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SIMA Reference Architecture
Part 1: Activity Models

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National Institute of Standards
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Introduction

This document is a part of the definition of a reference architecture for the integration of manufacturing software applications in the areas of design, fabrication and assembly of discrete electro-mechanical parts. The reference architecture is an element of the Systems Integration of Manufacturing Applications (SIMA) project at NIST (see Appendix A). The scope of the project, and therefore of the reference architecture, is limited to design engineering, manufacturing engineering, production systems engineering and production activities. Other aspects of the manufacturing enterprise, such as product planning, distribution and maintenance, are not within the scope of the project and are not included in the reference architecture.

Following the definitiions in the SIMA Background Study [Bark95], we use the term *reference architecture* to mean:

- the identification of types of systems that perform, or support human agents in performing, the activities within a given domain, and
- the identification of the nature and content of the interfaces required among those systems.

Accordingly, the reference architecture has three parts:

- Part 1 — the Activity Model — provides a model of the generic activities involved in the manufacturing process, and the information flows required to support those activities.
- Part 2 — the Systems Model — identifies the manufacturing application systems, both human and automated, which perform these activities, and the interfaces required for those systems to support the identified information flows.
- Part 3 — the Information Models — define formally and in detail the objects and information which appear in the interfaces.

This document is Part 1 — the Activity Model. It represents the first step toward the goal of the SIMA architecture project — to identify the functions and interfaces required of manufacturing applications software systems. It is intended to provide a frame of reference for SIMA projects and similar industrial projects, which are developing “standard interface specifications”. As a frame of reference, it permits such specification projects to name and “locate” the interfaces they intend to specify and assists those projects in defining the scope of those interface specifications, by identifying the functions the interface is intended to support.

Companion documents will provide the other parts of the reference architecture and define a corresponding “engineering architecture” specifying for each interface the means of information exchange to be used and the representation forms for the information. Multiple engineering architectures which correspond to the reference architecture, but use different mechanisms or forms for interchange, are possible.

A complex of manufacturing application software that conforms to the reference architecture will have a further architectural refinement, which we call an “implementation architecture”, identifying specific software and hardware systems, option choices and configurations.

SIMA Reference Architecture

Part 1: Activity Models

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Part 1: Activity Model

This part of the reference architecture describes the principal technical activities involved in the "art-to-part" aspects, i.e. the engineering and production activities, of a manufacturing enterprise engaged in the production of electro-mechanical products. Other aspects of the enterprise, such as product planning, distribution and maintenance, are not modeled here, although relationships to them are modeled where appropriate. Management activities in the engineering and production phases are modeled, but not in depth, since details of the management activities are "business rules" of the particular organization and vary significantly over corporations involved in the same enterprise.

The goal of the activity models is to identify the information flows required to perform the technical activities efficiently and effectively. A secondary goal is to identify those activities which are supported by (off-the-shelf) software systems. Taken together, these represent the first step toward the goal of the SIMA architecture project: to identify the functions and interfaces required of manufacturing applications software systems.

The models describe the activities and information flows common to most organizations involved in the manufacture of electro-mechanical products. As a consequence, the models tend to be somewhat abstract in the specification of both functions and information flows. In some cases, a generic standard which supports many special cases of a common information flow exists or can be developed, and thus conforms directly to the generic flow identified in the model. In other cases, the detailed information required to support one manufacturing domain differs significantly from the detailed information required to support another, and these distinctions will be further elaborated in the information models (Part 3).

It is our belief that the activities modeled herein are fundamental to the enterprise of manufacturing. Since 1905, the basic engineering activities involved in the design of electro-mechanical systems, and in the specification of the related manufacturing systems and processes, have hardly changed. The means of performing the activities, the knowledge needed and available, the degree of automation in them, and the technologies they specify and use, have all changed dramatically, but the nature of the engineering activities has changed very little. In the near future, the way in which these functions are performed, by combinations of human and machine brains and brawn, will continue to change rapidly, but the functions performed will not. And consequently, the information which is needed to perform the function well will not change in concept, although it may change in magnitude and in detail. Because the models in this paper represent *what* is done rather than *how* it is done, although they represent the manufacturing enterprise "as is", we believe the models also represent the manufacturing enterprise "to be".

The activity models were developed by NIST experts drawing extensively on previous work by CAM-I [Ferr91], SEMATECH [SEMA91], the ESPRIT/IMPPACT project [Bjor92] and ISO TC184 [ISO93] [ISO94]. Because the intention was to identify the interfaces required of software systems, the activity models were expanded only to that level of detail at which a modeled activity represents a specific kind of engineering or production assignment that might be supported by individual software packages. (Where possible, off-the-shelf software currently available was used as a guideline.) Unsurprisingly, many of the modeled activities are still primarily performed by human agents using at most general-purpose office automation software.

The overall view maintained in these models is that of the engineering or production manager responsible for assigning the engineering or production tasks and ensuring that the results of one task are provided to another. In practice, that is multiple separate individuals and more than one level of management. The levels of decomposition in the models are mostly for convenience in isolating areas of concern. While there is some correlation to domains of management responsibility, no relationship between the activity decompositions and the organization structures is intended.

While an effort was made to maintain a common domain throughout the development of these models, it became apparent to the modelers that the engineering and production activities in the design and manufacture of assemblies are similar to, but in many ways significantly different from, the activities in the design and manufacture of discrete parts. Although a “common” model is presented here, some of the activities are much more important and detailed for discrete parts, while others are more important and more detailed for assemblies. This change in emphasis will be apparent in the descriptions and details of the activities.

Most important to the purpose of the models, however, is that the information sets can be characterized. The models attempt to separate the information into cohesive sets and identify the expected producers of an information set and the expected uses of the information. This characterization of an information set is important to defining the scope of an information model — a detailed description of the information objects — for the information set. (And it purposely avoids the common practice of modeling all the data produced by a given software package without regard to the needs of the users.)

Not all instances of a modeled activity will use all of the information sets modeled as provided to it, and some may not produce all of the modeled outputs. Some information sets will be relevant only to assemblies and others only to discrete parts, and still others will be relevant to both but have very different detailed content in the two applications. These issues are important in the development of the information models and are recognizable in the characterizations given here.

The models were documented using the formal methods and diagrammatic techniques defined by IDEF0 [FIPS183], with some unusual conventions. The diagram conventions are summarized in Appendix B.

This Part of the SIMA Architecture consists of two sections. Section 1.1 consists of the IDEF0 diagrams of the activities, and text descriptions of the activities identified in the diagrams. Section 1.2 provides descriptions of the information flows appearing in the IDEF0 diagrams in section 1.1.

1.1 Activities

This section contains detailed descriptions of the product realization activities in the form of IDEF0 diagrams and accompanying text. The information flows appearing in the diagrams are described in section 1.2.

The complete node tree for the SIMA manufacturing activity model is as follows:

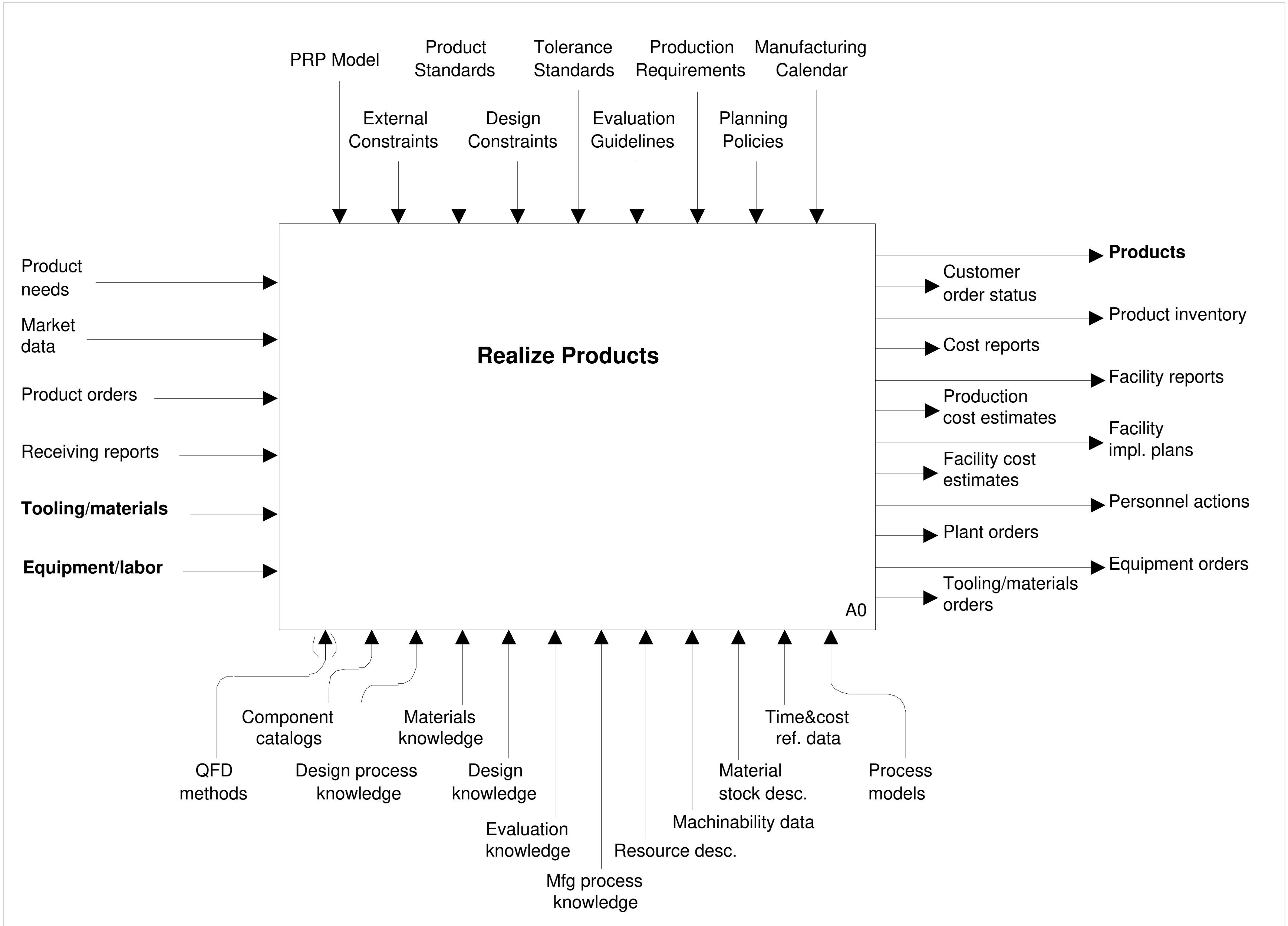
A0: Realize Products
- A1: Design Product
  - A11: Plan Products
  - A12: Generate Product Specifications
  - A13: Perform Preliminary Design
    - A131: Develop Functional Decompositions
    - A132: Evaluate and Select Decomposition
    - A133: Develop Preliminary Configurations
    - A134: Consolidate Configurations
    - A135: Evaluate Alternative Designs
    - A136: Select Design
  - A14: Produce Detailed Designs
    - A141: Design System/Component
    - A142: Analyze System/Component
    - A143: Evaluate System/Component Design
    - A144: Optimize Designs
    - A145: Produce Assembly Drawings
    - A146: Finalize System/Component Design
- A2: Engineer Manufacture of Product
  - A21: Determine Manufacturing Methods
    - A211: Derive manufacturing features
    - A212: Select stock materials
    - A213: Select processes
    - A214: Select Major Resources
    - A215: Develop Preliminary Cost Estimates
  - A22: Determine Manufacturing Sequences
    - A221: Specify Operations
    - A222: Sequence operations
    - A223: Specify Part Routing
    - A224: Optimize & Validate Plan
  - A23: Engineer New Processes
  - A24: Develop Tooling Packages
    - A241: Select Tooling and Assemblies
    - A242: Design Tooling Assemblies
    - A243: Design Special Tooling
    - A244: Estimate Tooling Cost
  - A25: Develop Equipment Instructions
    - A251: Derive in-process workpiece configurations
    - A252: Specify tooling requirements
    - A253: Generate Operator instructions
    - A254: Generate Machine Programs
    - A255: Validate equipment instructions
  - A26: Finalize Manufacturing Data Package

- A261: Develop Final Cost Estimates
- A262: Release Resource Package
- A263: Release Scheduling Package
- A264: Update Plan library

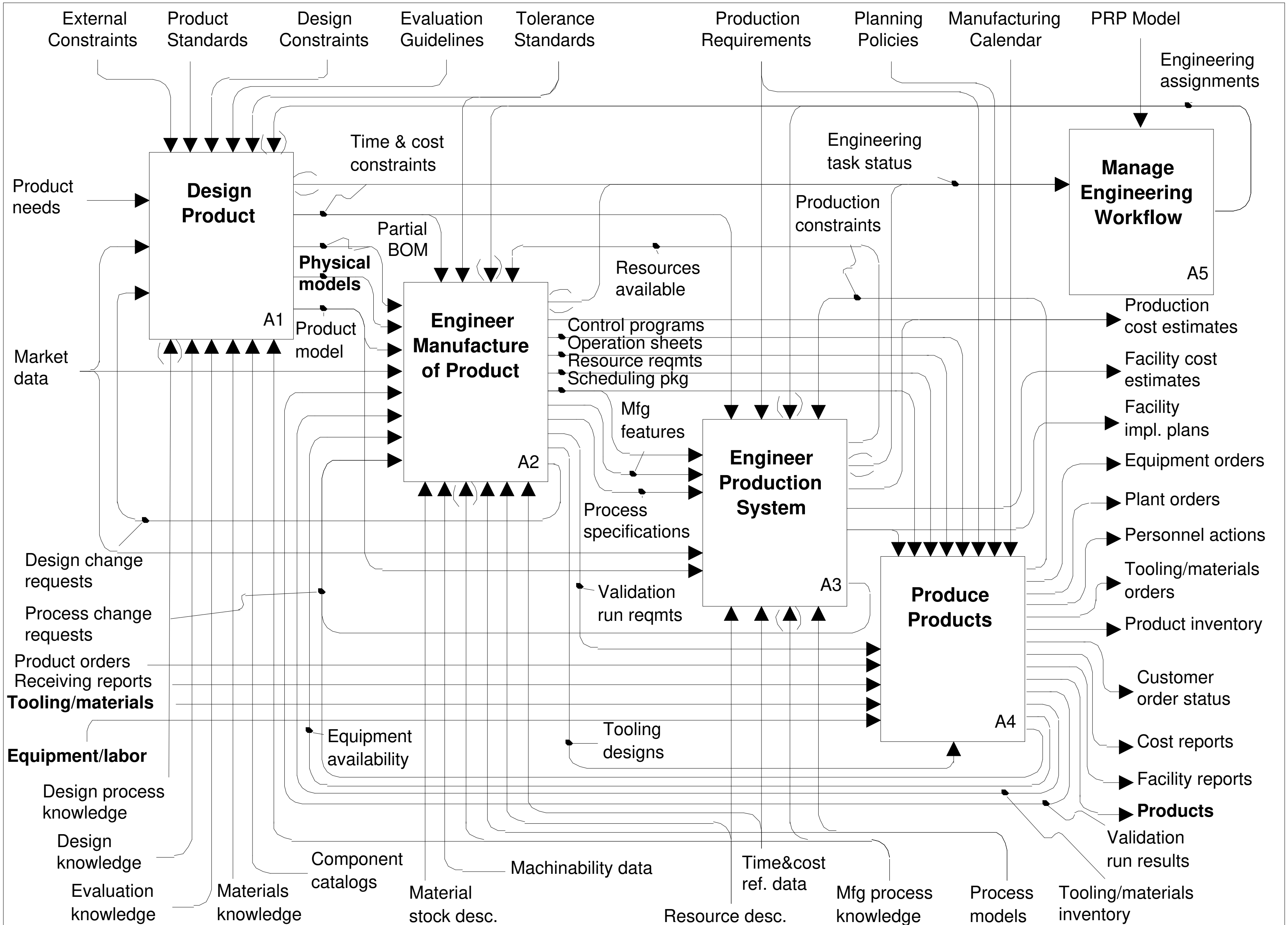
A3: Engineer Production System
- A31: Define Production Engineering Problem
  - A311: Identify Project Type
  - A312: Identify Part Mix
  - A313: Identify Related Parts
  - A314: Identify Critical Dates
  - A315: Identify Target Costs
  - A316: Identify Manufacturing Constraints
- A32: Specify Production & Support Processes
  - A321: Specify Process Requirements
  - A322: Specify Process Flows
  - A323: Specify Materials Flow Requirements
  - A324: Specify Support Systems Requirements
- A33: Design Production System
  - A331: Specify Production Equipment
  - A332: Specify Control & Automation Systems
  - A333: Develop Facility Layout
  - A334: Design Information System
  - A335: Integrate System Designs
- A34: Model and Evaluate System
- A35: Define Implementation Plan

A4: Produce Products
- A41: Develop Production Plan
  - A411: Create Master Schedule
  - A412: Define Capacity Requirements
  - A413: Create Production Orders
  - A414: Monitor Production Orders
- A42: Define Production Jobs
  - A421: Define Jobs
  - A422: Generate Tool and Stock orders
  - A423: Release Jobs
  - A424: Monitor Job Completion
- A43: Manage Tooling and Materials
- A44: Schedule Jobs
  - A441: Generate Job Schedule
  - A442: Generate Operations Schedules
  - A443: Generate Delivery Schedules
  - A444: Track Jobs
- A45: Control Production
  - A451: Direct Personnel and Machines
  - A452: Control and Monitor Jobs
  - A453: Coordinate Equipment Groups
  - A454: Control Equipment
- A46: Manage Production Facilities
- A47: Provide Production Facilities

A5: Manage Engineering Workflow



SIMA Manufacturing Activity Model Node: A-0 Realize Products



SIMA Manufacturing Activity Model   Node: A0   Realize Products

A0: Realize Products

This activity represents all principal technical activities involved in the manufacture of products, including product design activities, manufacturing engineering activities, production planning and engineering activities, and production activities. It also touches on a number of technical management activities.

The inputs modeled for this activity are seen as originating from other activities of the manufacturing enterprise, or possibly from sources external to that enterprise. The outputs modeled for this activity are those intended more or less exclusively for other activities of the enterprise. Many of the information units produced in the manufacturing activities for consumption by other manufacturing activities, however, may also be of interest to other aspects of the enterprise.

A1: Design Product

Identify and conceptualize a marketable product, and create the complete description of it. (Expanded on page 9.)

A2: 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. By extension, the process of making the product includes measurement and inspection activities performed during production for process control and quality assurance. (Expanded on page 15.)

