NIST Advanced Manufacturing Series 300-1

Reference Architecture for Smart Manufacturing
Part 1: Functional Models

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**National Institute of
Standards and Technology**

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Abstract

This document is a part of the definition of a reference architecture for the integration of manufacturing software applications in the areas of fabrication and assembly of discrete electro-mechanical parts. This document captures, at a high level of abstraction, the engineering and operations functions involved in producing discrete products, and the general nature of information flows among them. The function elements provide a frame of reference for product- and facility-specific functions in a production system, and thus for specifications for manufacturing software/hardware systems components. Assigning these narrower functions to components begets a systems architecture, for which the information flows described in this document identify the necessary interactions among the components. The information flow elements also provide a frame of reference for specifying the information involved in those interactions and in the corresponding component interfaces. In short, these models are part of a framework for specifying production systems' architectures, and the related architectures for the software systems that support production systems engineering.

Introduction

This document is a part of the definition of a reference architecture for the integration of manufacturing software applications in the areas of fabrication and assembly of discrete electro-mechanical parts. The reference architecture is an element of the Smart Manufacturing Systems Design and Analysis program at NIST. The scope of the program, 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 program and are not included in the reference architecture. In general, the design concerns are limited to those that affect production systems engineering and production operations, which are the primary concerns of the NIST Smart Manufacturing projects. Related engineering and manufacturing business operations are addressed only to the extent that they affect these activities.

Following the definitions in the Systems Integration for Manufacturing Applications (SIMA) Background Study [1], we use the term *reference architecture* to mean:
- identification of the functions required to accomplish a set of objectives in a given domain;
- identification of types of systems (*components*) that perform, or support human agents in performing, the activities that implement those functions; and
- identification of the nature and content of the *interfaces* required among those systems.

This document is intended to capture, at a high level of abstraction, the engineering and operations functions involved in producing discrete products, and the general nature of

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information flows among them. The function elements provide a frame of reference for product- and facility-specific functions in a production systems, and thus for specifications for manufacturing software/hardware systems components. Assigning these narrower functions to components begets a systems architecture, for which the information flows described in this document identify the necessary interactions among the components. The information flow elements also provide a frame of reference for specifying the information involved in those interactions and in the corresponding component interfaces. In short, these models are part of a framework for specifying production systems architectures, and the related architectures for the software systems that support production systems engineering.

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Overview of the Model

The functional model presented here describes the principal technical activities involved in the engineering and production activities of a manufacturing enterprise engaged in the production of complex electro-mechanical products. The emphasis here is on production systems engineering functions, which result in the design of the actual production systems for a given product or family of products. The model is intentionally at a high level of abstraction. The details of any of these functions are very dependent on the nature of the products and the engineering practices of the particular organization, which vary significantly over corporations involved in the same general enterprise.

The goal of the functional models is to identify the required activities and the information flows required to perform those activities efficiently and effectively. A secondary goal is to identify those functions which are supported by off-the-shelf software systems, which may be the ready-made components of an actual production systems architecture. Taken together, these models represent the first step toward the goal of the NIST Smart Manufacturing Systems Design and Analysis program: to provide a framework for defining smart manufacturing systems architectures.

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 that supports many special cases of a common information flow exists or can be developed, and thus it 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 other work.

It is our belief that the activities modeled herein are fundamental to the enterprise of manufacturing. For more than a hundred years, 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 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 that is needed to perform the functions will not change in concept, although it may change significantly in magnitude and in detail. Because the models in this paper represent *what* is done rather than *how* it is done, they represent the manufacturing enterprise "as is," but also the manufacturing enterprise "to be."

The activity models were developed by NIST experts drawing extensively on previous work by CAM-I [2], SEMATECH [3], the ATHENA project within the 6th EU Framework Programme for Research and Technological Development [4], and ISO Technical Committee 184 Automation systems and integration [5]. A starting point for this activity was a previous NIST

publication in this same area [6], which emphasized design engineering activities and process specification activities coupled to a simple model of production systems specification. The primary thrust of that work was how a manufacturing facility will be *used* to make the product. Because our project is about the design of smart manufacturing systems, this document concentrates on how the manufacturing facility is *designed* to make the product.

Because our intention was to identify the functions and interfaces required of manufacturing software systems, the models were expanded only to a level of detail at which a modeled activity represents a specific kind of engineering or production function that might be supported by an individual software/hardware component. (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.

The primary domain of these models is the manufacture of assembled products and subassemblies. The viewpoint taken, however, is that modern assembly plants are flexible enough to deal with a variety of product variants. This may be accomplished by dynamic process adaptation, or configuration changes in rapidly reconfigurable components.

Most important to the purpose of the models, however, is that the information requirements can be characterized. The models attempt to separate the information into cohesive sets and to identify the functions that are expected to produce an information set and the functions that are expected to use it. This characterization of information sets is important to defining the scope and content of component interfaces. (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. Many information sets will have very different detailed content in different product and facility applications. These issues are important in the development of specific information models and interface specifications. The characterizations of information flows given in this document attempt to identify areas of wide variation.

The models were documented using the formal methods and diagrammatic techniques defined by IDEF0 [7], with some unusual conventions. The diagram conventions are summarized in Appendix A.

This document consists of two sections. Section 1 consists of the IDEF0 diagrams of the activities, and text descriptions of the activities identified in the diagrams. Section 2 provides descriptions of the information flows appearing in the IDEF0 diagrams in section 1.
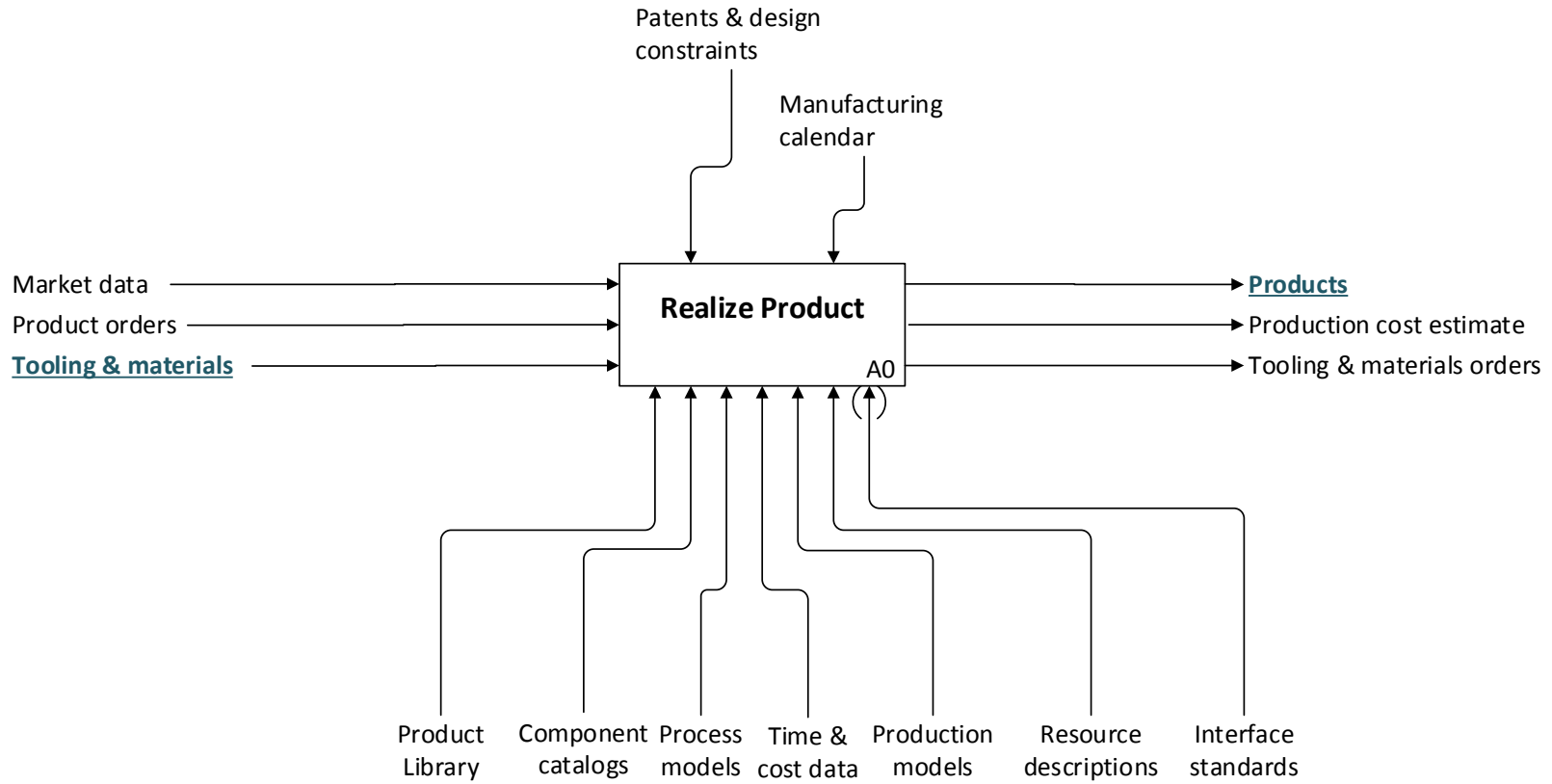
1   Activities

