern each object's behavior [IUL 97b]. We have also implemented a business process model, or workflow, for each object. This model describes the flow of each object through its allowed states, the data associated with the product at each state, and the requirements for moving from one state to next. This is what Matrix™ refers to as a policy. It ensures data integrity and proper information flow within the METK.

Pro-Engineer**™** is a Computer-Aided Design (CAD) application that can be used to create solid model representations for the geometry of the final product and the geometry of the initial part blank.

ICEM**™** Part is a generative process planning application. It applies a user-defined knowledge base of feature definitions, jigs/fixtures, machine tools, cutting tools, and manufacturing methods, to the design. It outputs specific information about the machines, cutting tools, fixtures, and Numerical Control (NC) programs needed to change the product design into a real product.

VNC™ is a simulator that uses solid models of the machine tool, fixtures, cutters, and part blank together with an emulator of the machine controller to generate and visualize the output of the NC program.

[1] **Certain commercial software and hardware products are identified in this paper. This does not imply approval or endorsement by NIST, nor does it imply that the identified products are necessarily the best available for the purpose.**

Figure 1. System Diagram for METK Project

The purpose of this document is to specify the information requirements for a generic process plan specification. Such a specification would be used to integrate other planning and validation software applications. The scope and domain of the specification, a review of the related literature and standards, the basic definitions, and the information requirements are presented.

```
HEADER Section
plan_id=P12345
part_name=Air_frame_test_part
Creation_date=10/24/96
planner=Mike Iuliano

RESOURCE Section
machine_id=CINC_MILA_T30
tool_name=1/4" TWIST_DRILL
tool_name=1/2" CENTER_DRILL
tool_name=1/8" BALL_NOSE_END_MILL
tool_name=SHANK_END_MILL
fixture_name=vise
workpiece_name=Air_frame_blank
nc_program=Air_frame.cnc

PROCEDURE Section
Step 1   LOAD_MACHINE
  machine_id = CINC_MILA_T30
  machine_controller = GE2000
  end_step
Step 2   LOAD_TOOL
  Tool_name = TWIST_DRILL
  tool_id = T266
  magazine_slot = 1
  end_step
Step 3   LOAD_TOOL
  Tool_name = CENTER_DRILL
  tool_id = T271
  magazine_slot = 2
  end_step
Step 4   LOAD_TOOL
  Tool_name =BALL_NOSE_END_MILL
  tool_id = T268
  magazine_slot = 3
  end_step
Step 5  LOAD_TOOL
  Tool_name =SHANK_END_MILL
  tool_id = T234
  magazine_slot= 4
  end_step
Step 6   MOUNT_FIXTURE
  fixture_name = vise
  fixture_id =  V178
  ref_frame = x_axis
  x,y,z_offset = 152.4, 101.6, 44.45
  units = inches
  end_step
Step 7   LOAD_WORKPIECE
  workpiece_name = Air_frame_blank
  workpiece_id = W123
  ref_frame = fixture_name
  x, y,z_offset =  0, 0, 0
  units = inches
  end_step
Step 8  LOAD_NC_PROGRAM
  nc_program = Air_frame.cnc
  end_step
Step 9  RUN_NC_PROGRAM
  nc_program = Air_frame.cnc
  end_step
```

Figure 2. Example of a Simple Process Plan

2.0 Scope and Domain

2.1 Overview

The domain for this IMES is discrete parts manufacturing with emphasis on metal-removal machining operations (The CAME Forum participants rated these operations with a high level of importance [SMI 95].). Other manufacturing operations will be considered in the future including material handling and inspection.

This document describes the requirements for a workstation-level, process plan specification. This plan provides instructions for either a real, or a simulated, workstation - simulations are used to validate instructions before they are executed on the real system. This document's focus is a single workstation that contains a machine tool and its operator. Nevertheless, it is likely that these requirements can be used for process plans for other kinds of workstations and simple routings between workstations.