A3: Engineer Production System

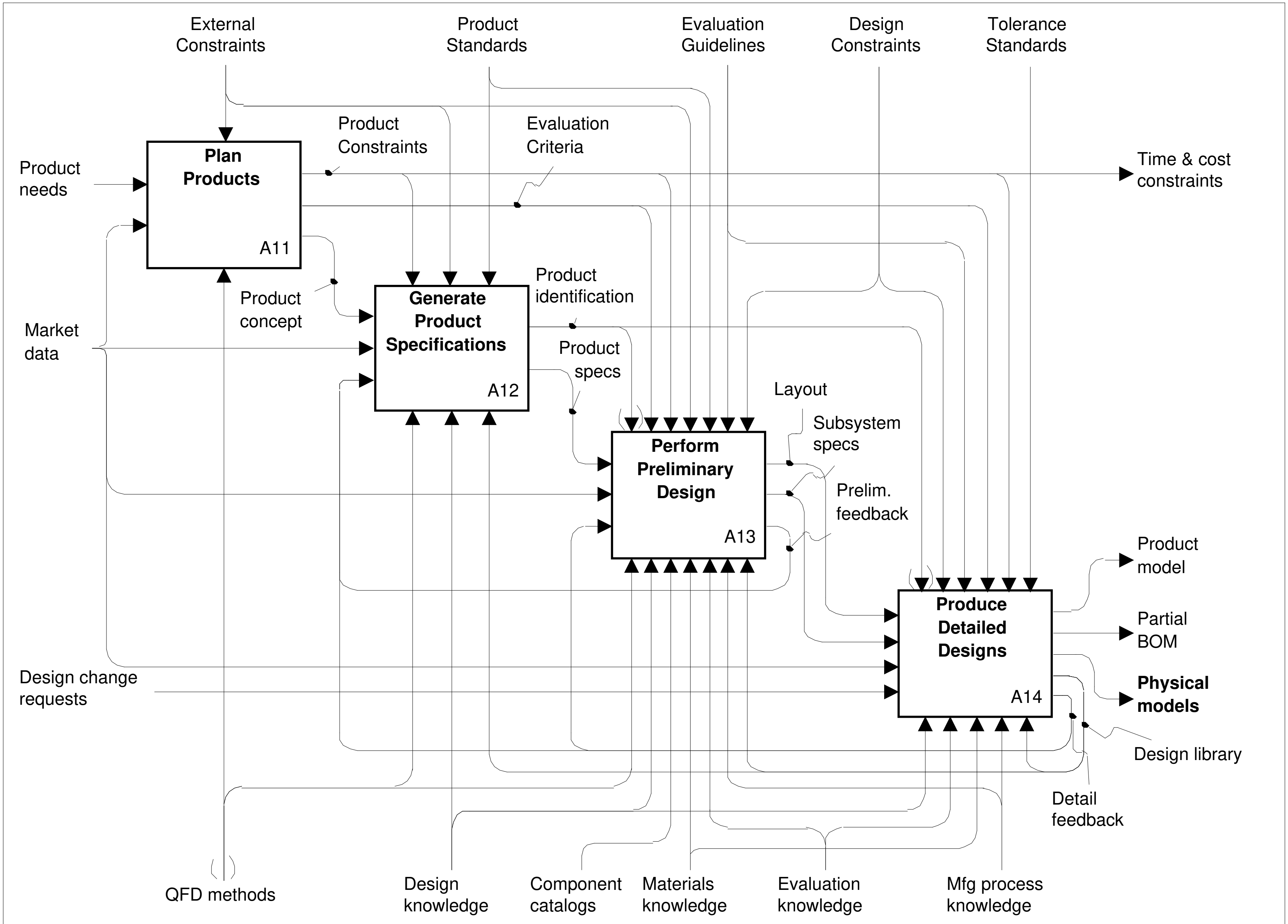
Design new or modified production facilities for the manufacture of a particular collection of Parts. A *facility* may be a plant, a shop, a line, a manufacturing cell, or a group of manufacturing cells. This activity encompasses both design-from-the-walls of such a facility and reengineering of all or part of such a facility to improve the production of certain products. It includes identification of the parts, products and processes for which the production system is to be tailored, identification of the equipment to be installed or replaced, (re)design of the floor layout, and development of an implementation plan for the (re)designed production system. (Expanded on page 29.)

A4: Produce Products

Provide and maintain the production facilities and produce the Parts according to the specifications in the process plans. This involves defining the production schedules and controlling the flow of materials into and out of the production facility, scheduling, controlling and executing the production processes themselves, providing and maintaining the production equipment and the human resources involved, developing and tracking the tooling and materials, etc. (Expanded on page 38.)

A5: Manage Engineering Workflow

Specify engineering tasks, controls, reviews and approvals. Define the sequence of these engineering activities and the required resulting information objects, and their due dates, if appropriate. Assign tasks to engineers and track completion of those tasks. (Not further developed in this cycle.)



SIMA Manufacturing Activity Model Node: A1 Design Product

A1: Design Product

Identify and conceptualize a marketable product, and create the complete description of it.

A11: Plan Products

Depending on (potential) market needs and customer requirements, develop the idea for a product and characterize it in terms of function, target price range and relationship to existing products of the manufacturing firm. Define cost constraints, performance constraints and other marketability factors. Perform market analysis, cost-benefit analysis. Develop product development and marketing plans.
(This activity is out of the scope of SIMA and will not be further developed.)

A12: Generate Product Specifications

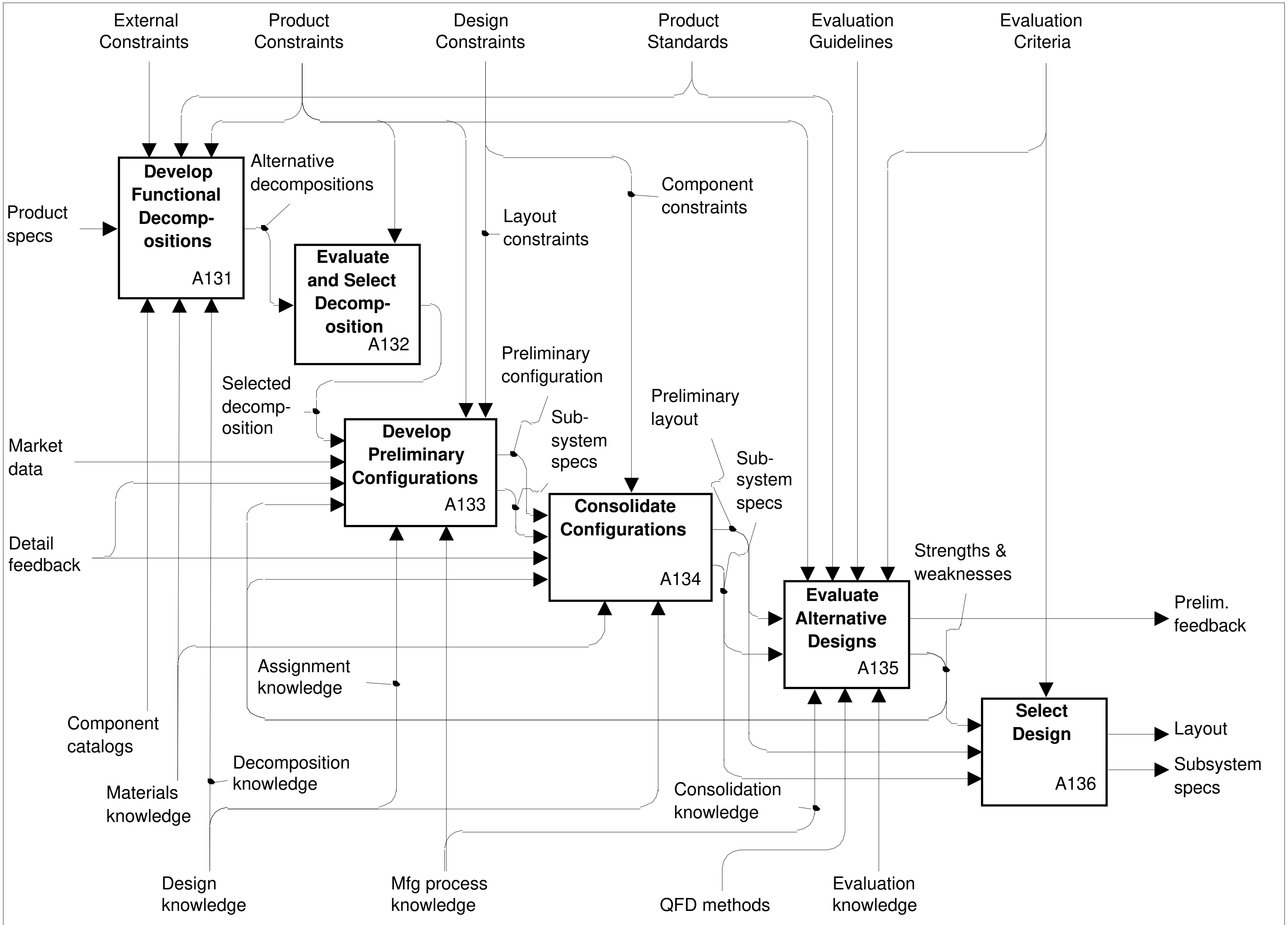
From the conceptual product specification, formulate an engineering specification for the product. This involves mapping the customer requirements into engineering requirements, and refining the engineering requirements in consideration of the relevant laws, regulations, product standards, etc., and also of the existing patents in the same area. This process may involve determination of the relationship of the new product to the firm's library of existing product designs. (Not further developed in this cycle.)

A13: Perform Preliminary Design

Decompose the design problem into a set of component design problems and develop the specifications for each component problem. Define the integration of the components into product in a set of interface specifications and a preliminary layout model. This process will be somewhat iterative, as the early phases of the component design will generate new considerations and changes. Primary results are the product layout drawing and annotations and the component design specifications. (Expanded on page 11.)

A14: Produce Detailed Designs

For each subsystem (or component) that is not off-the-shelf (or identical to an existing in-house design), and for the component integration, produce all specifications needed to completely describe the subsystem for manufacture. This includes drawings and geometry, materials, finish requirements, fit requirements and assembly drawings, tolerances, etc. (Expanded on page 13.)



SIMA Manufacturing Activity Model Node: A13 Perform Preliminary Design

A13: Perform Preliminary Design

Decompose the design problem into a set of component design problems and develop the specifications for each component problem. Define the integration of the components into product in a set of interface specifications and a preliminary layout model. This process will be somewhat iterative, as the early phases of the component design will generate new considerations and changes. Primary results are the product layout drawing and annotations and the component design specifications.

A131: Develop Functional Decompositions

Map product specifications to functions, decompose functions into directly implementable subfunctions, map subfunctions to conceptual devices. Alternative decompositions, based on alternative technologies and approaches, are developed.

A132: Evaluate and Select Decomposition

Consider all alternative decompositions in the light of product constraints (envelope, weight, cost, aesthetic properties, etc.) and the engineering and production capabilities of the firm, and select the one with the highest probability of success.

A133: Develop Preliminary Configurations

Generate the first geometric form of the product, identifying the subsystems and their physical and logical relationships to one another. This is iterative and will require changes resulting from further design of the subsystems and possible consolidations.

A134: Consolidate Configurations

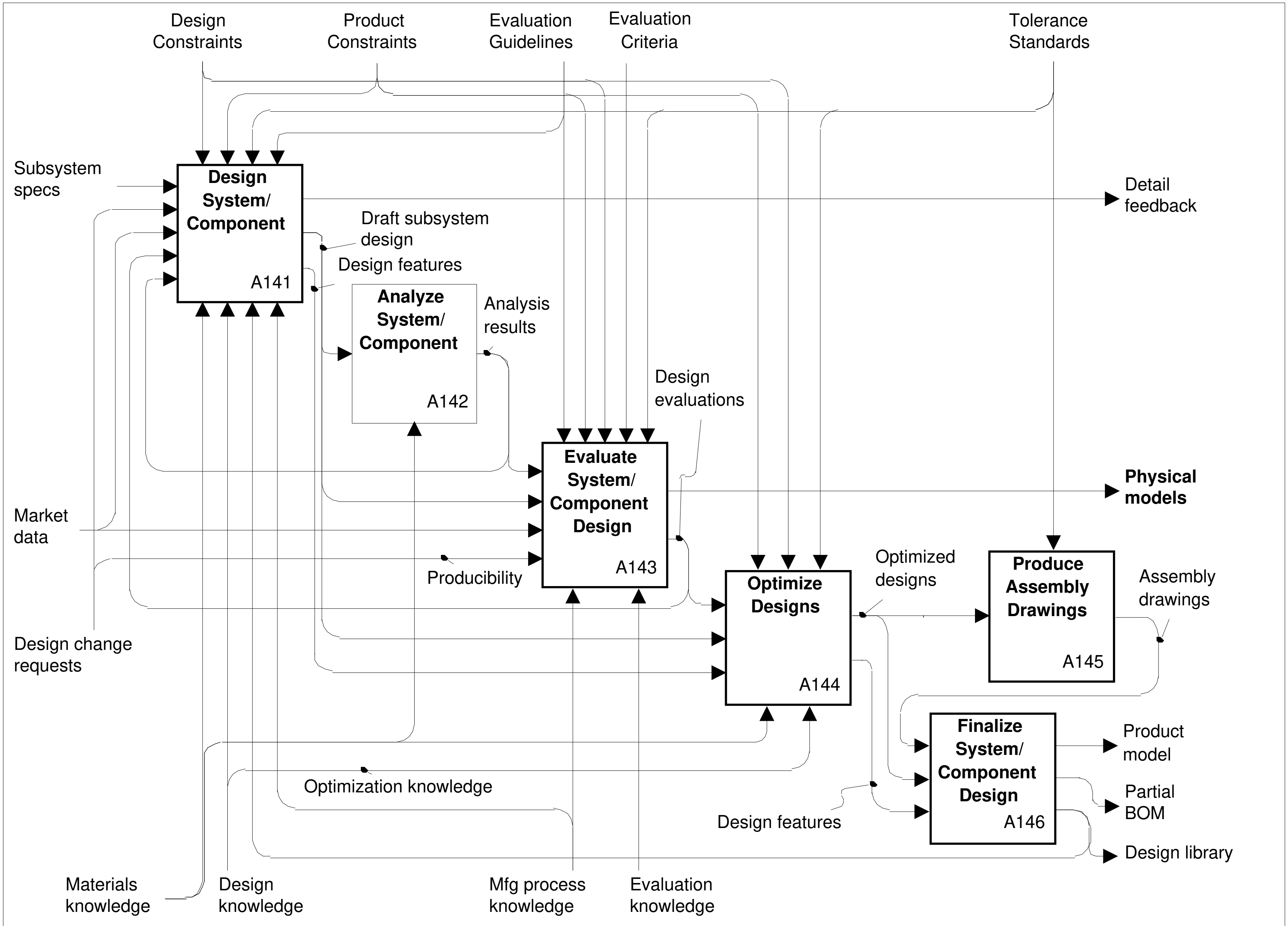
Identify opportunities to merge separate functionalities into a single mechanical or electrical subsystem, which will economize on space or power or replication or processing.

A135: Evaluate Alternative Designs

This step involves preliminary analysis of the performance of the required functions, evaluation of the design against the “ilities” (availability, reliability, maintainability, usability, and perhaps producibility and assembleability), and evaluation of conformance with standards and specifications. In many cases, the analysis may involve a preliminary simulation of the selected system with visual analysis of the performance, although quantitative evaluations are also possible, particularly when some of the components are off-the-shelf. Results of the analysis are the strengths and weaknesses of each design, which may result in another preliminary design iteration to combine best features. This activity may also produce feedback to the product specification activity to get very difficult or costly specifications modified.

A136: Select Design

Identify the best possible solution to refine further. Formalize layout and subsystem specifications for the detail design phase.



SIMA Manufacturing Activity Model Node: A14 Produce Detailed Designs

A14: Produce Detailed Designs

For each subsystem (or component) that is not off-the-shelf (or identical to an existing in-house design), and for the component integration, produce all specifications needed to completely describe the subsystem for manufacture. This includes drawings and geometry, materials, finish requirements, fit requirements and assembly drawings, tolerances, etc.

A141: Design System/Component

Each component (or device) is detailed in geometry and materials (with all the tolerance information) so that the product can be manufactured. In some cases, this involves identification of the *group technology* — the features of the component that are used to perform a design classification — so that similar designs can be identified in the firm's knowledge base of previous designs. This is an iterative process, modified by the results of analysis and evaluation, layout and interface changes, and changes requests from the manufacturing engineering activities.

A142: Analyze System/Component

Perform engineering analyses of the characteristics and behavior of components and subsystems. Determine and quantify the response of the designed system to both external and internal signals (e.g., forces). Both mathematical and visual simulations may be used.

A143: Evaluate System/Component Design

Determine whether and how well the design meets functional and performance specifications and satisfies other qualitative and quantitative constraints, including cost. Rapid Prototypes may be developed in order to perform mechanical and aesthetic evaluations. Downstream producibility feedback becomes a part of this evaluation.

A144: Optimize Designs

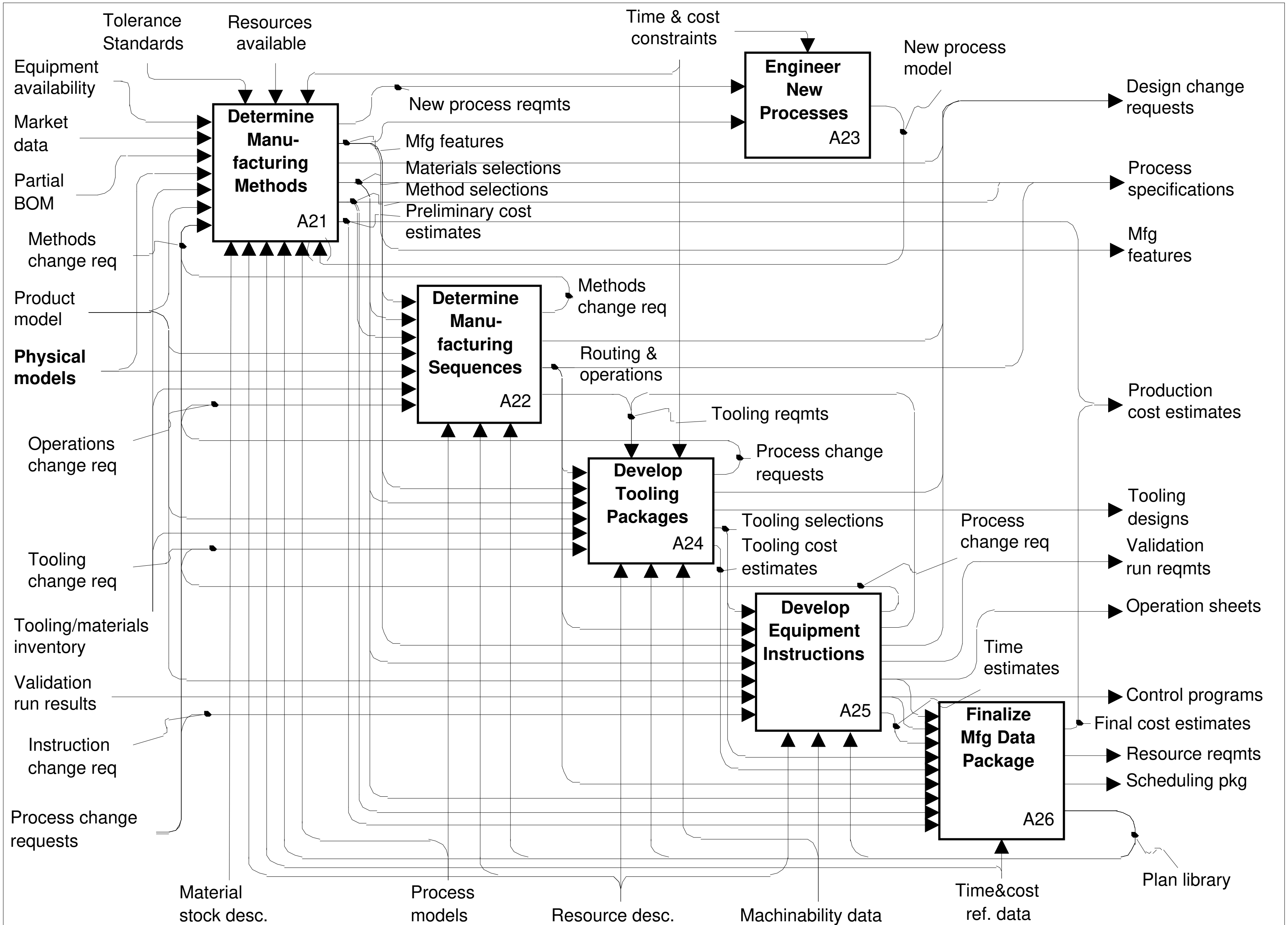
Create a rigorous mathematical model of the system and optimize interrelated design parameters using various mathematical and engineering techniques.

A145: Produce Assembly Drawings

Develop the set of drawings showing how the components are assembled into subassemblies and the subassemblies are assembled and connected to create the final product. In some cases, this is a detailed enhancement of the layout drawings; in other cases, it is an entirely different set of views of the product components.