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 2.
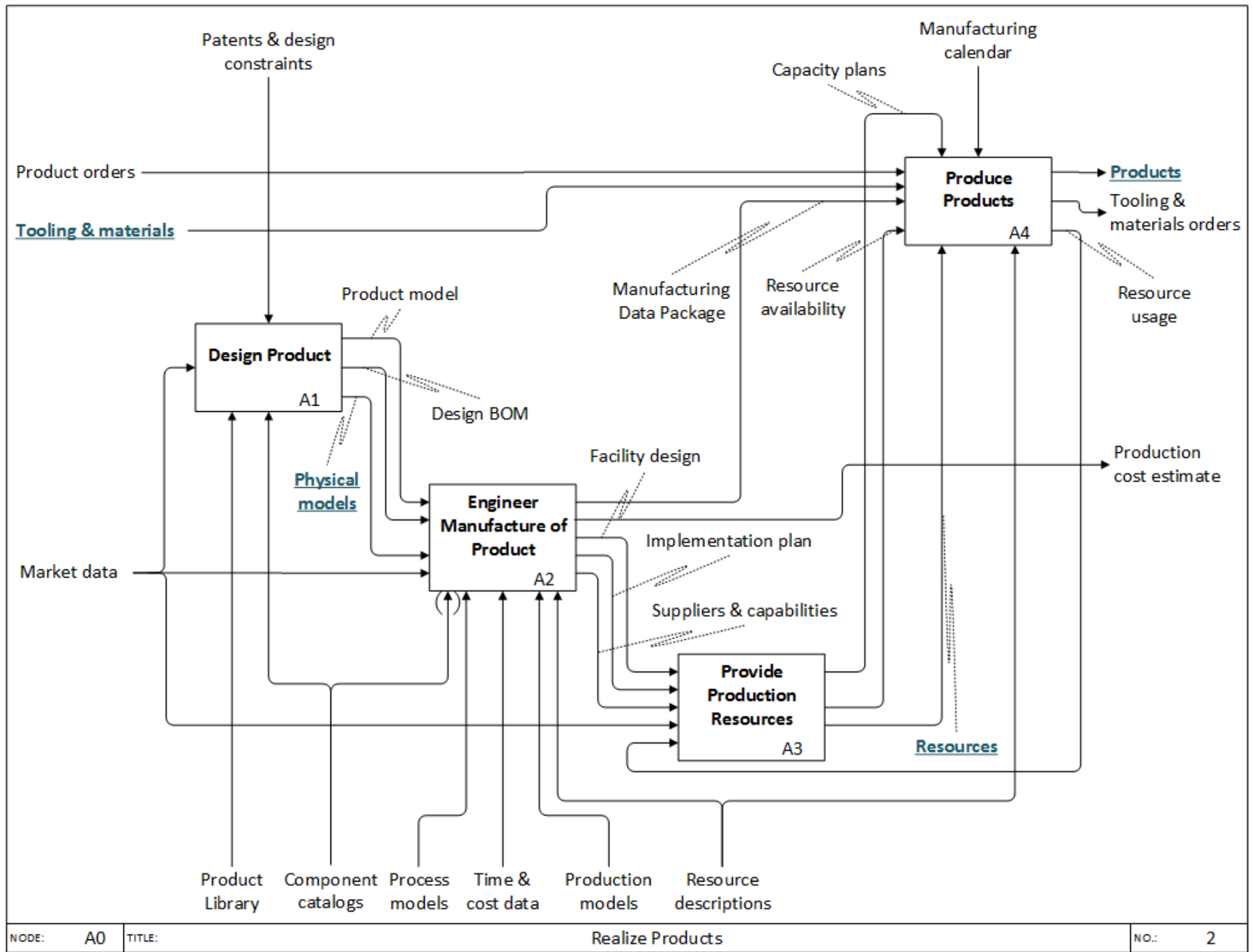
The complete node tree for the Smart Manufacturing activity model is as follows:

A0: Realize Products
    A1:   Design Product
        (not expanded)
    A2:   Engineer Manufacture of Product
        A21: Define Engineering Problem
        A22: Define Production Processes
            A221: Specify Process Requirements
            A222: Specify Materials Requirements
            A223: Specify Process & Material Flows
            A224: Specify Process Details
            A225: Estimate Production Cost
        A23: Design Production Systems
            A231: Specify Production Equipment
            A232: Specify Instrumentation & Control Systems
                A2321: Identify Control Requirements
                A2322: Identify Instrumentation Requirements
                A2323: Identify Communications Requirements
                A2324: Integrate System Specifications
            A233: Specify Support Systems
            A234: Develop Facility Layout
            A235: Integrate and Test System Designs
        A24: Develop Implementation Plan
            A241: Identify & Evaluate Supply Sources
            A242: Decide Make/Buy for Parts
            A243: Develop Facilities Plan
            A244: Develop Manufacturing Plans
    A3:   Provide Production Resources
        A31: Develop Capacity Plans
        A32: Create Supply Sources
        A33: Acquire Major Resources
        A34: Manage Plant Resources
    A4:   Produce Products
        A41: Plan Production
        A42: Manage Materials
        A43: Schedule Jobs
        A44: Perform Jobs
            A441: Direct Personnel and Machines
            A442: Control and Monitor Jobs
            A443: Coordinate Equipment Groups
            A444: Control Equipment

Patents & design
constraints

Manufacturing
calendar

Market data →

Product orders →

Tooling & materials →

Realize Product

A0

→ **Products**

→ Production cost estimate

→ Tooling & materials orders

Product
Library

Component
catalogs

Process
models

Time &
cost data

Production
models

Resource
descriptions

Interface
standards

| NODE: | A-0 | TITLE: | Functional Product Realization Model | NO.: | 1 |

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| NODE: | A0 | TITLE: | Realize Products | NO.: | 2 |

6

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. (This function is not expanded in this document.)

A2: Engineer Manufacture of Product

This activity includes some or all of the following, according to the nature of the product and the available facilities.
- Define the set of materials, processes, and resources that is needed to produce a certain volume of a given product or product line
- Define the routing of the product workpieces through a sequence of processing equipment stations, together with appropriate operator and machine instructions for each station
- Define the setup or configuration of processing equipment stations that enables such a routing to produce the desired parts
- Specify the reconfiguration of a part of a plant that will enable the production of the desired parts, by reorganization, reconfiguration, and replacement of processing stations and materials flow systems.
- Specify the development of a new plant, or a "from the walls" reconstruction of an existing facility to enable the production of a target product or product line.

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.)

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
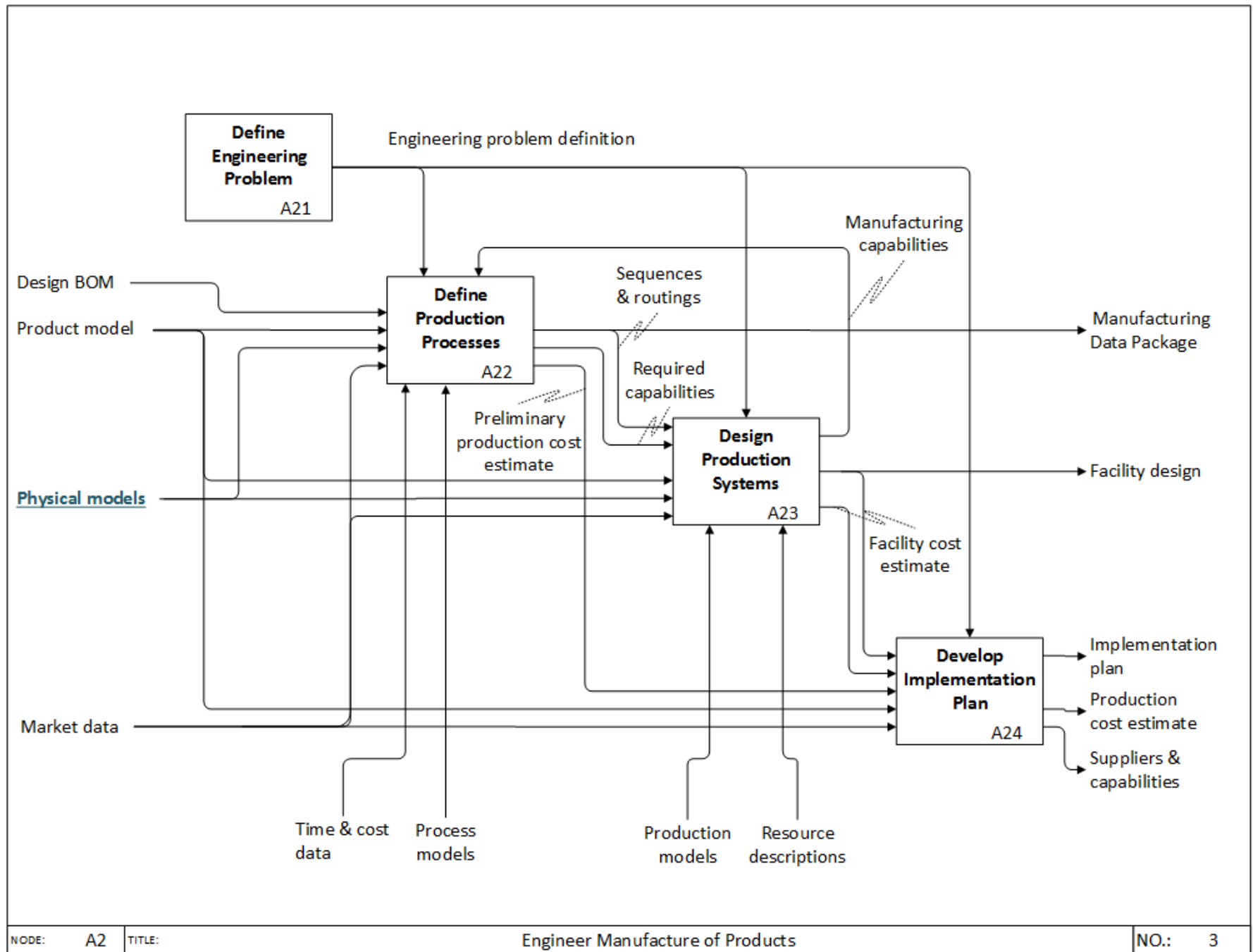
tailored, identification of the equipment to be installed or replaced, (re)design of the floor layout, and development of an implementation plan for the (re)designed production system.
(Expanded, on page 10.)

A3: Provide Production Resources

Using customer orders and projected demand for the products of the facility, specify the required resource levels for the facility, create the corresponding resources – plant, equipment, and workforce -- and, maintain the required resource levels. Acquire and maintain equipment. Maintain workforce levels and skills. Provide and maintain physical plant, grounds, and utilities. Monitor resource utilization and cost. Create and maintain contractual relationships with suppliers that will provide the required volumes of parts, tooling, and services. Manage the implementation of major facility redevelopment plans, and oversee commissioning of new and reengineered facilities.
(Expanded, on page 24.)

A4: Produce Products

Produce the parts and products according to the specifications in the corresponding Manufacturing Data Packages. 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, assigning human and machine resources to production activities, managing tooling and materials, tracking work-in-progress, job/lot completion, resource utilization, and product yield.
(Expanded on page 26.)

Define Engineering Problem

A21

Engineering problem definition

Manufacturing capabilities

Design BOM

Product model

Define Production Processes

A22

Sequences & routings

Manufacturing Data Package

Required capabilities

Preliminary production cost estimate

Design Production Systems

A23

Facility design

Physical models

Facility cost estimate

Develop Implementation Plan

A24

Implementation plan

Production cost estimate

Market data

Suppliers & capabilities

Time & cost data

Process models

Production models

Resource descriptions

NODE:	A2	TITLE:		Engineer Manufacture of Products	NO.:	3

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A2:   Engineer Manufacture of Product

This activity includes some or all of the following, according to the nature of the product and the available facilities.

- Define the set of materials, processes, and resources that is needed to produce a certain volume of a given product or product line
- Define the routing of the product workpieces through a sequence of processing equipment stations, together with appropriate operator and machine instructions for each station
- Define the setup or configuration of processing equipment stations that enables such a routing to produce the desired parts
- Specify the reconfiguration of a part of a plant that will enable the production of the desired parts, by reorganization, reconfiguration, and replacement of processing stations and materials flow systems.
- Specify the development of a new plant, or a "from the walls" reconstruction of an existing facility to enable the production of a target product or product line.

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.

