

# **A Machining and Measurement Process Planning Activity Model for Manufacturing System Interoperability Analysis**

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## Table of Contents

<b>Abstract.....</b>	<b>1</b>
<b>1 Introduction.....</b>	<b>1</b>
<b>2. A Review of Machining and Measurement Process Planning Activity Models .....</b>	<b>4</b>
<b><i>2.1 Integrated Machining Process Planning Activity Model .....</i></b>	<b><i>4</i></b>
<b><i>2.2 STEP AP219, AP224, AP240 .....</i></b>	<b><i>4</i></b>
<b><i>2.3 High-level Inspection Process Planning Activity Model.....</i></b>	<b><i>5</i></b>
<b>3. An activity model for manufacturing system integration and interoperability analysis .....</b>	<b>6</b>
<b><i>3.1 Activity model .....</i></b>	<b><i>6</i></b>
<b><i>3.2 Detailed Process Planning Activity Model.....</i></b>	<b><i>10</i></b>
<b><i>3.3 Execution and Analysis and Reporting Activity Model.....</i></b>	<b><i>39</i></b>
<b><i>3.4 Glossary for the Data in the Activity Model.....</i></b>	<b><i>44</i></b>
<b>4. Conclusions.....</b>	<b>49</b>
<b>5. References:.....</b>	<b>51</b>

## Table of Figures

Figure 1: Information exchange between different manufacturing activities and software systems.....	2
Figure 2: A-0 level activity .....	8
Figure 3: A0 activities.....	9
Figure 4: A2 activity – machine-then-inspect process planning.....	12
Figure 5: A2’ activity – inspect-while-machining process planning.....	14
Figure 6: A21/A21’ activity – high-level machining process planning.....	18
Figure 7: A211/A211’ activity – machining feature sequence generation .....	20
Figure 8: A212/A212’ activity – machining operation generation.....	22
Figure 9: A23/A22’ activity – plan high-level measurement processes .....	24
Figure 10: A231/A221’ activity – determine measurement scope and accuracy requirement .....	26
Figure 11: A232/A222’ activity – determine dimensional measurement method.....	28
Figure 12: A22 activity – low-level machining process planning .....	30
Figure 13: A24 activity – low-level measurement process planning.....	32
Figure 14: A23’ activity – integrated machining and measurement process planning.....	34
Figure 15: A231’ activity – determine measurement features.....	36
Figure 16: A234’ activity – low-level measurement operation planning .....	38
Figure 17: A4 activity – execute production.....	41
Figure 18: A5 activity – analyze and report.....	43

# **A Machining and Measurement Process Planning Activity Model for Manufacturing System Interoperability Analysis**

## **Abstract**

Manufacturing systems consist of many activities. Each of these activities may include one or more software and hardware systems. In order to make these software and hardware systems interoperable, the data exchange and sharing among them must be seamless. One of the key issues that impedes achieving manufacturing interoperability is how to standardize data sharing and exchange. An activity model for machining and measurement process planning was developed at the National Institute of Standards and Technology to address the current information exchange situations and some of the barriers. This model represents functional activities in manufacturing systems with emphasis on process planning. Current standards and specifications for information exchange between different activities are identified. The purpose of this model is to provide a broad view for standard developers and industry experts to comprehend the common data flow between these activities and therefore to avoid multiple definitions for the same data.

**Key Words:** machining process planning, measurement process planning, activity modeling, interoperability analysis, standards harmonization

## **1 Introduction**

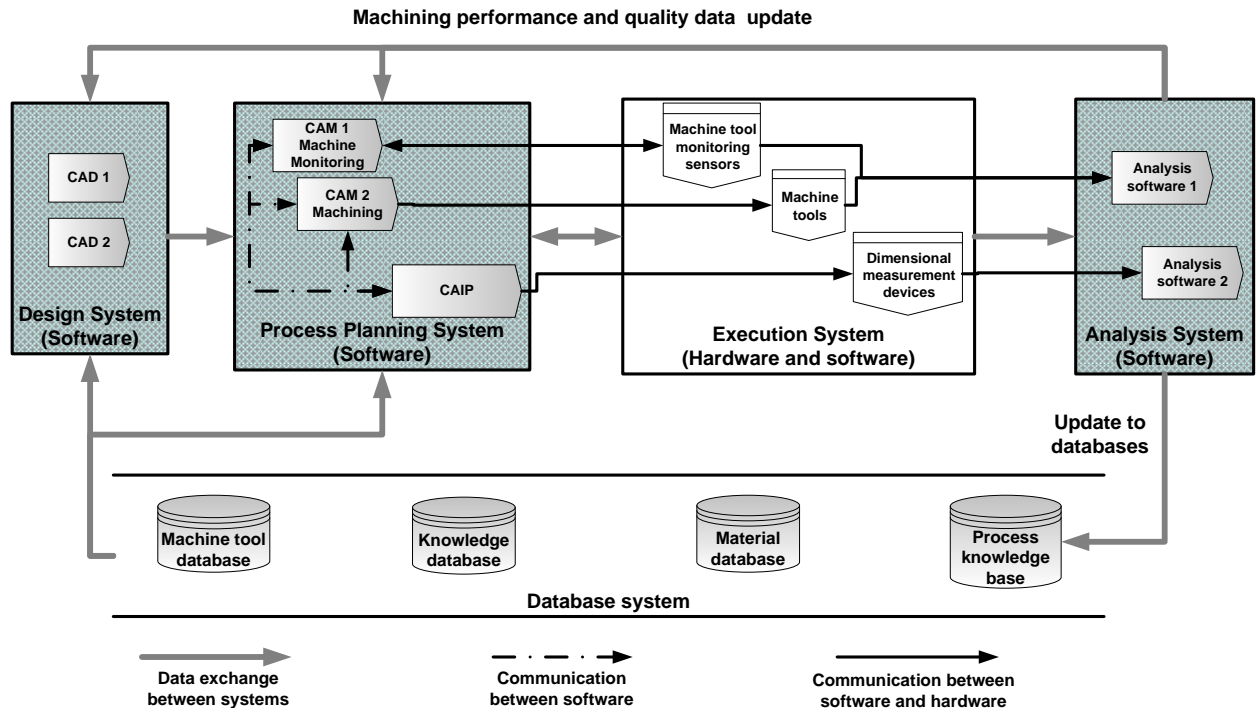
This document describes an IDEF0 (Integration Definition for Function Modeling) activity model of machining and measurement process planning for manufacturing system integration and interoperability analysis. To be of real value, this document, together with the IDEF0 diagrams, should not be static but should be subject to periodic review. Toward this end, all comments and criticisms are welcome.

