A Process Model For Production System Engineering

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Abstract

The Systems Integration for Manufacturing Applications (SIMA) Production Project at the U.S. National Institute of Standards and Technology (NIST) is working on the integration of a software tools environment for engineering production systems. This paper describes a process model for the engineering production systems and how that model is being used to integrate the commercial software tools into a workstation environment. The tools used to implement the environment are commercial off-the-shelf software products offered by a number of different vendors. The project is being undertaken as a collaborative effort between NIST researchers, several universities, and U.S. manufacturers.

Keywords

Manufacturing system engineering, process modeling, engineering tool integration

1 INTRODUCTION

Just as computer-aided design and engineering tools have revolutionized product design during the past decade, computer-based tools for production system engineering could revolutionize manufacturing. The major problem today is the lack of software integration--engineers need to move data between tools in a common computing environment. A current NIST study of engineering tools has identified more than 400 engineering software products marketed today, almost all of which are incompatible with one another. Unfortunately, the interface and database standards do not currently exist that would enable the construction of integrated tool kits.

Tool kit environments are needed which integrate clusters of functions that manufacturing engineers need to perform related sets of tasks. The Production System Engineering environment under development by NIST and collaborators will provide functions to specify, design, engineer, simulate, analyze, and evaluate a production system. Other functions included within the environment are project management and budgeting. Examples of production systems which may eventually be engineered using this environment include: transfer lines, group technology cells, automated or manually-operated workstations, customized multi-purpose equipment, and entire plants. The initial focus for this project is on small production lines used to assemble power tools.

The NIST focus for this project under the Systems Integration for Manufacturing Applications Program, Barkmeyer (1995) and the NIST/Navy Computer-Aided Manufacturing Engineering Program, McLean (1993) is on providing the models, integrated framework, operating environment, common databases, and interface standards for a wide variety of emerging tools and techniques for designing manufacturing processes, equipment, and enterprises. This paper outlines a process model which has developed for production system engineering and the tools which are being used to implement the model in an integrated computing environment. Section 2 presents an overview of the model. The Sections 3 through 7 describes the second level of decomposition of the model into: problem definition, process specification, system design, modeling and evaluation, and engineering project management. Section 8 briefly describes the effort to develop and integrated environment and outlines future work.

2 OVERVIEW OF THE PROCESS MODEL

A process model is one of several models that are needed to implement an integrated engineering tools environment. The process model defines the functions that tools must perform in order to engineer a production system. The model also defines inputs, outputs, controls, and mechanisms for carrying out the functions. The process model is a key reference document for defining the data flows and interfaces between the modules in the integrated environment.

The process model for production system engineering has been developed using Integrated Definition Method (IDEF0) modeling techniques and the Meta Software Design/IDEF tool, see Meta (1994). The model defines the tool kit functions and data inputs/outputs for each function. Detailed information models are under development which further specify each data input and output identified in the process model. The information models are being used to implement shared databases, exchange files, messages, and program calls for passing information between the commercial software tools.

The zero level of the model identifies the production system engineering function, its inputs, and its outputs. The first level of the model decomposes the engineering process into five major functions or activities: 1) define the production system engineering problem, 2) specify production processes required to produce the product, 3) design the production system, 4) model the system using simulation and evaluate its performance under expected operating conditions, and 5) prepare plans and budgets. Inputs to the production system engineering function include:

- production requirements,
- product specifications,
- quality, time, and cost constraints, and
- manufacturing resources.

Outputs of the function include:

- process specifications,
- simulation models,
- performance analyses,
- system specifications,
- implementation plans, and
- budgets.

Figures 1 and 2 illustrate the first two levels of the IDEF0 model. The model further decomposes each of these functions and data flows into sub-levels. Brief summaries of the sub-levels are presented in the sections that follow.

3 ENGINEERING PROBLEM DEFINITION

The first step in engineering the production system is clearly identifying the problem which is to be solved. Problem definition data will influence how all of the other production engineering functions are carried out. This activity is primarily one of gathering and organizing data from a number of different sources. Ultimately data gathered as a part of this activity would be recorded in template forms, imported from other applications, and maintained in a shared database. Critical data which must be identified to initiate the engineering process includes:

- Product data and key product attributes - product name, part number, model number, description, functionality, product structure (bill of materials), material composition, dimensions, weight, reference drawings, part geometry models, part family or group technology classification codes, technical specifications, reference documents,

- Production system and engineering project type - new production system (e.g., plant, line, cell), modification to existing system (i.e., product or process changes), relocation of system to new site, phaseout of a production system,

- Manufacturing constraints and issues - market forecast and production rates required (minimum, normal and peak production rates in units/hour, units/shift, units/day, units/year), production capacity, level of automation versus manual operation expected, information and control system requirements, target production site(s), floor space limitations, quality and yield requirements, safety stock requirements, storage availability, known environmental or safety hazards, production plant calendar

- Critical milestone dates and schedules - production ramp up plan, target dates for: system requirements specified, system design completed, requests-for-proposals issued, systems installed, testing completed, training completed, system operational, post production support, system phaseout,

- Expected or estimated costs - product price, manufacturing cost, system implementation, operating costs,

- Manufacturing data for related products - production engineering data for this or previously manufactured products (in some cases all outputs from previous engineering projects), competitor products and sites, possible benchmarking sites.

With the exception of critical milestone dates, most of the information outlined above may at some point be used by the next function, i.e., the specification of production and support processes. All data may be used directly by other downstream functions, if appropriate. During the course of the production system engineering process, downstream functions may provide feedback suggesting changes to the problem definition data.

4 PRODUCTION AND SUPPORT PROCESS SPECIFICATION

The second phase of the production system engineering activity is to develop a process specification for the production and support operations required to manufacture the product, see Tanner (1985), Salvendy (1992), and Sule (1994). Data developed during this phase will ultimately take the form of directed graphs and/or flowcharts. Nodes in the graphs will contain attributes which identify processes and their parameters.

A manufacturing/assembly precedence structure diagram is developed from the product geometry data and bill of materials. From the precedence structure, processes and processing precedence constraints may be derived. The derivation process may be based on human experience and intelligence, or implemented as a rule-based expert system. Data developed by this function includes:

- Process identification - process name, process type (operation, storage, inspection, delay, transportation, information, or combined activity), process parameters,

- Process resources - input product components, output product (subassembly or part identifier), tooling and fixtures, staff and job skill requirements, process by-products and hazards,

- Process time and costs - process duration, estimated process cost, product value-added.

This process is recursive--high level processes are decomposed into subprocesses until all basic or primitive operations are specified. Constraints on groups of processes and operations are identified and precedence relationships are specified.