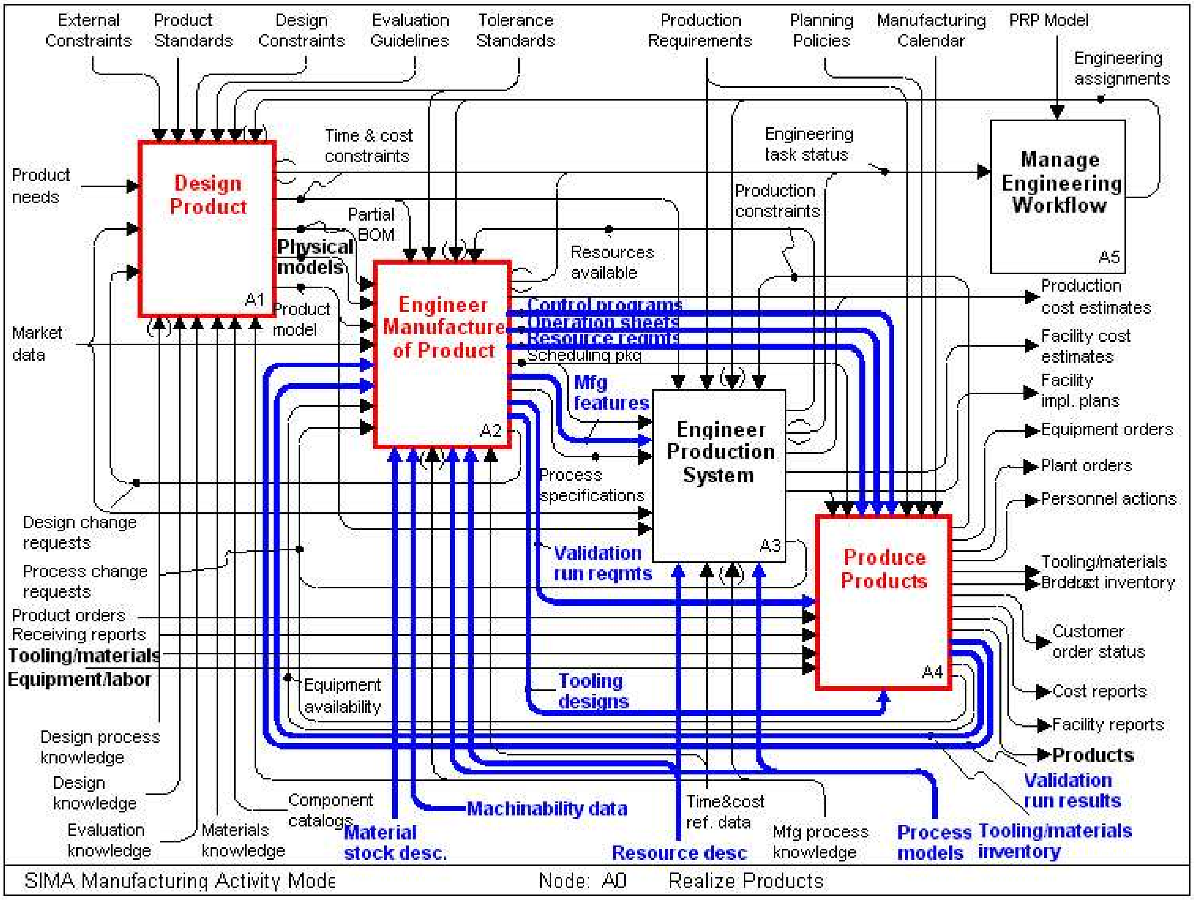

Figure 3. Node A0: Realize Product

2.2 Application Activity Model

The application activity model (AAM), shown in Figure 3 and Figure 4, provides more details concerning the scope and information requirements defined in this IMES. This model is taken from the SIMA Reference Architecture [BAR 96]. The SIMA Reference Architecture was developed using the $IDEF_0$ functional modeling technique. With $IDEF_0$, the functions or activities are represented as boxes that are labeled with short description of the activity. The inputs, controls, and mechanisms for each activity are shown as arrows entering the boxes and the outputs are shown as arrows leaving the boxes. The activities and information flows can be decomposed into more detailed activities and information flows at lower levels [IDE 81].

The highest level activity in any manufacturing enterprise is product realization. As shown in Figure 3, the manufacturing functions that comprise this activity (marketing, financing, sales, etc. are excluded) are design product, engineer manufacture of product, engineer production system, produce products, and manage engineering flow. Activity A1, design product, decomposes into plan products, generate product specifications, perform preliminary design, and produce detailed design [BAR 96]. Activity A2, engineer manufacture of product, decomposes into determine manufacturing methods, determine manufacturing sequences, develop tooling packages, develop equipment instructions, engineer new process, and finalize manufacturing data package (see Figure 4). Activity A3, engineer production system, decomposes into define the production engineering problem, specify production and support processes, design production system, model and evaluate production system, and define implementation plans [BAR 96]. Activity A4, produce products, decomposes into develop production plan, define production jobs, schedule production jobs, control production, and manage production facilities [BAR 96]. Activity A5, manage engineering workflow, decomposes into specify engineering tasks, control engineering tasks, review engineering tasks, and approve engineering tasks [BAR 96].

The following sections contain definitions of the activities and the information flows into and out of activities for the decomposition of A2, the most relevant to the METK. These are taken from [BAR 96].

2.2.1 Definitions of Activities

2.2.1.1 Engineer Manufacture of Product

Define the process of making the product, including the elementary stock materials and components to be acquired, the equipment, tooling and skills to be used and the details of that usage. Details include the exact sequence of setups and operations to be performed, and the complete instructions for each operation, whether by human or automated resources.

For engineering purposes, every product is decomposed into a collection of Parts. The manufacturing engineering process is performed on each Part separately. Each Part is either a fabricated Part or an assembly. No Part can be both. Likewise, manufacturing operations for any given Part are either fabrication processes or assembly processes, but not both. Any Part, however, may be subjected to inspection and finishing processes. The final product is itself a Part - it may be a single fabricated part or a final assembly. Thus this activity decomposes into many similar activities, each of which is "engineer manufacture of one Part".

This activity assumes the existence of a product model and related information produced by the Design activities, and includes activities which feed back to Design manufacturing consequences that may result in changes to the product model.

The results of this activity are used primarily to drive the production planning and production activities for the product. Production difficulties may lead to feedback into this activity requesting changes in the process specifications. The results of this activity may also be used to reengineer the production facility itself, in order to validate or improve the production of this product along with others. If such reengineering occurs, several decisions made in this activity may be changed as a result of the revised facility descriptions.

2.2.1.2 Determine Manufacturing Methods

Define the major processes involved in making the Part, and identify the types of machines and special skills to be used. Identify stock materials or components to be used, select and sequence the major processes to be performed. Any given Part will have either fabrication processes or assembly processes but not both. All Parts may have inspection processes

2.2.1.3 Determine Manufacturing Sequences

Define and validate the sequences of operations that makeup each major process, as defined by the process sequence and equipment selection. This includes fixturing, machine setup, batching, fabrication, assembly, and inspection processes. Define the routing package as the sequence of (types of) workstations or machines that the Part must go through.

A generative system or a variant system may perform this activity. A generative system, uses human or artificial intelligence and a knowledge base of process models based on Part features. A variant (or case-based) system uses a library of existing plans for similar parts, typically using group technology codes to identify the similarities.