Manufacturing processes consist of a broad range of activities covering many levels of functionalities in industry. These activities can be categorized into five main activities:

- design,
- process planning,
- production planning and scheduling,
- execution, and
- analysis and reporting.

Within each of these activities, multiple commercial software systems exist (shown in Figure 1). Some commercial software vendors offer products for multiple manufacturing

activities. The language of communication across the interfaces between these activities or between different software systems is typically proprietary. This proliferation of proprietary interface languages can be very costly to users, suppliers, vendors, and ultimately customers. This situation can be summarized as data incompatibility. An open, neutral, and extensible data model is an effective mechanism to resolve a data incompatibility problem. A data model describes the form, function and definition of all the pieces of information about specific applications. The data model also captures the relationship between pieces of information. In order to provide sharable data among commercial systems, the data should be available to all vendors in a neutral format that is not biased toward any particular product. In addition to openness and neutrality, the extensibility of the data model is also a requirement. An extensible data model can incorporate new data that meet future data needs. With an open, neutral, and extensible data model, data exchange and communication among manufacturing activities and software systems are possible.



**Figure 1: Information exchange between different manufacturing activities and software systems**

A “standard” is such an open and neutral data format that is unbiased and beneficial for both vendors and users. Industry mostly depends on standards organizations to establish and develop suitable standards or specifications for data exchange and system

communication<sup>1</sup>. There are many standards committees working on standardizing data exchange between different manufacturing activities. Each standard committee focuses on a certain manufacturing area. However, many data are shared between different manufacturing activities. If standard committees do not communicate with each other, the common data shared by multiple manufacturing activities are easily defined differently in different standards. In reality, lots of efforts in the standards community have been spent to harmonize data definitions across different standards. It is, therefore, important to provide a “big picture” for standards developers to avoid this situation. Information that needs to be presented in this “big picture” includes:

- how manufacturing activities interact with each other,
- what standards have been developed and/or are still under development, and
- what activities each standard intends to cover.

With this information, standards committees are able to figure out the common data shared by different manufacturing activities. If any of the data is modeled in existing standards, the data model can be inherited in new standards.

Developing an activity model is the first step towards the “big picture”. An activity model is a representation of the functions and data interface requirements for engineering processes (in this case for manufacturing processes). The activity model sets the context in which some data are exchanged between functions, and other data are shared by functions via data repositories. Activity modeling allows data modelers to capture prerequisite information for developing data models. This activity model identifies the major activities in manufacturing processes with its focus on process planning activity using IDEF0 notation. In this activity model, manufacturing processes are considered to be those that produce discrete or batch products (batches of discrete parts) using Computer Numerically Controlled (CNC) machines. As with any IDEF0 model, the application activity model is dependent on a particular viewpoint and purpose. The viewpoint of this activity modeling is that of a manufacturing engineer. The purpose of this activity modeling is to clarify activities involved in process planning and lay out existing standards and specifications for these activities.

Process planning is an essential link between design and production planning in the product development process. Traditional process planning can be categorized into machining process planning and measurement process planning<sup>2</sup>. These two systems are mostly isolated from each other since most of the measurements are carried out on CMMs which are physically isolated from machining. However, with emerging new

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<sup>1</sup> Very often proprietary data formats were developed in industry for emerging technologies first. When standardization for some data formats becomes needed, standard organizations collaborate with industry to develop suitable standards/specifications.

<sup>2</sup> Some CNC controllers have measurement cycles to carry out limited on-machine measurements; however, these measurements are manually planned and coded by the CNC operators.

standards providing sufficient information for process planning, it is possible to integrate machining and measurement process planning in an automated way. In this way, measurements can be planned automatically to take place between machining processes to provide process-intermittent feedback through time-efficient analysis systems. Thus, a more informed and flexible manufacturing process can be formed.

Both the separated process planning (machine-then-inspect process) and the integrated process planning (inspect-while-machining) activities are modeled here. This activity model also identifies standards and specifications (both published and under development) that are associated with these manufacturing activities. Different industry users can refer to this activity model for suitable standards/specifications for the process planning procedure they prefer.

## **2. A Review of Machining and Measurement Process Planning Activity Models**

This section briefly reviews activity models developed for specific machining and measurement activities. These models were developed in industry, academia, and standards committees in the machining and measurement areas.

### ***2.1 Integrated Machining Process Planning Activity Model***

In 2003, Shaw C. Feng at Manufacturing Systems Integration Division, Manufacturing Engineering Laboratory, National Institute of Standards and Technology, in the US carried out a research plan to integrate existing machining process planning activity models [1, 2]. The machining process planning activity models reviewed in this research include the CAM-I model [3], the Integrated Modeling of Products and Processes Using Advanced Computer Technologies (IMPPACT) model [4], the Automated Airframe Manufacturing Process (AAP) model [5, 6], STEP AP224 model [7], and STEP AP213 model (later on renamed as AP240). It was found that these activity models captured basic functions in machining process planning. However, they did not address some present industrial needs, such as machining feature derivation, intermediate machining feature generation, tolerance specification for intermediate features, shop-floor routing planning, material stock selection, setup determination, cost estimation, shop-floor routing, and design change recommendations. This research consolidated the reviewed activity models and extended them with additional features covering the aforementioned industrial needs.

### ***2.2 STEP AP219, AP224, AP240***

STEP AP219 [8] has an activity model for dimensional inspection processes. It identifies four main activities of dimensional inspection processes: inspection administration and archiving, inspection planning, inspection execution, and analysis of inspection. The



inputs of this activity model are inspection order, manufacturing process plan, part, and acquired Dimensional Measurement Equipment (DME) tools and fixtures. The outputs include inspected part, analysis results feedback and statistical results. This activity model contains relatively complete activities for inspection processes; however, it only focuses on representation of administration and archiving data for inspection processes. It does not address inspection operation data; neither does it address the connection between measurement and machining.

STEP AP224 includes an activity model for manufacturing mechanical parts. This model was developed for defining the context under which the data are transferred from computer aided design systems to computer aided process planning systems. The model has the following sub-activities: manage manufacturing process, capture digital product data definition, generate manufacturing data, and operate shop floor. Only the second sub-activity is within the scope of this Application Protocol (AP). It addresses capturing special notes, extracting manufacturing features from part shape, defining surface finish and hardness, and extracting tolerances. Although the management of manufacturing process is out of scope, the AP224 model mentioned activities related to manufacturing process management such as request and order parts, determine production cost and schedule, manage equipment and materials, etc.