A146: Finalize System/Component Design

Create and approve for release a product version consisting of a detailed set of design drawings and component specifications: function, geometry, material, finish, processing notes, assemblies, assembly notes, etc. Note: As change requests are processed, alterations to the design occur in many places, and the finalization produces a successor version. What is important here is that an engineering management process intervenes in the technical design process to define a consistent archival design document set for release to manufacturing engineering, production, or maintenance.



SIMA Manufacturing Activity Model Node: A2 Engineer Manufacture of Product

A2: 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 component *Parts*, each of which is either a fabricated (piece) part or an assembly, and no Part is both. The manufacturing engineering process is performed on each Part separately. That is, the manufacturing operations to be planned 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. Before this activity is decomposed into the set of "engineer manufacture of one Part" activities, the design product model is recast into the "manufacturing product model".

The results of this activity are used primarily to drive the production planning and production activities for each Part, and the product as the final Part. Production difficulties may lead to feedback into this activity requesting changes in the process specifications. The results of this activity may also be used in reengineering the production facility itself, in order to make possible 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.

Some manufacturing engineering activities, notably operation sheet and control program validation, may require use of production facilities and therefore must be scheduled into several production activities, such as machine use, tooling preparation, and materials management.

A21: 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, including cutting and forming processes, assembly processes, finishing processes and inspection processes. Any given Part will have either fabrication processes or assembly processes but not both. (Expanded on page 18.)

A22: 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, setups, batching, fabrication, assembly and inspection processes. Define the routing plan — the sequence of (types of) workstations or machines that the Part must go through. (Expanded on page 20.)

A23: 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. (Not further developed in this cycle.)

A24: Develop Tooling Packages

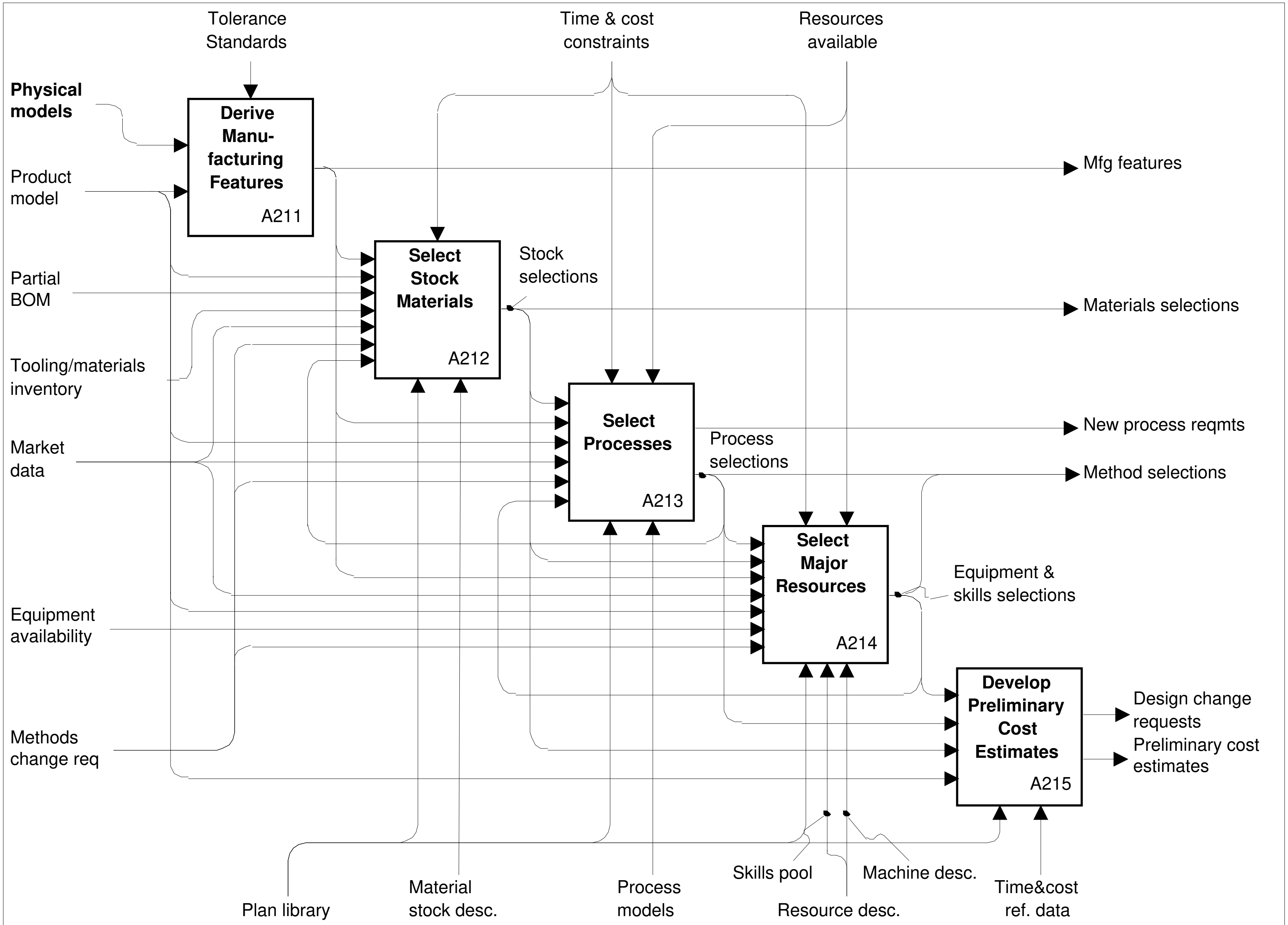
Complete specifications for the required tooling, including cutting tools, molds, dies, fixtures, end-effectors, probes, sensors, etc. This includes design and/or assembly specifications for the tool or fixture, and may include special instructions for use and estimated in-service life. (Expanded on page 22.)

A25: Develop Equipment Instructions

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. (Expanded on page 24.)

A26: 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. (Expanded on page 27.)



SIMA Manufacturing Activity Model Node: A21 Determine Manu- facturing Methods

A21: 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, including cutting and forming processes, assembly processes, finishing processes and inspection processes. Any given Part will have either fabrication processes or assembly processes but not both.

This activity is highly interactive with many of the activities under A22: Determine Manufacturing Sequences.

A211: Derive manufacturing features

Recast the part geometry and topology in terms of features to be created and/or zones of material to be removed from stock materials. Define the associated datums for reference in manufacturing operations. Allocate design tolerances to manufacturing features. If appropriate, assign group technology codes based on processing features to the part. Examine the design features, fabrication features and product model to determine which features must be inspected to ensure either the success of further processing operations or the quality of the resulting part.

A212: Select stock materials

Identify the specific stock materials and off-the-shelf components to be used and their quantities.

A213: Select processes

Choose the major processes that transform material stocks into the final product, including fabrication and assembly processes. (Two major processes are distinct when they require different equipment or different configurations or capabilities of similar equipment.) Associate the processes with design or manufacturing features and the related datums and tolerances.
Develop the inspection plan. Determine what features are to be measured or otherwise inspected and what the qualifying criteria are.

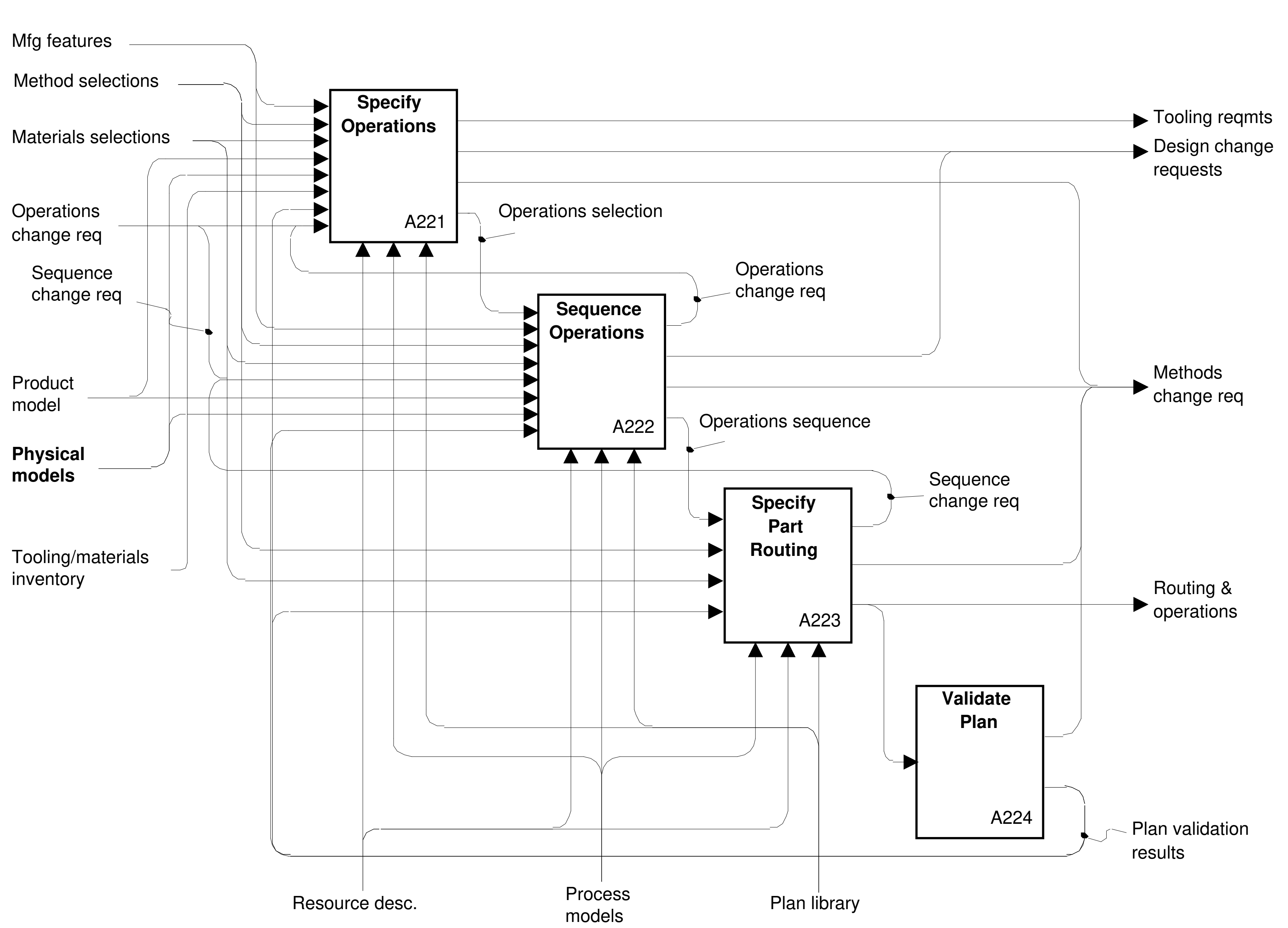
A214: Select Major Resources

Choose the (type of or specific) machine, workstation or skilled artisan to be used for each process (fabrication, assembly or inspection). If facility is predefined, identify the corresponding major resources; otherwise, specify the processing requirements and capabilities which identify the types (and quantities) of the major human and equipment resources which must be acquired.

For inspection, determine which inspection processes are to be performed at inspection stations and which are to be performed at fabrication and assembly stations.

A215: Develop Preliminary Cost Estimates

Estimate the processing time, materials, equipment and manpower costs for the major fabrication, assembly and inspection processes selected. This may result in recommendations for design changes to permit lest costly processes to be used. The estimates of process cost are necessarily crude, since general time guidelines rather than detailed time estimates are used.



SIMA Manufacturing Activity Model Node: A22 Determine Manu- facturing Sequences

A22: 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, setups, batching, fabrication, assembly and inspection processes. Define the routing plan — the sequence of (types of) workstations or machines that the Part must go through.

This activity may be performed by a *generative* system or a *variant* system. 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.

A221: Specify Operations

For each major process, specify the component operations of that process, including the associated manufacturing features and/or parameters which characterize the operations. It is common to specify fabrication, assembly and inspection operations separately at this stage. Special tooling requirements may be identified in this activity.

A222: Sequence operations

Specify the sequence in which the operations will be performed.

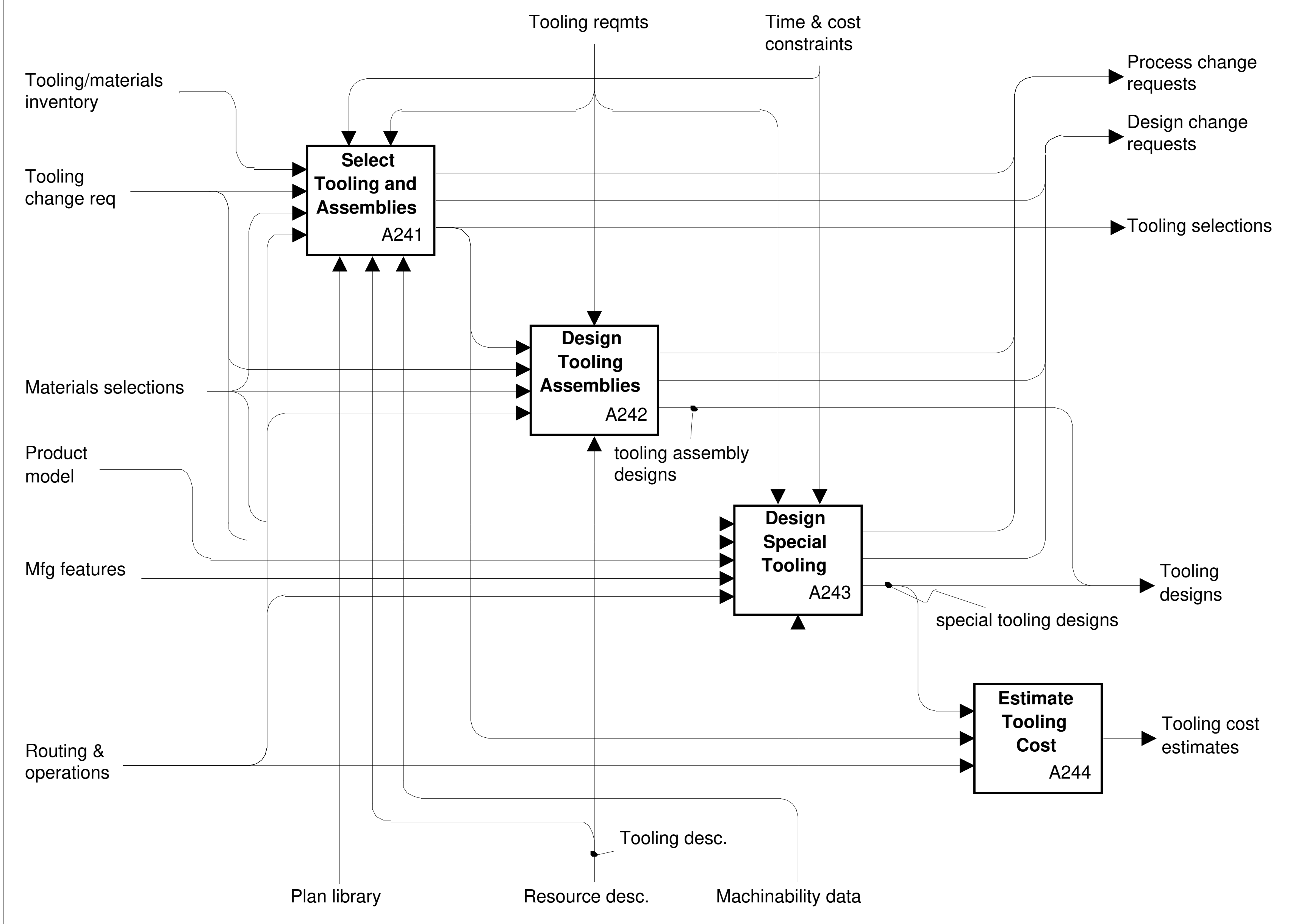
A223: Specify Part Routing

Merge the fabrication, assembly and inspection operation sequences to generate the routing plan for the part. Specify the sequence of workstation types required to implement the processing and inspection sequences, how workpieces will be handled into and out of each workstation, and possibly the means by which workpieces will be transported from one workstation to another. Specify for each workstation the (merged) sequence of operations to be performed in that workstation.

A224: Optimize & Validate Plan

Review and evaluate the plan against part quality and performance objectives. Using prototype fabrication, assembly, inspection, material handling and transportation processes, or simulations of them, verify the draft process plan and the major resource requirements. Identify desirable modifications and/or approve the plans. This activity may also produce a rough estimate of *yield* - the percentage of parts which will survive inspection.

This activity is sometimes called “value engineering” or “quality engineering”.


Tooling reqmts
Time & cost constraints
Tooling/materials inventory
Tooling change req
Materials selections
Product model
Mfg features
Routing & operations
Select Tooling and Assemblies
A241
Design Tooling Assemblies
A242
Design Special Tooling
A243
Estimate Tooling Cost
A244
Process change requests
Design change requests
Tooling selections
tooling assembly designs
Tooling designs
special tooling designs
Tooling cost estimates
Tooling desc.
Plan library
Resource desc.
Machinability data

A24: 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.

A241: Select Tooling and Assemblies

Identify off-the-shelf tooling and tooling assemblies which will meet the requirements of the process plans, as opposed to tooling which must be designed specially for the purpose.

A242: Design Tooling Assemblies

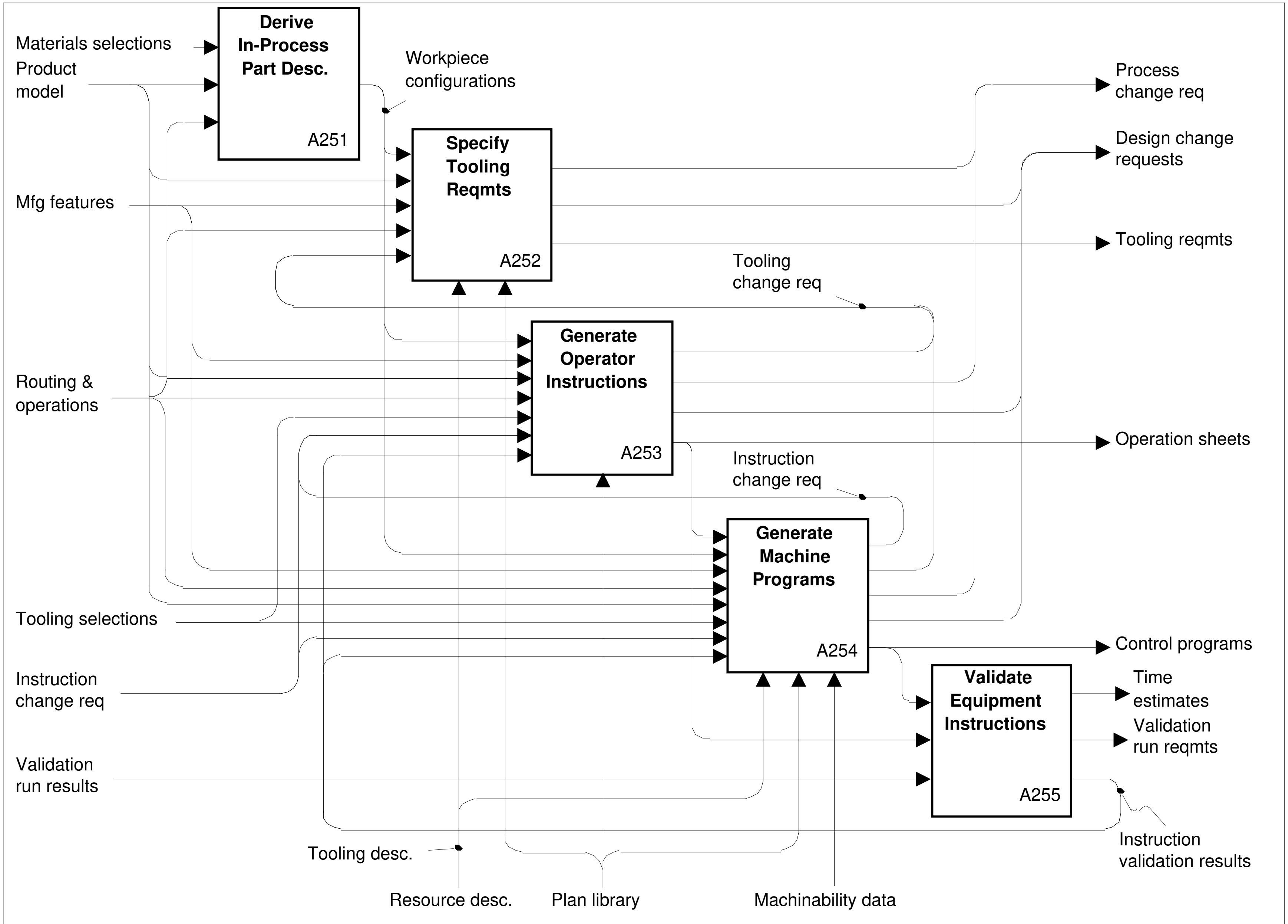
Where the process plans require tooling made-up from standard components, generate the tool or fixture assembly drawings, component specifications and setting specifications.