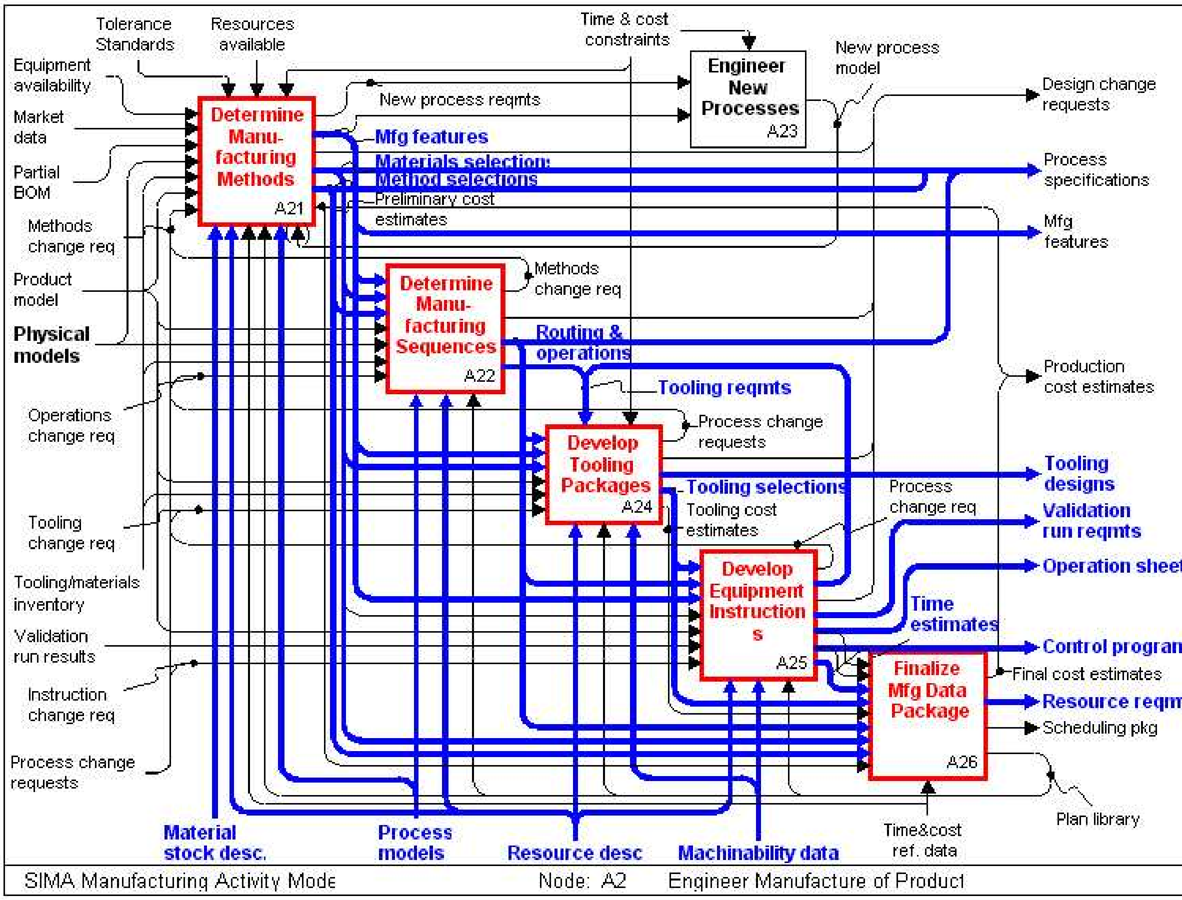

Figure 4. Node A2: Engineer Manufacture of Product

2.2.1.4 Engineer New Processes

If the fabrication, assembly or inspection plans call for handling materials or performing processes that the firm has never done before, it may be necessary to engineer the process itself. That is, determine how to perform a new process by designing new or modified machines, new tools and end-effectors, new measurements, and process controls. The result is conceptually a new body of process knowledge, which can then be selected, in the overall plans.

2.2.1.5 Develop Equipment Instructions

For each station in the Routing package, define and document exactly what steps must be taken by the machines and by the human operators and specialists, in order to accomplish the operation sequence assigned to that station. This includes operation sheets, assembly instructions, numerical control programs, robot programs, etc. In the case of machining operations, one of the documents must be the machine control programs. These , in turn, will lead to detailed specifications for the tooling required for the operations.

This process includes the selection of the process parameters, tools, setups, machines, fixturing devices, and operations sequence. These selections are considered to include an exercise in optimization to achieve a number of goals such as improve the quality and reduce the cost. In many cases, these are competing goals, so that for different Parts and facilities different goals may be emphasized and different compromises will be considered optimal.

2.2.1.6 Develop Tooling Packages

Complete specifications for the required tooling, including cutting tools, molds, dies, fixtures, end-effectors, probes, sensors, etc. This includes design and/or assembly specifications for the tool or fixture, and may include special instructions for use and estimated in-service life.

2.2.1.7 Finalize Manufacturing Data Package

This is the final phase of manufacturing engineering. The engineering activities of one cycle are complete at this point. In this phase, accurate time and cost estimates are produced, the engineering information is assembled into the required packages for production use, and each such package is reviewed and signed off. This process may involve some reorganization and summarization of information to meet requirements of the production systems and corporate production management. This version of the manufacturing data package for the Part is archived for future reference.

2.2.2 Definitions of Information Flows

This section contains the descriptions of all the information flows, which are inputs, outputs, controls, and mechanisms, that appear in the decomposition of activity A2. The flows appear here in alphabetical order. Since $IDEF_0$ does not distinguish between "subset" and "subtype" notions for information groups, we adopt the convention that a label appearing on an arrow to/from an "external" information object represents a subset, i.e., a part of the more inclusive information set represented by the common arrow. This section attempts to clarify the subset and subtype notions associated with information flows by using the following notations:

X = Y indicates that information type X is a particular use/form of the more general information type Y. By implication, information type X could use whatever representation is selected for type Y.

X: (Y) indicates that information type X is part of the more inclusive information type Y. By implication, the representation of type Y must include a means for representing information of type X.

X = Y: (Z) indicates that information type X (being defined) is a kind of Y but a part of type Z.

2.2.2.1 Control programs

Instructions for numerically controlled fabrication machines, coordinate-measuring machines, assembly machines, robots, etc. A control program specifies the sequence of machine motions and actions associated with one or more operations on the operation sheet, in the form of machine-readable instructions for the machine controller. Control programs usually contain process control parameters appropriate to the process and the material being formed or manipulated: feed rate, spindle speed, end-effector motion speeds, tension, temperature, etc.

2.2.2.2 Design change requests

Requests from downstream engineering activities feeding back to design activities for changes to the part design. Such changes relate to improving producibility or reducing production cost, or to making production possible with on-hand equipment and tooling. While this is modeled as a directed information flow, the actual flow is a bi-directional negotiation.

2.2.2.3 Equipment availability

The current and planned levels of utilization of the workcells, machines and personnel in a target production facility. This information is an output of production planning and scheduling activities, possibly at several levels, that is provided to manufacturing engineering activities. Some engineering activities may treat the availability data as a constraint while others may use it only as an informative source.

2.2.2.4 Final cost estimates = Production cost estimates

Best estimates of the manufacturing cost of the Part, based on the time estimates for use of manufacturing resources and skilled labor, plus tooling, materials, handling and in-work transportation costs.

2.2.2.5 Instruction change requests: (Process change requests)

Feedback from production activities requesting changes in the detailed instructions to the machines and the machine operators. This also includes changes to operator instructions needed to support or facilitate the machine programs (Programming feedback).

2.2.2.6 Machinability data

Reference data that specify properties of materials with respect to specific cutting and forming processes. For machining, this includes machining speeds and feed rates for using specific cutters to machine parts made of a specific type of material, and possibly under particular choices of coolant/lubricant. In some cases, this includes characterization of thermal effects, surface finish, and chaff/chip formation.

For stamping, bending and die cutting, this includes characterization of both surface and internal deformation and changes in the material properties for various angles and depths of bend and cut.

2.2.2.7 Manufacturing features

Identification of the principal features of the Part that affect processing and inspection decisions. These may include (some of) the design features, but primarily relate to materials and processes actually selected for the fabrication, assembly, or inspection of the Part. Features may be codified using some firm-specific or industry-specific classification codes, commonly called Group Technology (GT) Codes.

2.2.2.8 Market data

Estimates of the total volume of the product that could be sold, its market life, and the production rate required to meet the projected market opportunity.

2.2.2.9 Material stock descriptions

Characteristics of the raw or off-the-shelf materials that are processed into the fabricated or assembled parts. This includes physical characteristics (shape, size, composition, etc.) and economic characteristics: cost and availability.

2.2.2.10 Materials selections = Bill of Materials: (Process specifications)

A usually incomplete bill of materials for the part, including the stock materials and off-the-shelf components from which it is to be made.

2.2.2.11 Method selections: (Process specifications)

Basic specifications for the approach to the manufacture of the Part: the major processes to be employed (Process selections), and the principal equipment and/or human resources required to perform those processes (Equipment & skills selections). This may include special processing capability requirements, such as maintenance of specific tolerances, temperatures, pressures, or environments.

2.2.2.12 Methods change requests: (Process change requests)

Negotiations for changes in stock/component selection or changes in major processes and equipment.