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 or "part family" separately. (A *part family* is a set of slightly different designs that can be produced by the same sequence of processes with minor differences in material or process controls.) 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".

The results of this activity are the drivers for the production planning and production activities for each Part, and for the product as the final Part. The results of this activity may be used directly to make the Part using existing resources. It 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. Production difficulties or plant resource changes may lead to feedback into this activity requesting changes in the process specifications.

A21: Define Engineering Problem

Delimit the production engineering problem to be solved. Determine which of the possible engineering activities identified above are within the scope of the task. Identify the product, product line, or part mix for which the processes and facilities are to be specified. Define the work elements to be undertaken and the constraints on the process and facility design. For a complex product/part mix, this activity may produce a hierarchy of production engineering problem definitions for which all of the Production Engineering activities are separately or jointly performed. (Not further expanded.)

A22: Define Production Processes

Define the process of making the product, including the base 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.
(Expanded, on page 13.)

A23:   Design Production Systems

Design new or modified production facilities for the manufacture of a particular collection of Parts, including the major processing equipment, material storage and delivery systems, instrumentation systems, control systems, and support systems. As appropriate, specify additional tooling, fixtures, and preparation stations. Where necessary, specify additional physical plant facilities, networks and information systems.

A *production system* may be a plant, a shop, a line, or some element(s) of a shop or line. 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.

For a complex product/part mix, this activity may produce a hierarchy of production engineering problem definitions for which all of the A2 activities are separately or jointly performed.
(Expanded on page 16.)
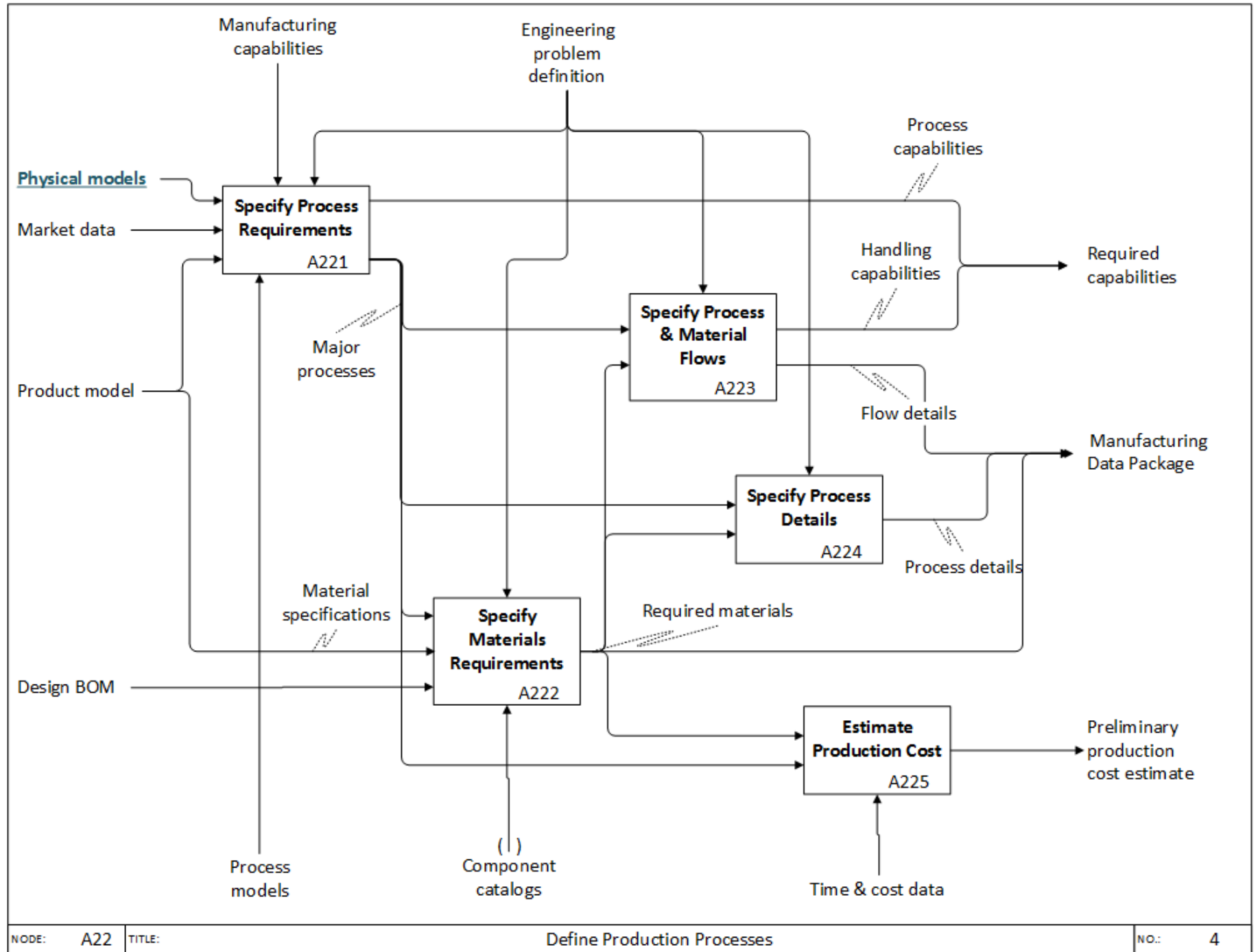
A24: Develop Implementation Plan

When a satisfactory manufacturing process sequence has been identified, and corresponding facility additions and modifications, if any, have been identified, then the "make" cost basis for make/buy decisions is available. For parts and subsystems that may be externally supplied, develop the comparable "buy" estimates of cost and lead time, and decide make/buy subsystem by subsystem. In general, this process will interact with the Process and System Design activities, as the manufacturing engineering activities move down the assembly tree.

Create detailed plans and budgets for performing any required major facilities modifications. For those "make" activities that require lesser configuration changes, determine sources and lead times for tooling and fixtures, and plan the reconfiguration activities. For those parts/subsystems to be bought, identify suppliers, lead times, and required inventories.

Construct the overall plan for the product as a combination of "make" and "buy" for components, facilities construction and reconfiguration. Determine a target manufacturing start date and a schedule for prior events. Provide the related budgets and cost estimates.
(Expanded, on page 21.)

Manufacturing capabilities

Engineering problem definition

Process capabilities

Physical models

Market data

Specify Process Requirements

A221

Handling capabilities

Required capabilities

Product model

Major processes

Specify Process & Material Flows

A223

Flow details

Manufacturing Data Package

Specify Process Details

A224

Process details

Material specifications

Specify Materials Requirements

A222

Required materials

Design BOM

Estimate **Production Cost**

A225

Preliminary production cost estimate

Process models

Component catalogs

( )

Time & cost data

| NODE: | A22 | TITLE: | Define Production Processes | NO.: | 4 |

A22: Define Production Processes

Define the process of making the product, including the base 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.

A221: Specify Process Requirements

Define the major processes involved in making the product (family). Identify those processes that are common to multiple products in the mix and those which are unique to particular Parts. Identify those processes already supported in the target facility. (Using, expanding, or replicating those processes is usually less expensive.) Identify the types and capabilities of equipment to be used. Identify requirements for special operator skills and certifications.

A222: Specify Materials Requirements

Identify materials and component parts to be used in making the product. This includes both materials that become part of the product itself and materials that are consumed in the processing activities.

A223: Specify Process and Material Flows

Define the sequencing of the selected processes. Develop a detailed process flow specification 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 specifications take into account available resources, time, cost, and other manufacturing constraints.

From the process flow specifications, develop a materials flow diagram, that outlines how in-process materials are moved through manufacturing and assembly. Also specify flows of additional materials and components into the processes. Using the flow diagrams and the estimated volumes, identify the requirements for materials storage, buffering, transportation, packaging, and handling in the production system, and the related materials handling, transportation, and storage equipment.

A224: Specify Process Details

For each station in the process flow, define and document exactly what steps must be taken by the machines and by the human operators and specialists, in order to accomplish the process assigned to that station. This includes operation sheets, assembly instructions, numerical control programs, and robot programs. These specifications will be used in production on the factory floor.

Complete specifications for the required tooling, including cutting tools, molds, dies, fixtures, end-effectors, probes, and sensors. This includes design and/or assembly specifications for the tool or fixture, and may include special instructions for use and estimated in-service life. These specifications will be used directly to acquire tooling and fixtures for service on the factory floor.
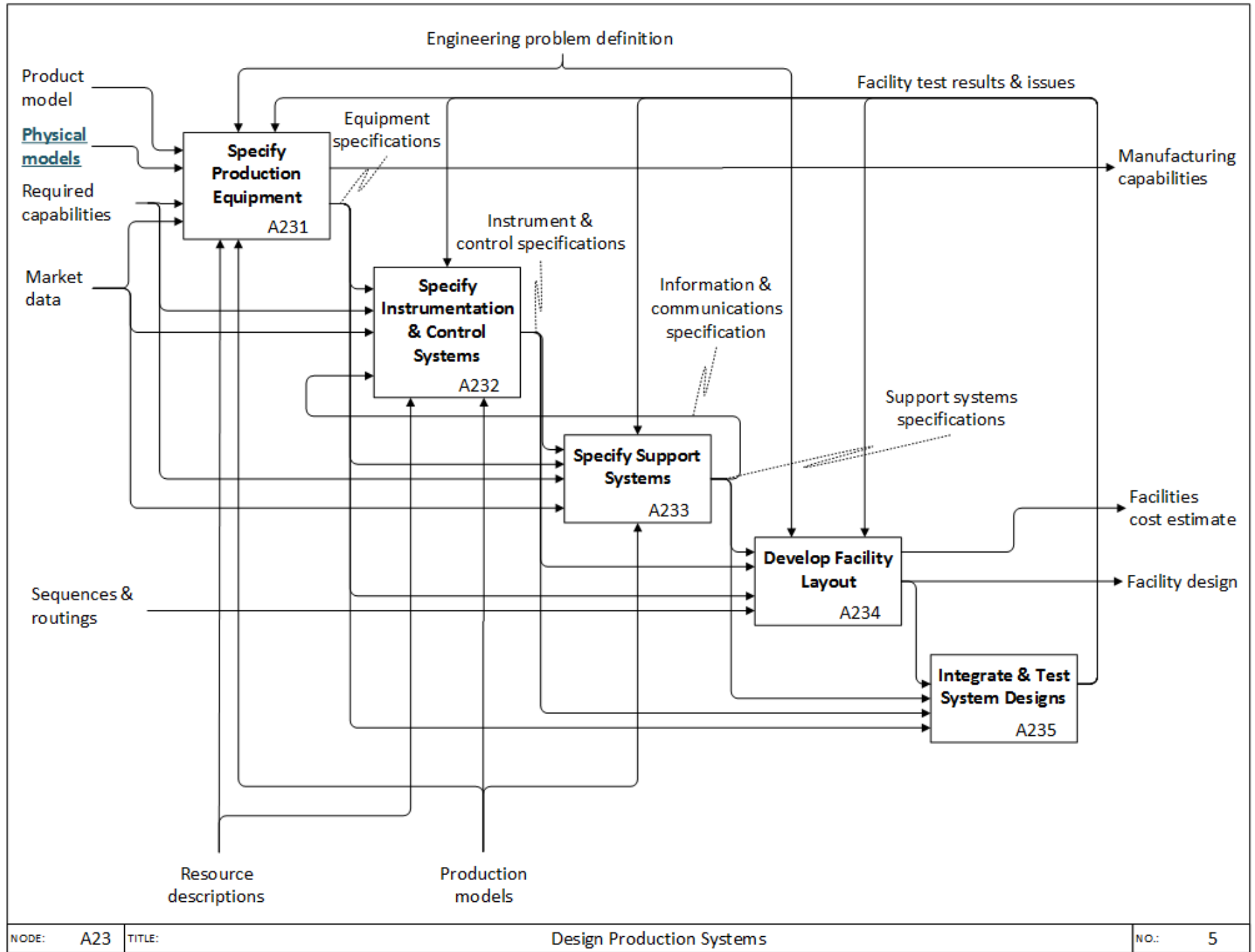
If necessary, specify materials preparation details, kit construction, and special handling

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operations.