Process specifications are perhaps best represented as diagrams and/or tables. Graphical editing functions and human interaction are normally required to layout diagrams in an understandable form. Large diagrams may be unwieldy and should be decomposed into multiple levels of sub-diagrams.

Other process specification data which may be developed as part of this phase include:

- activity relationship matrices are defined which describe how different processes relate to each other, e.g., required proximity or location.
- specification of requirements for processes, tooling, job skills, timing and line balancing, quality control, process audits,
- development of process and inspection plans, process description sheets,
- development of time standards for operations,
- ergonomic analyses of manual tasks,
- value engineering analysis (i.e., determination of job activities/steps which can be eliminated).

Processing scenarios may also be defined which describe how production will be carried out before, during, and after the new production system is implemented.

Process specifications next must be reviewed and revised to correct errors, inconsistencies, etc. Feedback requesting changes to the problem definition, as the process specification is developed. As the system design is developed in the next phase, feedback may be provided indicating required changes in process specifications.

5 PRODUCTION SYSTEM DESIGN

The third phase of the engineering process is production system design. This activity includes the design of the physical processing systems, material storage and delivery systems, and information management/control systems for the production system. The production system design problem is addressed in Sule (1994). The mechanical assembly system and flexible manufacturing system problems are described, respectively in Nevins (1989) and Draper (1984). Facility layout is presented Apple (1977) and Francis (1992). Manufacturing system architecture, design, and specification development processes are defined in Rechtin (1991), Bertain (1987), Rembold (1993), Compton (1988), and Purdy (1991).

A generic decomposition of production system design is: 1) define system requirements for each process, 2) assign requirements to system modules, 3) develop system operating scenarios for the modules, 3) identify candidate systems/machines/tooling for each module, 4) evaluate alternative technologies and candidate offerings, 5) determine number of systems required based on processing cycle time and required throughput, 6) conduct system build or buy analyses, 7) select systems for acquisition, and 8) developed detailed design for overall system based upon build and buy decisions.

Other related activities outside of the scope of system design are: 1) procurement of systems, i.e., preparation of request-for-proposals, evaluation of proposals, and awarding of contracts, 2) system development, i.e., building of modules, unit testing, and integration testing of built and bought modules, 3) system operation, and 4) post production support.

The generic production system design process can also be viewed in terms of the specific types of systems involved, i.e., process, logistics support, and information. The remainder of this section briefly summarizes considerations associated with the design of each of these elements of the overall production system.

The design of the processing system involves: the selection of a hierarchy of processing systems to implement the modules (including plants, centers, lines, cells, stations, equipment, devices, and tooling), assignment of processes to the systems, estimation of resource utilization levels, and balancing of production systems.

The design of the logistics systems can be divided into two related problems: production material logistics and plant logistics. Production material logistics includes: determination of production material requirements (raw materials, components, packaging, carriers), estimation of consumption rates, determination of sourcing strategies (make-or-buy analyses and supplier selection), lead times, and shipping (air/land/sea) methods for source materials.

Plant logistics concerns the systems which move and store materials within the facility. Plant logistics involves: determination of floor space and volumetric requirements for each process/machine/system, identification of production and tooling material storage requirements (i.e., loading docks, staging areas, centralized storage areas, line side storage), selection of storage systems (i.e., automated storage and retrieval systems, manual storage systems, production line buffers and feeders), specification of material flow through the facility (i.e., raw materials, components, work-in-process, and finished goods from the dock to lines through lines and back to dock), selection of material handling systems (e.g., hand truck, fork lift, conveyor, AGV), determination of stock replenishment strategies, design of safety and environmental systems, development of physical plant layout in two and three dimensions, and evaluation of logistics system for further production capacity growth capabilities.

Production information systems may include: monitor and control systems, communications, display and user interface systems, database management systems and their databases, data collection systems, production information systems, peripheral devices (e.g., printers, magnetic scanners, monitors, bar code readers, infrared tracking systems), production accounting and reporting, SPC/SQC systems, time and attendance recording, and preventive/corrective maintenance support systems. The information systems design activity includes: requirements specification, architecture development, process and information modeling, detailed design, interface specification, integration and test planning, and user documentation development.

The output of the production system design phase are detailed system specification documents. The phase may provide feedback to problem definition and process specification phases indicating changes which must occur as a result of design analyses. The next phase is the simulation modeling of the system which has been specified by production system design.

6 SYSTEM MODELING AND EVALUATION

Once a design, or partial design, for the production system is specified, it should be modeled and evaluated using simulation technology. The purpose of this phase is to better understand the dynamics of the proposed system and help ensure that it satisfies the constraints outlined in the problem definition phase. Inputs to this phase are derived from all of the previous phases. Pegden (1990), Askin (1993), and Carrie (1988) describe the simulation modeling process. Knepell (1993) describes the evaluation and validation of models.

The first step in developing a simulation model for the system is to define a problem statement and simulation objectives, i.e., what is expected to be learned from the simulation model. The types of alternative models to be considered and constructed need to be identified, e.g., discrete event simulation, material flow, system mechanics and kinematics, ergonomic, and/or manufacturing process. Appropriate simulation tools must be selected based on the types of models to be constructed. Next, system performance measures must be identified. Some examples of performance measures include: throughput, cycle time, work-in-process, machine downtime, and machine utilization.

Next, the system simulation model elements and their behaviors must be specified. Model elements used will depend on the types of simulations to be constructed. Elements of these models may include the attributes associated with: manufacturing resources, servers, queues and selection criteria, workpieces/loads/objects, arrival distributions, processes, system movements and material flows, timing distributions, failure and repair rates, etc. The information needed to derive the model elements will be drawn from problem definition, process specification, and system design data. The actual simulation models may then be constructed using the selected simulation tools.

Another critical activity in the modeling and evaluation phase is the development of test data for the simulation runs. This activity includes: identification of data sources, gathering of test data, formatting and loading the data, and determining the number of simulation runs required to produce significant results. Once the simulation has been constructed and the test data has been loaded, the models can be run and evaluated.

The simulations must be validated, i.e., it is necessary to determine whether results are believable based on experience, other data, etc. There are two aspects to this problem: 1) does the simulation program behave as expected, and 2) does the outcome reflect reality. If the results are not correct or creditable, either the simulation must be fixed, models modified, or the test data may need to be changed. Some examples of evaluations that may be performed on the results include: verification of the accuracy of model, analysis of errors and failures, bottlenecks, throughput, flowtime, expected yields and quality, interference problems, collisions, etc.