2.2.2.13 New process model = Process models

Specification of a new process, including function, capabilities, limitations, and machine and tooling requirements. (The new process becomes part of the firm's process knowledge base, and may include a formal model or process description used by automated systems.)

2.2.2.14 New process requirements

Requirements specifications for a fabrication, assembly or inspection process with which the firm has no experience, or for a major change to a process with which the firm is familiar.

2.2.2.15 Operations change requests: (Process change requests)

Feedback from engineering and production activities requesting reconsideration of the selected operations or the selected operations sequence. This is usually a result of problems in maintaining product quality during the production process, such as affects of one operation on the results of another, or the inability of a machine to maintain specified tolerances for a particular operation.

2.2.2.16 Operations sheets

An operations sheet is a plan that defines in detail the operations to be performed on the workpiece at a given workstation. It specifies the sequence of setup, fixturing, cutting/forming, assembly, and inspection steps that are to be performed, including (where appropriate) identification of the control programs that perform those steps and the process control parameters that are manually controlled.

For human operators, the operation sheet may include detailed text and drawings. For totally automated workstations and cells, the operations sheet is similar to a control program, but it specifies a sequence of tasks and control programs to be given to the component machines of the workstation/cell.

For major resources, which are complex pieces of equipment capable of performing steps from multiple jobs simultaneously, there may be multiple levels of operations sheets. The top level is a sequence of operations to be performed by the component subsystems (or "stations") of the complex cell, and for each of these high-level operations, there may be a corresponding operations sheet detailing the execution of that operation in the specified subsystem.

2.2.2.17 Partial BOM = Bill of Materials

Identification of off-the-shelf components or stock materials to be used, to the extent that these are selected by the design engineer. For assembled Parts, it is the list of components and subassemblies. For a fabricated Part, it may include stock materials suggested by the designer, particularly when the properties of a particular stock form, in addition to the generic material properties, are important to the design. Stock material is distinct from composition in that it identifies a particular off-the-shelf form of the composition material.

2.2.2.18 Physical Models

Non-functional models of parts and subsystems made by rapid (and other) prototyping processes.

2.2.2.19 Plan library

Process and inspection plans for previously produced products from which those for similar parts can be identified, using classification codes, for example. (Used in variant planning and in plan validation.)

2.2.2.20 Preliminary cost estimates = Production cost estimates

Estimates of the processing time, materials, equipment and labor costs for the major fabrication, assembly and inspection processes for the Part. The material cost estimates are good, but the estimates of process cost are necessarily crude, since they are based on general time guidelines rather than detailed time estimates.

2.2.2.21 Process change requests

Changes to the manufacturing engineering specifications requested by downstream planning and production activities. Such change requests are usually negotiable. They result primarily from concerns about product quality and cost or concerns about availability of resources: equipment, tooling, materials.

Requests from the production activities relate to changing the resource consumption for manufacture of a given product, in order to permit a product to be built on schedule within existing or planned capabilities. This is necessary when equipment failure or priority orders, change the available resources unexpectedly. Requests from later process planning stages usually relate to simplifying or optimizing a part of the plan.

All elements of the process specification are subject to Change request negotiations: Process & materials, Operations selection and Sequencing, Tooling and machine/operator Instructions.

2.2.2.22 Process models

A standard, predefined set of operations and related specifications that are used to fabricate, assemble or inspect specific part types or part features. In general, such operations are parametrized by specific design dimensions, datums and tolerances. (Used in generative planning, whether human or automated).

2.2.2.23 Process specifications

The high-level engineering specifications for the manufacture of the Part: the principal stock materials or components from which it is to be made (Material selections), the major processes to be employed (Process selections), and the principal equipment and/or human resources required to perform those processes (Equipment & skills selections). This represents ongoing interchanges among process and production engineering activities, with the consequence that the process definition is in varying degrees of detail at different times. In later stages, it will include routings, operations sequences (Routing and operations), and special processing notes, quality control specifications, process control specifications, process measurement specifications and process tracking/audit requirements.

2.2.2.24 Product model

A computer-interpretable representation of the product and subassembly layouts, and all the specifications for each component, including:

For parts to be fabricated:
materials of which the component is made, component dimensions, geometry and topology surface finish notes on special processing procedures

For (sub)assemblies:
- the (partial) bill of materials: the list of component Parts
- the assembly configuration: how the components fit together
- fit specifications: tightness requirements for fits, bindings, and seals

In general:
- quantitative quality controls: tolerances, datums, limits, and fits
- design features: features of the Part that are important to the designer in making decisions and identifying similarities.
- design intent: statements that govern the product or design process. Also statements of the interrelationships of the design choices themselves, including the use of off-the-shelf components.

2.2.2.25 Production cost estimates

Estimates of the cost of manufacture of the Parts (and the final product), taking into account materials, tooling, processing and labor, inspection, scrap rate, etc. These estimates can be produced at various stages in the engineering activities with different confidence levels and may relate to either as-is or to-be production facilities.

2.2.2.26 Resource descriptions

Technical descriptions of the manufacturing resources, which the engineer may have available for the production of the product. Descriptions of Manufacturing Resources cover several important subtypes: Machine descriptions, Tooling descriptions, and human resource descriptions (Skills pool).

2.2.2.27 Resource requirements

Identification of the resources required to produce a given batch size of each Part. This includes a Final Bill of Materials, major equipment and human resource skills required to perform the manufacturing tasks (Equipment requirements, Skills requirements) and the aggregated Tooling list.

2.2.2.28 Resources available

The workcells, machines, and personnel to be considered available in the target manufacturing facility when specifying the production processes for a given product, and possibly some indication of expected capacity. This information may specify the entire facility, or the portion not currently allocated to other production plans, or a portion specifically allocated to the particular product being planned. The information may define the facility as is, or the facility to be, depending on the business plans for the product and the facility.

2.2.2.29 Routing & operations (plan)

The sequence of operations needed to transform stock materials and/or component parts into a Part batch and ensure the quality of the Parts in the batch. This includes specification of the sequence of workstation (types) to be visited, including both processing stations and inspection stations, and the sequence of operations to be performed at each workstation. This is sometimes called the "macro" plan.

There is a difference between the routing plan and the "routing sheet" that accompanies the part batch in production. The routing sheet schedules the part batch to a sequence of specific stations by number or operator. The routing plan may specify particular stations but in facilities that have multiple stations that can be configured identically, the plan often specifies only what type of station.

2.2.2.30 Scheduling package

A plan that specifies the sequence of workstations or workstation types to be visited by the workpiece-in-process, including both processing stations and inspection stations. For each station the plan specifies:

- the station or station type
- special operator/artisan skills required at that station
- the tooling and materials required at that station
- the size of the part lot to be processed at one time
- the length of time required to process the lot through that station
- the identification of the operations sheets and control programs for that station

2.2.2.31 Time & Cost constraints

Limitations imposed by product (price) planning and other corporate decisions on acceptable manufacturing cost and time-to-market for a product.