STEP AP240 [9] has an activity model for exchange, archiving and sharing process plans for machined parts. The scope of this AP is to represent the data contained within a process plan; but not the data necessary to perform process planning functions. The manufacturing processes defined in this activity model include forming, welding, material removal, assembly, and conditioning or finishing processes. Therefore, the activity model focuses on addressing the tooling and equipment related process planning activities for different machining process types. They include: Engineer Manufacturing Methods and Part Routing, Engineer Process, Develop Tooling Packages, Develop Equipment Instructions, and Finalize Manufacturing Data Package.

## ***2.3 High-level Inspection Process Planning Activity Model***

In 2007, NIST proposed a High-level Inspection Process Planning (HIPP) activity model. This model was developed to define high-level inspection process planning for both dimensional and non-dimensional measurement processes. The activities include: determine measurement scope, determine dimensional measurement method, develop quality measurement operation plan, develop reaction plan, and generate support data. The inputs to this model are product definitions, geometry and Geometric Dimensioning and Tolerancing (GD&T), production schedule, batch size, criticality weighting, and product quality plan. The output is quality measurement process plan. This activity model is designed for production manufacturing processes. However, the detailed inspection process planning activities are not within the scope of this model.

All the above reviewed activity models are captured in IDEF0 diagrams. They focus on different areas of machining or measurement processes in manufacturing systems with different levels of production scale. Basic functions for either machining or measurement

are captured. However, some of the activity models are still incomplete. Furthermore, they do not address the connection between machining and measurement processes.

### **3. An activity model for manufacturing system integration and interoperability analysis**

This section describes an activity model that consolidates machining and measurement process planning activities together with association to product design, execution, and analysis and reporting activities. This activity model is developed using IDEF0. It specifies functions and data requirements for machining and measurement process planning. It also identifies the information flow from the upstream design activity to downstream execution and analysis activities. Current standards and specifications for information exchange between these activities are indicated in the IDEF0 diagrams.

#### **3.1 Activity model**

This section presents a model of activities in discrete part manufacturing processes with a focus on process planning activity. The model addresses the five main activities to manufacture a part: design, process planning, production scheduling, execution, and analysis and reporting (A1, A2, A3, A4, and A5). The focus is A2—process planning—activity, which is modeled in two different ways: machine-then-inspect process planning in A2 and inspect-while-machining process planning in A2'. The activities derived from integrated process planning activity all have apostrophe marks. It is important to note that IDEF0 diagrams are often interpreted to imply a strict sequence of activities. That is not the intention in this case. Rather, the numerous data flows representing feedback from one activity to another are expressly omitted to avoid cluttering the diagrams. For example in Figure 3, each of the activities A1-A5 should be considered to be providing data to each of the other activities in the figure.

The A-0 diagram (shown in Figure 2) shows the context in which the product manufacturing activity takes place. The input data includes design specifications, product quality plan and raw material. This activity requires control from customer requirements, standards for quality and GD&T standards. The mechanism to carry out this activity consists of personnel, equipment, resource databases, and knowledge databases. The outputs of this activity are design update/change record, product, and performance record. The overall activity on level A-0 is decomposed into five activities (A1-A5) in Figure 3. These activities are: design product, plan processes, plan production schedule, execute production, and analyze and report.

In Figure 3, A0 diagram shows the relationships and information connections between these activities. For each activity, there are several data formats that the generated information can be saved in. A product definition (generated from A1 activity) can be saved in one of the following data formats Initial Graphics Exchange Specification (IGES) [10], ISO 10303 AP203 [11] or ISO 10303 AP214 [12]. The product definition is

then process planned through activity A2. Plans may be saved in a number of different data format depending on the process types. A machining process plan can be kept in one of the following data formats: ISO 10303 AP224<sup>3</sup> (only for machining feature sequence), ISO 10303 AP240, ISO 10303 AP238 [13], ISO 14649 [14], or Automatically Programmed Tool (APT). A measurement process plan can be saved in one of the following data formats: ISO 10303 AP219, Dimensional Measuring Interface Standard (DMIS) [15] input, Advanced Product Quality Planning and Control Plan (APQP) [16], Exchange of Quality Inspection Process Plans (eQuiPP)<sup>4</sup> [17], or Inspection ++ Dimensional Measurement Specification (I++DMS) [18]. Some of these data formats are developed for saving high-level process plan information, while others are for low-level information. There is no standardized data format for production planning and scheduling activity (A3 activity) output. After a process plan is executed in activity A4, the measurement result can be saved either in a DMIS output file or a Dimensional Markup Language (DML) [19] file. Machining execution output data (such as machine monitoring data and on-machine measurement results) is normally saved as text files.

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<sup>3</sup> ISO 10303 AP 224 only defined machining feature information. Therefore, a machining plan saved in AP224 only contains machining features and its sequence.

<sup>4</sup> eQuiPP is an ad hoc working group under DMSC board to develop a complete and precise measurement process plan for the execution of all types of quality measurements.