After the results of the simulation are reviewed, it may be necessary to revise design specifications and the system models, process specifications, or even basic assumptions spelled out in the problem definition. Some of the results of simulation, e.g., timing data, may be fed forward in to the engineering project management phase.

7 ENGINEERING PROJECT MANAGEMENT

Another parallel phase in production system engineering is the development of engineering project management data. Project management and budgeting is described in Kerzner (1984). These functions include: development of project plans, preparation of budgets, establishment of configuration management controls, and generation of reports. Principal inputs to this activity include: problem definition and system design specification data. Timing information may be drawn from simulation results.

Project planning involves defining the production system engineering project in terms of: phases, tasks, resources, and timing data. Possible phases may include: feasibility study, planning, needs and requirements analysis, detailed design, acquisition and installation, testing, training, pilot and full production operation, and phaseout. Critical milestones are identified as part of the phase definition activity.

Each major project phase is specified in terms of tasks and sub-tasks. Task precedence constraints and overlap options are identified. Required resources associated with each task are identified. Staff responsibilities are specified on each task. Resource balancing may be required. Timing information is also estimated for each task, including: expected or required start, end dates, estimated task durations and lead times. From this data, schedules may be generated and critical paths determined.

Cost factors and their analysis is an extremely important part of the system design and implementation process. Malstrom (1984) provides detailed guidance on manufacturing cost engineering processes that can be used to develop cost estimates and budgets. Budget cost categories that may be considered include: project phase, planning, labor, tooling, capital equipment, projected maintenance, information and control system, operational, training, licensing and inspection, construction, installation, material (components, consumables), overhead (utilities, labor multipliers, area usage), and rental costs.

The budgeting process includes: gathering of cost data, entering data into spreadsheets or databases by budget categories, projecting estimates where data is unavailable, generating summaries by categories, and producing budget reports. Budgeting data is review for significant deviations from targets and opportunities for savings are identified. Budget data is then used to generate feedback, if required to the problem definition and production system design phases.

Another critical activity included in this phase is the configuration management of engineering data and project documents. Principles of configuration management are outlined in Daniels (1985). This activity includes: identification of key documents, definition of revision control/review/promotion policies and procedures, identification of organizational responsibilities, establishment of notification procedures for project staff, establishment of security policies and access control mechanisms, and the placement of documents and data under configuration management.

The final activity in the management area is generation and publication of reports that summarize the results of each of the other phases. Functions included in this activity include: outline development, document editing and assembly, layout and formatting, and printing. This activity draws input from all of the other functions in this phase and the other phase.

Once plans, budgets, configuration management policies, and reports are completed they need to be reviewed to ensure that they are realistic and meet the requirements established in the problem definition phase. If not, either the plans need to be changed or information must be fed back to problem definition and/or system design to re-scope the system.

8 INTEGRATED ENGINEERING TOOLS ENVIRONMENT

The process model for production system engineering is being implemented as an integrated tools environment through the collaborative efforts of NIST, academia, and industry. Academic collaborators include: the University of Kansas, California Polytechnic University, Ohio University, and Brigham Young University. Black and Decker Corporation is collaborating on the production system engineering process and providing test data on production lines. Although a number of engineering tool vendors have provided software for integration into the environment, the final selections of software tools has not been completed.

The production engineering environment is being implemented on a high performance personal computer. Commercial software tools used in the implementation of the engineering environment include: a business process re-engineering/flowcharting package, a plant layout system, a computer-aided design system, a manufacturing simulation system, a spreadsheet tool, a project management system, and a relational database management system. Other tools are under consideration for incorporation into the environment at a future time.

The interoperability of the commercial engineering tools that are available today is extremely limited. As such, users must re-enter data as they move back and forth between different tools carrying out the engineering process. Project collaborators will: define generic information models for production system engineering data, specify interfaces for integrating tools, develop prototype integrated environments and shared databases, and implement test case production system engineering projects. Examples of the types of shared data under consideration by the collaborators for the common database includes: production requirements, product specifications, process specifications (diagrams, flowcharts, plans, routings, operation sheets, programs), equipment specifications, budget spreadsheets, project plans, simulation models and model elements, setup illustrations, plant layouts, information models, interface specifications, system descriptions, estimated yield data, process capabilities, and quality data.

A long term objective of the project is to improve the productivity of users by creating an integrated environment where changes to data and decisions automatically percolate through the various tools contained within system. Project results will provide a basis for defining interface standards that will facilitate the integration and interoperability of commercial tools in the future.

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10 BIOGRAPHIES

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S. Leong: Joined NIST in 1994, after sixteen years in the manufacturing industry. Responsible for the design, development and implementation of factory automation systems at Ford Motor Company, John Deere, and IBM. Provided consulting services to manufacturers for design and implementation of manufacturing execution and shop floor control systems since 1987. Research interests include manufacturing engineering tools integration, engineering data validation, and production system engineering.