2.2.2.32 Time & cost reference data

Standardized data that specify estimated times and costs for standard operations. These data are standardized in the sense that the organization prescribes their use in preliminary cost estimations.

2.2.2.33 Time estimates

Estimates of the total manufacturing time at each station in the routing, subdivided by operation and sometimes step, and distinguishing the elapsed time, operator time, and time-in-use of the machines. These estimates are used in estimating production capacity and maintenance requirements, and in scheduling the routing plan.

2.2.2.34 Tolerance standards

Industrial or corporate standard engineering tolerances, tolerancing techniques and limitations.

2.2.2.35 Tooling change requests: (Process change requests)

Feedback from instruction generation and production activities requesting changes in tooling requirements and tooling selections or designs.

2.2.2.36 Tooling cost estimates: (Production cost estimates)

Estimates of the cost of the tooling required for some Part batch size. For off-the-shelf tooling and assemblies, this includes materials, preparation, storage and handling, and decommissioning (disassembly, inspection, regrinding, etc.). For special tooling it also includes the cost of design, engineering and production of the tooling.

2.2.2.37 Tooling designs

Specification of the required form and function of a tool, fixture, probe, etc., which is to be assembled from standard components or manufactured expressly for this process. There are two major subtypes:

- Tool assembly designs: specifications for assembling a tool or fixture from standard components,
- Special tool designs: designs for tooling that must be fabricated for the job.

2.2.2.38 Tooling requirements

Specifications for the tooling, end-effectors, and fixtures required at the processing station. Specifications
may include tool selections, but often identify only the general type of tool and mount requirements and the specific operations to be performed with the tool, including relevant starting and ending part geometries, clearances, etc. These specifications may be input to an in-house design activity or an external tooling firm.

2.2.2.39 Tooling/materials inventory

Inventory levels (quantity on-hand and on-order, order status, etc.) for raw/in-process/finished materials, tools, fixtures, and other components.

2.2.2.40 Validation run requirements

Requirements from engineering activities for production facilities used to perform validation runs of routing plans and control programs. This may include machines, operators, made-up tooling, materials, etc. (This is input to the production resource scheduling activities in shops where there are no separate facilities for validating engineering specifications.)

2.2.2.41 Validation run results

Results, including both reports and artifacts, of process plan and control program validation runs. (When the validation functions are actually performed in the production facility, the validation run is considered a production management operation, because it involves all the production preparation and scheduling activities.

2.3 The AAM and the METK

Activities A2, engineer manufacture of product, and A5, manage engineering workflow, overlap the METK project. Activity A5 does not impact the development of a process plan specification. However, the six activities that make up A2 do (see Figure 4). Activities A21, A22, and A24 provide crucial inputs into activity A25. Activities A25 and A26, the interfaces between them, and two outputs - control programs and resource requirements - have the most impact on the process plan specification. The decomposition of activity A25 is shown in Figure 5 (Definitions of these activities and additional information flows are given below). Activities A251 - A254 generate the final inputs to the process plan, and activity A255 validates that plan.

The METK project is not concerned with developing detailed specifications for the content, structure, and format of the individual data elements that make up the process plan. These are being done by other standards organization. For example, [ANS 80, 92, and 93] specify standards related to numerical control programs, and [ISO 98] specifies draft standards related to data representations for cutting tools. Rather, the METK goal is the development of a specification for a structure that 1) includes references to all required data elements, and 2) captures all relationships among these elements. This structure is the key to automated plan validation.

There are a number of different types of validation that could be performed, such as data integrity, resource availability, collision detection, and a comparison between the nominal and actual part. The METK project is in the process of developing a definition for validation, and a methodology for implementing that definition. Parts of this methodology will be implemented in each of the software applications in the toolkit. The initial focus is on collision detection and nominal vs actual part. comparisons. These will be done using the simulation package.

<u>2.3.1 Definitions of Additional Activities</u>

For each station in the routing plan, define and document exactly what steps must be taken by the machines and by the human operators and specialists, in order to accomplish the operation sequence assigned to that station. This includes operation sheets, assembly instructions, numerical control programs, robot programs, etc. In the case of machine-controlled operations, one of the documents must be the machine control program. These specifications will lead to detailed specifications for the tooling required for the operations.