This process is performed only when agreement on the major processes, resources, and flows is reached. Testing the detailed specifications may require use of production facilities and therefore must be scheduled into several production activities, such as machine use, tooling preparation, and materials management.

A225: Estimate Production Cost

Given the process requirements at an appropriate level of detail and the materials to be used, estimate the production cost per unit of product in terms of the time of the committed resources, and the cost of materials, and imposed plant overheads.

Engineering problem definition

Product model

Physical models

Required capabilities

Market data

Specify Production Equipment

A231

Equipment specifications

Facility test results & issues

Manufacturing capabilities

Instrument & control specifications

Specify Instrumentation & Control Systems

A232

Information & communications specification

Specify Support Systems

A233

Support systems specifications

Facilities cost estimate

Develop Facility Layout

A234

Facility design

Sequences & routings

Integrate & Test System Designs

A235

Resource descriptions

Production models

| NODE: | A23 | TITLE: | Design Production Systems | NO.: | 5 |

A23: Design Production System

Design new or modified production facilities for the manufacture of a particular collection of Parts, including the major processing equipment, material storage and delivery systems, instrumentation systems, control systems, and support systems. As appropriate, specify additional tooling, fixtures, and preparation stations. Where necessary, specify additional physical plant facilities, networks, and information systems

A *production system* may be a plant, a shop, a line, or some element(s) of a shop or line. 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.

For a complex product/part mix, this activity may produce a hierarchy of production engineering problem definitions for which all of the A2 activities are separately or jointly performed.

A231: Specify Production Equipment

Using the process specifications for the selected product(s), specify the major equipment (processing, inspection, and material handling equipment) that is to make up the resulting facility. Identify the existing equipment in the plant or area and any other equipment available for use, and determine those to be used and/or modified. From catalogs and other sources, identify new equipment to be installed (make, model, quantity, configurations). Specify required reconfigurations of existing 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.

A232: Specify Instrumentation & Control Systems

Specify configurations of controllers for automated and semi-automated manufacturing systems and material handling systems. Specify the data acquisition instruments that are necessary for maintaining process continuity and product quality. Specify supporting communications requirements.
(Expanded, on page 19.)

A233: Specify Support Systems

Using the process and materials specifications, identify requirements for supporting systems, including safety systems, tooling and materials management systems, information systems, and plant utilities.

Specify materials storage systems, parts delivery areas, tool cribs, tool and kit building stations, materials preparation stations, and others as needed. Specify requirements for part/product packaging and shipping stations. In some cases, specify scrap, rework, and materials recovery facilities.

Where needed, define the requirements for higher-level information systems for the facility. Such systems support the information requirements for the process controllers, the materials handling control systems, and other support systems. They may also capture process data and part quality data for later analysis, and provide interfaces to external systems in the enterprise. Specify the physical computer and communications resources, including the plant network, if any. The design takes into account available hardware and software systems, existing communications equipment and media, and required practices.

Specify power requirements, heating/air-conditioning requirements, and other plant 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.)
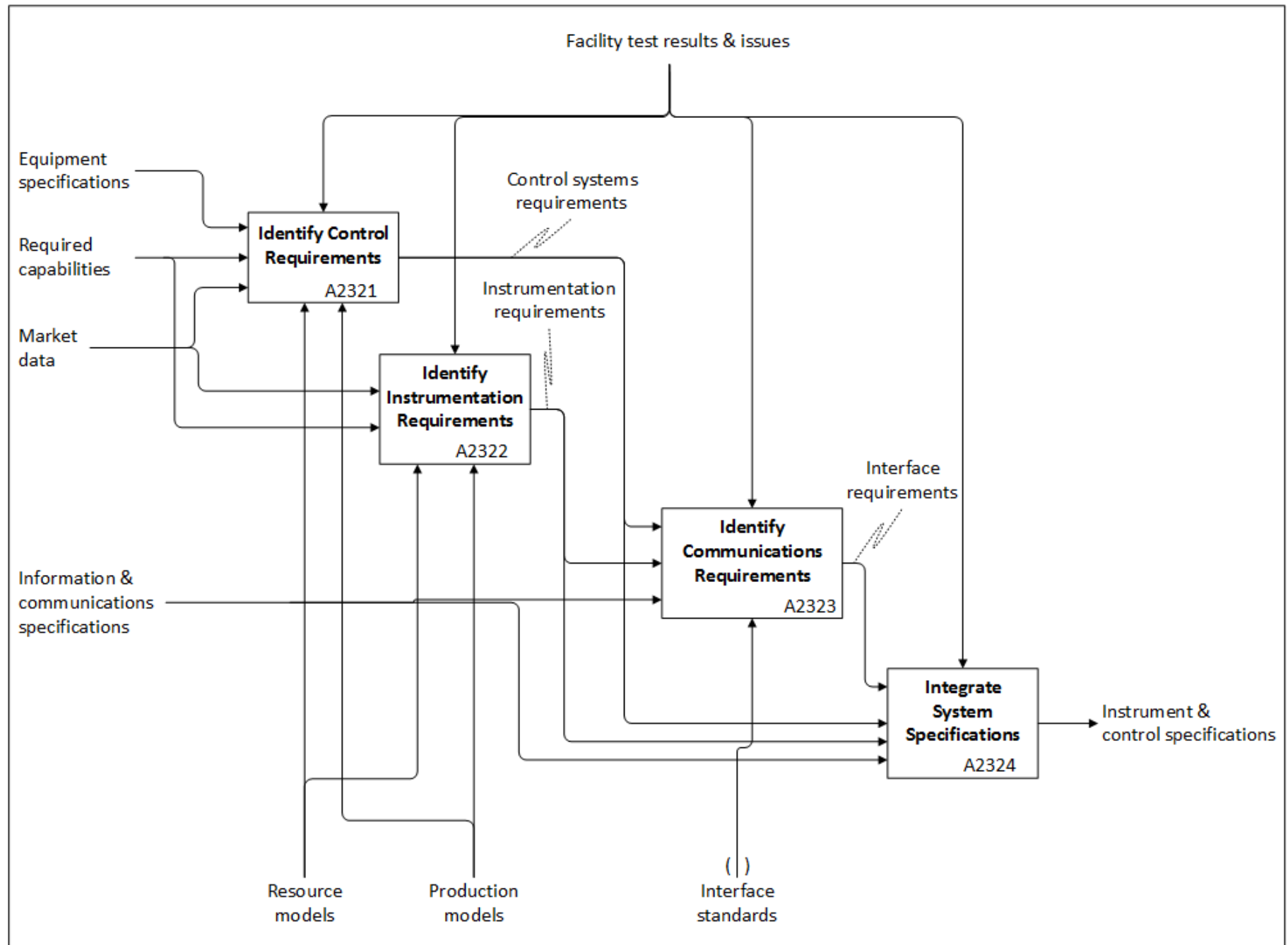
A234: Develop Facility Layout

Using the process and materials flow 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. Locate instrumentation and control systems. Identify cabling paths and shielding requirements; identify equipment paths, walkways, hazards and maintenance accesses. Design the floor plan 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 flow plan to improve performance.

A235: Integrate & Test System Designs

Combine the physical systems plant layout and the information system plant layout. After reviewing the space requirements and flow of materials and information, changes may be requested to either design.

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.

Facility test results & issues

Equipment specifications

Required capabilities

Market data

Identify Control Requirements

A2321

Control systems requirements

Instrumentation requirements

Identify Instrumentation Requirements

A2322

Information & communications specifications

Identify Communications Requirements

A2323

Interface requirements

Integrate System Specifications

A2324

Instrument & control specifications

Resource models

Production models

Interface standards

| NODE: | A232 | TITLE: | Specify Instrumentation & Control Systems | NO.: | 6 |

A232: Specify Instrumentation & Control Systems

Specify configurations of controllers for automated and semi-automated manufacturing systems and material handling systems. Specify the data acquisition instruments that are necessary for maintaining process continuity and product quality. Specify supporting communications requirements.

A2321: Identify Control Requirements

For the given processing equipment, material handling, and other support systems, specify the requirements for equipment controllers and station/group/line control systems. Specify required capabilities of controllers in terms of features, interfaces, supported languages and data forms, process simulation capabilities, among others.