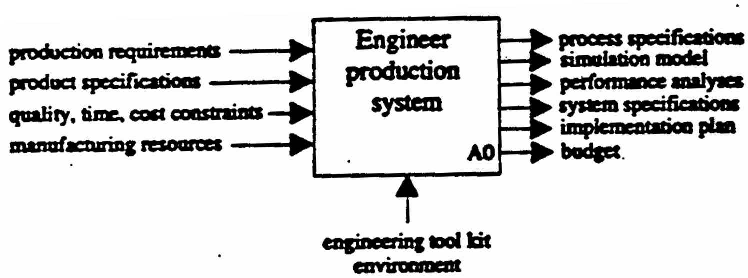


Figure 1. Top level of the production system engineering IDEF model

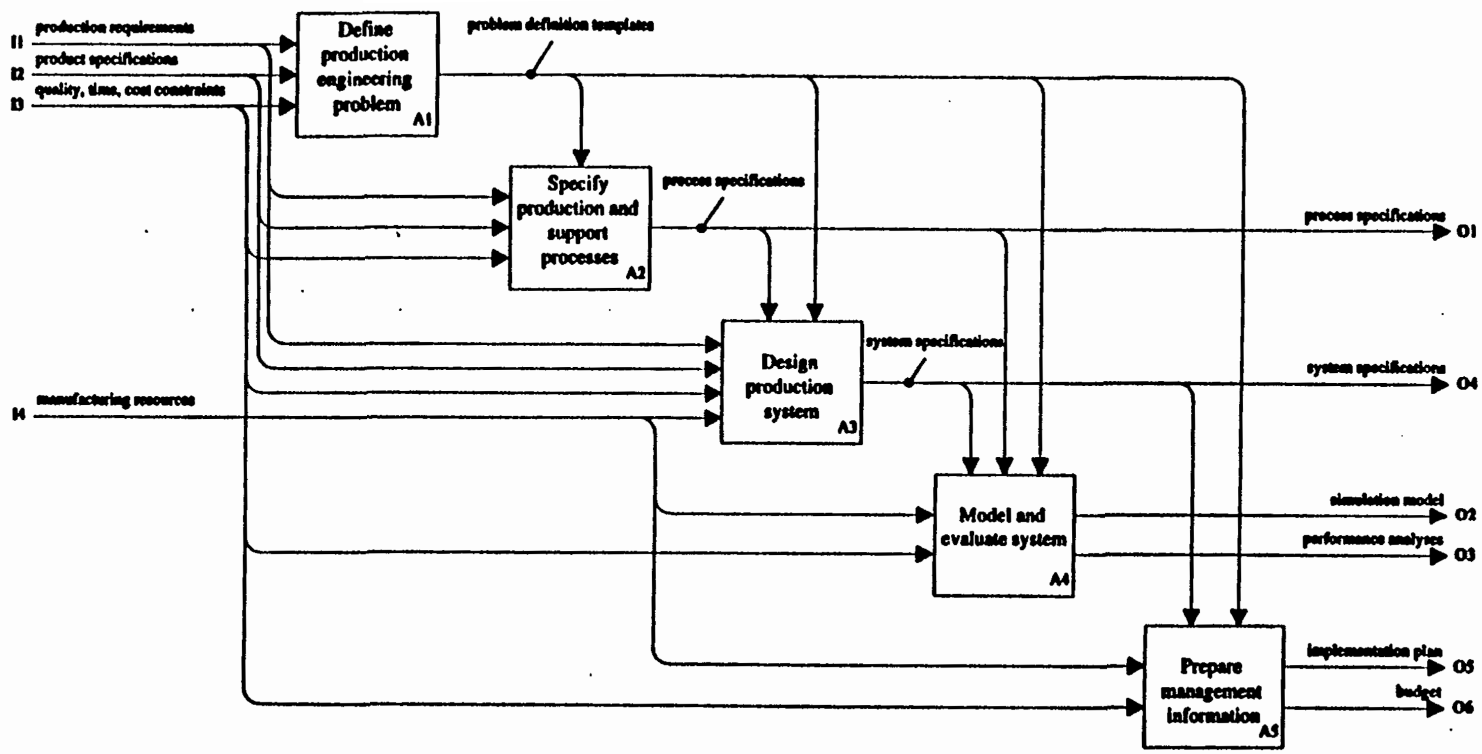