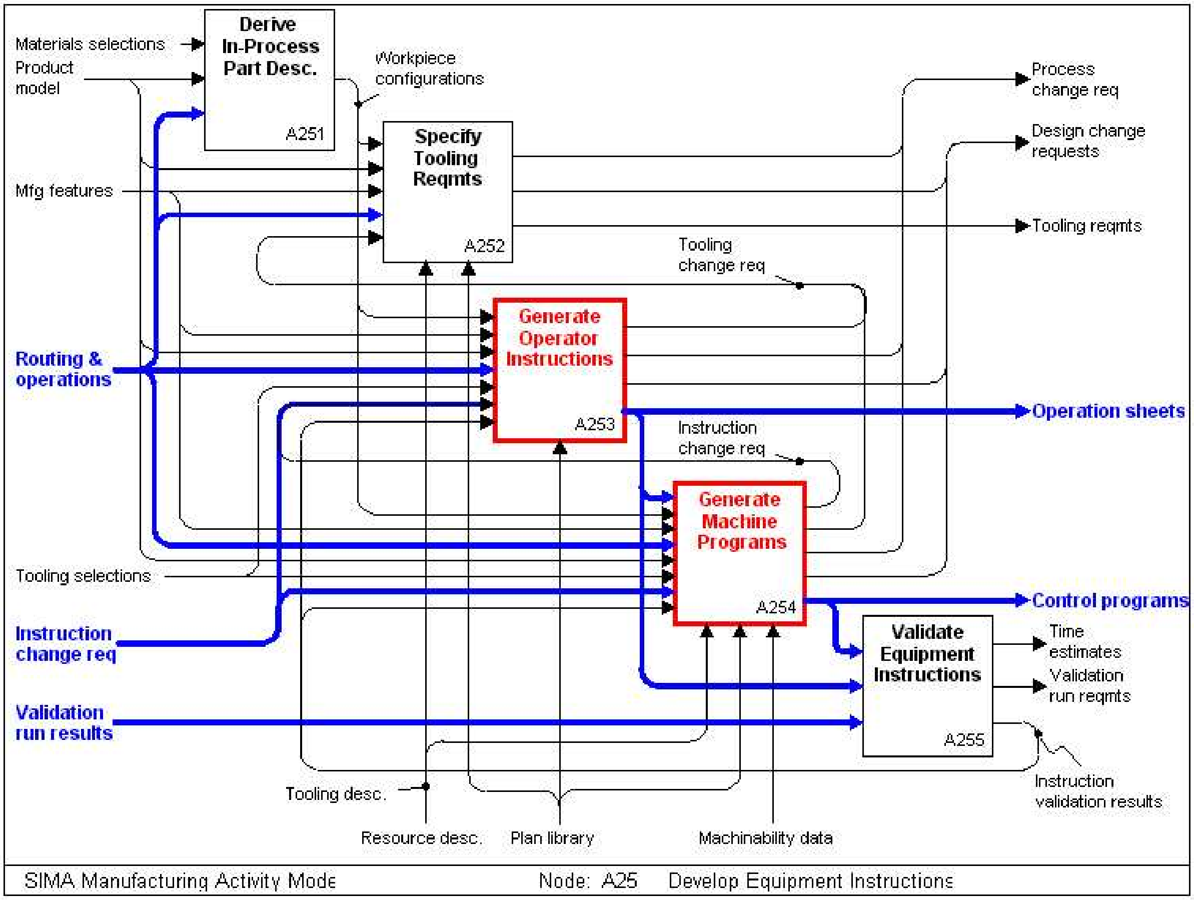

Figure 5. Decomposition of Node A25

This process is considered to include optimization of the instructions -- the process parameters, tools, setups, machines, fixturing devices, and operations sequence -- to improve the process in quality, productivity, and cost reduction. In many cases, these are competing goals, so that for different Parts and facilities different goals may be emphasized and different compromises will be considered optimal.

2.3.1.1 Derive in-process workpiece configurations

Define intermediate geometries of a workpiece at some stages in a process and associated dimensions, tolerances, and surface finishes that are important to later processes.

2.3.1.2 Specify tooling requirements

Specify the tooling, end-effectors, fixtures, and consumable materials required at the processing station. Specifications may include tool selections, but often identify only the general type of tool and mount and the specific operations to be performed with the tool, including relevant starting and ending part geometries, clearances, etc.

2.3.1.3 Generate operator instructions

Specify the sequence of fixturing and processing steps to be executed at each workstation. Create operation sheets for shop-floor operators. Document and illustrate part orientations relative to the machine and to part datums, identify fixtures and fixturing requirements.

2.3.1.4 Generate machine programs

Generate programs for the direct control of automated machining, assembly, handling and inspection systems, such as machine tools, wire layers, welders, robots, and coordinate measuring machines. Programs are created in a form recognizable and executable by the machine controller.

Specify the parameters of the automated process. For machine tools, these parameters include machining speeds, feed rates, coolant on/off timing, tool change timing, and maximum depth of cut. For handling devices, these parameters include minimum/maximum force, end-effector surface requirements, etc.

2.3.1.5 Validate equipment instructions

Verify and approve for production use the operator and equipment instructions and all the data sets that define the required tooling, fixtures, setups, operations, and machine control parameters. The verification may be any or all of analysis, implementation or simulation. Based on simulation or implementation, estimate the total manufacturing time at each station in the routing, including setups, operation sequences, process parameters, control programs, etc. In most cases, separate estimates are made of the elapsed time, operator time, and time-in-use of the machines.

2.3.2 Definitions of Additional Information Flows

Additional information flows include instruction validation results, tooling descriptions, tool selections, and workpiece configurations.

2.3.2.1 Instruction validation results

Feedback to the instruction generation activities from the instruction validation activities, including both information and artifacts. The results may include estimates of time, cost, and yield, and also indications of performance difficulties and special areas of concern for part quality. The results may directly identify problems that indicate a need for changes to the machine and operator instructions.

2.3.2.2 Tooling descriptions: (Resource descriptions)

Detailed descriptions of each type of tooling that is used in the facility manufacturing processes:

- Tools: including special tools and standard tools and components: cutters, holders, collets, etc.
- Fixtures: clamps, jigs, special-purpose fixtures end-effectors, including grippers, vises, etc. -
- Inspection tools: gages, probes, and sensors, etc.
- Shop materials: rouge, flux, adhesive, coolant, lubricant, etc.

The database should include types, catalog numbers, properties (kinematic structure, geometric characteristics, capabilities, size or dimensions, accuracy, etc.), drawings or models, functionalities, accessories, maintenance requirements, warranties, and prices.

2.3.2.3 Tooling selections

Identification of a specific tool (or fixture or end-effector) to meet each set of tooling requirements. Tooling selections may refer to off-the-shelf tools, made-up tool assemblies with associated drawings and specifications, or to tools specially designed for the purpose, which have complete design and possibly production specifications. Tooling selections may also indicate the number of "sister" tools (i.e., instances of the type) required to make a specified Part batch.

2.3.2.4 Workpiece configurations

Geometries, dimensions, and tolerances that describe a workpiece at the end of a processing stage with respect to datums and features that are important to handling, fixturing, or alignment for a subsequent stage.

2.4 Related Work

2.4.1 AP213

One of the most comprehensive efforts to define information requirements for a process plan specification is AP213, “Numerical Control (NC) Process Plans for Machined Parts” [ISO 94]. Part of the Standard for the Exchange of Product Model Data (STEP) effort, ISO 10303-213 is an Application Protocol (AP) for archiving, sharing, and exchanging process plan information. AP213 deals specifically with computer-readable NC process plans for machined parts. National standard committees, international standard committees, and industrial participants developed it through a collaborative effort. This group summarized the typical information found in a process plan [HAR 91]. This information is shown in Figure 6.

AP213 defines the context, scope, and information requirements for representing a process plan. It contains an information model that specifies the data elements (as well as the relationships between those elements) that make up a process plan. These data elements and their relationships are part of the Application Reference Model (ARM). The ARM is then mapped to an ISO 10303-resource model called an Application Interpreted Model (AIM). To determine the potential for using AP 213 as a representation for such a plan, we carried out an extensive analysis of the AP 213 ARM information model and how it was constructed [IUL 97a]. Figure 7 depicts the basic data components of AP 213 ARM and the relations among them. This figure illustrates that, as far as AP213 is concerned, a process plan is composed of one or more activities that can be decomposed into sub activities. An activity is linked to the product definition data and is determined by the product shape. An activity describes the processing and resources required. Certain data is considered in-scope and certain data is considered out-of-scope.

Data considered to be inside the scope of AP 213 include planning information contained in the NC process plans for machined parts, task instructions required to manufacture a part using numerical control NC machines, required NC programming information, and in-process inspection information. Data considered to be outside the scope of AP 213 includes preplanning NC process information, production planning, scheduling, continuous processes, make/buy analysis, costing, form features and drawings, operations planning, inspection planning, actual execution of the plan, and the NC source program.

Typical Information Captured in a Process Plan

Process Plan Identifier
Part Number and Version
Page Number
Part and Product Name
Organization Name (for customer and manufacturer)
Facility/Location
Time and Data Information (for process plan creation, revision, and effective dates)
Status Information
Operation Number
Operation Name and Description
Version Control Information (revision date and description)
Process Planner
Approval
Drawing Number
Graphical Illustrations
Operation Instructions
Engineering Change Information (and Effectivity)
Legend for Symbols
Notes
In-process Inspection Instructions
Machinery Information (machine data and paramters)
Resource Identifier
Layout/Setup Information (instructions)
Material Code
Engineering Data
Work Standards (standard operation time)
Operator Information (level and skill requirements)

Figure 6. Summary of Information Requirements from Sample Process Plan

The results of the AP213 analysis are:

1. The date that an NC process plan is created is an important piece of information, and it should be recorded in process plan data. This piece of information is not defined in the ARM.