A2322: Identify Instrumentation Requirements

For the given processes, physical routings, and quality control requirements, specify required instrumentation and logical or physical placement of measurement devices. Specify required instrument configurations and interface capabilities. Identify data rates and communications requirements.
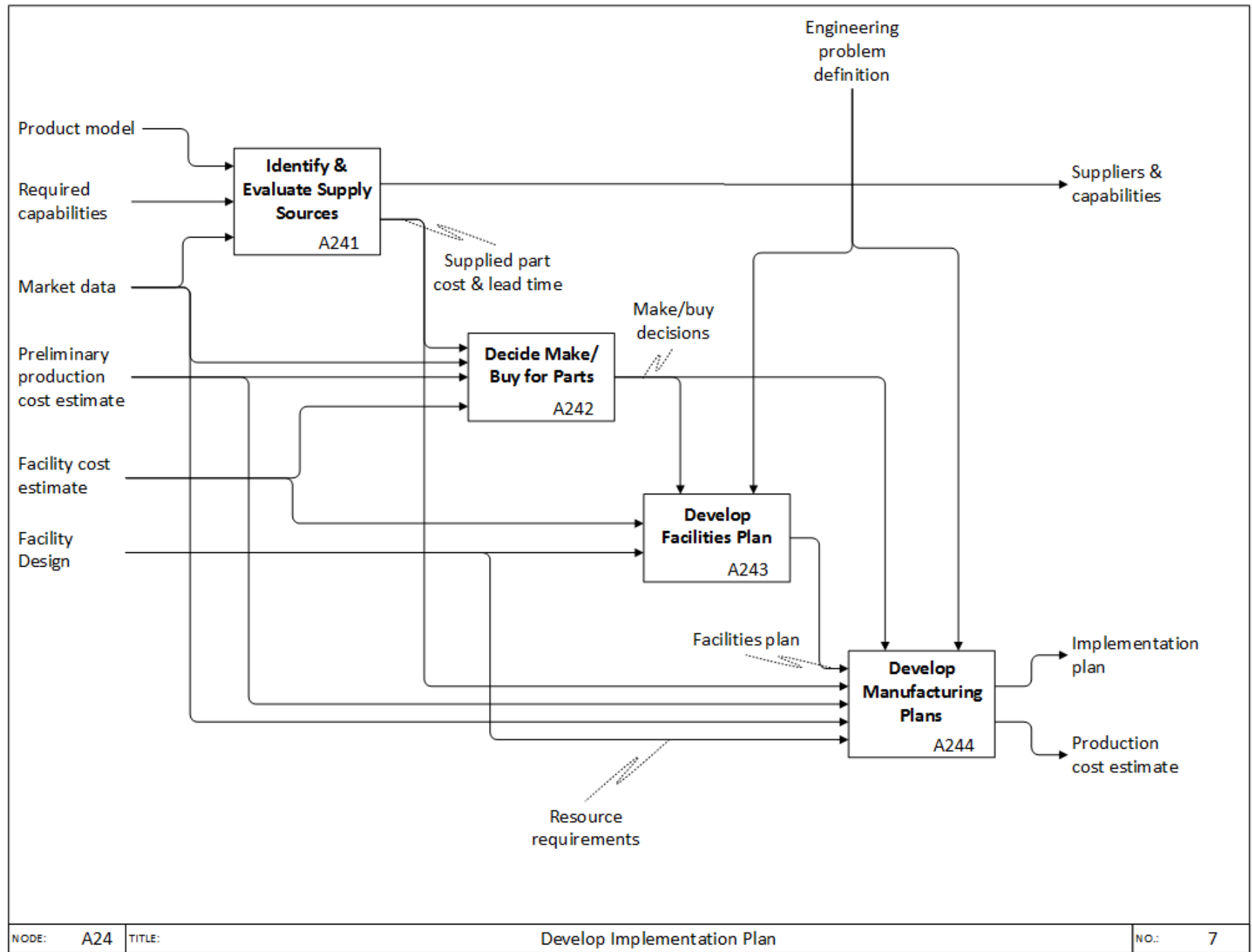
A2323: Identify Communications Requirements

For the given controllers, instrumentation systems, and supporting information systems, design the communications system, including the physical network, the physical and logical connections for all systems and appliances. Specify the software interfaces to be used for the logical communications between systems.

A2324: Integrate System Specifications

Design the integrated instrumentation and control network(s) for the production system. Specify links between instrumentation and control systems, and among instrumentation, control, and safety systems. Specify links between factory floor systems and supporting information systems. Simulate and test the communications system for the production facility, and revise component specifications as needed.

Engineering problem definition

Product model

Identify & Evaluate Supply Sources

A241

Required capabilities

Market data

Suppliers & capabilities

Supplied part cost & lead time

Make/buy decisions

Preliminary production cost estimate

Decide Make/ Buy for Parts

A242

Facility cost estimate

Facility Design

Develop Facilities Plan

A243

Facilities plan

Develop Manufacturing Plans

A244

Implementation plan

Production cost estimate

Resource requirements

| NODE: | A24 | TITLE: | Develop Implementation Plan | NO.: | 7 |

A24: Develop Implementation Plan

When a satisfactory manufacturing process sequence has been identified, and corresponding facility additions and modifications, if any, have been identified, the "make" cost basis for make/buy decisions is available. For parts and subsystems that may be externally supplied, develop the comparable "buy" estimates of cost and lead time, and decide make/buy subsystem by subsystem.

In general, this process will interact with the Process and System Design activities, as the manufacturing engineering activities move down the assembly tree.

Create detailed plans and budgets for performing any required, major, facility modifications. For those "make" activities that require lesser configuration changes, determine sources and lead times for tooling and fixtures, and plan the reconfiguration activities. For those parts/subsystems to be bought, identify suppliers, lead times, and required inventories.

Construct the overall plan for the product as a combination of "make" and "buy" components, facilities construction, and reconfiguration. Determine a target manufacturing start date and a schedule for prior events. Provide the related budgets and cost estimates.

A241: Identify and Evaluate Supply Sources

For parts and subsystems that may be externally supplied, identify potential suppliers. Determine ability of suppliers to meet predicted order volumes. Identify part cost and lead times. Evaluate potential suppliers according to organization-specific evaluation criteria, which may include supplier viability, software systems compatibility, and other factors. Based on these evaluations, develop the "buy" cost estimates for each part.

Similarly, for required tooling and fixtures that are not currently available, identify supply sources.

A242: Decide Make/Buy for Parts

Based on supplied part-cost estimates, and production cost estimates for making the parts, make the make/buy decision for each part. This decision causes a split in the further functions for providing each part.
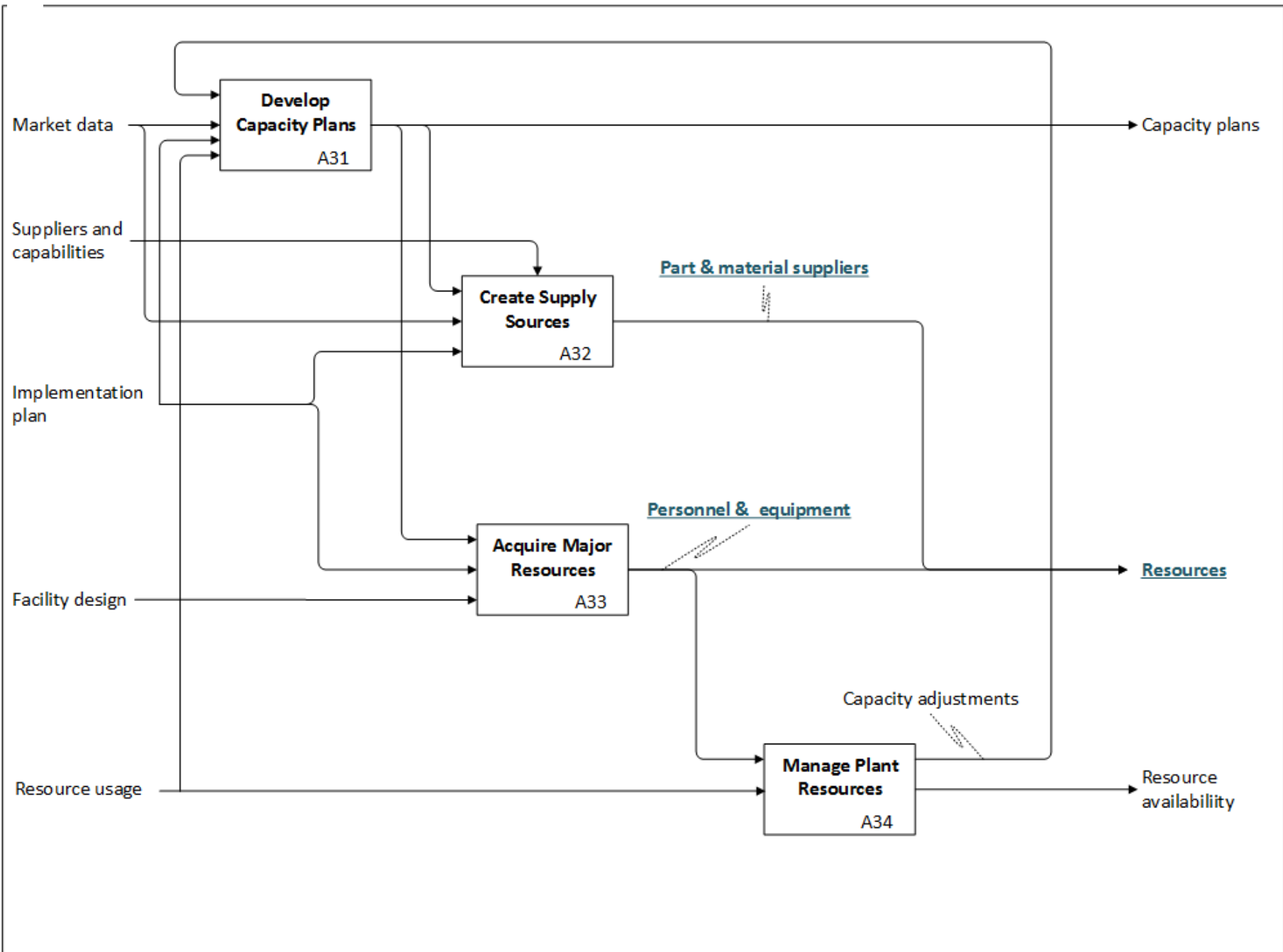
Also, decide make/buy for additional tooling, fixtures, and carriers that are required for the product manufacture.

A243: Develop Facilities Plan

For those parts/subsystems that are to be made, if major facility construction or modification is necessary, create the detailed plans, develop budgets for the components of the plan, and final cost estimates for the reengineered facility.

A244: Develop Manufacturing Plan

Complete the overall plan for the product, including the facilities reengineering plan and/or minor changes to station or line configurations for the set of parts to be made and for the final product. Given supplier lead times for parts, tooling, and materials, estimate required inventory sizes and order volumes. Provide a target schedule for manufacturing start. Refine production cost estimates, and create a budget for startup activities.

Market data → **Develop Capacity Plans** A31 → Capacity plans

Suppliers and capabilities

Create Supply Sources A32

Part & material suppliers

Implementation plan

Acquire Major Resources A33

Personnel & equipment

Facility design

Resources

Capacity adjustments

Manage Plant Resources A34

Resource usage → Resource availability

| NODE: | A3 | TITLE: | Provide Production Resources | NO.: | 8 |

A3:   Provide Production Resources

Using customer orders and projected demand for the products of the facility, specify the required resource levels for the facility, create the corresponding resources – plant, equipment, and workforce – and, maintain the required resource levels. Acquire and maintain equipment. Maintain workforce levels and skills. Provide and maintain physical plant, grounds, and utilities. Monitor resource utilization and cost. Create and maintain contractual relationships with suppliers that will provide the required volumes of parts, tooling, and services. Manage the implementation of major facility redevelopment plans, and oversee commissioning of new and reengineered facilities.

A31: Develop Capacity Plans

Using market projections, customer order experience, and, the production resource requirements for the products from their manufacturing plans, determine the manufacturing resource levels that will be required in order to meet the overall expected demand on the factory. This includes workforce personnel and skills, equipment and tooling, and plant utilities. As customer order experience is acquired and actual production schedules appear, the actual used and unused capacity, and the actual product yields, are monitored and used to update the long-term projections.