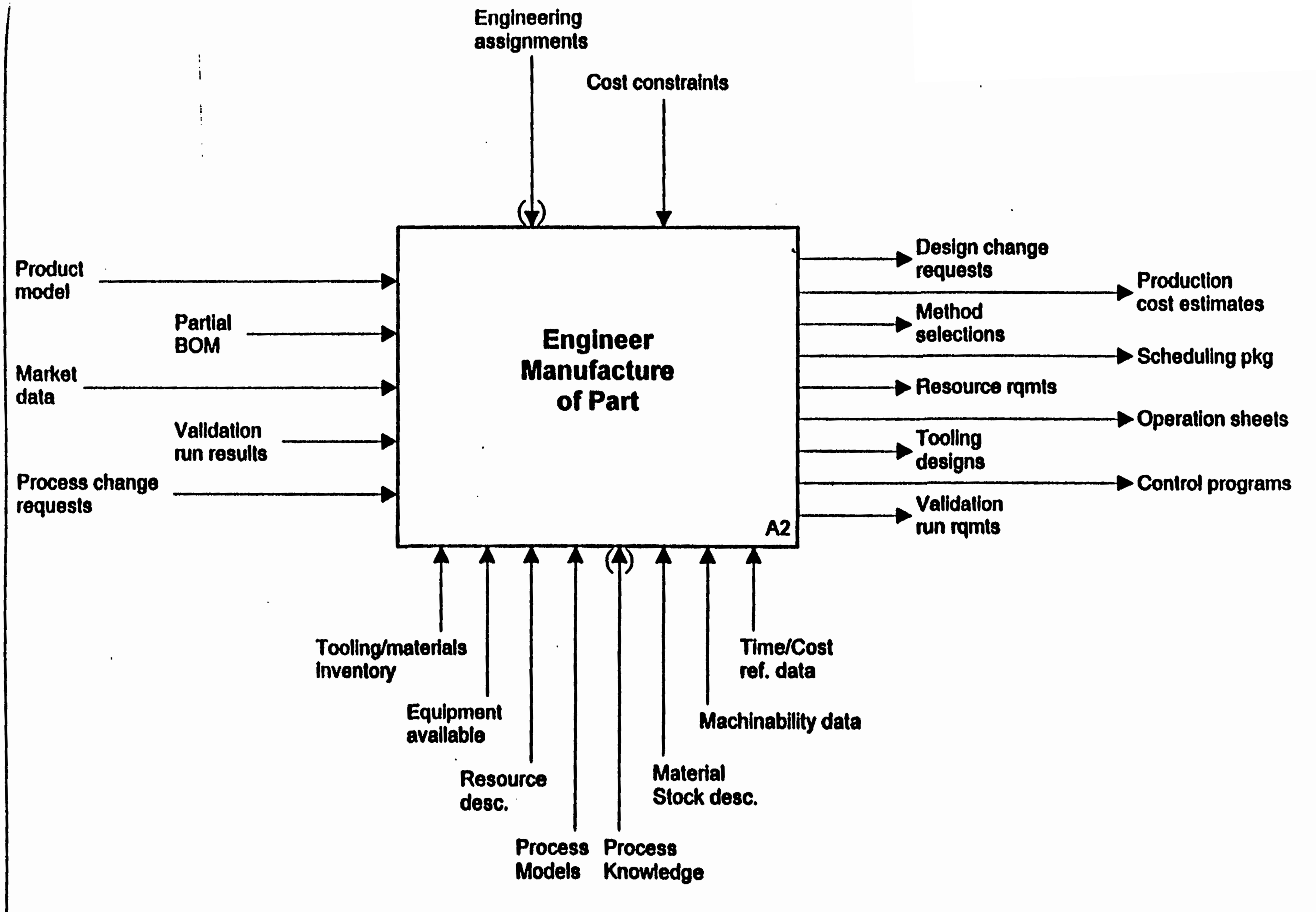
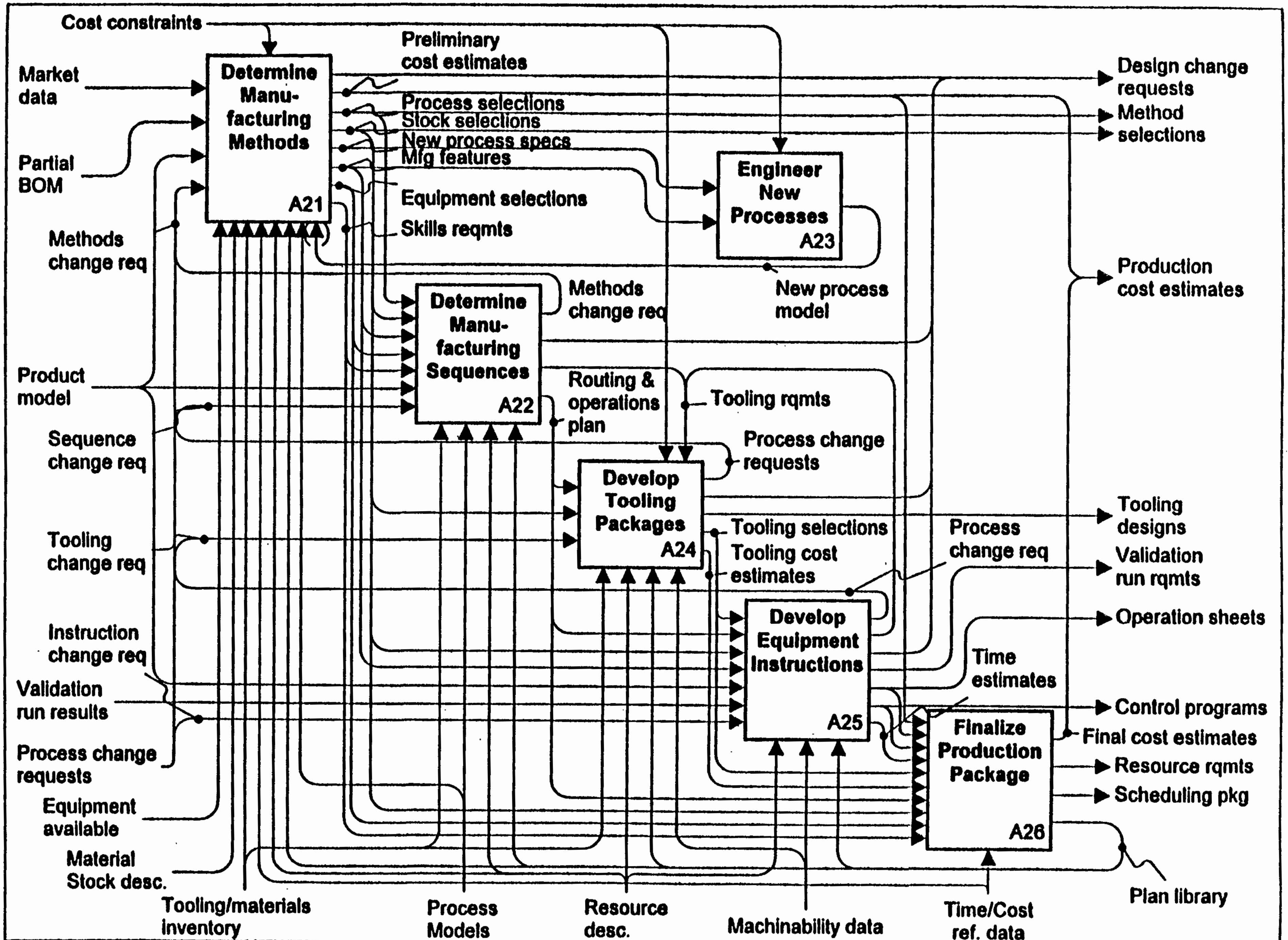
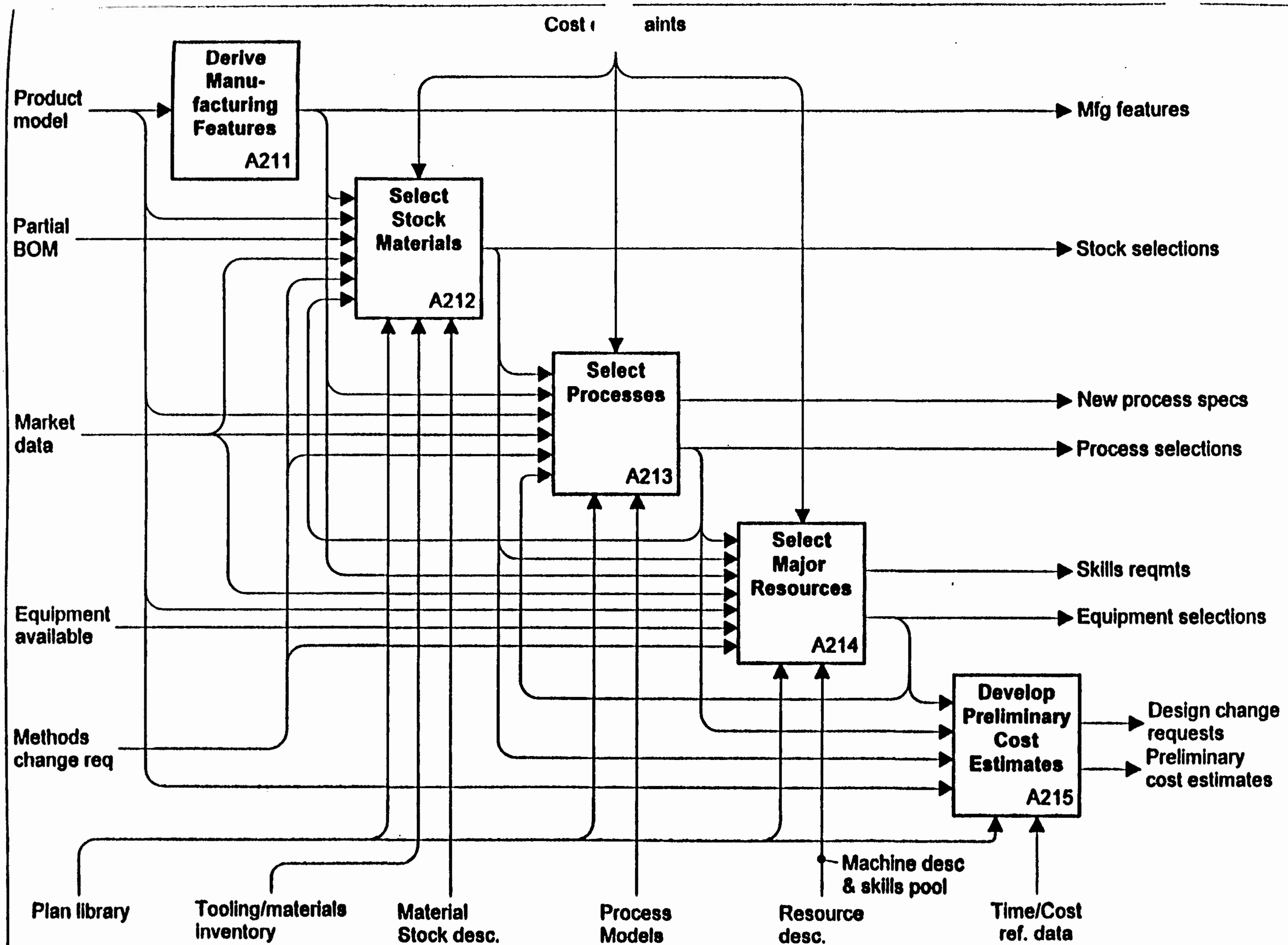