A243: Design Special Tooling

Where the process plans require tooling that cannot be acquired off-the-shelf or made up from standard components, specify the functional and physical requirements of this special tooling and initiate the corresponding design and engineering process. In principle, the result of this process is a new tool or fixture that is referenced in the process plans.

A244: Estimate Tooling Cost

Estimate the cost of the tooling required for some volume of Part production. For off-the-shelf tooling and assemblies, this includes materials, preparation, storage and handling, and decommissioning. For special tooling it also includes the cost of design, engineering and production of the tooling.



SIMA Manufacturing Activity Model Node: A25 Develop Equipment Instructions

A25: Develop Equipment Instructions

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.

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.

A251: Derive in-process workpiece configurations

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

A252: 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.

A253: 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.

A254: Generate Machine Programs

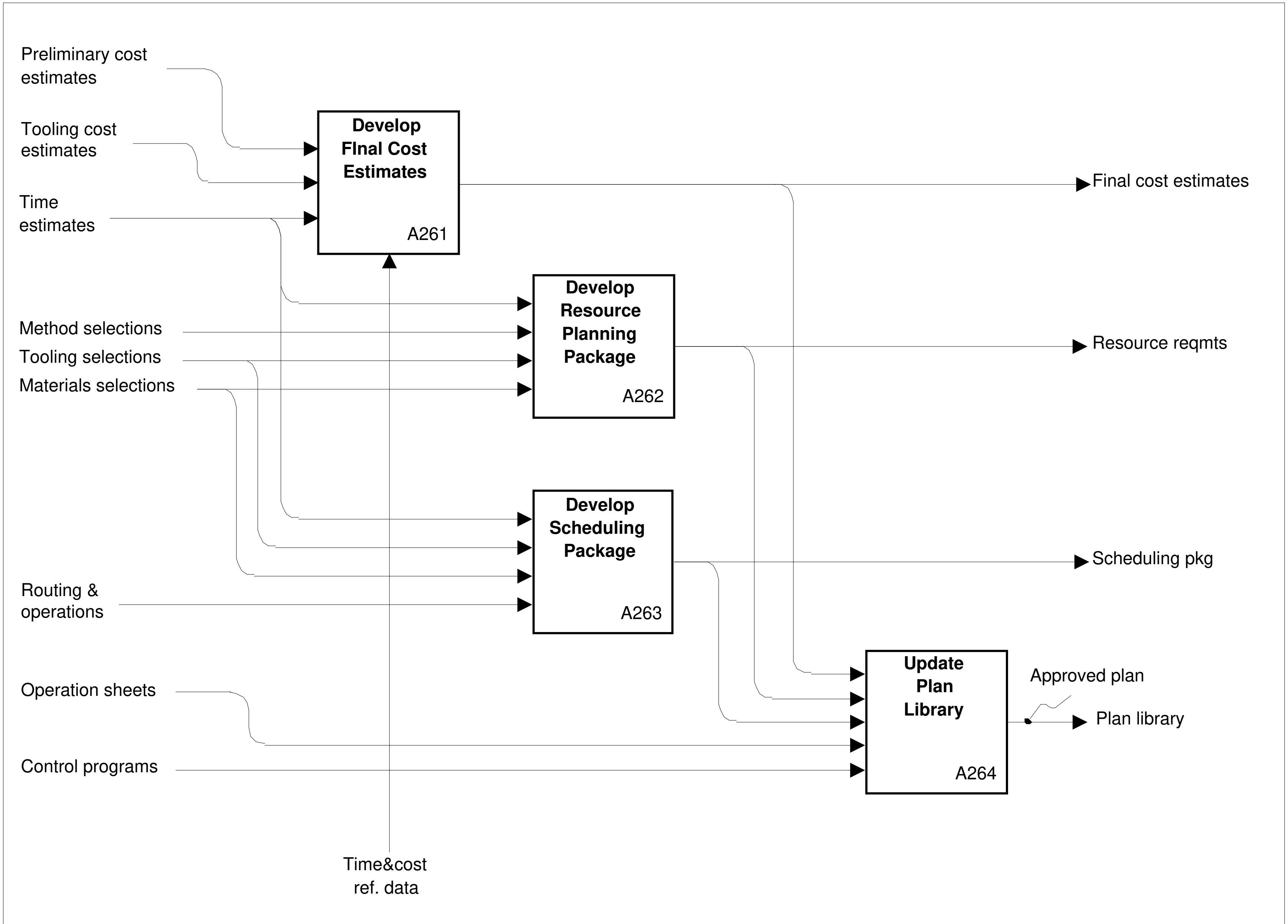
Generate programs for the direct control of automated machining, assembly, handling and inspection systems, such as machine tools, wire layers, welders, robots, and coordinate measuring machines. Programs are created in a form recognizable and executable by the machine controller.

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.

A255: 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.



SIMA Manufacturing Activity Model Node: A26 Finalize Mfg Data Package

A26: 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.

A261: Develop Final Cost Estimates

Determine the manufacturing cost of the Part in terms of materials, time and resources. Based on the time estimates for use of manufacturing resources and skilled labor, plus tooling, materials, handling and in-work transportation costs, estimate the total cost of production of the Part.

A262: Release Resource Package

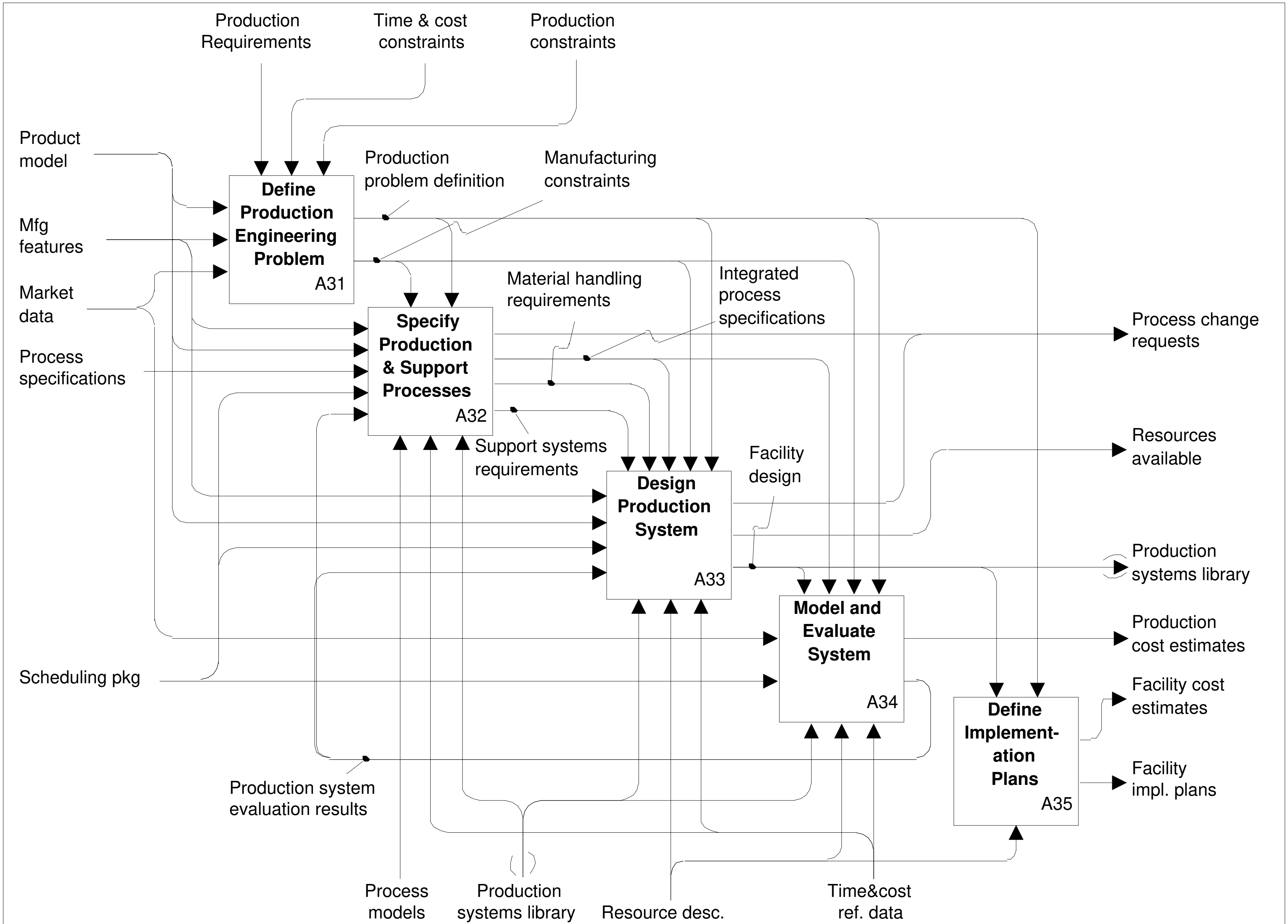
Summarize resource requirements: equipment and manpower time, tooling and materials quantities, expected yields, etc., to provide inputs for production planning processes.

A263: Release Scheduling Package

Summarize production workflow requirements: equipment routing, together with machine usage, manpower skills and time, tooling, materials, etc. for each station in the routing.

A264: Update Plan library

Complete plan package and enter the new approved plans into the local plan reference library or archive.



SIMA Manufacturing Activity Model Node: A3 Engineer Production System

A3: Engineer Production System

Design new or modified production facilities for the manufacture of a particular collection of Parts. A "facility" may be a plant, a shop, a line, a manufacturing cell, or a group of manufacturing cells. This activity encompasses both design-from-the-walls of such a facility and reengineering of all or part of such a facility to improve the production of certain products. It includes identification of the parts, products and processes for which the production system is to be tailored, identification of the equipment to be installed or replaced, (re)design of the floor layout, and development of an implementation plan for the (re)designed production system.

A31: Define Production Engineering Problem

Delimit the production engineering problem to be solved: identify the part mix for which the facility is to be designed and the physical plant or area to be used. Define the work elements to be undertaken and the (external) constraints on the (re)design. For a complex product/part mix, this activity may produce a hierarchy of production engineering problem definitions for which all of the A3 activities are separately or jointly performed. (Expanded on page 31.)

A32: Specify Production & Support Processes

Develop a specification for the production and support processes required to manufacture the target part mix. This activity may be performed jointly with activity A2: Engineer Manufacture of Part, in specifying the manufacturing processes. This activity, however, concentrates on identifying processes common to multiple Parts in the mix or to other Parts manufactured in the same facility. In addition, this activity specifies the necessary support operations for the production system — materials management, tooling preparation and management, materials flow, equipment maintenance and workspace requirements, etc. (Expanded on page 33.)

A33: Design Production System

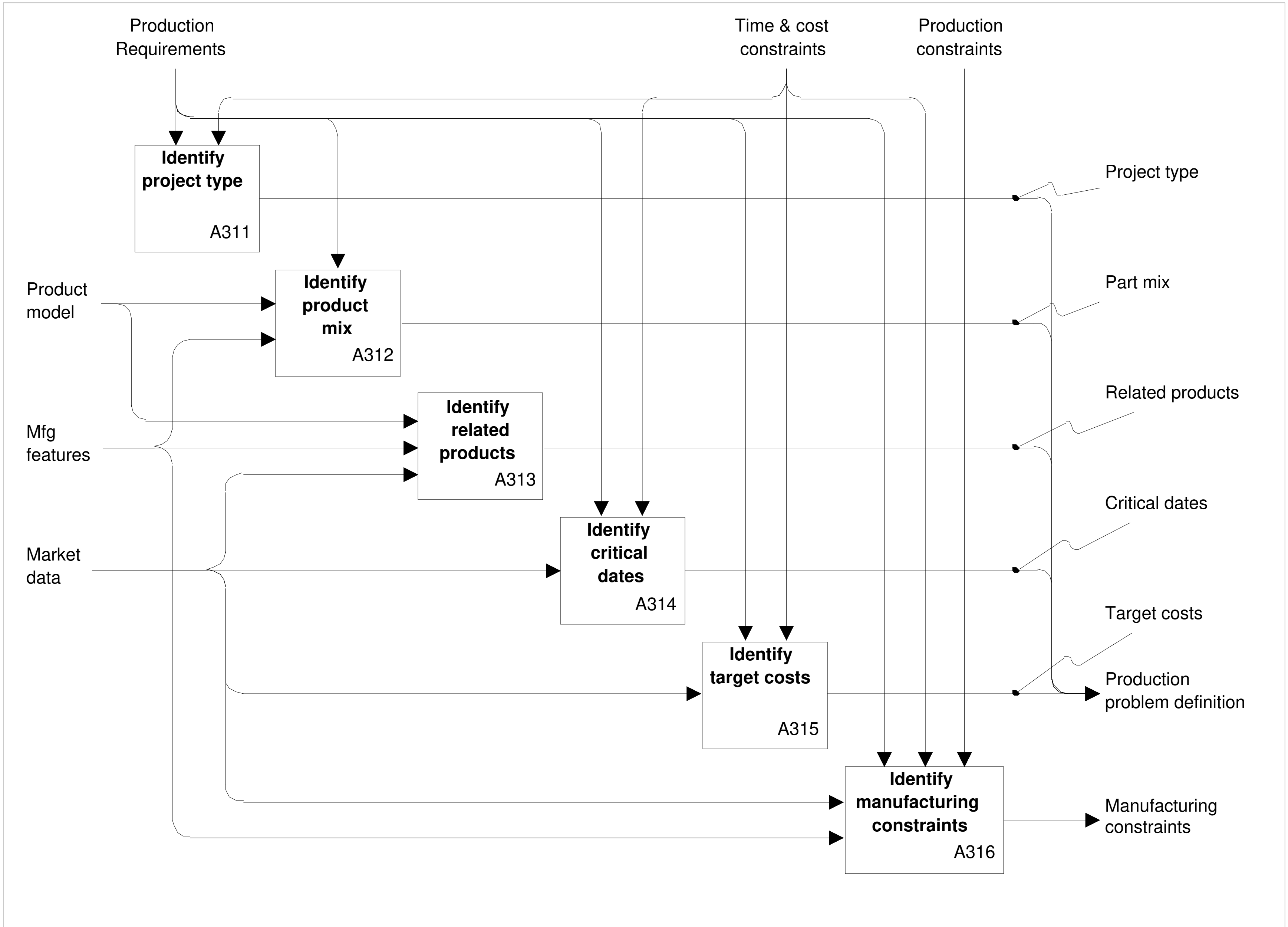
Design the physical processing systems, material storage and delivery systems, automated control systems and information management systems for the production facility. This includes selecting major equipment items, tooling and controllers, information systems, networking equipment, etc. It also includes developing the facility layout and specifying physical plant requirements. (Expanded on page 35.)

A34: Model and Evaluate System

Using both simulation and actual performance measurements, analyze the dynamics of the proposed system. Test the facility design against the expected production demand for the selected part mix. Identify quality concerns, performance bottlenecks, etc. and feedback results to the process specification and production system design activities. (Not further developed in this cycle.)

A35: Define Implementation Plan

When a satisfactory design has been found, specify the implementation plan for building or remodeling the facility to conform to the design. This may include licensing, site preparation, building and plant construction, equipment acquisitions, staffing, installation, state inspection, etc. Develop budgets for the components of the plan and final cost estimates for the reengineered facility. (This is primarily a business activity and not further developed in this cycle.)



SIMA Manufacturing Activity Model Node: A31 Define Production Engineering Problem

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A311: Identify Project Type

Determine the scope of the engineering activity: build a facility from scratch, build a production system in an area of an existing facility, reengineer the systems for a product line, make process improvements for a particular part or parts, etc.

A312: Identify Part Mix

Identify the set of Parts and processes the production system is to support. Identify current facilities used for these functions, if any, and gather performance data.

A313: Identify Related Parts

Review current and past Parts for similar process requirements; identify associated manufacturing facilities. Survey competitor products and manufacturing sites.

A314: Identify Critical Dates

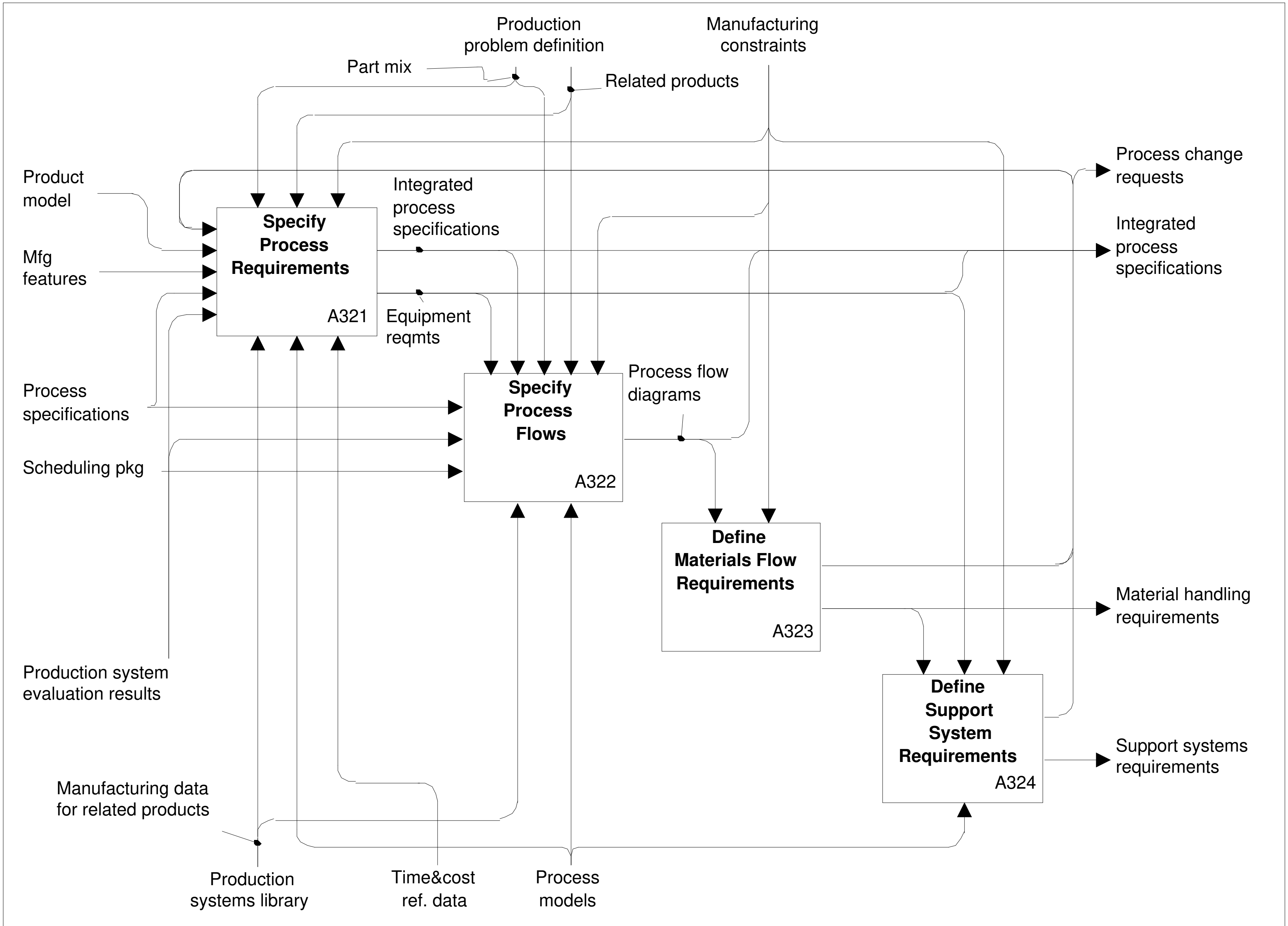
Identify critical dates for the design, installation, operation, and possibly phaseout of the system.