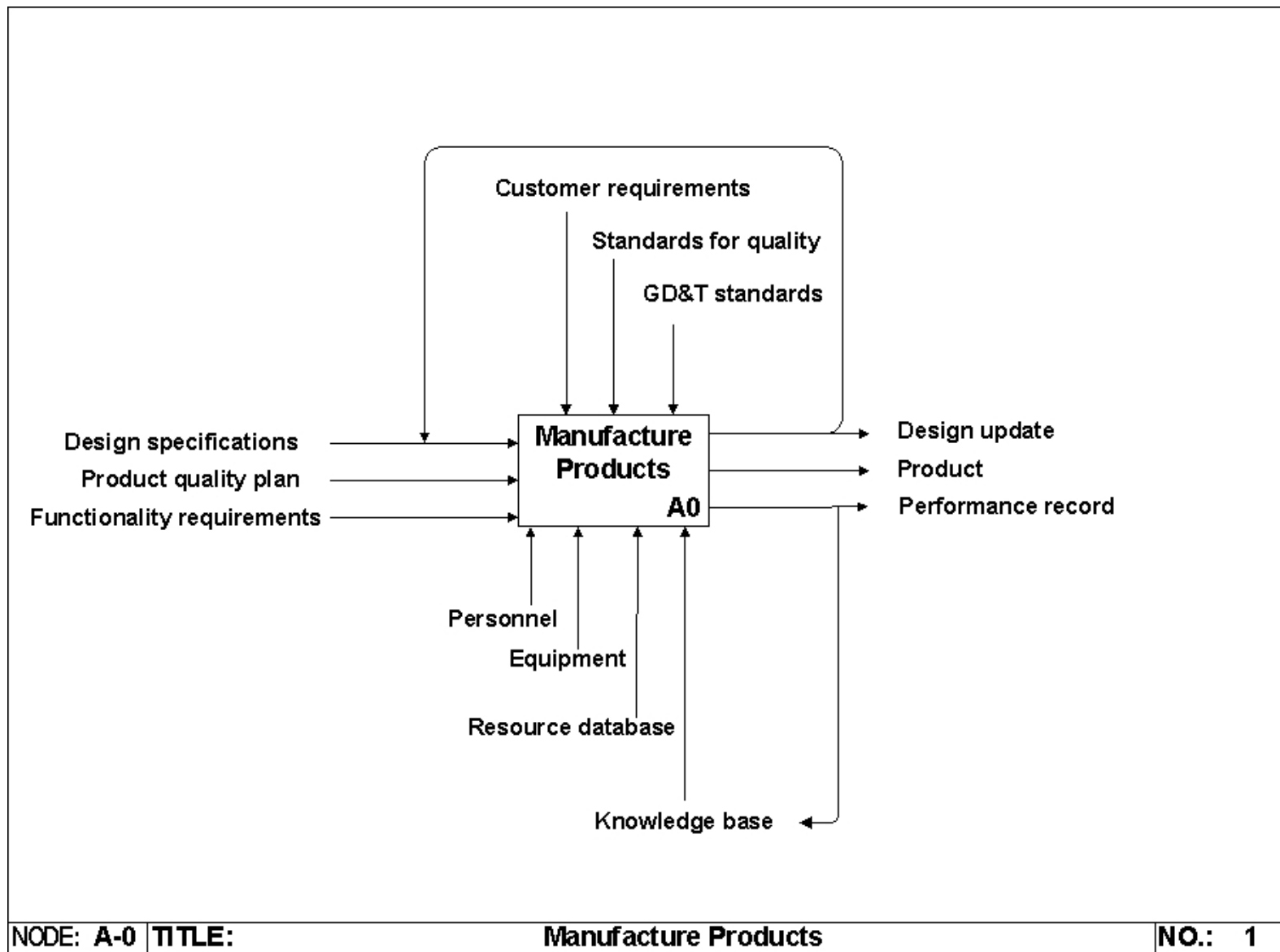


Figure 2: A-0 level activity

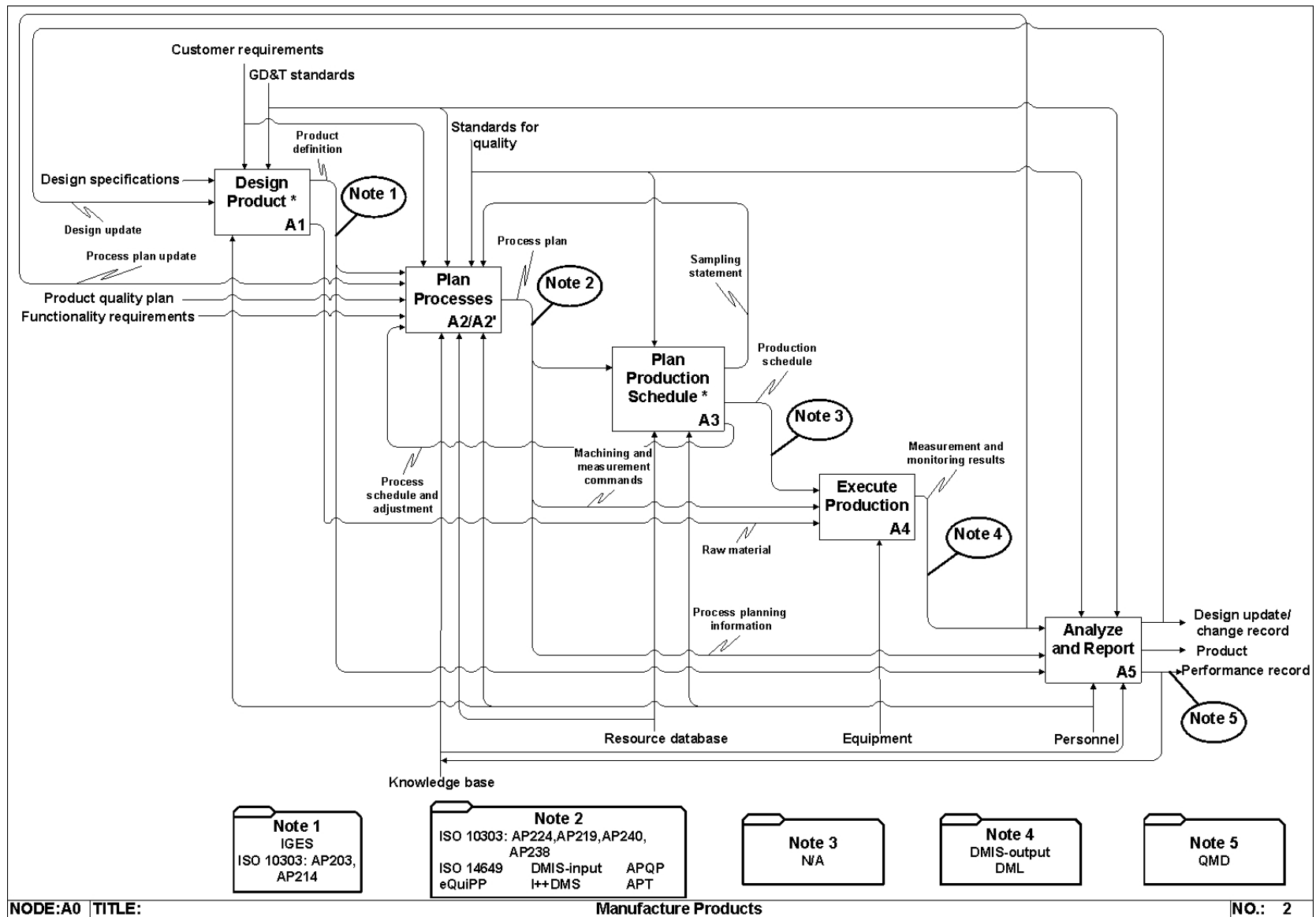


Figure 3: A0 activities

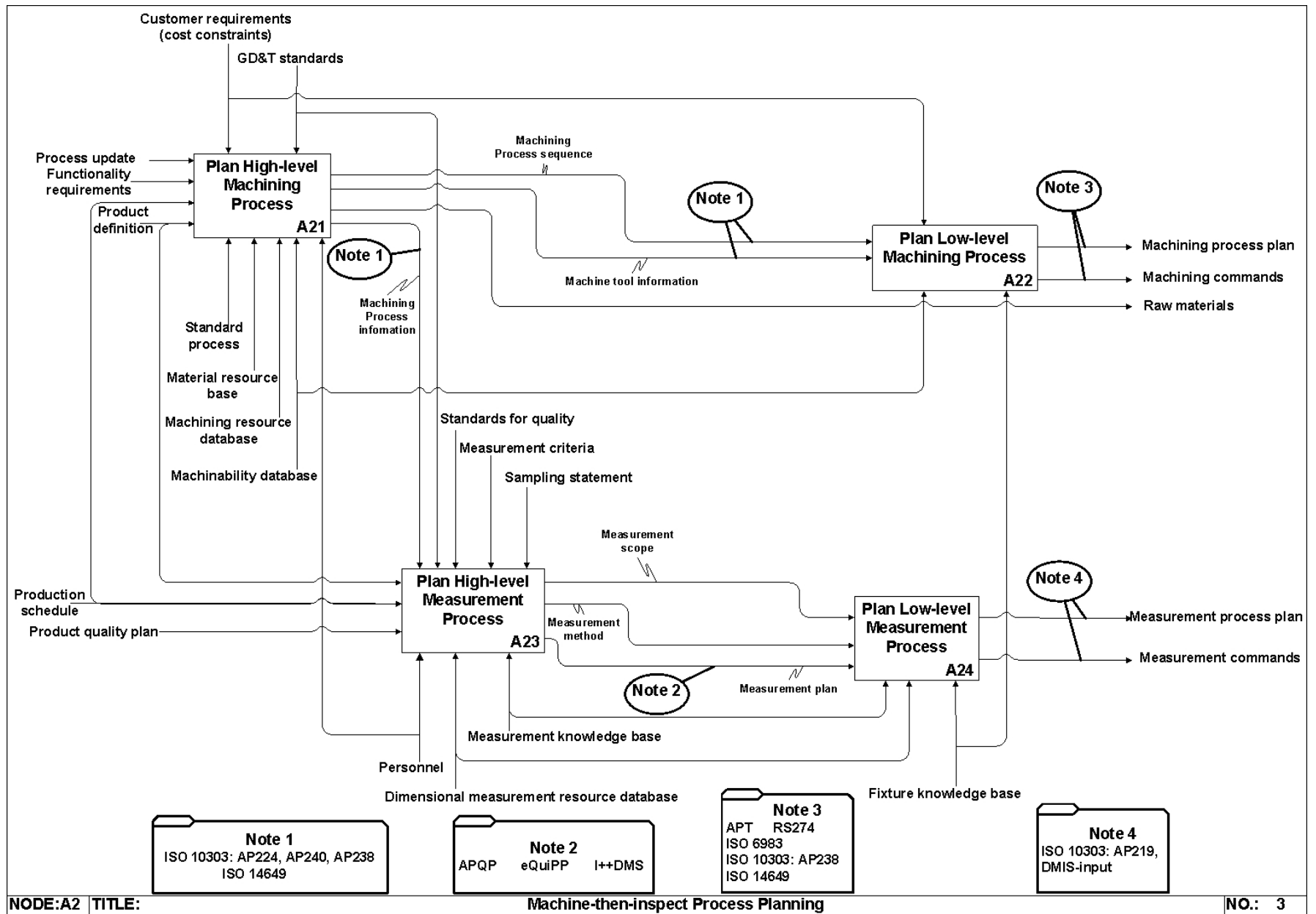
The measurement results are analyzed in A5 activity and necessary updates are reported to A1 and/or A2/A2' activities. The analysis result can be saved as a Quality Measurement Data (QMD) [20] file. A1 and A3 activities are out of the scope of this report; therefore, they are not further decomposed. Interested readers can find detailed IDEF0 diagrams of A1 activity in ISO 10303 AP203, where the design product activity is described in detail.

### ***3.2 Detailed Process Planning Activity Model***

A2/A2' activity generates process plans for machining and measurement. This activity can be decomposed in two ways: machine-then-inspect process planning activity (A2) and inspect-while-machining process planning activity (A2'). In manufacturing systems, the measurement process mainly has three functions:

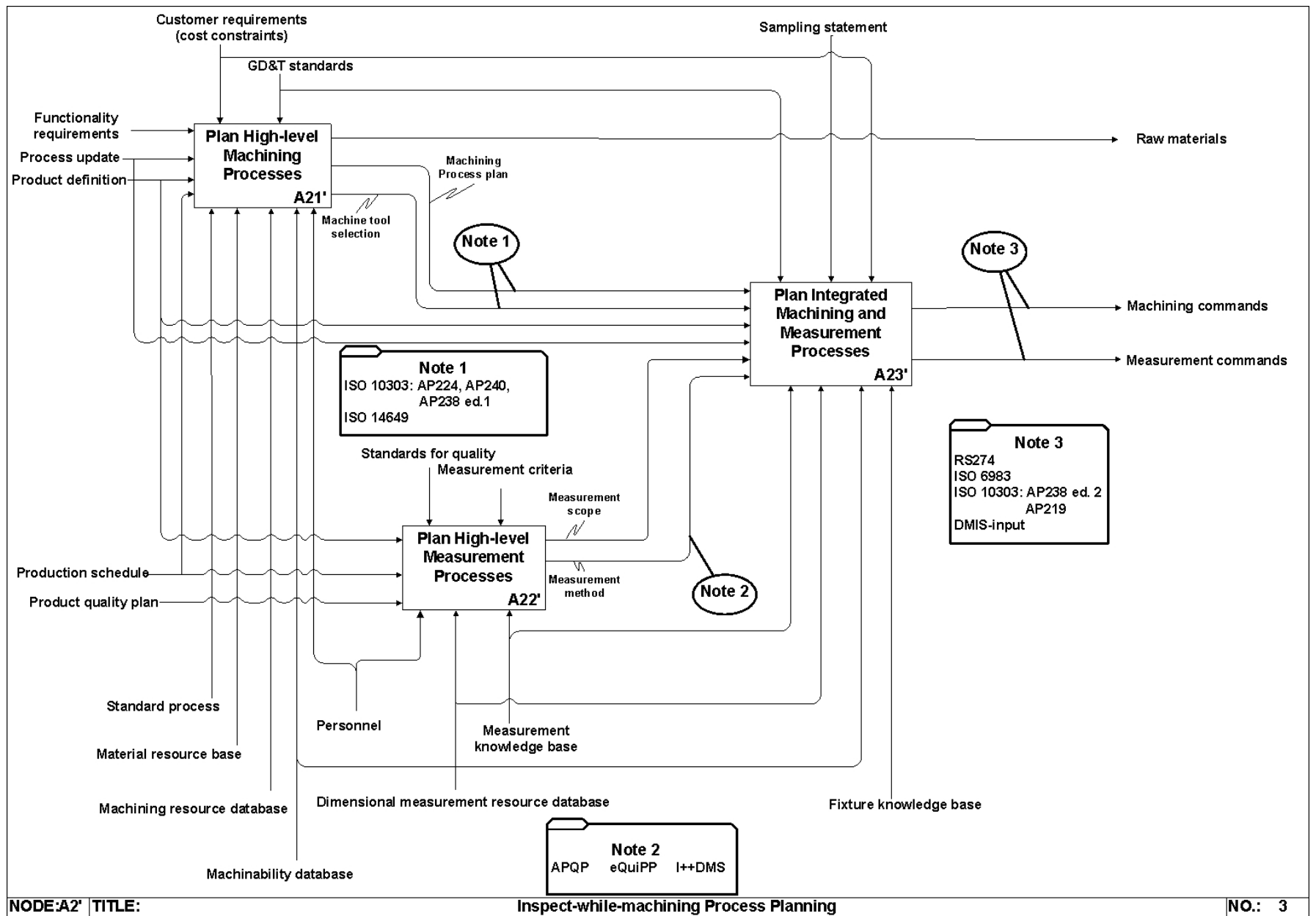
- 1) to inspect a part for the purpose of determining whether the part is within the required tolerances. This is usually carried out after the part has been manufactured. The purpose of this is usually to determine if the part is usable, but the result could also be used to change the product design or manufacturing process in the future.
- 2) to inspect a batch of parts to determine whether the batch meets quality requirements according to statistical criteria. A sampling plan is needed for this case.
- 3) to inspect a part during manufacturing for the purpose of process control. This is done during manufacturing. Operations carried out after inspection would vary depending on the result of the inspection.

For the first and the second functions, machining process information is mostly used as control information for measurement process planning (shown in Figure 4). The machining and measurement process planning are carried out separately. For the second functions, machining and measurement are planned in an integrated manner. Machining process information is one of the inputs to measurement planning activities (shown in Figure 5).



**Figure 4: A2 activity – machine-then-inspect process planning**





NODE:A2' TITLE:

Inspect-while-machining Process Planning

NO.: 3

**Figure 5: A2' activity – inspect-while-machining process planning**

Activity A2 is further decomposed into four sub-activities A21 to A 24 in Figure 4. Activity A21 generates high-level machining process plans, which consist of raw material type, machining process sequence, machining process information and machine tool information. The output of this activity can be saved in one of the following data formats: ISO 10303 AP224, ISO 10303 AP240, ISO 10303 AP238, or ISO 14649.

Activity A22 generates a machining process plan and/or machining commands. The machining process plan can be saved as an ISO 10303 AP 238 file or an ISO 14649 file, which require a postprocessor to interpret them into machining commands. The machining commands can be saved in one of the following format: APT, RS274, or ISO 6983 [21] (RS274 and ISO 6983 are also known as G-codes). The measurement process planning is carried out in a parallel fashion in activities A23 and A24. Activity A23 generates a high-level measurement plan including measurement scope, method and plan. Activity A24 generates a low-level measurement plan that consists of a measurement process plan and measurement commands. Activity A23 output can be saved as an APQP file, an eQuiPP, or an I++DMS file. The output generated from activity A24 can be saved as an ISO 10303 AP219 file or a DMIS input file.

Activity A2' is decomposed into three sub-activities A21' – A23' in Figure 5. The outputs from activities A21' and A22' are processed through activity A23' to generate combined machining and measurement commands. The machining commands can be saved as an RS274 or ISO 6983 file. The measurement commands can be saved as an ISO 10303 AP219 file or a DMIS input file. The combined commands can be saved either as an ISO 10303 AP238 edition 2 file or a combined RS274/ISO6983 and DMIS input file for integrated machining with in-process measurement.

Activity A21' is equivalent to activity A21. Therefore, they share the same sub-activities. A21/A21' can be decomposed into two sub-activities A211/A211' and A212/A212' shown in Figure 6. The former activity generates a machining feature sequence. Based on product definition and functionality requirements, raw material is also selected by this activity. The latter activity generates machining operations which consists of a machining process plan and machine tool information. Activity A211/A211' consists of four sub-activities: A2111/A2111' to A2114/A2114' shown in Figure 7. The functions of these sub-activities are: specify material stock, derive machining features, select machining processes, and determine machining feature sequence. Activity A212/A212' can be decomposed into four sub-activities: A2121/A2121' to A2124/A2124' shown in Figure 8. Their functions are: determine intermediate machining features, specify part setups and machine tools, calculate intermediate machining tolerances, and develop machining instructions.