Figure 2. First level of decomposition of the production system engineering model

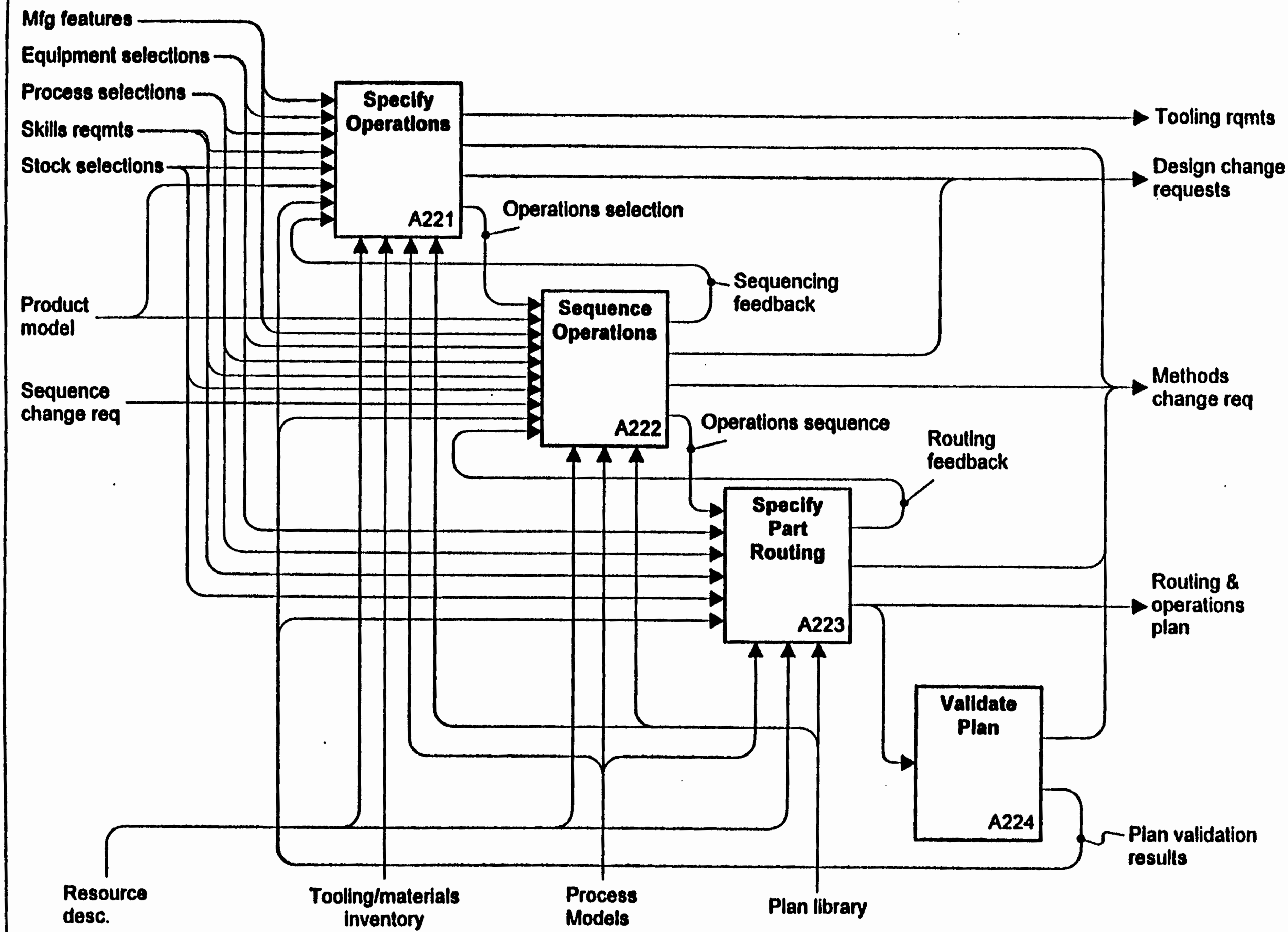

Engineering assignments
Cost constraints
Product model
Partial BOM
Market data
Validation run results
Process change requests
Engineer Manufacture of Part
A2
Design change requests
Production cost estimates
Method selections
Scheduling pkg
Resource rqmts
Operation sheets
Tooling designs
Control programs
Validation run rqmts
Tooling/materials inventory
Equipment available
Resource desc.
Process Models
Process Knowledge
Material Stock desc.
Machinability data
Time/Cost ref. data