A32: Create Supply Sources

Using market projections for planned products, estimate order volumes for component parts, materials, and other production materials and tooling. From the identified potential suppliers and experience with them, develop preferred supplier lists. Create supply contracts covering the projected volumes for some period of time.
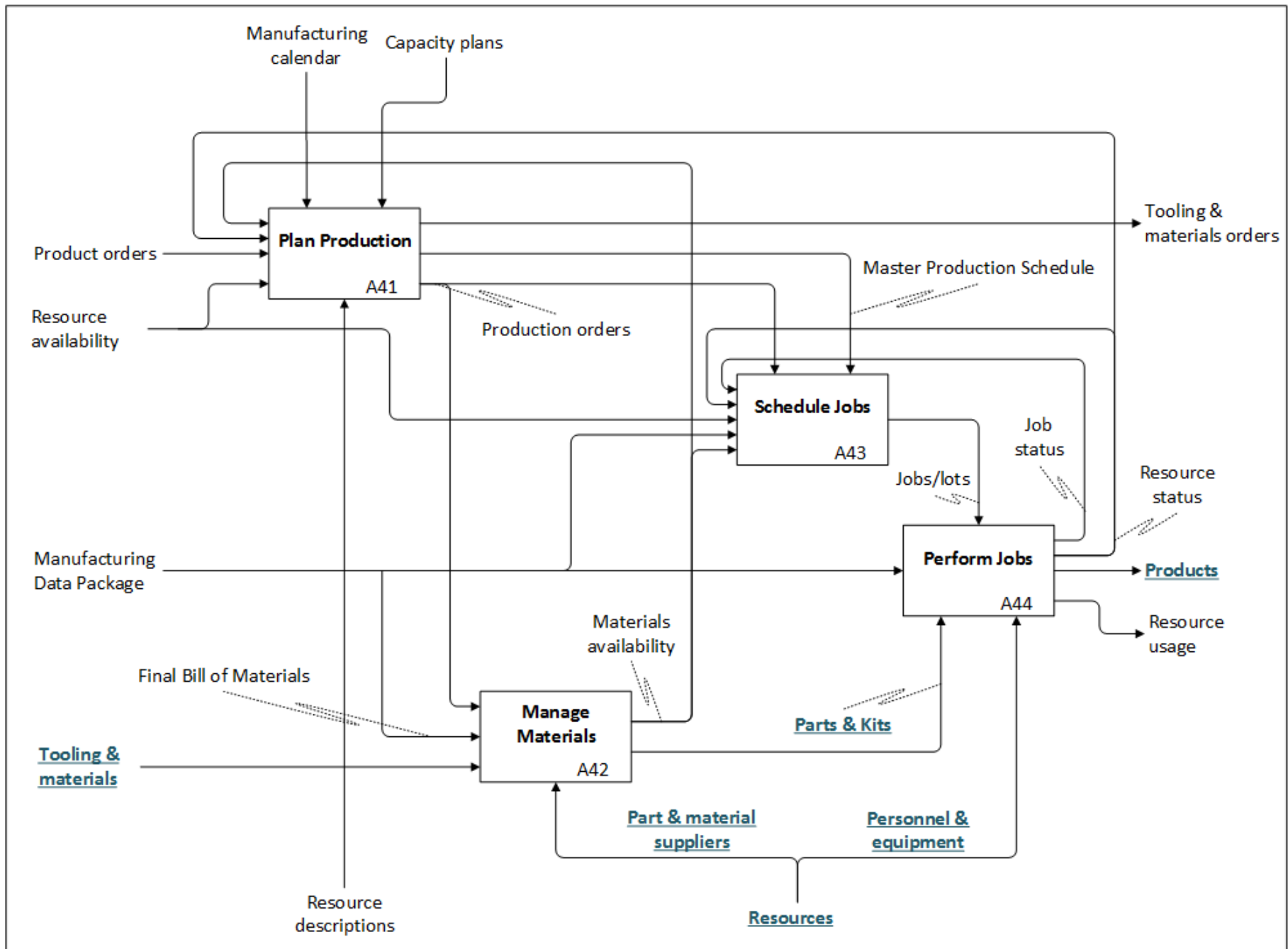
A33: Acquire Major Resources

According to the identified capacity requirements, maintain the projected workforce levels and operating shifts. Manage activation and mothballing of major plant lines and stations. Create equipment and plant maintenance contracts as needed.

In those cases where major facility modifications are needed, acquire the major equipment items, and implement the facility development plans. (In most cases, this activity is contracted to a plant construction firm.) Schedule and oversee commissioning of the new or reengineered facility.

A34: Manage Plant Resources

Allocate workforce personnel, monitor work hours and assignments, and, maintain workforce skills and certifications. Maintain major and minor equipment items per schedules and as needed. Maintain plant services and utilities. Monitor health and safety systems and performance data. Track workforce and equipment utilization. Identify problems that have longer-term impacts on production capacity, manage furloughs, and provide downtime estimates.

Manufacturing calendar

Capacity plans

Plan Production
A41

Product orders

Resource availability

Tooling & materials orders

Master Production Schedule

Production orders

Schedule Jobs
A43

Job status

Jobs/lots

Resource status

Manufacturing Data Package

Perform Jobs
A44

Products

Resource usage

Materials availability

Final Bill of Materials

Manage Materials
A42

Parts & Kits

Tooling & materials

Part & material suppliers

Personnel & equipment

Resource descriptions

Resources

| NODE: | A4 | TITLE: | Produce Products | NO.: | 9 |

A4: Produce Products

Produce the parts and products according to the specifications in the corresponding Manufacturing Data Packages. 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, assigning human and machine resources to production activities, managing tooling and materials, tracking work-in-progress, job/lot completion, resource utilization, and product yield.

A41: Plan Production

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. Create and coordinate the production orders for the Parts that 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. Monitor completion of production orders and part/product output volumes.

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

A42: Manage Materials

Manage materials, tools, fixtures, and part inventories. Track orders, receipt, assignment, location, and use of tooling and materials. Test and inspect incoming materials. Prepare tooling and fixture assemblies according to specification. Prepare parts and materials in the proper quantities and combinations for jobs/lots. Prepare tooling and materials kits. Decommission used tooling. Recapture and process reusable and recyclable materials.
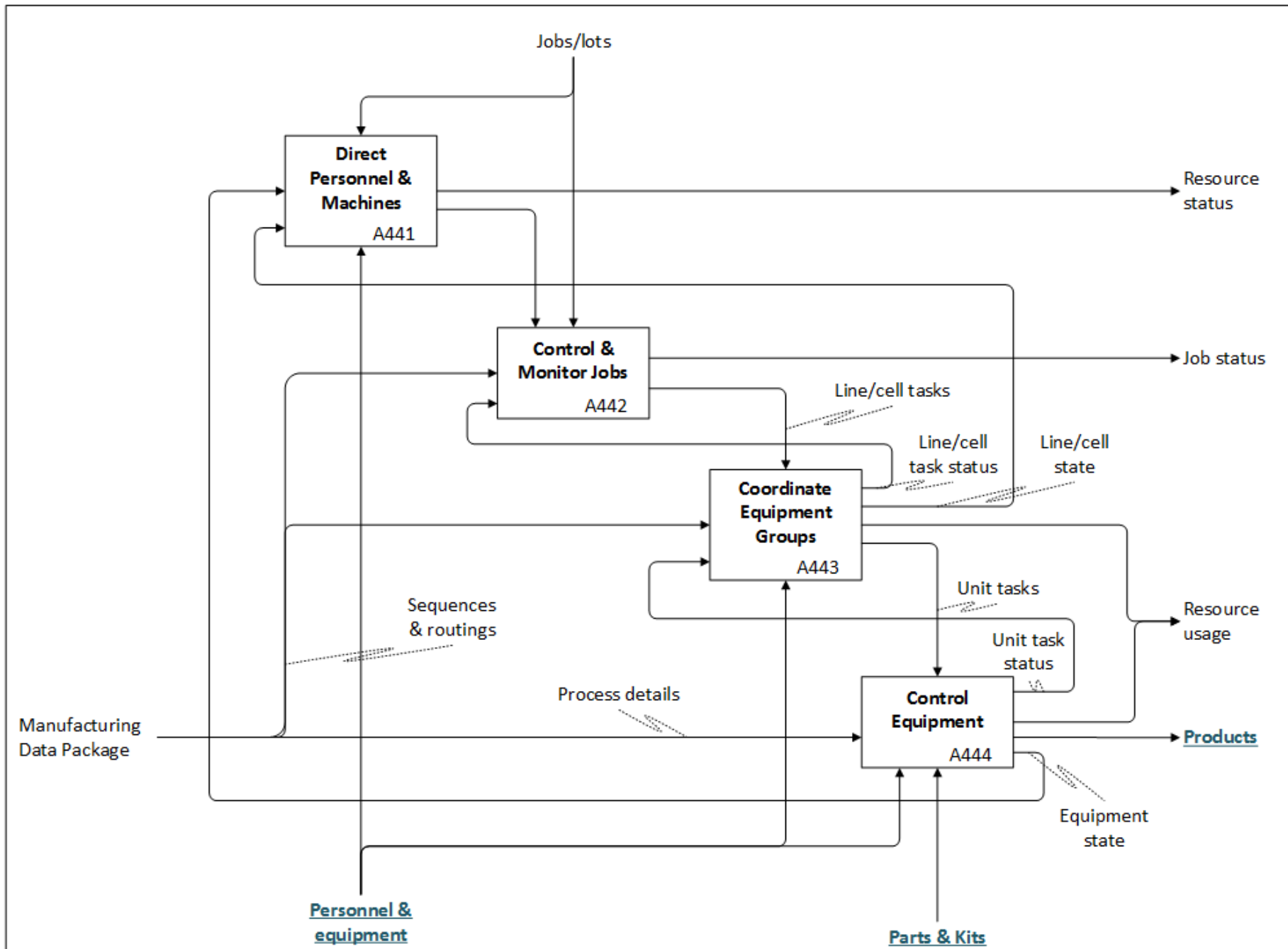
A43: Schedule Jobs

Decompose production orders into manageable lots and jobs for the factory floor. Schedule job/lot preparations and starts. For facilities in which dynamic routing of work-in-process ("product") to manufacturing stations is the norm, define the assignment and schedule for each job/lot to each station. Monitor job/lot progress and completion. Monitor rework and other processing exceptions. Monitor yield, and create additional lots when needed.

A44: Perform Jobs

Implement the production schedule. Assign qualified personnel to stations as required by scheduled activities. Identify human and equipment resource shortages and specify overtime requirements required to meet production schedules. Monitor performance of personnel and equipment, diagnose problems, and take corrective actions. Determine equipment status and failures.