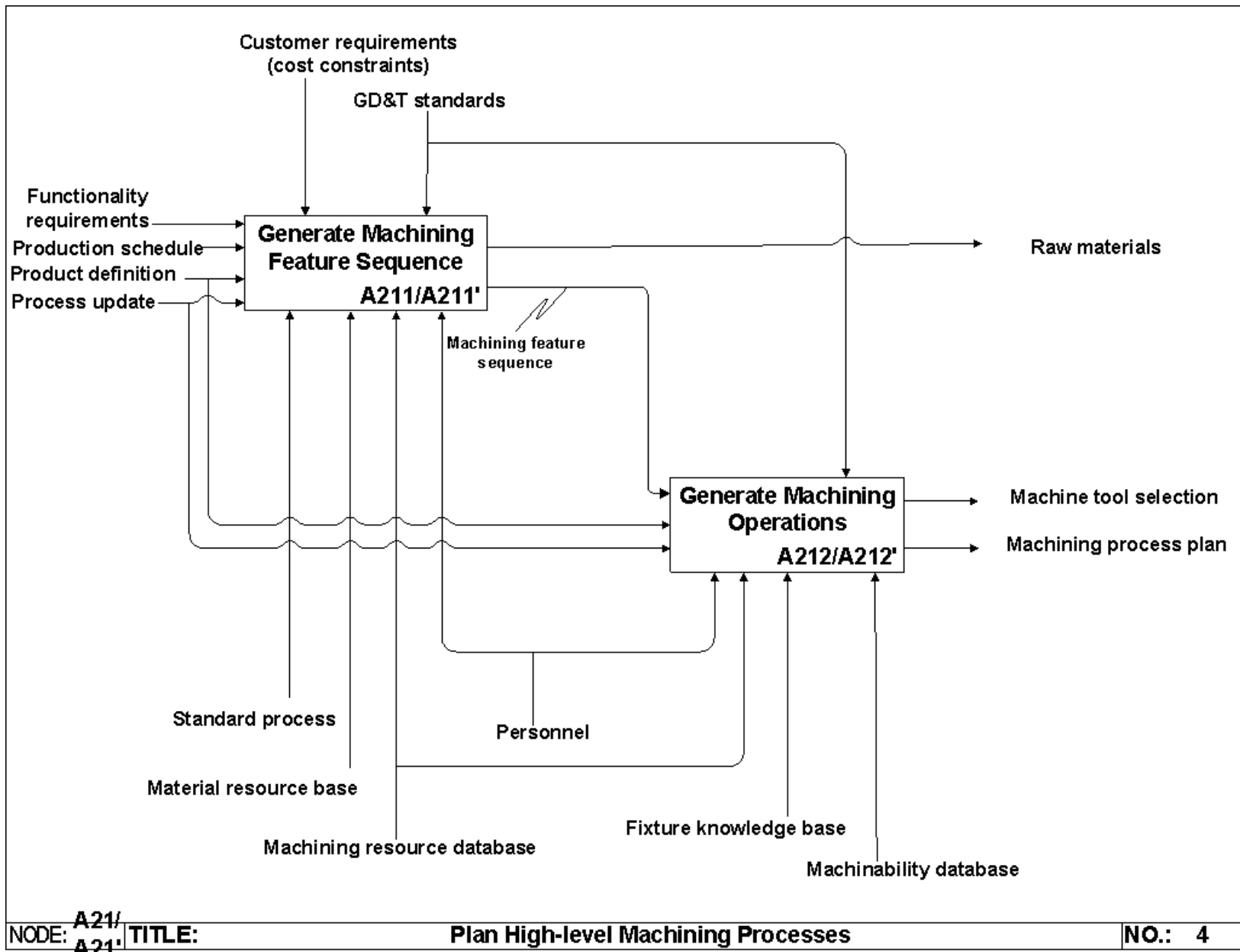
Activity A22' is equivalent to activity A23. They can be decomposed into two sub-activities: A221'/A231 and A222'/A232 shown in Figure 9. Their functions are determining measurement scope and accuracy requirement and determining dimensional measurement method, respectively. The former activity consists of four sub-activities shown in Figure 10. Measurement requirements are first identified then three sub-

activities are carried out in parallel to specify consumer's risk, state traceability requirements, and determine measurement tasks. The latter activity consists of the four sub-activities shown in Figure 11. Based on product quality plan, measurement scope, and production schedule, the measurement method(s) is chosen. It can be one or a combination of the following three methods: gage measurement, in-process measurement, and CMM. Each of them has a corresponding activity to generate measurement method specifications. Both in-process measurement and coordinate measurement methods are connected with sensor selection activity to generate sensor specifications.

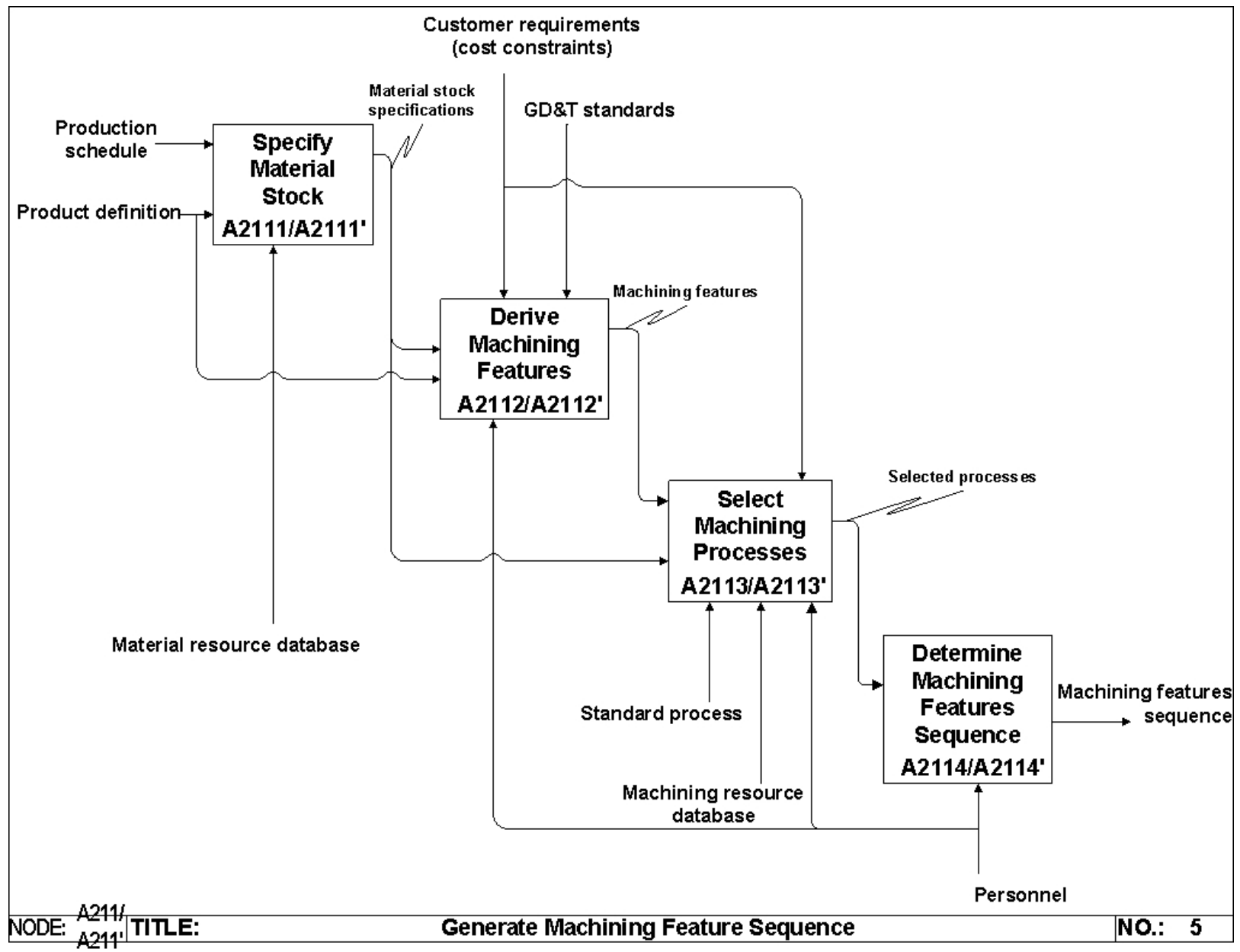
Activity A22 shown in Figure 12 (refer to upper level activity A2 in Figure 4) generates machining commands. It is decomposed into four sub-activities A221 through A224. Suitable cutters are first selected for each machining process. Then, machining strategy and tool path are generated based on the machinability database. Simulation and validation are performed before real machining is carried out. Necessary updates are fed back to previous activities.