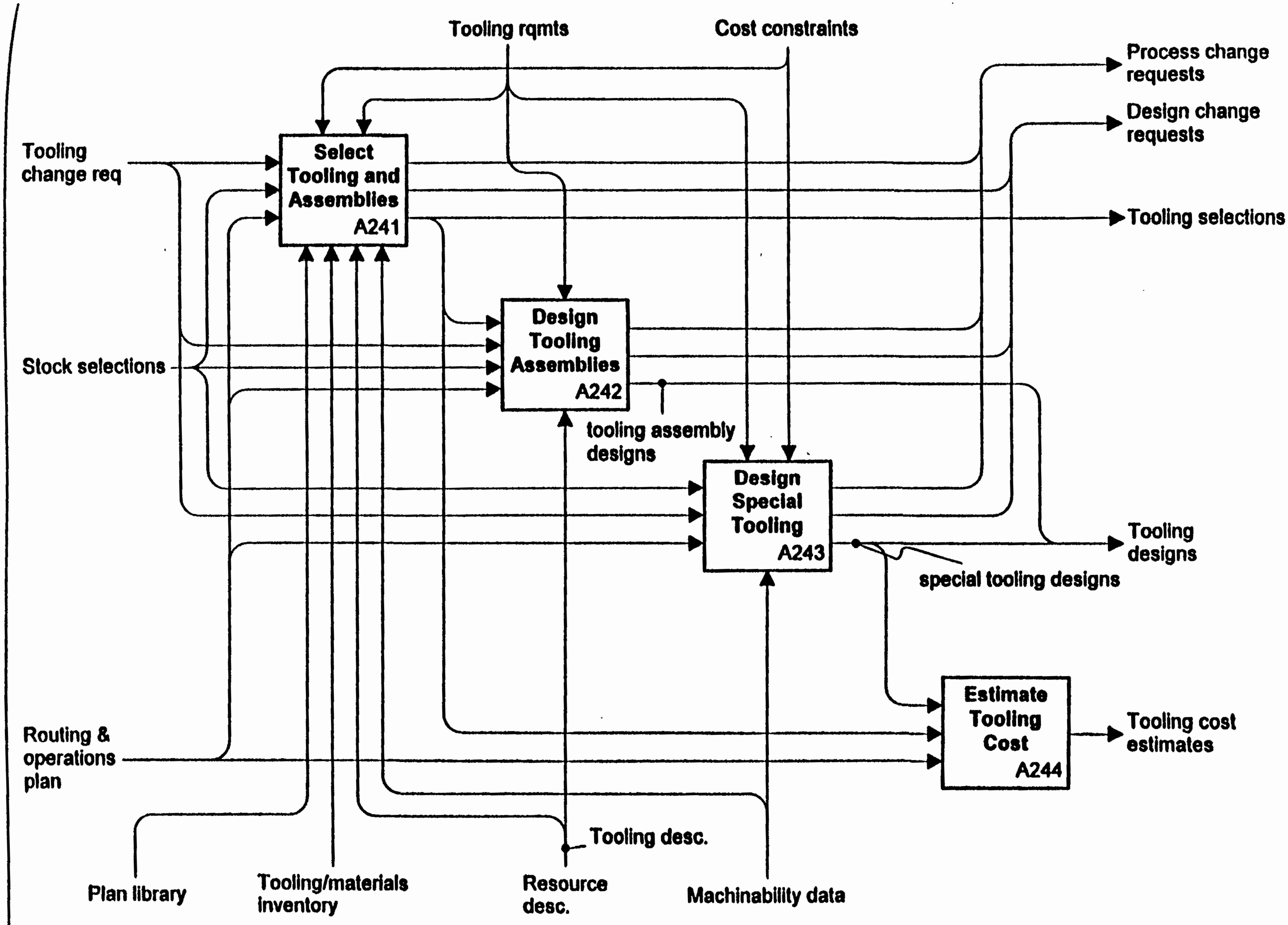


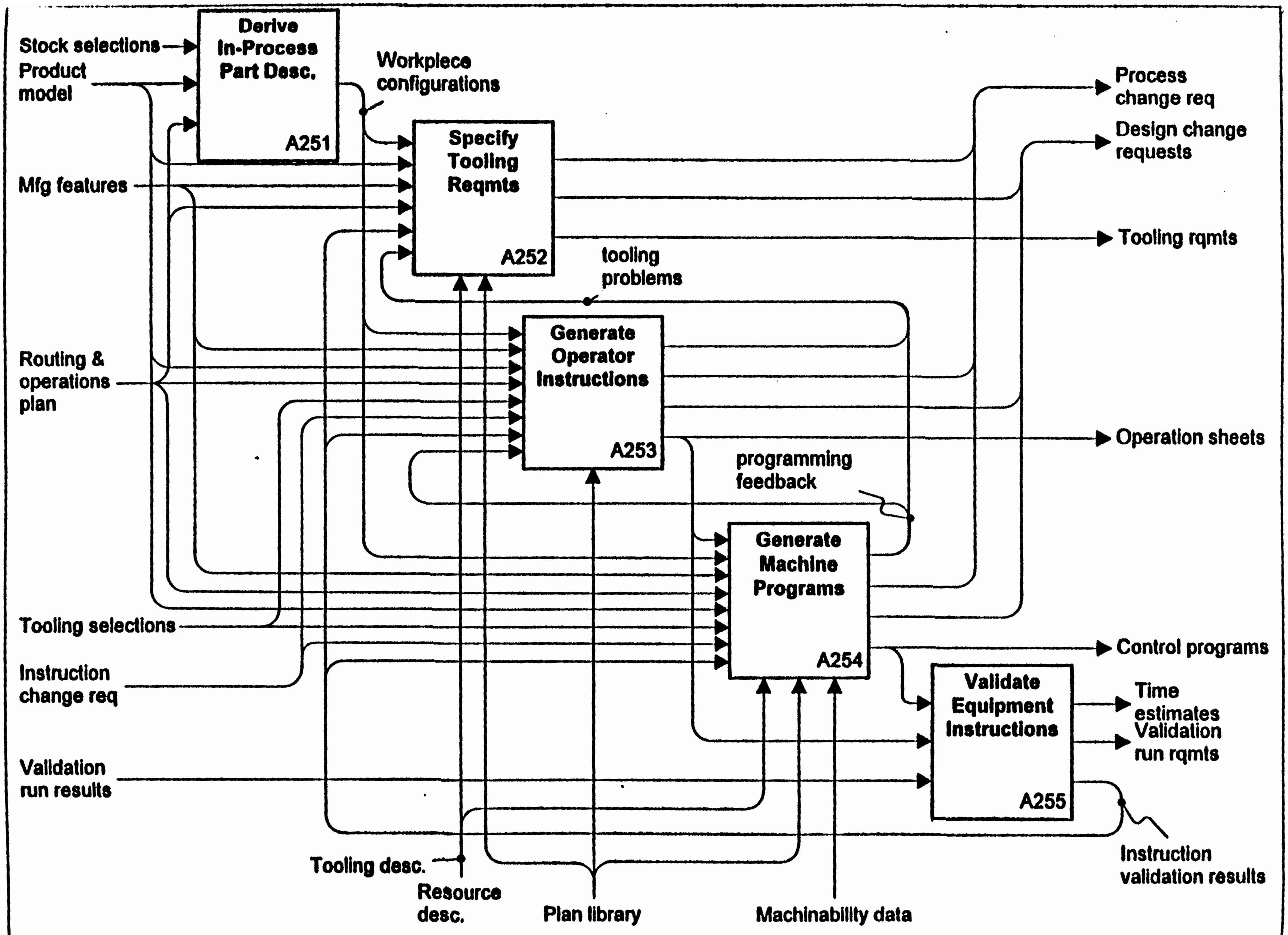
07/17/95 | SIMA Manufacturing Activity Model | Node: A2 | Engineer Manufacture of Part | Page: A2-2