Produce the parts and products according to the detailed specifications in the Manufacturing Data Package. Execute the fabrication, assembly and inspection operations, and/or control the equipment that performs them. Control and monitor the parameters of the processes. Capture and store product measurements and process measurements. Monitor the time-on-task and time-in-service for equipment and tooling. Identify problems and anomalous behavior.

Jobs/lots

Direct Personnel & Machines

A441

Resource status

Control & Monitor Jobs

A442

Job status

Line/cell tasks

Line/cell task status

Line/cell state

Coordinate Equipment Groups

A443

Unit tasks

Resource usage

Unit task status

Sequences & routings

Process details

Manufacturing Data Package

Control Equipment

A444

Products

Equipment state

Personnel & equipment

Parts & Kits

NODE: A44	TITLE:	Perform Jobs	NO.: 10

A44:   Perform Jobs

Implement the job schedule: start lots, perform the fabrication, assembly and inspection operations, move product-in-work, track lot 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.

A441: 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. Report unplanned resource outages (workforce shortage, equipment downtime, inventory shortages), and develop interim plans to minimize impact on production schedules.

A442: Control and Monitor Jobs

Implement the production schedule. Direct job/lot starts. Direct routing of lots to processing and inspection stations. Direct flows of materials and tooling onto the factory floor. Track lots and workpiece status and monitor job status against schedule. Make dynamic adjustments to schedules and priorities.

A443: Coordinate Equipment Groups

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

A444: Control Equipment

Per the detailed process specifications in the Manufacturing Data Package for the product, execute the fabrication, assembly and inspection operations and/or control the equipment that 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.

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. It also includes the physical objects represented as flows in bold face with underscores in the diagrams. Each flow name below is followed by a parenthesized list of numbers of the diagrams where the flow appears. The flow descriptions 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. In this section, the notations:

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 (underscored) indicates that X represents physical objects, not information objects.

Capacity adjustments *(diagram 8)*

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

Capacity plans *(diagrams 2, 8, & 9)*

Nominal aggregate quantities of human and machine resources that are to be made available and committed to projected production operations during specific planning periods.

Component catalogs *(diagrams 1, 2, & 4)*

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

Control system requirements *(diagram 6)*

Specification of the control systems required for automated equipment, including both processing equipment and material handling equipment. Requirements include control capabilities, survivability, support for specific standards, and software. Specifications include identification of make and model of controller, configurations, features, processing options, and communication options.

Design BOM *(diagrams 2, 3, & 4)*

The Bill of Materials for a product, as identified by the product design team. This Bill of Materials calls out the parts needed to make up an assembly, or for a fabricated part, including a compound or alloy or a family of compounds or alloys. Alternatively, it may include "product data sheets" providing required part characteristics for selection from a number of supplier catalogs. The relationship to the Final Bill of Materials in the Manufacturing Data Package is very much dependent on the manufacturing engineering process, which will select specific parts and materials from specific supply sources that may or may not be exactly what was requested in the Design BOM.

Engineering problem definition *(diagrams 3, 4, 5, & 7)*

The specification of the production systems engineering problem, beginning with the type of the engineering activity, one of:

- Process specification: Define the set of processes, resources, and materials that is needed to produce a certain volume of a given product or product line, possibly limited to existing facilities
- Micro-planning: Define the routing of the product workpieces through a sequence of processing equipment stations, together with the configuration of processing equipment stations that enables such a routing to produce the desired parts, and appropriate operator and machine instructions for each station
- Re-design: Specify the reconfiguration of a part of a plant that will enable the production of the desired parts, by reorganization, reconfiguration, and replacement of processing stations and materials flow systems.
- Plant design: Specify the development of a new plant, or a "from the walls" reconstruction of an existing facility to enable the production of a target product or product line.

The specification includes the scope of the design, the product mix, and the production requirements in terms of part and product volumes, and quality considerations. For design activities, it also includes the physical plant or area to be used, and the time available for design, acquisition, and construction. It may also include identification of other products and facilities from which design ideas and performance expectations can be drawn.

Equipment specifications *(diagrams 5 & 6)*

Specifications for the kind and quantity of processing machines, equipment, and facilities. Equipment may be specified as make, model and configuration, or by its required capabilities. In the latter case, the requirements are derived from its role in the process of making instances of the product family, and the characteristics of the product-in-work in that phase of the processing.

Equipment state *(diagram 10)*

Report of current state of a major equipment item or station. This includes 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, and employee x out on sick leave.

Facilities plan *(diagram 7)*

The detailed plan for creating or revamping the manufacturing facility for some mix or family of products. This includes equipment acquisitions, staffing, installation schedules, and budgets for the components of the plan.

Facility cost estimate *(diagrams 3 & 7)*

Estimates of the total cost of (re)building the facility according to the plan, including plant, utilities, equipment and tooling, installation, training, etc.

Facility design *(diagrams 2, 3, 5, 7, & 8)*

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, and transport systems and routings. This includes both drawings and functional specifications, that is, models of the facility from various points of view.

Facility test results & issues *(diagrams 5 & 6)*

Results of modeling and test of the Facility design, interpreted as issues for the various production systems design activities.

Final Bill of Materials (Manufacturing Data Package) *(diagram 9)*

The complete Bill of Materials for the Part/Product in exploded form, with quantities of all materials needed for some lot size of the Part. This may include any special materials that will be consumed in the process of making the Part lot. Examples include temporary fasteners, spacers, lubricants, coolants, adhesives, etc., depending on how the lot is "kitted" when it is started. (Alternatively, consumables may be included in some aggregate form as part of operating requirements (or tooling) for processing stations.)

Flow details (Manufacturing Data Package) *(diagram 4)*

The specification for the sequence of processes for a product lot, and the flow of the product-in-work from process to process. This, includes any special requirements for handling the product through the transition. This is sometimes called the "routing". For variants of a product, this can include alternative routings that bypass processes or route the lot to variant-specific processes. For components and materials added to a product-in-work, this specification also identifies the point at which these additional materials enter the process, and any associated handling requirements for them.

Handling capabilities (Required capabilities) *(diagram 4)*

Required capabilities for holding, mounting, moving, and positioning materials, components, and product lots in work. Important concerns are loads, volumes, shapes, and resistance to specific torques that will be applied during processes.

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

Implementation plan *(diagrams 2, 3, 7, & 8)*

The overall plan for producing the product. It includes facility construction and modifications, if any, and selections of equipment, or types of equipment. It also includes equipment configurations for implementing the production processes, together with required operations personnel, skills, and certifications. It specifies parts to be supplied externally, with candidate suppliers and part volumes, and parts to be made in-house together with their implementation plans.

Information & communications specifications (Support systems specifications) *(diagrams 5 & 6)*

Specifications for interface to the plant information and communications systems, as appropriate to control and instrumentation systems on the factory floor. This is the means for transmitting control programs and parameters, lot setups and routings, and similar information from the planning and scheduling systems to the control systems. It may also be the means of recording process and lot "run" data and equipment performance data. It may also be the means by which equipment and instrumentation on the floor communicates active status to unspecified observers and analytical processes.

Instrument & control specifications *(diagrams 5 & 6)*

The complete package of specifications for control and instrumentation systems in the new or revised facility. It includes identification of make and model of controller and instrument data centers, configurations, features, processing options, and communication options. Similarly, it includes make and

31

model of instruments and sensors, connections to data centers, control systems, or plant information systems, physical mounting on machines or stations, or logical or physical placement on the process line.

Instrumentation requirements *(diagram 6)*

Requirements for acquiring data – measurements and state determinations – about the product-in-work, which is used to activate machines or processes, modify control parameters, route items, measure quality, and measure performance. Some of these requirements may be met by equipment that is a (possibly optional) feature of a controller or machine. Most are met by instruments whose sole purpose is to make and communicate such measurements. These requirements are often stated in terms of the characteristics of such instruments and their placement in the process sequence. This may include bar code and RFID readers, motion and intrusion detectors, dimensional measuring devices, thermal measurement devices, pressure sensors, and so on.

Interface requirements *(diagram 6)*

Specifications for required interactions among control systems, instrumentation systems, and facility information systems, and for the communications that enable those interactions. The standard form is a "layer cake" of interface specifications, with physical connection and signaling at the bottom, some software/hardware mechanisms that ensure reliable transmissions of data above it, and finally higher-level protocols that provide access to specific functions and information sets. Most of these details are specified in terms of interface standards.

Interface standards *(diagrams 1 & 6)*

Well-defined and widely implemented specifications for mechanisms used at various levels of interface between communicating software/hardware information systems. These include diverse standards (alternate mechanisms) for physical connection and signaling, for reliable transmissions of using them, for higher-level protocols that provide access to specific functions and information sets, and for data representation forms and structures.

Jobs/lots *(diagrams 9 & 10)*

A job is a requirement to manufacture some number of instances (a *lot*) 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 that defines the sequence of steps required to make the lot, where each *step* requires a different major processing resource -- a different kind of equipment or a different equipment configuration. The first step of a job is always the preparation of the base materials needed to make the lot, and the direction to take that step is referred to as the 'start' of the job/lot. How the remaining steps in the Job are taken is very much dependent on the nature of the product, the structure of the facility, and the operations practices.

Job status *(diagrams 9 and 10)*

Report of the state of all scheduled jobs and the corresponding product lots. 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 rescheduled.

Line/cell state *(diagram 10)*

Report of current state of an assembly line or group manufacturing cell. The primary state information is the ability of the line/cell to operate, whether at capacity or at reduced capacity; and, if it is currently not operational, whether the problem is temporary or longer term. Detailed state information could include

the status reports for line/cell components.

Line/cell tasks *(diagram 10)*

Commands to a line controller or group cell controller to add a particular job, step, or step sequence to its list of things to be done, together with priority and possibly a due date/time. For a line controller, this is effectively the job start, but after initial materials preparation and delivery. In a primarily human station, this is often implied by the arrival of a lot of workpieces at the station and detailed in the "traveler" papers that accompany it.

Line/cell task status *(diagram 10)*

Reports from a line or cell controller, or a workstation on the status of a Line/cell Task assignment. This includes not only 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.

Major processes *(diagram 4)*

Specifications for the operations that create the major changes in the product-in-work from the base materials to the final product. This includes fabrication and assembly, and inspection operations, which influence the final disposition of the product. Major processes are distinguished by 1) the use of different kinds of equipment with different capabilities, or by 2) significantly different setups for the machines, or by 3) significantly different skill requirements. In general, major processes are characterized by the type of equipment and skills required, and any special features that are critical to the selection of equipment, configuration, and operator.

Make/buy decisions *(diagram 7)*

For each component part of a product, and sometimes for fixtures and tooling for the product-in-work, the decision as to whether it will be procured from a supplier ("buy") or assembled or fabricated in-house, either in the same facility or a sister facility ("make"). Many such decisions are made on the basis of organizational policy or availability in catalogs. Others are made-to-order and require a comparison of in-house capability, resource availability, and cost with supplier capability, quality, responsiveness, and cost.