A315: Identify Target Costs

Identify the acceptable per-product cost of manufacture over time. Given anticipated sales volume, specify the corresponding range of acceptable costs of installing and operating the production facility.

A316: Identify Manufacturing Constraints

Identify production system expectations and limitations, available resources, required practices and possible hazards.



SIMA Manufacturing Activity Model Node: A32 Specify Production & Support Processes

A32: Specify Production & Support Processes

Develop a specification for the production and support processes required to manufacture the target Part mix. This activity may be performed jointly with activity A2: Engineer Manufacture of Part, in specifying the manufacturing processes. This activity, however, concentrates on identifying processes common to multiple Parts in the mix or to other Parts manufactured in the same facility. In addition, this activity specifies the necessary support operations for the production system — materials management, tooling preparation and management, materials flow, equipment maintenance and workspace requirements, etc.

A321: Specify Process Requirements

Identify the processes required to manufacture the target Part mix. Identify those processes which are common to multiple Parts in the mix and those which are unique to particular Parts. Identify those processes which may already be available in the target facility. (Using, expanding, or replicating those processes is usually less expensive.) Develop requirements for major equipment.

This activity uses results of, and provides feedback to, Activity A21: Determine Manufacturing Methods. In many cases, these activities may be performed jointly.

A322: Specify Process Flows

Develop a detailed process flow diagram for the target Part mix. Identify flows common to multiple Parts and estimate volumes of those flows. Identify unique flows for particular Parts, including departures from and returns to the mainstream, and estimate flow volumes. The flow diagram graphically outlines how materials are moved through manufacturing and assembly. This flow diagram is based on the Routing and operations sequences specified for the individual Parts (or on the final form in the Scheduling Package). The flow specifications take into account available resources, time, cost and other manufacturing constraints.

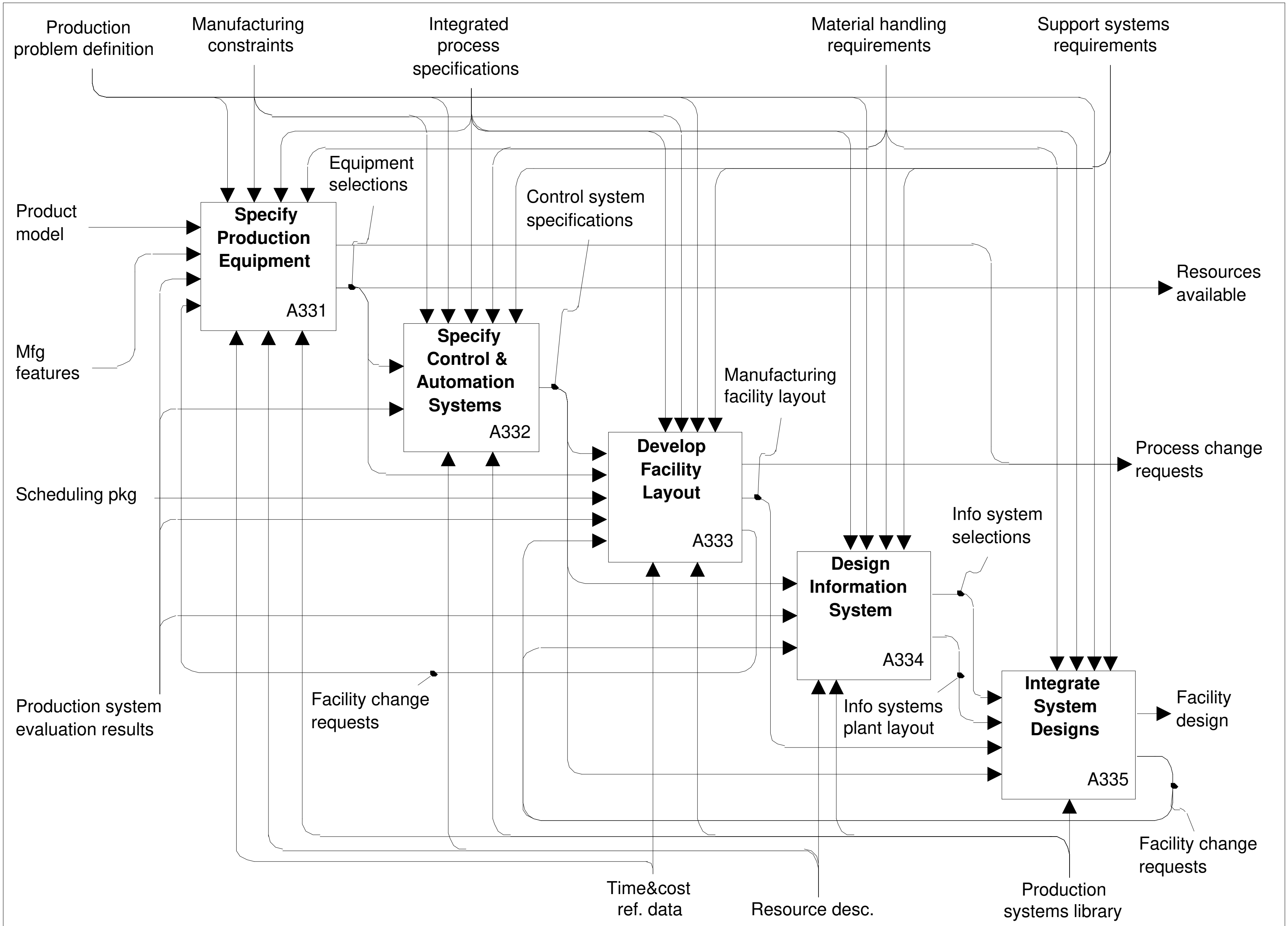
This activity uses results of, and provides feedback to, Activity A22: Specify Manufacturing Sequences. In many cases, these activities may be performed jointly.

A323: Specify Materials Flow Requirements

Using the process flow diagrams and the estimated volumes, identify the requirements for materials storage, buffering, transportation, packaging and handling in the production system. This may include requirements for material handling/buffering/transport equipment. Packaging requirements may include specifications for assembly kits and other specific forms of carriers.

A324: Specify Support Systems Requirements

Specify requirements for part/product packaging and shipping stations. Using the process and materials specifications, identify requirements for supporting systems, such as parts and materials storage and inventory systems, parts delivery areas, tool cribs, tool and kit building stations, etc. In some cases, this may include specification of scrap, rework and materials recovery facilities.



SIMA Manufacturing Activity Model Node: A33 Design Production System

A33: Design Production System

Design the physical processing systems, material storage and delivery systems, automated control systems and information management systems for the production facility. This includes selecting major equipment items, tooling and controllers, information systems, networking equipment, etc. It also includes developing the facility layout and specifying physical plant requirements.

A331: Specify Production Equipment

Using the process specifications for the selected Part mix, specify the equipment (machines, workstations, artisans, etc.) which is to make up the resulting facility. Identify the equipment which is present in the plant or area at the outset and any other equipment which may be available, and determine which of those are to be used. From catalogs and other sources, identify new equipment to be installed (make, model, quantity, configurations). This activity includes selection of processing equipment, inspection equipment and materials handling and transport equipment.

This activity may also include recommending changes to the processes selected in order to reduce the cost or improve utilization of equipment. For some project types, this activity may be reduced to identifying the equipment available and reconfiguring it to balance the utilization among the parts in the Part mix.

A332: Specify Control & Automation Systems

Determine the automation systems required for the facility, including controllers for automated and semi-automated manufacturing systems and material handling systems, and the data acquisition and controls necessary for the maintenance of product quality.

A333: Develop Facility Layout

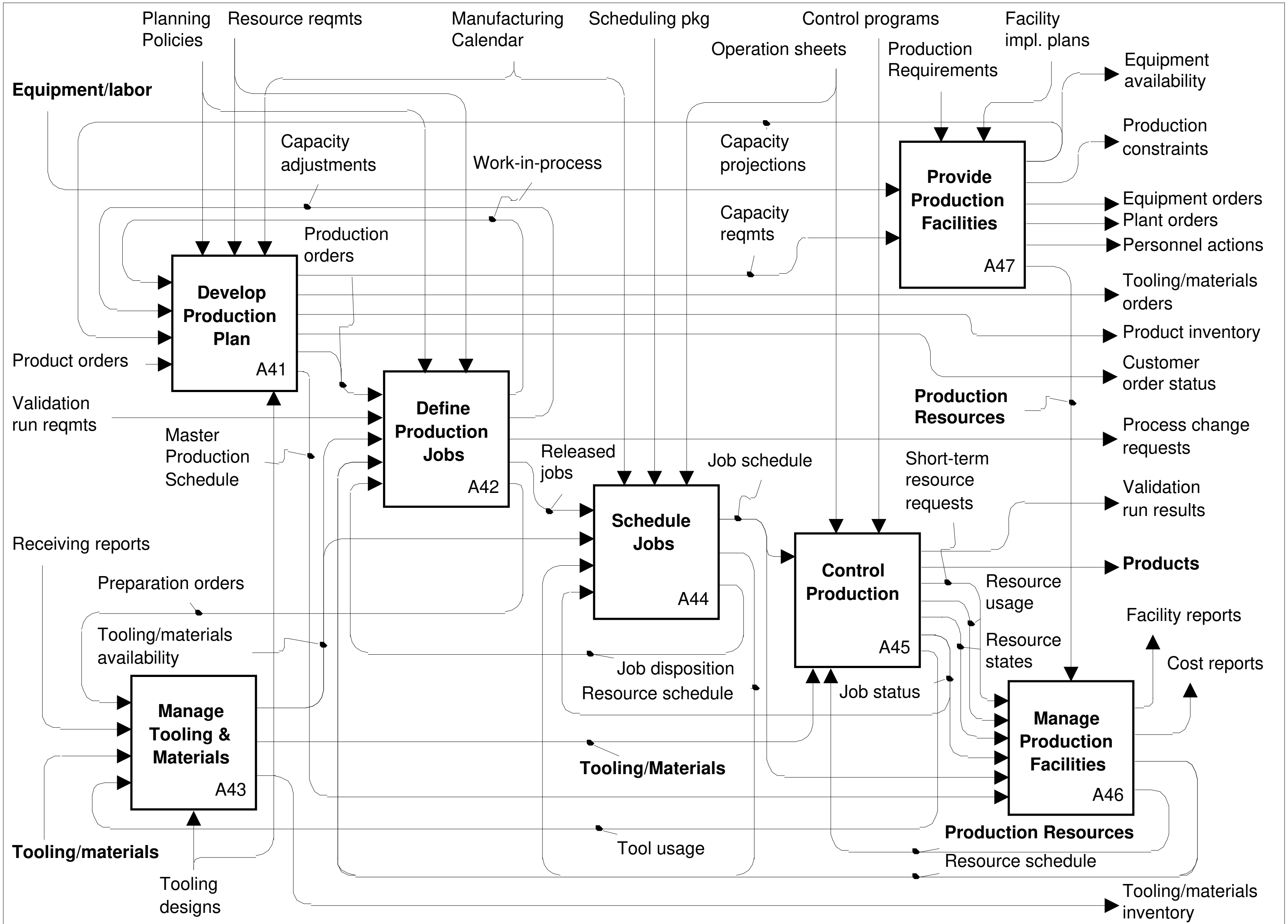
Using the process and routing specifications for the selected Part mix, and the equipment selections, define an optimal layout for the equipment to maximize performance and/or quality over the Part mix. Specify workstation configurations. Identify and configure the necessary material handling and transport equipment. Design the floorplan for all of the above, including storage areas and pathways for human and material movement. This may result in recommendations for changes in the equipment selections to improve interactions or for changes in the routing plan to improve performance or quality.

A334: Design Information System

Based on the degree of automation and the information requirements for ensuring product quality, the information requirements for management of the production systems, and the information requirements for support systems and interfaces to external systems in the enterprise, specify the information systems necessary for the facility. Specify the physical layout of the computer, controller and communications systems, including the plant network, if any. The design takes into account available hardware and software systems, existing communications equipment and media, and required practices.

A335: Integrate System Designs

Combine the physical system plant layout and the information system plant layout. Identify cabling paths and shielding requirements; identify equipment paths, walkways, hazards and maintenance accesses. Specify power requirements, heating/air-conditioning requirements and other operating requirements. (Depending on the project type, this activity may involve specifying building architecture and/or power systems and heating/air-conditioning systems and layout instead of requirements.) After reviewing the space requirements and flow of materials and information, changes may be requested to either design.



SIMA Manufacturing Activity Model   Node: A4   Produce Products

A4: Produce Products

Provide and maintain the production facilities and produce the Parts according to the specifications in the process plans. This involves defining the production schedules and controlling the flow of materials into and out of the production facility, scheduling, controlling and executing the production processes themselves, providing and maintaining the production equipment and the human resources involved, developing and tracking the tooling and materials, etc.

A41: Develop Production Plan

Using customer orders and projected demand for the products of the facility, define the Master Production Schedule -- the expected product output of the facility over a fairly long term. Define corresponding capacity requirements and projections. Define and coordinate the production orders for the Parts which make up the products, and any related tooling and materials. This includes those orders which are jobs to be performed in the facility and those which are sent to external suppliers. (Expanded on page 41.)

A42: Define Production Jobs

Using the production orders derived from the Master Production Schedule, define *jobs* or *batches* of Parts to be made in the facility, and supporting tasks for the preparation of tooling, kits and materials. Coordinate the production of components and assemblies and the preparation of materials and tooling with the manufacturing processes. Issue jobs to the scheduler when the requisite components, materials and tooling (will) become available. (Expanded on page 43.)

A43: Manage Tooling and Materials

Manage materials, tools, fixtures, and component inventories. Track order, receipt, assignment, location, and use of tooling and materials. Prepare tooling and fixture assemblies according to specification. Test and inspect incoming materials. Prepare raw materials in the proper quantities, combinations and rough sizes for part batches. Prepare tooling and materials kits. Decommission used tooling (breakdown, regrind, etc.). Recapture and process reusable and recyclable materials.

This is a loose collection of related activities which are viewed differently by different organizations, somewhat according to the kinds of products they make. (Not further developed in this cycle.)

A44: Schedule Jobs

Define the detailed production schedule for all jobs which have been released: which workstations will perform which operations on which part lots when. (Expanded on page 45.)

A45: Control Production

Implement the production schedule, perform the fabrication, assembly and inspection operations, move tooling and workpieces, track job and workpiece status on the floor. (Expanded on page 48.)

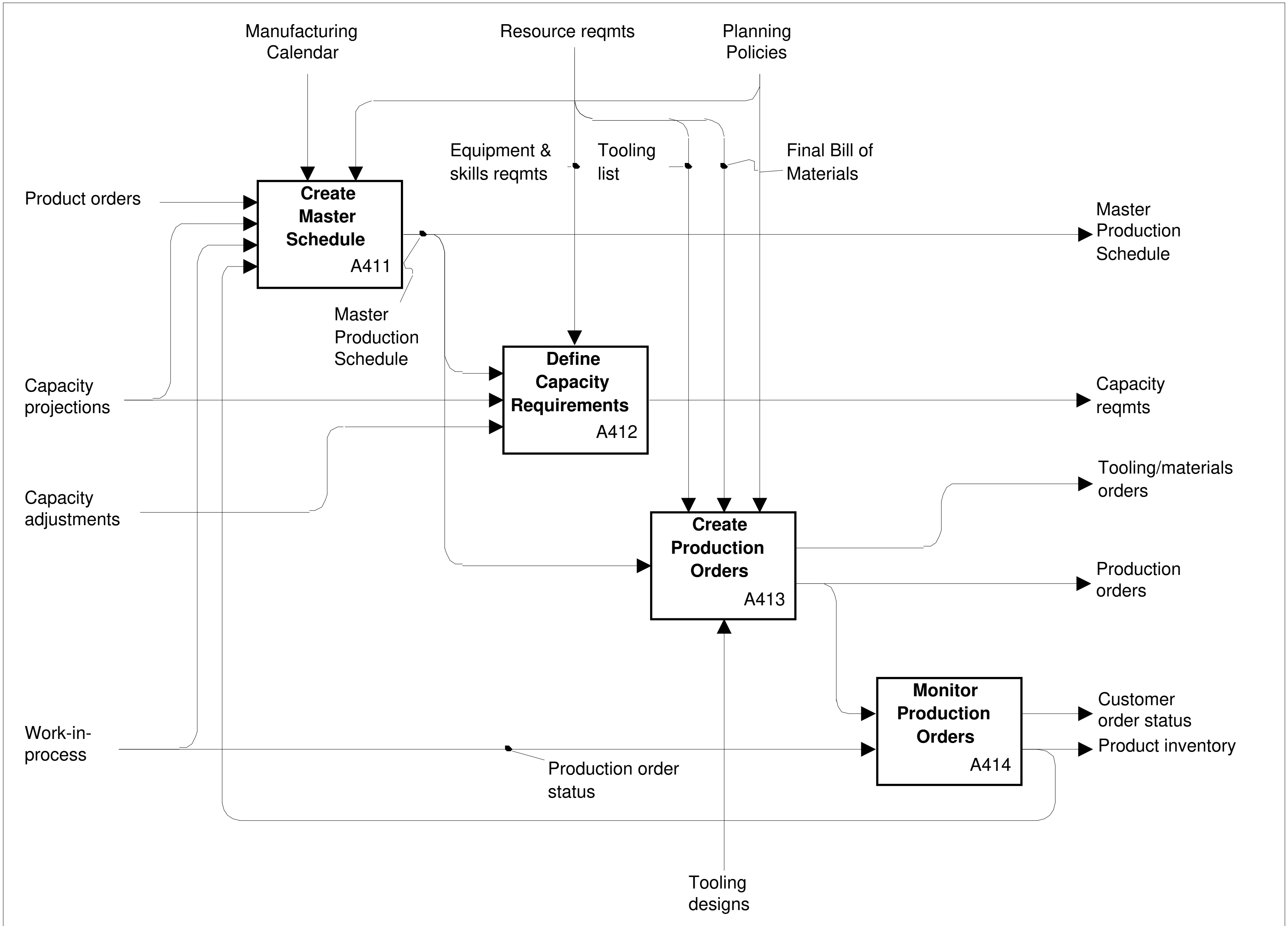
A46: Manage Production Facilities

Schedule personnel and equipment availability, provide preventive and remedial maintenance, maintain physical plant and utilities. Monitor actual production throughput and production costs.

(Not further developed in this cycle.)

A47: Provide Production Facilities

Per capacity requirements and facility modification plans, schedule facility modifications, equipment acquisitions, installations, upgrades and replacements. Define and maintain workforce levels. Provide capacity estimates. (Not further developed in this cycle.)