2. Tool names can not be represented in AP 213. Tool name is different than tool id. A tool name can be 1/4" end mill, 1/2" twist drill, 2", etc. There is no Tool_name attribute in AP 213. Without an attribute in AP213, the information can not be shared among planning systems.

3. There is no straightforward way to represent the mounting of a fixture on a machine tool. The position of a fixture relative to the machine origin and its orientation relative to the machine axes are critical to the verification of the NC program.

4. The name of actions, that is procedural steps, cannot be represented directly in AP 213. There is no attribute in the ARM entity called Activity to capture the name of the activity.

5. It is possible to support simple sequencing of activities, but arbitrary relationships between activities cannot be supported easily at this time.

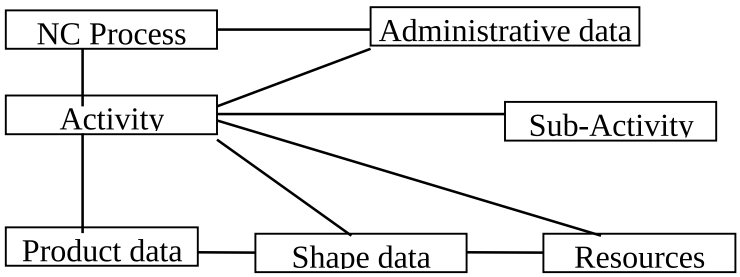

Figure 7. Simplified AP213 data model

We can draw three general conclusions from these results. First, there are important philosophical differences regarding the concept of a process plan between AP213 and METK. In AP213, a process plan is viewed as a collection of the data needed to manufacture a part. Formal models are defined in AP213 to support the exchange of information between applications that **create** that data. In METK, a process plan is viewed as a recipe that includes both the data and the instructions needed to manufacture a part. Formal models are needed in METK to support the exchange of information between applications that generate process plans and applications that **execute** those plans. Second, in spite of these differences, a mapping can be defined so that the AP213 ARM model can support the execution of process plans with simple, linearly-ordered tasks like those shown in Figure 2. The mapping is not simple, but it could be implemented in a custom interface. Finally, this interface would require substantial modifications to support process plans with more complicated precedence relations - such as AND/OR graphs, conditional branching, and parallelism - among the steps in the procedure specification.

Therefore, AP213 cannot be used directly as a specification for a process plan interface for the METK.

2.4.2 The Process Specification Language (PSL) Project

The goal of the NIST Process Specification Language (PSL) project is the creation of a neutral, generic language for process specification, which can serve as an interlingua for the integration of multiple, "process-related" manufacturing applications [SCH 96]. This language will be common to all such applications, meaning that it will be generic enough to be decoupled from any particular application, but robust enough to be able to represent process information for every application. Additionally, the PSL will be sufficiently well defined to ensure the complete and error-free exchange of process information. It will do this either by serving as the application "native" language or as a "second" language for communication.

A requirements analysis for the PSL project has been completed [SCH96], to determine the information requirements that were intrinsic to process specification. They include core requirements, outer core requirements, extensions, and application-specific requirements. Many of the core requirements (such as resource, simple sequences, tasks, and durations) and outer core requirements (such as alternative tasks, instructions, and complex sequences) are requirements for the METK project as well. METK requirements that could be considered extensions include quality analysis, performance measurements, and parallelism. No additional application- specific requirements have been identified.

There are three major differences between the METK project and the PSL project: representation of process, scope, and expected completion. The METK project will base its representation on a formal information model, with textual definitions of the meanings of the entity and attribute names within the model. The PSL project will base its representation on formal semantics, which is an ontology containing logic-based axioms and definitions to define precisely the various concepts underlying a process specification. The METK project has a relatively narrow scope - the exchange of process information between process planning and NC validation applications. The PSL project covers all process-related, manufacturing applications. The METK project is addressing an integration problem that industry faces today. Therefore, the METK project hopes to develop a proposed specification within the next 1-2 years. On the other hand, the PSL project is addressing both industry's current integration challenges as well as the challenges they foresee in the future. Consequently, the timeframe for completion of the PSL project is 3-5 years.

3.0 Documents and Standards Review

The following documents and standards were reviewed during the preparation of this document:

Edward Barkmeyer, "SIMA Reference Architecture - Part 1:Activity Models, National Institute of Standards and Technology, Internal Report 5939, December 1996.

Bryan Catron and Steve Ray, "ALPS: A Language for Process Specification," International Journal of Computer Integrated Manufactring, Vol. 4, No. 2, pp. 105-113, 1991.

ISO/DIS 10303-213, "Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 213: Application Protocol: Numerical Control Process Plans for Machined Parts," Internal Organization for Standardization, 1 rue de Varambe, Case Posatale 56, CH-1211 Geneva, Switzerland, 1994.

S. Keith Hargrove, "A review of Computer-Aided Process Planning Systems and Application Protocol Development," National Institute of Standards and Technology, Internal Document - Unpublished, 1991.

Michael Iuliano, Albert Jones, and Shaw Feng, "Analysis of AP213 for Usage as a Process Plan Exchange Format," National Institute of Standards and Technology, NISTIR 5992, March, 1997.

Michael Iuliano, "Overview of the Manufacturing Engineering Toolkit Prototype," National Institute of Standards and Technology, NISTIR 5730, October 1995.

Michael Iuliano and Albert Jones, "Controlling Activities in a Virtual Manufacturing Cell," **Proceedings of WSC'96 Conference**, San Diego, CA, December 1996.

Charles McLean, "Interface Concepts for Plug-Compatible Production Management Systems," **Computers in Industry - IFIP WG 5.7: Information Flow in Automated Manufacturing Systems**, North Holland, Amsterdam, Netherlands, pp. 307-317, 1987.

Chuck McLean and Swee Leong, "Industrial Need: Production System Engineering Integration," National Institute of Standards and Technology, NISTIR 6019, May 1997.

Raytheon Andover, “Example Process Plans,” Internal Raytheon Document, 1996.

Mike Smith and Swee Leong, “Computer Aided Manufacturing Engineering Forum: First Technical Proceedings,” National Institute of Science and Technology, NISTIR 5699, March 1995.

Mike Smith and Swee Leong, “Computer Aided Manufacturing Engineering Forum: Second Technical Proceedings,” National Institute of Science and Technology, NISTIR 5846, August 1996.

4.0 Information Requirements
4.1 Units of Functionality

The concept for this information specification is that process planning information can be categorized into four types categories: the header information, parameter information, resource information, and procedure information. In essence, these may be viewed as the Units of Functionality (UOFs) for the process plan specification.