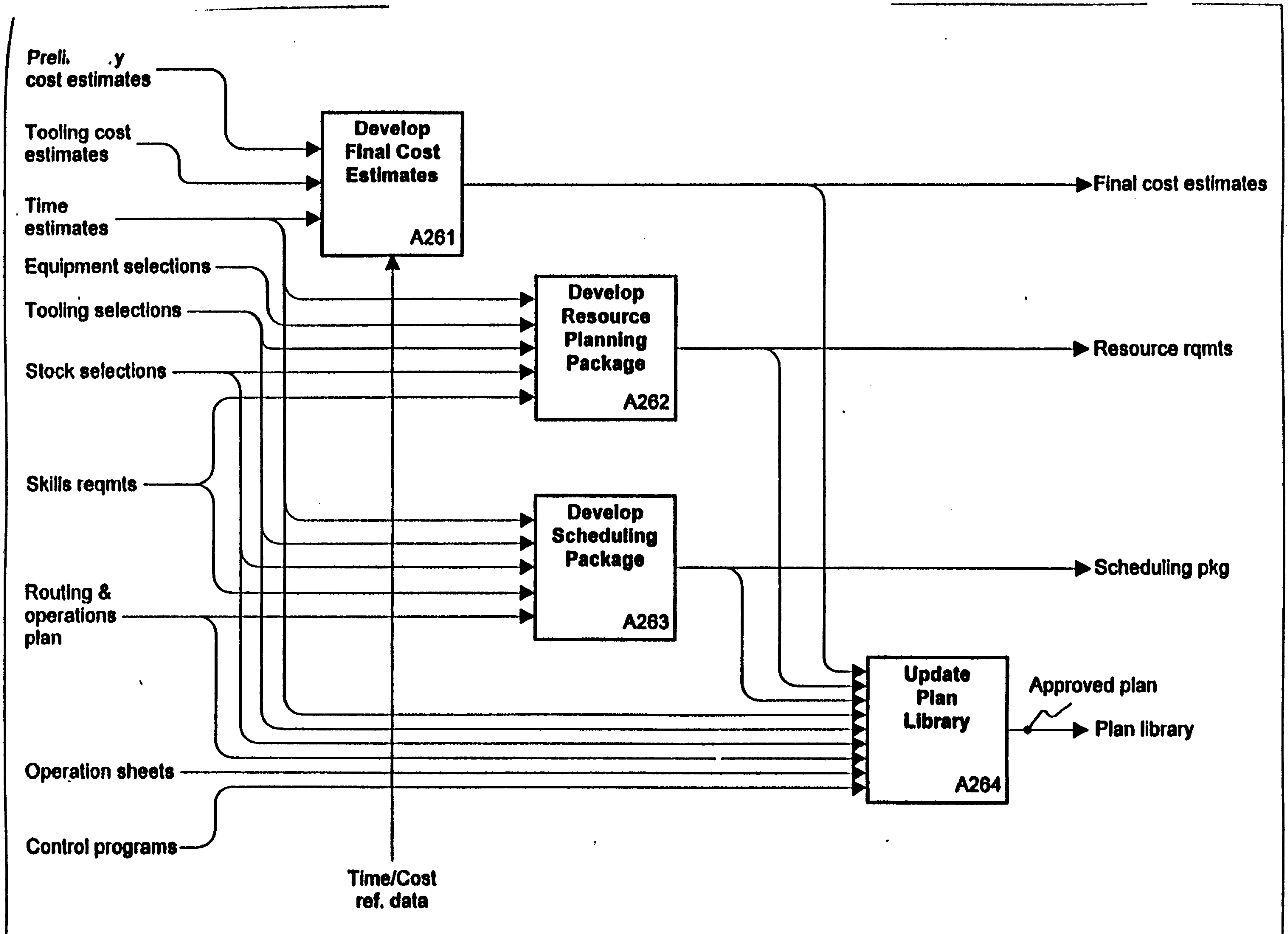
Cost constraints
Derive Manu- facturing Features
A211
Select Stock Materials
A212
Select Processes
A213
Select Major Resources
A214
Develop Preliminary Cost Estimates
A215
Product model
Partial BOM
Market data
Equipment available
Methods change req
Mfg features
Stock selections
New process specs
Process selections
Skills reqmts
Equipment selections
Design change requests
Preliminary cost estimates
Machine desc & skills pool
Plan library
Tooling/materials inventory
Material Stock desc.
Process Models
Resource desc.
Time/Cost ref. data


Mfg features
Equipment selections
Process selections
Skills reqmts
Stock selections
Product model
Sequence change req
Specify Operations
A221
Operations selection
Sequencing feedback
Sequence Operations
A222
Operations sequence
Routing feedback
Specify Part Routing
A223
Validate Plan
A224
Tooling rqmts
Design change requests
Methods change req
Routing & operations plan
Plan validation results
Resource desc.
Tooling/materials inventory
Process Models
Plan library


Tooling rqmts
Cost constraints
Process change requests
Design change requests
Tooling change req
Select Tooling and Assemblies
A241
Tooling selections
Design Tooling Assemblies
A242
Stock selections
tooling assembly designs
Design Special Tooling
A243
Tooling designs
special tooling designs
Estimate Tooling Cost
A244
Tooling cost estimates
Routing & operations plan
Tooling desc.
Plan library
Tooling/materials inventory
Resource desc.
Machinability data



Derive In-Process Part Desc.
A251
Specify Tooling Reqmts
A252
Generate Operator Instructions
A253
Generate Machine Programs
A254
Validate Equipment Instructions
A255
Stock selections
Product model
Mfg features
Routing & operations plan
Tooling selections
Instruction change req
Validation run results
Workpiece configurations
tooling problems
programming feedback
Process change req
Design change requests
Tooling rqmts
Operation sheets
Control programs
Time estimates
Validation run rqmts
Instruction validation results
Tooling desc.
Resource desc.
Plan library
Machinability data



Preli .y
cost estimates
Tooling cost estimates
Time estimates
Equipment selections
Tooling selections
Stock selections
Skills reqmts
Routing & operations plan
Operation sheets
Control programs
Develop Final Cost Estimates
A261
Develop Resource Planning Package
A262
Develop Scheduling Package
A263
Update Plan Library
A264
Time/Cost ref. data
Final cost estimates
Resource rqmts
Scheduling pkg
Approved plan
Plan library