SIMA Manufacturing Activity Model Node: A41 Develop Production Plan

A41: Develop Production Plan

Using customer orders and projected demand for the products of the facility, define the Master Production Schedule -- the expected product output of the facility over a fairly long term. Define corresponding capacity requirements and projections. Define and coordinate the production orders for the Parts which make up the products, and any related tooling and materials. This includes those orders which are jobs to be performed in the facility and those which are sent to external suppliers.

This activity is sometimes called Materials Requirements Planning (or MRP I).

A411: Create Master Schedule

Using the current customer orders and due dates, or market projections and the gross production requirements for the products, determine the product volumes that will be produced during each successive planning period covering some predetermined long term planning horizon (which can range from several months to several years). This is called the Master Production Schedule.

Entries in the Master Production Schedule identify end-products, quantities and target completion dates. For a make-to-order product, the entries in the Master Production Schedule will be (or be derived from) customer orders. For a make-to-inventory product, the entries will be based on projected demand, rather than actual orders. A single facility might have a mixture of make-to-order and make-to-inventory products.

A412: Define Capacity Requirements

Using the target production levels contained in the Master Production Schedule, determine the long term capacity requirements for the factory. As shorter term schedules are produced, the actual used and unused capacity, and the actual product yields are also monitored and used to update the long term projections.

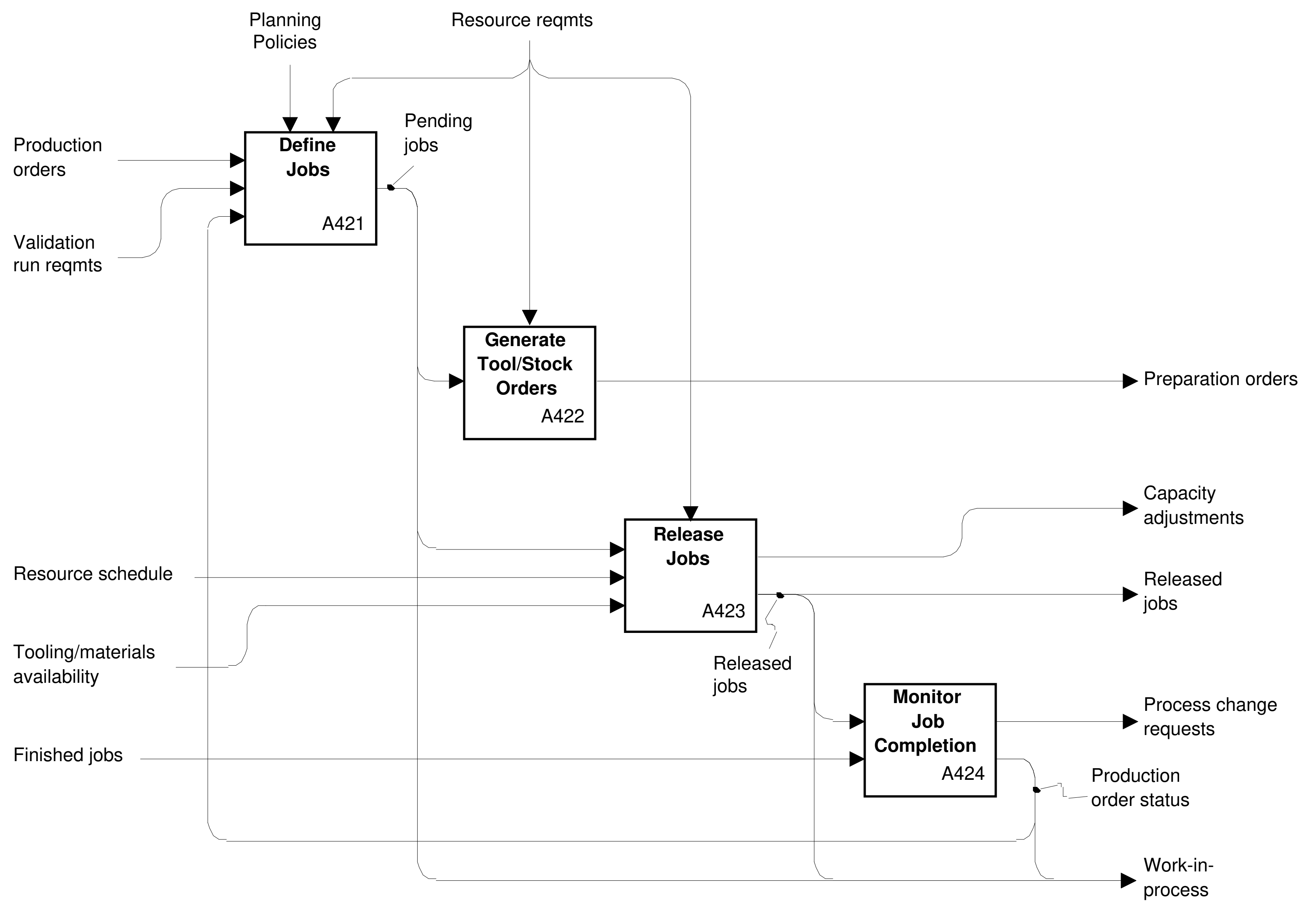
A413: Create Production Orders

Using the end items from the Master Production Schedule together with the exploded Bill of Materials for each of those end items and the expected yields from the manufacturing processes, create production orders for manageable quantities with specific due dates. One or more production orders may be required for each end item. The number of these orders will depend on the quantities required and the nature of the item (component, sub-assembly, tool, special fixture, etc.). The projected available capacity and manufacturing capabilities are used to determine which orders will be produced in-house (and in what facilities) and which will be sent out to bid.

For products made-to-order, the relationship between production orders and customer orders is the subject of both business decisions (such as priority and delivery schedule) and technical decisions (such as production capacity and materials availability).

A414: Monitor Production Orders

Using work-in-process, completion and delivery reports from the production facilities, monitor the status of the production orders. Update product inventory levels and production rate and yield statistics. Maintain the relationship between production orders and customer orders, if any, and update projected and actual completion status for customer orders.



SIMA Manufacturing Activity Model Node: A42 Define Production Jobs

A42: Define Production Jobs

Using the production orders derived from the Master Production Schedule, define Jobs, for *lots* or *batches* of Parts to be made in the facility, and supporting tasks for the preparation of tooling, kits and materials. Considering the lead times and processing times required, coordinate the production of components and assemblies and the preparation of materials and tooling with the manufacturing processes. Issue jobs to the scheduler when the requisite components, materials and tooling become available.

This activity is sometimes called Manufacturing Resource Planning (or MRP II).

A421: Define Jobs

Decompose or aggregate those production orders which are produced in-house into batches or lots. These batches/lots are called Jobs, and each is scheduled, monitored, and tracked as single entity, with a system-maintained job identifier. Some jobs are to make products, some are to make components or subassemblies, and some are to make tooling and fixtures. There may also be jobs to make prototypes or test engineering specifications, and jobs to perform setup or maintenance processes, depending on the way in which facility usage is planned.

For those jobs which produce products (or components of products), as distinct from tooling, this activity maintains the relationships, if any, between these jobs and the production orders. The relationship of jobs to orders may be complex, involving both business decisions, such as priorities, and technical decisions, such as batch sizes and expected yield.

A422: Generate Tool and Stock orders

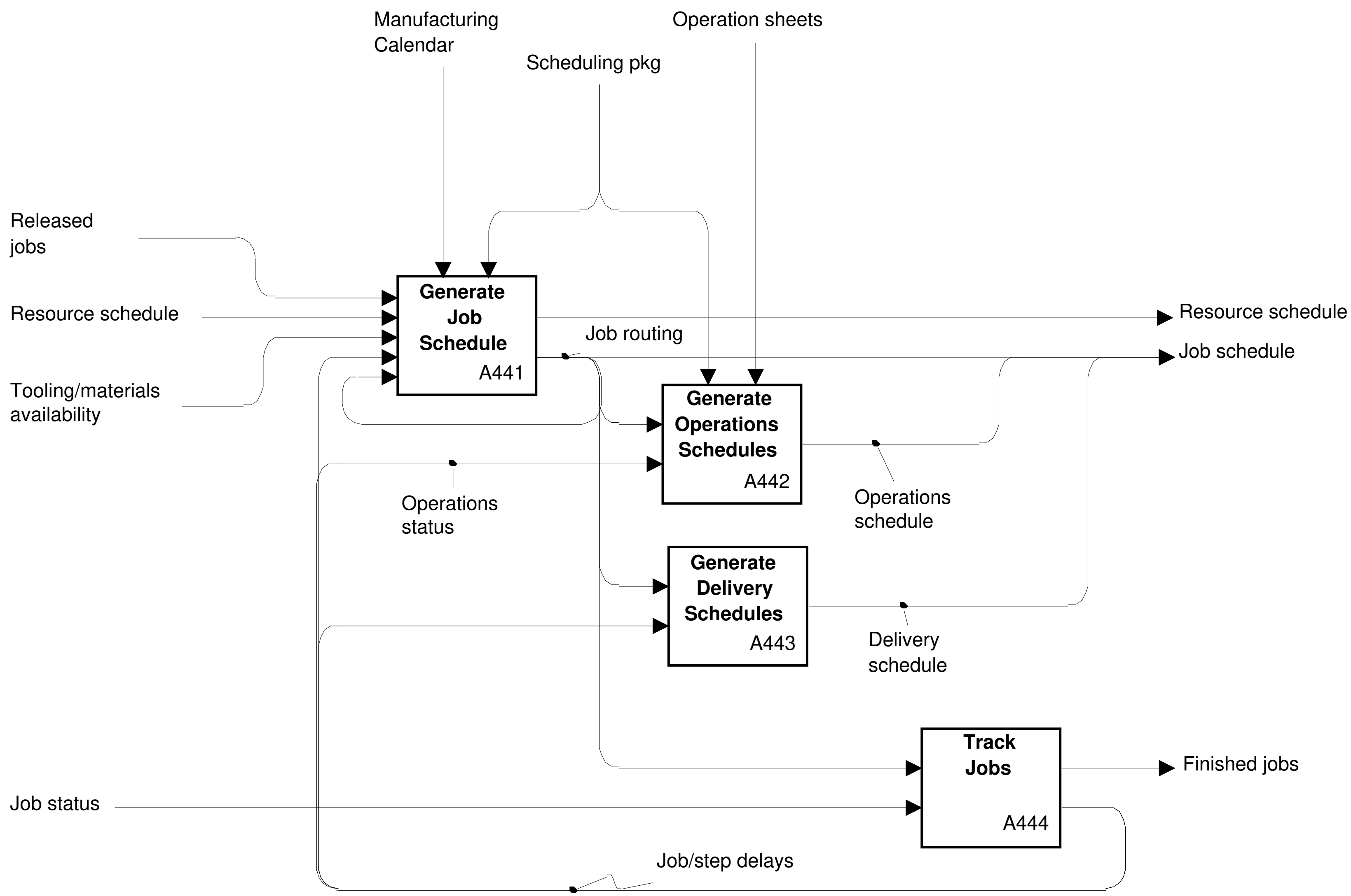
Using the most up-to-date production schedule, including due dates for customer orders, issue orders for the required tools, raw/in-process materials, fixtures, and other components specified in the Bill-of-materials from appropriate inventory managers. The delivery of these items must be scheduled so that the jobs can begin with sufficient lead times to meet the production schedule.

A423: Release Jobs

Using the current and projected resource availability and the anticipated availability times for components, tooling and materials, release jobs to the shop (scheduler) for production and specify when they must be completed. Revise estimates of used and unused resource capacity. This activity determines the *work-in-process* for the facility.

A424: Monitor Job Completion

Using feedback from the shop-floor and scheduling system, note completions of released jobs and update work-in-process and status of the corresponding production orders.



SIMA Manufacturing Activity Model | Node: A44 | Schedule Jobs

A44: Schedule Jobs

Define the detailed production schedule: which workstations will perform which tasks on which part lots when. This activity uses the *scheduling package* provided by the manufacturing engineers to define the sequence of workstation types required for a Part lot, the task to be performed at each station (defined in detail by the operations sheet) and the materials and time required to perform the task at each workstation. According to projected resource availability, the tasks are assigned to specific workstations at specific times. This implies estimating or scheduling the materials handling operations needed to deliver the tooling, materials and in-process workpieces to the assigned workstation by the time specified.

In some cases, a workcell comprising multiple resources which can simultaneously perform several independent tasks is scheduled according to its capacity by the facility scheduler and then a refined scheduling process occurs within the workcell itself. The facility and workcell scheduling may occur simultaneously (with interactions) or consecutively.

A441: Generate Job Schedule

Using the current job schedule, maintenance and employee schedules, the scheduling package for the job (the routing plan and per step resource requirements), and the availability of the required materials and tooling, insert the newly released jobs into the existing detailed production schedule. Assign the planned steps to specific major resource stations at specific times, and generate the *job schedule* that defines the scheduled itinerary for each Part batch.

This activity may be performed incrementally, or a queue of waiting jobs may be developed and the scheduling of all waiting jobs for a particular time period may be undertaken at one time.

A442: Generate Operations Schedules

For those workstations/cells which comprise multiple equipment units capable of performing simultaneous tasks, schedule the operations within the job steps assigned to the cell, interleaving steps from separate jobs and performing them in parallel where possible, to optimize equipment utilization and meet the step completion times on the Job schedules. Generate the corresponding schedules for assignment of the operations to the subsystems of the workcell.

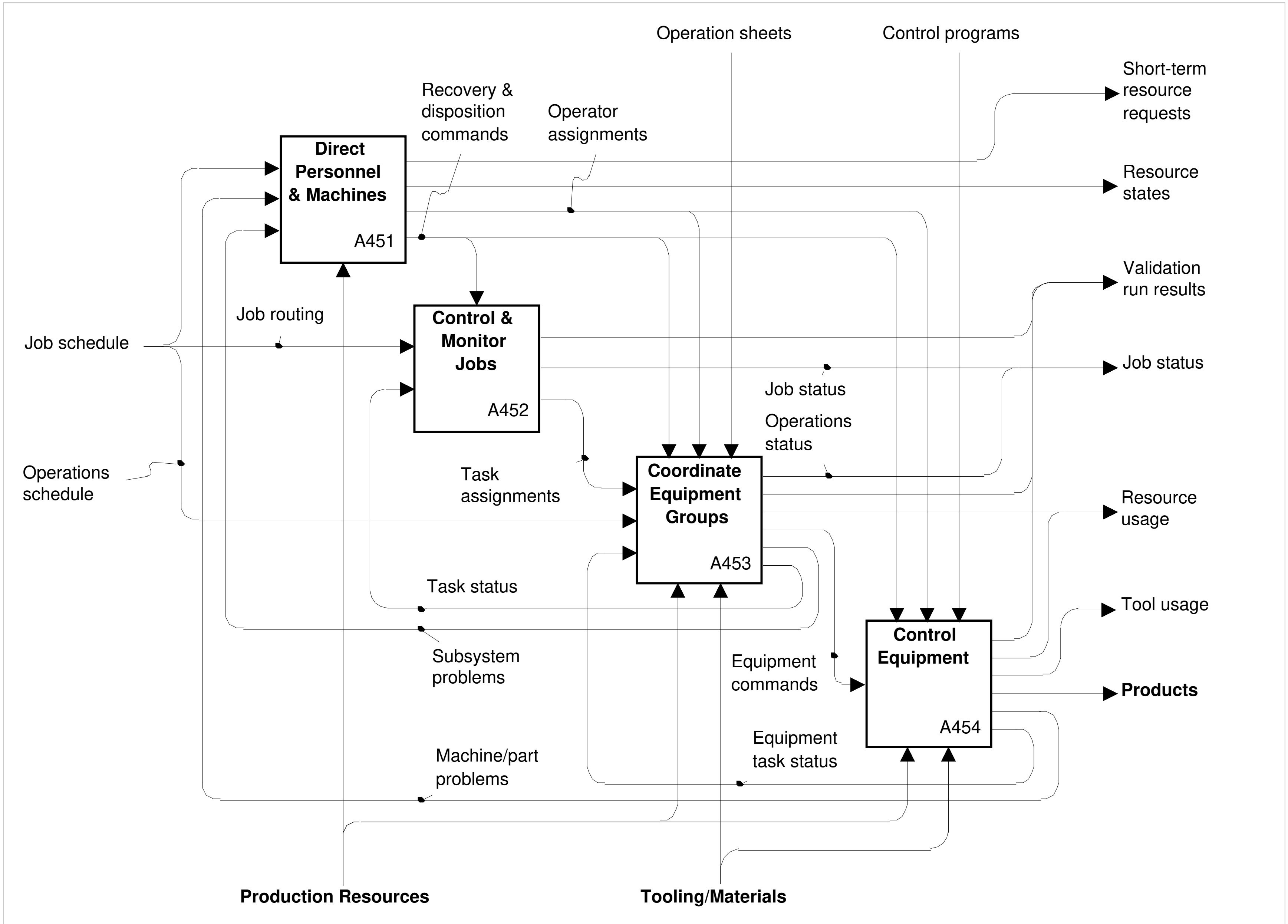
This activity is often performed dynamically in the workcell. The workcell scheduling process is usually much simpler than the facility scheduling process, especially when the workcell has unique resources or when the multiple resources are essentially equivalent machines with an internal materials handling system.

A443: Generate Delivery Schedules

Using the routing sheets, and schedules for tooling, components and other materials from the job schedule, generate pickup and delivery schedules for all tools, fixtures, raw/in-process/finished materials, and other components specified in the Bill-of-materials so that they are present when and where they are needed. (In many cases, these schedules are developed dynamically, using *dispatch rules* to prioritize and respond to delivery requests as they are posted.)

A444: Track Jobs

For each job on the floor, track its progress including where it is physically, the current step in the process routing, and the expectation of completion on schedule. Problems require the job routing schedule to be revised.



SIMA Manufacturing Activity Model Node: A45 Control & Execute Production

A45: Control Production

Implement the production schedule, perform the fabrication, assembly and inspection operations, move tooling and workpieces, track job and workpiece status on the floor.

The details of this activity vary significantly from one production domain to another. What is described here is a generic model of production control activities, not the specific production activities controlled.

A451: Direct Personnel and Machines

Assign personnel to workstations, monitor performance of personnel and equipment and identify problems. Provide expertise in problem diagnosis and take corrective actions. Determine equipment status and failures.

Identify human and equipment resource shortages and specify overtime requirements required to meet production schedules.

A452: Control and Monitor Jobs

Implement the production schedule. Direct routing of jobs to workstations; direct delivery of tooling and materials. Track lots and workpieces and monitor job status against schedule. Make manual adjustments to schedules and priorities.

A453: Coordinate Equipment Groups

Assign tasks to subsystems involving independently controlled machines or human resources. Define the interactions of such subsystems; coordinate the actions of subsystems in the performance of a single task. Coordinate the physical and temporal interactions of equipment systems (both human and automated) performing different tasks within a work area/volume.

A454: Control Equipment

Execute the fabrication, assembly and inspection operations and/or control the equipment which performs them. Control and monitor the parameters of the process. Monitor the time on task and time in service for equipment and tooling. Identify problems and anomalous behavior.

1.2 Information Flows

This section contains the descriptions of all the information flows — inputs, outputs, controls and resources — appearing in the IDEF0 diagrams in section 1.1. It also includes the physical objects represented as flows in bold face in the diagrams. The flows appear here in alphabetical order.

Since IDEF0 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.

<u>**X**</u> (underscored) indicates that X represents physical objects, not information objects.

Alternative decompositions

Description of the design problem as a set of subproblems, each of which is characterized by a particular collection of engineering specifications. In general, there will be many of these for a given Part, since this is a creative task.

Analysis results

Results of engineering analysis of the draft component or subsystem design: structural behavior, thermal behavior, electrical behavior, effects of vibration, performance of specific functions, etc.

Approved plan: (Plan library)

The collection of archival manufacturing engineering information for a given version of the plans for a given Part. This represents the unit which receives final approval and becomes part of the Plan library.