The four units of functionality include:

Header UOF;
Resource UOF;
Parameter UOF;
Procedure UOF;

The units of functionality and a description of the functions that each UOF supports are given below. The application objects included in the UOF are defined in section 4.2.

4.1.1 Header UOF

The Header UOF includes the following objects:

administrative information
product information
part information
customer information
facility information
quality information
cost information

4.1.2 Resource UOF

The Resource UOF includes important information about the resources required to implement the process plan. It contains the following objects.

resource type
resource name
resource identifier
resource description
resource quantity

resource file

4.1.3 Parameter UOF

The Parameter UOF includes information about run-time variable required for the execution of the process plan. The following objects are used by the parameter UOF:

parameter identifier
parameter name
parameter association
parameter value

4.1.4 Procedure UOF

The Procedure UOF describes the activities, or work elements, required to complete the process plan. The procedure UOF is structured as a collection of procedure steps. At each step an activity, or work element is executed to complete the step. Each work element may contain one or more attributes describing more information about the activity. The procedural section may also contain information on the relationship among the steps, such as whether the steps are executed sequentially or in parallel. For this document, however, we are assuming that the steps are executed sequentially. The only object used by the procedure UOF: is work element

The information required for these UOFs is generated by the process planning function and then interpreted by the simulation function.

4.2 Application Objects

The application objects are defined in this section. Each application object is an element that embodies a unique application concept and contains attributes specifying the data elements of the object.

4.2.1 Administrative Information

The administrative information object is defined by a process plan identifier, a process plan name, a process plan description, a creation date, a creation time, a revision identifier, a revision date, a revision time, a process planner identifier, a process planner name, and a process plan notes.

4.2.1.1 Process Plan Identifier

The unique identifier for the process plan.

4.2.1.2 Process Plan Name

The unique name for the process plan.

4.2.1.3 Process Plan Description

The word or group of words that comprise the unique designation of a process plan.

4.2.1.4 Creation Date

The date of the original creation of the process plan.

4.2.1.5 Creation Time

The time of the original creation of the process plan.

4.2.1.6 Revision Identifier

The unique identification, within an organization, of a change that has been incorporated into the process plan.

4.2.1.7 Revision Date

The date of the most recent revision of the process plan.

4.2.1.8 Revision Time

The time of the most recent revision of the process plan.

4.2.1.9 Process Planner Identifier

The unique identifier of the person within an organization responsible for creating this process plan.

4.2.1.10 Process Planner Name

The word or group of words that comprise the unique designation of a planner.

4.2.1.11 Process Plan Notes

The word or group of words that may provide additional information about the process plan.

4.2.2 Product Information

A product identifier and a product name define the product information object.

4.2.2.1 Product Identifier

The unique identification of the product for which the part is produced.

4.2.2.2 Product Name

The word or group of words that comprise the unique designation of a product.

4.2.3 Part Information

A part identifier and a part name define the part information object. This object identifies the part to be made using this plan.

4.2.3.1 Part Identifier

The unique identification of the part for which the process plan was generated.

4.2.3.2 Part Name

The word or group of words that comprise the unique designation of a part.

4.2.4 Customer Information

A custom identifier and a customer name define the customer information object.

4.2.4.1 Customer Identifier

The unique identifier of the organization for which the process plan is prepared and executed.

4.2.4.2 Customer Name

The word or group of words that comprise a unique designation of a company.

4.2.5 Facility Information

A facility identifier and a facility description define a facility information object. The part will be manufactured at the facility defined by this object.

4.2.5.1 Facility Identifier

The unique identifier of the facility where the process plan is executed.

4.2.5.2 Facility Description

The word or group of words that comprise a unique designation of a facility.

4.2.6 Quality Information

A quality coordinator and a quality level code define a quality information object. This object provides general information about the quality requirements for the part.

4.2.6.1 Quality Coordinator

The unique identifier of the person within an organization responsible for assuring the quality conformance of the process plan and the part.

4.2.6.2 Quality Level Code

A code indicating the quality requirements of the part for which the process plan is generated.

<u>4.2.7 Cost Information</u>

A cost estimator and a cost estimate define the cost information object. This provides general information about the cost estimated for executing and completing the plan.

4.2.7.1 Cost Estimator

The unique identifier of the person within an organization responsible for estimating the cost of executing and completing the process plan.

4.2.7.2 Cost Estimate

The monetary value of the estimate for executing and completing the process plan.

<u>4.2.8 Resource Type</u>

A type of resource. Examples include a machine, a controller, a tool, a fixture, a work piece, a numerical code (NC) program, or an employee.

<u>4.2.9 Resource Name</u>

A description of the type of resource.

<u>4.2.10 Resource Identifier</u>

The unique identifier for the resource used in the process plan.

<u>4.2.11 Resource Description</u>

The word or group of words that comprise the unique designation of a resource description.

<u>4.2.12 Resource Quantity</u>

The number of this type of resource required to complete the process plan.

<u>4.2.13 Resource File</u>

The identifier for the file that contains additional pertinent information on the resources required for executing the process plan.

<u>4.2.14 Parameter Identifier</u>

A unique identifier for a parameter.

4.2.15 Parameter Name

The word or group of words that uniquely described a parameter.

4.2.16 Parameter Association

A description of the association the parameter has with other entities in the process plan. Examples include a resource parameter or an activity parameter.

4.2.17 Parameter Value

A value to the parameter.

4.2.18 Work Element

The word or group of words that uniquely describes a specific action or activity required for a procedure step. An activity description, an activity value, an activity resource, an activity time estimate, and an attribute define a work element.

4.2.18.1 Activity Description

The word or group of words that uniquely describe the work element.

4.2.18.2 Activity Value

The value ascribed to an activity identifier. The intent is for the activity value to be an action verb that describes the activity.

4.2.18.3 Activity Resource

The resource or group of resources required for completing an activity.

4.2.18.4 Activity Time Estimate

The time estimate for the completion of the activity.

4.2.18.5 Attribute

An attribute is a characteristic of an activity within a process plan. An attribute identifier, an attribute description, an attribute type, and an attribute value define an attribute.

4.2.18.5.1 Attribute Identifier

The unique identifier for an attribute of an activity.

4.2.18.5.2 Attribute Description

The word or group of words that uniquely describes an attribute of an activity.

4.2.18.5.3 Attribute Type

A description of the type of attribute.

4.2.18.5.4 Attribute Value

The value ascribed to the attribute.

4.2.18.6 Immediate Predecessor

The activity or group of activities that precede the execution of the current activity.

4.2.18.7 Step Identifier

A step is a part of the total procedure within a process plan, and it may contain one or more activities. The unique identifier for a procedure step within the process plan.

5.0 Summary

This Requirements Document has described the information requirements for a process plan specification for the Manufacturing Engineering Toolkit (METK) Project. This specification will be used in the METK as an interface between process planning and simulation. The units of functionality in this specification are header, parameters, resources, and procedures. The application objects for each of these units of functionality are also defined in this document. These objects will be the basis for the development of formal information models for the process plan specification.

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