Manufacturing calendar *(diagrams 1, 2, & 9)*

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

Manufacturing capabilities *(diagrams 3, 4, & 5)*

The actual manufacturing capabilities that will be created by a production facility that meets the current facility design. In theory, this should include the "required capabilities" created by the current proposed process designs for the product(s). But, it may be somewhat different because of feasibility or cost limitations, and may then be interpreted as a constraint on the process design.

Manufacturing Data Package *(diagrams 2, 3, 4, 9, & 10)*

The complete specifications for the manufacture of a given lot size of the Part: the complete list of base materials or components from which it is to be made (Required materials), and the materials preparation and pre-positioning requirements, if any; the sequence of processes on the product-in-work and the corresponding major equipment, either by station or by type, together with configuration and tooling specifications; the required configurations of (and fixtures for) the handling and transport equipment; the detailed specifications for the automated operations -- control programs and parameters; and the detailed instructions for human operators.

The various elements of the Manufacturing Data Package are developed by different activities at different times, and the corresponding subsets are called out in the diagrams in Section 1 and separately documented in this section.

Market data *(diagrams 1, 2, 3, 4, 5, 6, 7, & 8)*

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 *(diagram 9)*

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

Material specifications (Product model) *(diagram 4)*

The required raw material for fabrication of a part or the list of nominal components for an assembly, as specified by the product design. This is an input to a manufacturing engineering process that determines the material requirements for the manufacturing processes.

Materials availability *(diagram 9)*

Actual and anticipated inventory levels for raw materials, parts, and tooling for the near term. This is up-to-date materials inventory information from the materials management activities, used in production planning and scheduling.

Part & material suppliers (Resources) *(diagrams 8 & 9)*

Contracted suppliers for the parts and materials that are to be "bought" as components of the product(s) to be manufactured. They may be supply catalog items, manufacturing services, or made-to-order items. There is accompanying information containing supplier evaluations, related catalog entries, costs, and lead times.

Parts & kits *(diagram 10)*

Physical component parts of a product (assembly) or raw materials for a fabricated product, provided from materials inventory to the factory floor. A *kit* is a structured collection of parts, and, possibly, tooling or consumables, that is the set of materials for a product lot. Parts going to the factory floor are usually *kitted* (packaged or fixtured in some transport device) at a materials preparation station, which is sometimes considered the first step in a lot start. But some parts and kits are prepositioned at, or separately fed into, manufacturing stations where they are processed into the product.

Patents & design constraints *(diagrams 1 & 2)*

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

Personnel & equipment (Resources) *(diagrams 8, 9, & 10)*

The major in-house resources available for manufacturing the product and any parts to be made within the facility – primarily the workforce and the major equipment.

Physical models *(diagrams 2, 3, 4, & 5)*

Non-functional models of parts and subsystems made by rapid (and other) prototyping processes, for the purposes of presentation, engineering analysis, and manufacturing engineering.

Preliminary production cost estimate *(diagrams 3, 4, & 7)*

An estimate of the per-lot cost of manufacturing the product based on the specification for the processes, and using standard reference costs for expected resource utilization. cf. Production cost estimate.

Process capabilities (Required capabilities) *(diagram 4)*

The major processes needed for the manufacture of the parts and products, and any special process requirements, such as ability to process specific materials, deal with unusual sizes and shapes, or maintain certain tolerances. It may also include identification of the principal processing equipment characteristics and specific skills requirements for human resources performing those processes.

This represents one side of ongoing interchanges among process engineering and facilities engineering activities, with the consequence that the process definition is in varying degrees of detail at different times. The other side of the interchange is the "Manufacturing capabilities" of planned and available equipment.

Process details (Manufacturing Data Package) *(diagrams 4 & 10)*

The detailed specifications for the individual processes involved in the manufacture of a given lot size of the product, and for the processing stations that will perform those processes. The basic specification is a sequence of processes to be implemented by specific equipment stations or types. The detailed specifications elaborate each of those processes.

For the equipment, this includes the type and configuration/setup, the required tooling at the station, and any special concerns. For any human operators, it will identify required skills and certifications. It will also identify any incoming or prepositioned parts and materials that are added at the station. For the process, it may identify a standard process or a specific control program, together with the (nominal) control parameters. In addition, it may provide an operations sequence for human operators in the form of operator instructions.

Process models *(diagrams 1, 2, 3, & 4)*

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.

Product Library *(diagrams 1 & 2)*

(Also called a Design Library) The specifications for products that have been previously designed by the organization. It serves as a basis for new designs that are similar in structure or have similar features, and may also be similar in their manufacturing requirements.

Product model *(diagrams 2, 3, 4, 5, & 7)*

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

For parts to be fabricated:
- materials of which the component is made
- component dimensions, geometry and topology
- surface finish (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

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- 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 orders *(diagrams 1, 2, & 9)*

Quantities of specific products to be produced by the facility, usually with nominal delivery dates, as specified by enterprise sources external to the manufacturing activities. The relationship between these and the orders placed by actual customers is dependent on business decisions.

Production cost estimate *(diagrams 1, 2, 3, & 7)*

Best estimates of the cost of manufacturing the products and their components, taking into account use of manufacturing equipment and skilled labor, cost of materials and supplied parts, plus tooling, consumables, handling and in-work transportation costs, 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 models *(diagrams 1, 2, 3, 5, & 6)*

The body of knowledge available about 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.

Production orders *(diagram 9)*

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 product/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.

Products *(diagrams 1, 2, 9, & 10)*

The physical end products of the manufacturing processes, some of which are "final products" provided to external customers.

Required capabilities *(diagrams 3, 4, 5, 6, & 7)*

A specification of the processing and handling capabilities that are required for the manufacture of a given product or product family. It includes the basic processing capabilities, and also unusual features or quality requirements that distinguish resources that can be used for the manufacturing tasks. The capabilities may be stated in terms of standard processes and process parameters, or in types of machines, tooling, and tolerances, and/or in terms of workforce skills and certifications.

Required materials (Manufacturing Data Package) *(diagram 4)*

The complete list of materials with quantities needed to produce a particular Part or Product. This list may include base materials, components, and consumables such as fasteners, adhesives, lubricants, coolants, and coatings.

Resource availability *(diagrams 2, 8, & 9)*

The equipment and personnel to be considered available in the target manufacturing facility over some specified time periods when planning and scheduling the production processes for a given product. It may include 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.

Resource descriptions *(diagrams 1, 2, 3, 5, & 9)*

Technical descriptions of the manufacturing resources that the engineer may have available for the production of the product. There are several important subtypes: Machine descriptions, tooling descriptions, and human resource descriptions (Skills pool).

Resource status *(diagrams 9 and 10)*

Reports of current status 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, among others. The summary of this report is the ratio of active production capacity to planned production capacity.

Resource requirements (Facility design) *(diagram 7)*

An excerpt from the Facility design that identifies the major equipment resources to be acquired or allocated and possibly reconfigured, along with any specialized structural elements, tooling, handling devices, and maintenance equipment, and required personnel, skills and certifications.

Resource usage *(diagrams 2, 8, 9, and 10)*

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 asset utilization and cost reporting.

Resources *(diagrams 2, 8, & 9)*

The physical resources available for manufacturing activities: personnel, equipment, tooling and fixtures, materials, the plant and its utilities.

Sequences & routings (Manufacturing Data Package) *(diagrams 3, 5, & 10)*

The sequence of operations needed to transform base materials and/or component parts into a product lot and ensure the quality of the individual products in the lot. This includes specification of the sequence of station (types) to be visited, including both processing stations and inspection stations, and the processes to be performed at each station. This is sometimes called the "macro" process plan.

Supplied part cost & lead time *(diagram 7)*

For a given part/component of a product, a nominal cost of acquiring it from suppliers, and an estimated lead time between order placement and part delivery. This typically represents a weighted average of

quotations from multiple potential suppliers.

Suppliers & capabilities *(diagram 2, 3, 7, & 8)*

Identification of a set of potential suppliers for a specific set of parts, materials, or tooling, accompanied by 1) a description of their relevant manufacturing capabilities and limitations and 2) evaluations of capacity, performance, quality, cost, lead time, etc., based on prior or market experience. The set is usually an ordered list, with preferred suppliers at the top.

Support systems specifications *(diagram 5)*

Specifications for plant systems that are critical to manufacturing processes but not directly involved in them. This includes plant utilities (power, water, HVAC), communications systems, information systems, safety systems, and maintenance facilities. It also includes several materials management facilities: receiving stations, storage and inventory systems, parts delivery systems and materials preparation stations, tool cribs, tool and kit building stations, and, product packaging and shipping stations. It may also include scrap, rework and materials recovery facilities.

Most of these would rarely be specified for anything other than a new or replacement plant design, but additions and modifications to the existing plant may be specified for the support of new or revamped cells and lines.

Time & cost data *(diagrams 1, 2, 3, & 4)*

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

Tooling & materials *(diagrams 1, 2, & 9)*

Physical objects — tooling and consumable materials, fixtures and carriers, stock materials and component parts — that must be present at the preparation and processing stations for the products to be made.

Tooling & materials orders *(diagram 9)*

Orders to suppliers for raw materials, off-the-shelf parts and tooling; orders for externally supplied fabricated parts and subsystems, made-to-order tooling and fixtures, etc.

Unit tasks *(diagram 10)*

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.

Unit task status *(diagram 10)*

Response from the controller to unit 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.

Acknowledgements

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Appendix A: Interpretation of IDEF0 Diagrams

The Smart Manufacturing functional models were developed using the formal methods and diagrammatic techniques defined by IDEF0 [7], 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 subsequent 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.

Information flows into and out of an activity must be accounted for in some level of its decomposition (typically in its immediate refinement); that is, the information must flow into or out of one or more of the activities in the decomposition. Similarly, typically, 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.

There are, however, cases where a flow may not be used directly for one or more levels of refinement. These cases are supported in IDEF0 by what are called *tunneled arrows*. Flows that will not appear in the immediate refinement of an activity are indicated in IDEF0 as tunneled using a parenthesis where the arrow contacts the activity box. The refinement in which a tunneled flow emerges will have parenthesis at the unconnected end of the arrow, indicating to the reader of the diagram that the arrow will not be seen in the immediate parent of the decomposition in which it is shown. Any arrows with the parenthesis notation (i.e. at either end of a tunneled flow) are termed tunneled arrows.

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.

There are cases where only a subset of the data in a flow is used by an activity. These are shown in diagrams as subflows splitting off from the main flow and have labels describing the subset of the main flow they contain.

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, and materials needed to perform the task, but the emphasis in the Smart Manufacturing 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 are distinguished from other types of flows in the diagrams in this paper by their labels appearing in bold type with underscores.