Assembly drawings

The set of drawings showing how the components fit together into assemblies and specifying the characteristics of each fit and connection. In some cases, this is a detailed enhancement of the layout drawings; in other cases, it is an entirely different set of views of the product components.

Assignment knowledge: (Design knowledge)

Knowledge of the relationships between functions and device types and technologies.

Bill of Materials (BOM): (Resource requirements)

The Bill of Materials for a Part/Product identifies the quantities of all materials needed for some batch size of the Part. For an assembly, part numbers and quantities of every component; for a fabricated part, a quantity of a particular stock material.

Versions of the Bill of Materials appear in several activities with varying degrees of completeness. In particular, a partial Bill of Materials may be specified in early engineering phases, while the Final Bill-of-Materials is the complete form needed for production planning. In addition, a particular processing step may have a Bill of Materials for that step in the Part fabrication.

Capacity adjustments

Updated estimates of resource utilization, based on the resource schedule, current work-in-process, pending jobs, and actual facility performance.

Capacity projections

Estimates of the total quantity of human and machine resources already committed for projected production tasks during various planning periods.

Capacity requirements

Production capacity of various kinds required to meet the desired long-term production schedule. It may be stated in process capabilities and volumes or time quantities of equipment types and human skills.

Component catalogs

Information about parts and components which can be ordered from other firms and divisions, including engineering specifications, cost and lead times for orders.

Component constraints: (Design constraints)

Constraints on the subsystem and component designs imposed by corporate policy -- design styles, composition, technology used, product family similarity, etc.

Consolidation knowledge: (Design knowledge)

Knowledge of the extended capabilities and characteristics of structures and devices that allow them to perform more than one function simultaneously.

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.

Control system specifications

Specification of the control systems required for automated machines, including both processing machines and material handling equipment. Specifications include identification of make and model of controller, software releases, processing options and features and communication options.

Cost reports

Reports of actual costs of operating the production facility, including relationships to specific products and yields, work-in-process inventory, and other management reports of facility performance.

Critical dates

Identification of planned deadlines for completion of critical tasks in the production system development. The primary ones are the target to-market date for the product(s), the target production start date for the new/modified facilities, and the target design completion date for the production system. Intermediate milestones for the analysis, design and implementation activities may be included (although they are actually part of the workflow management activity). An estimate of the market life of the products and a corresponding estimate of the useful life of the production system is also important to many facility design decisions.

Customer order status

For those facilities in which production lots are tied to specific customer orders, the schedule and completion status for production of the items in the customer orders. (This is only a part of "customer order status" as managed by the larger enterprise.)

Decomposition knowledge: (Design knowledge)

Knowledge (experience, insight, algorithms) of how to breakdown a complex function into a complex of separable subfunctions.

Delivery schedule = Job schedule

A kind of job schedule for materials handling and transportation systems, specifying which lots of workpieces, tooling, etc., are to be picked up and delivered, where and when, and what carrier that delivery is assigned to. Many systems develop delivery schedules somewhat dynamically during the production process.

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 bidirectional negotiation.

Design constraints

Constraints on the product, subsystem and component designs imposed by corporate policy -- design styles, composition, technology used, ergonomics, product family similarity, etc. These may imply both layout constraints and component constraints.

Design evaluations

Interpretations of the engineering analyses and other evaluations to determine how well the design meets functional specs, performance specs, standards, etc.

Design features

Identification of features of a product or component which are important to the designer in making design decisions and identifying similarities with previous designs. This may include some kind of *group technology* coding scheme for automated identification of similarities.

Design features and codes are distinguished from *Manufacturing features* (and codes) in that the latter are intended to support manufacturing process decisions and may therefore emphasize different aspects of the part. (For example, two Parts which have very similar shape and materials but different tolerances may share common design features but have significantly different processing requirements, and therefore different manufacturing features.)

Design knowledge

That information which a human design engineer brings to bear on a design problem, including design techniques, and implementation techniques. Many different types of design knowledge are used in different activities: Decomposition knowledge, Assignment knowledge, Consolidation knowledge, Optimization knowledge.

Design library

The collection of existing designs performed by the enterprise, variously organized for retrieval. [For management purposes, the designs must be retrievable by product id and version, but for variant (*case-based*) design activities, the designs must be retrievable by product and component similarity. The function of the *design features* information is to encode such similarities.]

Design process knowledge

Knowledge of the accepted design techniques and procedures of the firm or industry.

Detail feedback

Results from the detail design phase which cause incoming subsystem specifications to be questioned and specific changes recommended.

Draft subsystem design = Product model

All the elements of the product model for a system/component that are needed to perform various engineering analyses and evaluations: typically materials (or components) and geometry for all analyses, and topology, tolerances, surface finish, and mating specifications for some analyses.

Engineering assignments

Task assignments to engineers from the Workflow Management system. An assignment identifies the engineering task to be performed and the information resources specific to that task (such as the product description and other results of previous engineering tasks).

Engineering task status

Reports from engineers, reviewers, supervisors to the Workflow Management system on the status of an engineering task assignment. Usually only completion is reported, along with identification of the new information objects, if any, created or modified by the engineering task. Other reports are possible, including partial progress (with accompanying draft information objects), estimated completion times, postponement, and even abandonment of the assignment.

Equipment & skills requirements: (Resource requirements)

The specific workstations or types of workstations required for production and inspection of the Part batch, and the amount of time consumed for each such resource. This includes both the machines and any special operator or artisan skills required for particular fabrication, assembly or inspection operations to produce parts of the required quality. It may also include estimates for labor for materials preparation, handling and storage, especially where those requirements are exceptional.

Equipment & skills selections: (Process specifications)

Identification of the workstations, equipment or equipment types to be used for each major fabrication, assembly or inspection process.

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.

Equipment commands

Commands to an equipment controller to perform one or more operations programmed as a unit. This may be a command to execute a particular control program or a command to perform an operation which is predefined in the controller.

Equipment orders

Orders (to the Procurement department) for the acquisition of major equipment and related tooling. May also include actions to surplus or scrap existing equipment and tooling.

Equipment requirements

Specifications for kind and quantity of processing machines, equipment and facilities. Support for characteristics of the product family — dimensions, weight, materials, finish, etc. — and any special processing capabilities are also included.

Equipment selections

Identification of the processing and handling equipment selected for the new or modified facility, including make, model, options and special features, specialized tooling, etc., and quantities of each type.

Equipment task status

Response from the controller to equipment commands, or to queries about the status of a particular operation. For example, “not yet started”, “busy” (and possibly “will finish in <duration>”), “done”, or some kind of problem indication.

Equipment/labor

The principal physical resources used for production activities — machines and manpower.

Evaluation criteria

Criteria and metrics developed for estimation of design quality during product planning, as a means of determining the probability of successful market for the design.

Evaluation guidelines

Design for availability, reliability, maintainability, disposability, and usability (quality concerns). This may also include producibility and assembleability, to the extent that process knowledge is incorporated directly in the design function. (Process constraints may also be reflected in feedback from manufacturing engineering functions).

Evaluation knowledge

Knowledge of how to judge design quality: judgement techniques, valuations and confidence factors in the conformance of a design to various desirable goals. This also includes prioritization and integration of the goals themselves.

External (design) constraints

Legal and regulatory constraints, patent rights and protections, technological constraints.

Facility cost estimates

Estimates of the total cost of rebuilding the facility to conform to the design, including plant, utilities, equipment and tooling, installation, training, etc.

Facility change requests

Recommendations from production systems integration activities for changes in other production systems design decisions. Most of these deal with integration of plant and safety requirements into facility layouts, but changes in the processing and handling equipment instead of, or in addtion to, changes in the layout may be required.
While this is modeled as a directed information flow, the actual flow is a bidirectional negotiation.

Facility design

A description of the manufacturing facility to be built, including processing equipment, handling equipment, controllers, information systems and networks, storage spaces and systems, floor plans, utilities and utility routings, transport systems and routings, etc. This includes both drawings and functional specifications, that is, models of the facility from various points of view.

Facility implementation plans

Planned changes to the manufacturing facility, to conform to a new design for part or all of the facility. This includes equipment acquisitions, staffing, installation schedules, etc., and budgets for the components of the plan.

Facility reports

Intermediate information units within the production domain that may be considered archival or of significant interest to enterprise functions outside of production: Master Production Schedule, job schedules, maintenance schedules, employee schedules, capacity projections, and statistical summaries of job status and machine status.

Final Bill of Materials = Bill of Materials: (Resource requirements)

The complete Bill of Materials for the Part/Product in exploded form, with quantities of all materials needed for some batch size of the Part. This may include any special materials which will be consumed in the process of making the Part batch, such as fasteners, spacers, adhesives, etc.; alternatively those may be considered “shop materials” and included (in some aggregate form) in the tooling list.

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.

Finished jobs

Report of the final completion or abandonment of a scheduled job, representing production of a (possibly reduced) batch of a specified Part or Product. This describes the change of state of workpieces from “in process” to either “completed product” or “scrap”.

Information system selections

Identification of the information systems supporting the new/modified facility, including computing hardware and operating systems, database systems, applications software systems, communications and network systems, etc. Includes quantity, make, model, special options and features for computing hardware and appliances, communications appliances and software packages.

Information systems plant layout

Floor plan for computer systems and communications hardware, together with cable paths for power and signal lines, insulation and protection requirements for hardware and cabling, and estimated utility requirements (power, cooling) for the information systems.

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).

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 which indicate a need for changes to the machine and operator instructions.

Integrated process specifications

The collection of manufacturing processes (fabrication, assembly, finishing, inspection) which are to be provided in a particular manufacturing facility, the sequencing of those processes required for the efficient manufacture of the product mix, the materials to be processed and the salient requirements for the workstations and equipment that will perform those processes, including process measurement and audit specifications. In some sense, this includes any and all of the information produced by the manufacturing engineering activities (A2: Engineer manufacture of Part), but is in practice restricted to those specifications which are relevant to the design of the production system. In particular, this information is the integration of the process specifications for the individual parts into a specification that covers the part mix, with the addition of inter-product timing and line balancing specifications.

Job: (Job schedule)

A job is a requirement to manufacture some number of instances (a *lot* or *batch*) of a given Part. Some jobs are to make products, some are to make components or subassemblies, and some are to make tooling and fixtures for other Parts made in the facility. There may also be jobs to make prototypes or test engineering specifications, and jobs to perform setup or maintenance processes, depending on the way in which facility usage is planned.

For each Job there is a plan which defines the sequence of steps required to make that batch, where each *step* requires a different major resource -- a different kind of equipment or a different equipment configuration. That plan is part of the Scheduling package. The operations which are to be performed within each step are defined by an *operations sheet*.

Job routing: (Job schedule)

A matrix showing which steps in the plan for each job are assigned to which major resources (machines and artisans) at which times, including the expected start and finish time for those steps, and the materials and tooling which must be at that workstation to perform the corresponding job step.

Job schedule

For each major equipment station (or artisan station or workcell), a list of the current jobs (and due dates) assigned to the station, together with the operations sheets, tools, fixtures, etc. needed to perform the job step at that station. This information is also called the *Dispatch list*.

In some cases, the job schedule is more conveniently decomposed into Job routings and multiple Operations schedules.

Job status

Report of the state of all scheduled jobs. State information contained in the report could include - completed, on time, late, waiting to be started, in process at machine x, waiting for something at machine x, aborted, and needs to be reschedule, etc. For workcells in which operations are separately scheduled, the job status report may include the operations status report.

Job/step delays

Results of tracking activities on the shop floor that indicate that a given job or step will not complete on schedule. This may have impact on the schedule for later steps in the same job or for other jobs waiting to use the assigned resources.

Layout: (Product model)

A specification for the relative placement of the component subsystems of a product and their mechanical and electrical interfaces. This usually takes the form of a drawing with annotations. A component which is a complex subassembly may have its own layout drawing if the design problem requires further factorization.

Layout constraints: (Design constraints)

Constraints on the product or subsystem configuration and layout imposed by corporate policy -- ergonomics and appearance, product family similarity, etc. Some of these constraints are intended to promote commonality of manufacturing or maintenance techniques and equipment.

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.

Machine descriptions: (Resource descriptions)

Descriptions of the major equipment resources, machines and workcells (machine complexes) used in manufacturing processes:

- fabrication machines (milling, turning, stamping, casting, molding, etc.)
- assembly machines (assembly robots, wire layers, presses, etc.)
- coordinate-measurement machines and inspection machines
- material handling and transport devices

For some activities, this is limited to the set of equipment on the shop floor, while for others, it may include entire vendor catalogs. The *equipment available* data typically limits the set of machines which is to be considered “available” for a given engineering activity.

Machine/part problems

Reports from the workstation controller/operator of problems with the machine or the workpiece, needing expert attention.

Manufacturing Calendar

Scheduled staffing times for the facility, including number of shifts and shift staffing/capacity for regular workdays, weekends, holidays, plant closings, etc.

Manufacturing constraints

Constraints on the production system design imposed by the product designs, the target product market, the available facilities, economics, company policies and other non-technical considerations. This information includes site selection and floor-space limitations, storage and delivery systems limitations, environmental and safety constraints, labor level and personnel skills constraints, technology constraints, etc. It also includes many separately defined information sets for the production systems:

- Manufacturing calendar,
- Production requirements,
- Production constraints,

and for the products:

- Product model,
- Manufacturing features,
- Market data,
- Time & cost constraints.

Manufacturing data for related products

Specifications and performance data for existing and previous production systems for similar products and processes. This may include knowledge of the production systems for competitors’ products.

Manufacturing facility layout

A floor-plan for the manufacturing facility, identifying and locating processing equipment, material handling equipment, machine controllers, storage spaces and systems, transport systems and routings, walkways, etc. This includes both drawings and functional specifications, that is, models of the facility from various points of view.

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. (This is used for searching plan libraries for process plan for similar parts.)

Manufacturing process knowledge

General knowledge of the manufacturing processes which could be used to fashion a given component or subsystem and the implementation capabilities provided, and the design limitations imposed, by such processes.

Market data

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

Master Production Schedule

A list of end products (assemblies, sub-assemblies, or individual parts) to be manufactured in each of the next N time periods. The list specifies product IDs, quantities, and the due dates.

Material handling requirements

Requirements for materials storage, buffering, transportation, packaging and handling in the production system. This includes requirements for material handling equipment, kits and special carriers, and transport systems, and possibly requirements for safe handling, storage and buffering of hazardous materials.

Material stock descriptions

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

Materials knowledge

Information about the characteristics of raw materials -- structural, chemical, thermal and electrical properties. This may include qualitative or quantitative estimates of cost and availability.

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.

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.

Methods change requests: (Process change requests)

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

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.)

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.

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.

Operations schedule: (Job schedule)

For major equipment resources which are themselves complexes able to perform tasks for multiple jobs at any given time, a schedule which further allocates the operations in a job step to the component resources of the complex at particular times. This schedule may interleave operations from multiple incoming jobs and may result in simultaneous performance of operations from different jobs.

Operations selection

For each major process, the individual fabrication, assembly and inspection operations to be performed, including the manufacturing (or inspection) feature the operation relates to and any parameters which characterize the operation. Each process has at least one.

Operations sequence

The sequence in which the selected operations for each process should be performed.

Operations sheets

An operations sheet is a plan which 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 which are to be performed, including (where appropriate) identification of the control programs which perform those steps and the process control parameters which 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 themselves equipment complexes 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.

Operations status: (Job status)

In a complex workcell, report of the state of all scheduled operations. The notions are identical to those of job status, except that a “job” of the workcell is a “step” in the plan for a larger “job” in the whole shop, and a “step” of the workcell plan is considered an “operation” by the shop scheduler.

Operator assignments

Functionally, a specification of the tasks/jobs each human operator is to perform. In fact, what is often specified is simply which operator is assigned to which equipment station and when, and the tasks/jobs are those scheduled for that station.

Optimization knowledge: (Design knowledge)

Knowledge of how to refactor a design based on functional decomposition in order to improve implementation, by recognizing and improving interfunctional and non-functional relationships.

Optimized designs = Product model

Complete product models for each component after improvement, combination and reorganization, etc.

Part mix

Identification of the specific collection or family of products and parts to be manufactured by a given production system or facility.

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.

Pending jobs

A mapping of customer orders or product quantity requirements to jobs or lots including Ids and due dates.

Personnel actions

Requests (to the Personnel department) to make (significant) changes in the workforce level and composition, by hiring, layoff, transfer, etc.

Physical Models

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

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.)

Plan validation results

Results of validating (usually simulating) the routing and operations plan against the selected stock and target product specifications. The results may include estimates of time, cost, and yield, and also indications of critical dependencies and bottlenecks and special areas of concern for part quality. The results may directly identify problems which cause the plan to be considered unacceptable.

Planning Policies

The business rules by which the manufacturing organization does production planning. This includes product prioritization, facility usage rules, make-to-inventory/make-to-order and selection of planning strategies, e.g. Just-In-Time, Critical Inventory Reserve, etc.

Plant orders

Orders for changes to the facility physical plant, including utilities, construction, installation of equipment, etc.

Preliminary configuration = Layout

An incomplete layout specification that identifies the decomposition of a system into its components and the principal interfaces among the components, and sketches an approximate physical layout.

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.

Preliminary feedback

Results from the preliminary design phase which cause incoming product specifications to be questioned and specific changes recommended.

Preliminary layout = Layout

An initial version of a Layout that will be refined to reflect the detailed design of the subsystems and components on it.

Preparation orders

Orders for the preparation of tooling, stock materials, kits, etc., for some steps in a pending job.

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 made necessary when the available resources are changed unexpectedly, by equipment failure or priority orders, etc. 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.

Process flow diagrams: (Process specifications)

A detailed process flow diagram for the product mix shows the sequence of processes for each product and the overall relationship among products and processes. The flow diagram graphically outlines how materials are moved through preparation, manufacturing, assembly, finishing, inspection, and possibly packaging, processes. It shows process and material flows common to multiple products in the mix and flows unique to particular products, including departures from and returns to the mainstream, and includes estimates of volume for each flow path.

Process identification

The specification of a process for which the details are available from some *process library* or knowledge resource. The identification usually includes the process name, the generic type of process (fabrication, assembly, finishing, inspection, packaging, storage, transportation, etc.), and the values of principal process parameters.

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)

Process selections: (Process specifications)

A list of the major processes involved in fabricating, assembling and inspecting the Part. Identification of the workstations, equipment or equipment types to be used for each major fabrication, assembly or inspection process. It may also include special capability requirements, such as the ability to hold particular tolerances. Major processes are distinguished by the use of different kinds of equipment, or by significantly different setups for the machines, or by significantly different skill requirements.

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.

Producibility: (Design change requests)

An evaluation of the expected lead time, complexity and cost of producing the Product/Part as designed. This usually includes identification of those features which have the greatest impact on time or cost, and may include suggested changes.

Product concept

Specification of a product in terms of customer requirements and relationship to existing products of the enterprise or its competition.

Product constraints

Constraints imposed by analysis of marketability of the product: principally cost and performance, but also aesthetic and ergonomic concerns.

Product identification

Information used for engineering management and administration tracking of the part/product: names, numbers, classification, project identification, version, revision number, etc.

Product inventory

Information describing the physical product batches for which production in the facility is complete, including their product ids or part numbers, quantities, associated orders, if any, and possibly test or inspection data.

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 (may be either composition or stock material)
- component dimensions, geometry and topology
- surface finish (roughness, hardness, coatings)
- 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 which are important to the designer in making decisions and identifying similarities. Features may be codified based on some classification system designed to determine similar parts (group technology codes for product design).
- design intent: statements of the relationships between specific design choices and specific constraints, specifications and guidelines which govern the product or design process. Also statements of the interrelationships of the design choices themselves, including the use of off-the-shelf components.
- notes on special handling procedures
- notes on special quality control procedures

Product needs

Market research determination of a product opportunity.

Product orders

Quantities of parts or products to be produced, usually with nominal delivery dates, as specified by enterprise sources external to the manufacturing elements. (The relationship of these orders to *Market data* or to the actual production quantities planned is determined by both business and technical decisions.)

Product specifications

Functional specifications, performance specifications, appearance specifications and other engineering specifications for the product.

Product standards

Accepted (or legislated) industrial standards for safety, composition, performance, etc.

Production constraints

Requirements and limitations on facility modification which are derived from ongoing production management considerations, including current and future production commitments. These include space and equipment availability, maintenance access, storage considerations, etc.

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.

Production order status: (Work-in-process)

Status of the Part quantities specified by the production orders. This includes quantities actually completed, quantities in process and projected completion dates, and quantities not yet in process. This may also include estimates of effective yield or gross and net quantities.

Production orders

Quantities of products and components to be made in the facility within a given time frame. This is derived from and reflects the Master Production Schedule. The quantities and time-frame reflect capacity estimates, rather than resource schedules. The relationship of production order quantities to customer orders depends on business rules and long-term planning. The relationship of production orders to batches/lots/jobs is dependent on the product, the facility and the manufacturing resource planning algorithms.

Production problem definition

The specification of the production systems engineering problem: the type of the engineering activity (design-from-scratch or re-engineer), the scope of the (re)design, the product mix for which the production system is to be (re)designed, the physical plant or area to be used, the time available for design, acquisition and construction, and the production requirements in terms of part and product volumes, quality considerations, etc. This may also include identification of other products and facilities from which design ideas and performance expectations can be drawn.

Production requirements

Long-term changes in production capacity required to meet estimated production demand for products/parts produced in the facility. Requirements are stated in terms of product range and volume, equipment capabilities and capacities, workforce levels, etc.

Production Resources

The major physical resources used for production activities: the machines and manpower used to move, fabricate, assemble and inspect Parts.

Production system evaluation results

Results of simulation and analysis of a draft facility design, identifying expected performance against given product mixes, including both quality estimators and throughput estimators, and problem areas, such as bottlenecks and queue lengths, curing times, etc.

Production systems library

The body of knowledge available about other production systems and facilities. In particular, this includes (usually detailed) designs and performance information for the existing production facilities of the manufacturing organization, but it may also include (usually less detailed) knowledge of the designs and performance of facilities of other organizations, particularly those who make competing products.

Products

The physical end products of the manufacturing processes.

Project type

The type of the production systems engineering project, one of:

- new plant or major facility
- new production system in an existing facility
- extension of an existing production system to new/additional products
- performance improvement of an existing system
- relocation of a production system
- phaseout of a production system

This also includes some specification of scope of the engineering project: how much of the manufacturing process is to be (re)designed.

PRP Model

The product realization process (PRP) model is the formal description of the engineering process and its management and approval rules as implemented by the manufacturing organization. The PRP Model may vary from one product family to another. The model is the basis for workflow management practices for a given product family.

QFD methods

Quality Functional Deployment (QFD) methods are methods for associating design decisions with product quality as perceived by the customer, importantly including the impact of one decision on another.

Receiving reports

Information from the Receiving department concerning deliveries on external orders for tooling, components, stock materials, shop materials, etc.

Recovery & disposition commands

Directions given by a supervisor or expert technician as to the disposition of a workpiece or operation after a failure of some kind. This may be “scrap it” or “change this process parameter and redo just the last operation” or “refixture and rerun” or “call it good”, etc. In some cases, it may involve directing staff and equipment to produce a substitute workpiece, or take the work to a different machine.

Related products

For a production systems engineering problem, those products for which the production processes are sufficiently similar to those of the target product mix that the production systems for those products may provide useful information for the design of the target production system.

Released jobs

Jobs for production of specific batches of parts/products, for which tooling and materials are scheduled to be available within the current planning horizon. Each job description represents a requirement to manufacture a specific quantity (a *batch*) of a single Part (which may be an assembly). It includes the batch size, a priority, and an earliest scheduling time (possibly for specific steps). For each Job there is a plan which defines the sequence of steps required to make that batch, where each step requires a different major resource -- a different kind of equipment or a different equipment configuration. That plan is part of the Scheduling package. The operations which are to be performed within each step are defined by an *operations sheet*.

Resource descriptions

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

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. (This is a summarization of the resource requirements in the scheduling package.)

Resource schedule

Expected schedule of availability of equipment and personnel for production tasks. This includes the equipment maintenance schedule — a list of pre-planned down periods for each machine for preventive maintenance including the start and end times for those periods — and the human operator and artisan schedules — a list of operators who are available for job assignment and start and end times for availability. This also includes unexpected updates to the availability because of machine failure, sickness, injury, etc.

Resource states

Reports of current/new states of personnel and equipment, including both scheduled and unexpected changes of state, such as equipment problem reports. State information could include: resource currently up and busy on job x, machine x currently down for pre-planned maintenance, or machine x currently down for remedial maintenance, employee x out on sick leave, etc.

Resource usage

Reports of time and process conditions for equipment and personnel in service, possibly associated with specific products (where business accounting demands that). This is a measure of in-service-usage of equipment often used to predict maintenance requirements, but it may also be a factor in cost reporting.

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.

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" process 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.

Scheduling package

A plan which 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
- (identification of) the operations sheets and control programs for that station

Selected decomposition

That decomposition of the functional specifications for the product or subsystem which is believed to have the highest probability of successful design and implementation.

Sequence change requests: (Process change requests)

Feedback from planning and production activities requesting changes in the operations sequencing. In general, such changes are to make the set of operations performed at a given workstation easier or more efficient, or to improve the quality of the product by eliminating undesirable effects of a later operation on the results of a previous one.

Short-term resource requests

Requests to provide overtime for specific staff, or to reschedule maintenance on equipment, or the like, in order to provide additional resources on a temporary basis to meet production schedules.

Skills pool: (Resource descriptions)

Identifications of the skills possessed by the human resources of the facility. This includes both standard skills and special skills and includes the ability to perform specific fabrication, assembly, and inspection operations and/or the ability to achieve certain levels of quality in performing the operations.

Special tooling designs: (Tooling designs)

Special tool designs specify in detail the geometry, materials, finishing requirements, etc., i.e. the *product model* for a tool to be manufactured. These may be sent to an in-house manufacturing engineering and production activity or to an external tooling firm.

Stock 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.

Strengths and weaknesses

Results of evaluation of a design that indicate the best and worst features of the design and suggest approaches to alternative or improved designs.

Subsystem problems

Reports from a workstation operator or complex workcell controller of problems with the (sub)systems in the station/cell that require human expert attention.

Subsystem specifications

Engineering specifications (function, performance and interface) specifications for each subsystem in the product/part configuration. At some level of decomposition, the subsystems will be elementary components or off-the-shelf subsystems.

Support systems requirements

Requirements for supporting systems such as parts and materials storage and inventory systems, parts delivery areas, tool cribs, tool and kit building stations, part/product packaging and shipping stations, etc. This may also include requirements for scrap, rework and materials recovery facilities.

Target costs

Cost guidelines for the production system, including per-product manufacturing cost (materials, processing and handling), system implementation cost (including lifetime and amortization cost), and other operating costs.

Task assignments

Commands to a workstation or a complex workcell to add a particular job step to its list of things to be done, together with priority and possibly a due date/time. In a primarily human station, this is often implied by the arrival of a batch of workpieces at the station and detailed in the “traveler” papers that accompany it.

Task status

Reports from a workstation or workcell on the status of a Task assignment. This includes not yet started, busy, done, but also indications of delays and estimated completion times and possible stalls because of problems with the available equipment or the workpiece. In a human-operated station, this can be automated, but is often verbal.

Time & Cost constraints

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

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.

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.

Tolerance standards

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

Tool usage

Updates to time and process conditions of tooling in service, or other indications of tool wear.

Tooling assembly designs: (Tooling designs)

Tool assembly designs specify the tooling components, the assembly drawing and the setting and positioning parameters. These are input to the tool preparation activities in the production facility.

Tooling change requests: (Process change requests)

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

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.

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, including clamps, jigs, special-purpose fixtures
- end-effectors, including grippers, vises, etc.
- gages, probes, and sensors
- 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.

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: specs for assembling a tool or fixture from standard components,
- Special tool designs: designs for tooling which must be fabricated for the job.

Tooling list: (Resource requirements)

The complete tooling list for some batch of the Part in exploded form, including all tools, fixtures, sensors, gages, probes, etc. The list identifies tool numbers, quantities, and source (off-the-shelf, locally assembled-to-order, locally made-to-order, externally made to order). This list may include estimates for consumption of shop materials (rouge, flux, adhesives, coolants, etc.) as well.

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.

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.

Tooling/Materials

These are the physical objects — tooling and shop materials, stock materials and component parts — that must be present at the production workstations for the products or parts to be made.
(While most organizations distinguish several subtypes of these things, because the organization manages and processes them differently, It is difficult to get agreement on the subtypes, and it was not necessary for this model.)

Tooling/materials availability

Response to *preparation orders* indicating expected times of availability of the requested tooling and materials. This information may be updated after the initial response to reflect improved estimates and ultimately availability of the prepared tooling/materials.

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.

Tooling/materials orders

Orders (to Procurement system) for raw materials, off-the-shelf parts and tooling, external orders for component fabrication, assembled and made-to-order tooling, etc.

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.)

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. In reality, it is a joint operation, involving both production personnel and engineering personnel.)

Work-in-process

Identification of Part batches completed, batches currently scheduled and in production on the shop floor, and batches not yet scheduled. For each batch, the batch size and either the effective yield or the estimated yield is identified. Completed batches have actual completion times, in-production batches have scheduled completion times, and unscheduled batches have estimated release dates.

The production of a Part batch is a Job, and every Part batch (and Job) is associated with some Production order(s). The Work-in-process report, therefore, can be seen as a Production order status report.

Part batches may identify the individual workpieces/Parts and each Part may be associated with a specific Production order (especially if the Production order directly reflects customer orders), or only the batch may be tracked.

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.

Appendix A: Overview of the SIMA Project

The Systems Integration for Manufacturing Applications (SIMA) project [Bloo94, Fowl95] is an agency-wide project at the National Institute of Standards and Technology, focussing on technologies and standards that enable manufacturing systems integration. The project is funded by the Information Infrastructure Technology and Applications component of the Government-wide High Performance Computing and Communication Program [HPCC94].

The overall objective of the SIMA project is to provide industry with open architectures and interface specifications that will facilitate the implementation of integrated systems supporting the product realization process that are built from commercially available software and hardware packages. This will be achieved through the use of a formal systems approach to the specification and implementation of integrated manufacturing systems. A suite of architectural models and interface specifications will be developed for the systems and activities within the scope of the project. These will be validated by the implementation and demonstration of one or more integrated systems based on commercially available software.

The models and specifications will provide guidance to software developers and vendors on making their packages easy to integrate within larger heterogeneous systems. They also will be used to identify critical areas for, and provide technical contributions to, the development of new standards and the improvement of existing ones.

The product realization process is defined as:

> *The process by which new and improved products are conceived, designed, produced, brought to market, and supported. The process includes determining customers' needs, translating these needs into engineering specifications, designing the product as well as its production and support processes, and operating these processes.*[1]

The SIMA project focuses on the technical aspects of the product realization process, in the expectation that they will support integration of the management and business-oriented aspects of the process. This section briefly outlines the activities covered by the SIMA project.

A primary intention has been to identify a body of work that is appropriate for NIST to undertake, that advances what has been done before, and that will have a high payoff in terms of value to industry. The primary aims in establishing the scope have been to ensure that:

- The project is feasible in terms of current resources and available technology
- The results are upgradable to accommodate future developments in engineering and information technology
- The domain is relatively self-contained, i.e., it has limited interfaces with other organizational activities
- The results are able to fit readily in the context of a larger enterprise system when appropriate

Since product realization processes are not the same for different types of products, it has been necessary to decide on a product domain appropriate for the project. Boundaries have also been defined for the range of product realization activities covered and the relationship to the development of information technologies.

Product domain

A significant sector of U.S. industry manufactures electro-mechanical products. Since NIST has significant expertise in that area, and there is significant opportunity for cycle-time reduction across the industry, that

1. *Improving Engineering Design: Designing for a Competitive Advantage*, National Research Council, 1992.

area was chosen as the primary product domain for the SIMA project. Because other major research programs are actively involved in the formulation of standard architectures and interfaces for the design and manufacture of electrical and electronic components, such products are treated by SIMA only as components to be assembled into the electro-mechanical products. Other product domains, for example in process industries, may be addressed by SIMA projects, where there is a significant overlap with the electro-mechanical products domain in either the software applications used or the information content of the required interfaces.

Scope of product realization activities

The SIMA activity model covers the following product realization functions:
- Design engineering
- Manufacturing engineering and production systems engineering
- Production

Design engineering — The design engineering function starts with the requirements for a new product. Its output is a completely documented specification of that product, including a geometric description. Although the design process can be subdivided in several different ways, for the purposes of this document it is divided into four phases, each with its own output:
- Product planning
- Functional design
- Configuration design (including layouts, subassemblies, materials, etc.)
- Detail design (including detailed drawings and product models, analysis results, etc.)

Manufacturing and production systems engineering — The manufacturing engineering activities determine how the product is to be made. The related production systems engineering activities determine the characteristics of the facility which makes it. The following activities are included:
- Process planning
- Inspection planning
- Assembly planning
- Facility planning, including space, equipment and layout
- Cost estimation
- Tooling design and planning
- Generation of machine control programs

Production — Production activities include the actual manufacturing processes that make the products and ensure their quality, together with all the management and preparation activities that support the efficient use of these processes. Production activities determine the products to be manufactured at any one time, the order in which they are produced, and the allocation of resources to their production. Production activities include:
- Physical shop-floor processes, including machining, sheet metal stamping, die casting and injection molding, finishing processes, inspection processes and mechanical assembly
- Materials requirements planning and manufacturing resource planning
- Production scheduling and control
- Tool management
- Inventory control
- Equipment maintenance and human resource management

There is a trend toward *concurrent engineering*, in which some of the activities in these areas are carried out in parallel, with significant interaction, in order to shorten the overall product realization cycle. It is important that the results of the SIMA project are compatible with this mode of operation.

Quality considerations pervade the whole of the product realization cycle. The SIMA project will identify and address a multitude of integration issues regarding the implementation of the quality function. The most obvious opportunities for improving implementation of the quality function involve improving communication between the activities to include all information needed to make good decisions.

Appendix B: Interpretation of IDEF0 Diagrams

The SIMA manufacturing activity models were developed using the formal methods and diagrammatic techniques defined by IDEF0 [FIPS183], with certain additional conventions.

The fundamental objects of an IDEF0 model are *activities*, *information flows* and *resources*. In IDEF0, *activities* represent functions and operations performed by humans, hardware/software systems or both (interactively). In the diagrams, activities are represented by boxes. Any modeled activity may have a *refinement* — a decomposition of the activity into component activities, each with its own information flows and resource requirements. By convention, the first diagram page of an IDEF0 model identifies the highest-level activity being modeled, the second diagram page models its (first-level) refinement — the *primary decomposition*, and each page represents the refinement of a single activity on some previous page. To show the relationships, each activity has a label, consisting of an A followed by some number of digits. The activities of the primary decomposition are designated A1, A2, ... The activities of each subsequent refinement are labelled by appending one digit to the label of the activity being refined.

All information flows into and out of an activity must be accounted for in its refinement, that is, the information must flow into or out of one or more of the activities in the decomposition. Similarly, resources required by an activity must be required by one or more of the activities in its decomposition. Conversely, the refinement of an activity should not introduce additional external information flows or resource requirements, although it may include new flows between activities of the decomposition.

It is important to note that IDEF0 does not model the timing of activities. The ordering of the activities by label-number does not imply time or precedence. IDEF0 does not distinguish among once-only, repeated and continuous activities. Most of the activities modeled here are repeated, even for the same product, until the technical quality of the outputs is deemed adequate. If activity A has an information flow to activity B and activity B has an information flow to activity A, then these activities may occur in parallel or be repeated consecutively until some stable state or terminal condition is reached. Whether these activities occur in parallel, or with staggered starts, or consecutively, is often a business rule of the organization. In most cases, we have attempted to clarify timing considerations in the text description of the activities.

Information flows represent collections of information objects which have a common purpose or content and together provide a complete information set. Each information flow has one or more activities which are its producers and one or more activities which are its consumers. Except for the external flows of the overall activity, all producer and consumer activities are modeled. Consequently, information flows are modeled by arrows in the diagrams leading from the producer to the consumer. Arrows emanating to/from labels at the edges of the page represent “external” flows — flows into or out of the activity which this page refines.

From the point-of-view of a single activity, its information flows are divided into three categories:

• *inputs* — that information which is needed to perform the activity. We adopt the additional conventions that inputs represent information which is used in its entirety by the activity and inputs may vary over repetitions of the activity for a given product. In the diagrams, inputs are arrows into the left side of the activity box.

• *outputs* — that information which is produced (or modified) by the activity. Some outputs are feedbacks to other activities producing input to this activity. In the diagrams, outputs are arrows exiting the right side of the activity box.

• *controls* — that information which represents rules under which the activity must operate. We adopt the convention that controls represent inputs which do not vary over repetitions of the activity and instances of the activity may not ignore any of the controls which apply to it. In the diagrams, controls are arrows into the top of the activity box.

In the Part 1 models, we treat *resources* as largely static information resources that the activity may use selectively according to the needs of each instance. That is, resources represent databases and knowledge bases. This is a rather unusual use of the IDEF0 facility — conventionally, resources represent people, equipment, materials needed to perform the task, but the emphasis in the SIMA models is on information requirements. In the diagrams, resources are represented by arrows into the bottom of the activity box.

In a few cases, it was considered useful to identify physical objects as inputs, outputs and resources — these appear in bold type in the diagrams.

References

[Bark95] Barkmeyer, E.J., Hopp, T.H., Pratt, M.J. and Rinaudot, G.R. (eds.), *SIMA Background Study — Requisite Elements, Rationale, and Technology Overview for the Systems Integration for Manufacturing Applications (SIMA) Program*, NISTIR 5662, National Institute of Standards and Technology, September, 1995, available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA.

[Bjor92] Bjorke, O., and Myklebust, O. (eds.), *IMPPACT — Integrated modeling of Products and Processes using Advanced Computer Technologies*, Tapir Publishing, Trondheim, Norway, 1992.

[Bloo94] Bloom, H., *Technical Program Description: Systems Integration for Manufacturing Applications*, NISTIR 5476, National Institute of Standards and Technology, July, 1994, available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA

[Ferr91] Ferreira, P.M., Lu, S.C.-Y., and Zhu, X., *Conceptual Model for Process Planning*, Consortium for Advanced Manufacturing International (CAM-I), Arlington, Texas, 1990.]

[FIPS183] Federal Information Processing Standards Publication 183, *Integration Definition for Functional Modeling (IDEF0)*, National Institute of Standards and Technology, December, 1993, available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA.

[Fowl95] Fowler, J.E. and Luce, M.E., *Systems Integration for Manufacturing Applications Program: 1995 Annual Report*, NISTIR 5839, National Institute of Standards and Technology, May, 1996, available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA.

[HPCC94] *High Performance Computing and Communications: Toward a National Information Infrastructure*, Report by the Committee on Physical, Mathematical and Engineering Sciences, Federal Coordinating Council for Science, Engineering and Technology, Office of Science and Technology Policy, published by the National Coordination Office for HPCC, 1994.

[ISO 93] ISO CD 10303-207, *Product Data Representation and Exchange — Part 207: Sheet Metal Die Planning and Design*, International Organization for Standardization, Geneva, 1993.

[ISO 94] ISO CD 10303-213, *Product Data Representation and Exchange — Part 213: Numerical Control (NC) process plans for machined parts*, International Organization for Standardization, Geneva, June, 1994.

[SEMA91] *Computer Integrated Manufacturing (CIM) Application Framework Specification v1.1*, SEMATECH Technology Transfer Report #93061697, Austin, Texas, September 1991.