Activity A24 shown in Figure 13 generates measurement commands. It consists of five sub-activities A241 to A245. The setup and fixture of each measurement process is determined first; then measurement features, measurands and uncertainties are determined. For batch production, a part sampling plan is determined in the next step and measurement paths are generated. The simulation and validation activity is then carried out for necessary update to the measurement path before real measurement is performed.

Activity A23' shown in Figure 14 (refer to upper level A2' activity in Figure 5) generates combined machining and measurement commands. It consists of five sub-activities A231' to A235'. The measurement features are first determined. Then, the sequence of machining and measurement operations is decided. Low-level machining and measurement operation planning are then carried out for each machining and measurement operations, respectively. Simulation and validation activity is performed to check machining and measurement commands. Activity A231' is decomposed into two sub-activities (shown in Figure 15): A2311' and A2312'. The former activity identifies critical tolerances based on the machine tool information from input and machinability information from database. The latter activity determines measurement features, measurands, and uncertainties. Activity A232' processes input machining process and measurement feature information and determines the sequence of machining and measurement operations. Activity A233' plans low-level machining operation. This activity shares the same sub-activities as activity A22 in Figure 12. Activity A234' is decomposed into three sub-activities A2341' through A2343' shown in Figure 16. The interactions between machining features and measurement features are detected first; then a point sampling strategy is developed and a measurement path is generated.

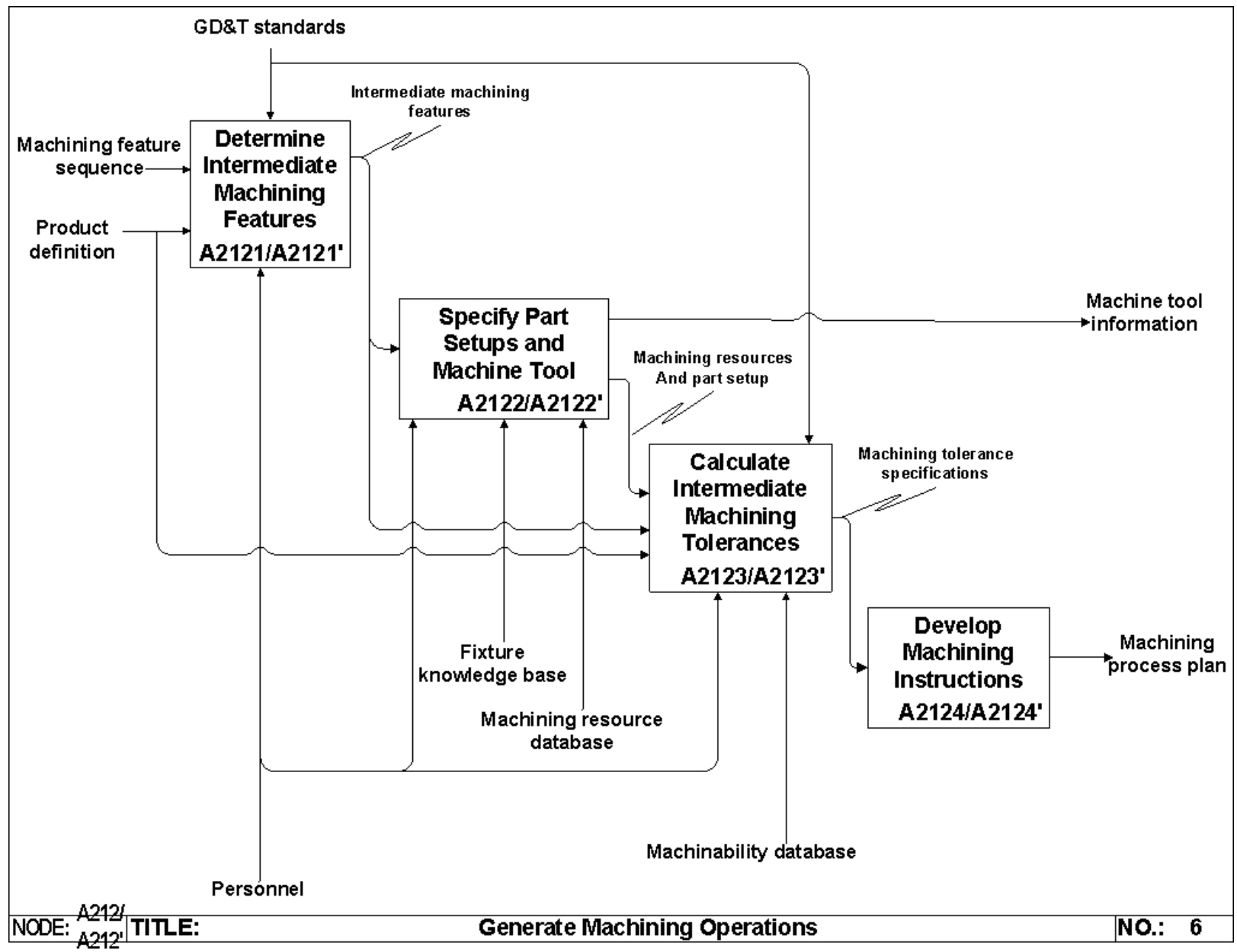


**Figure 6: A21/A21' activity – high-level machining process planning**

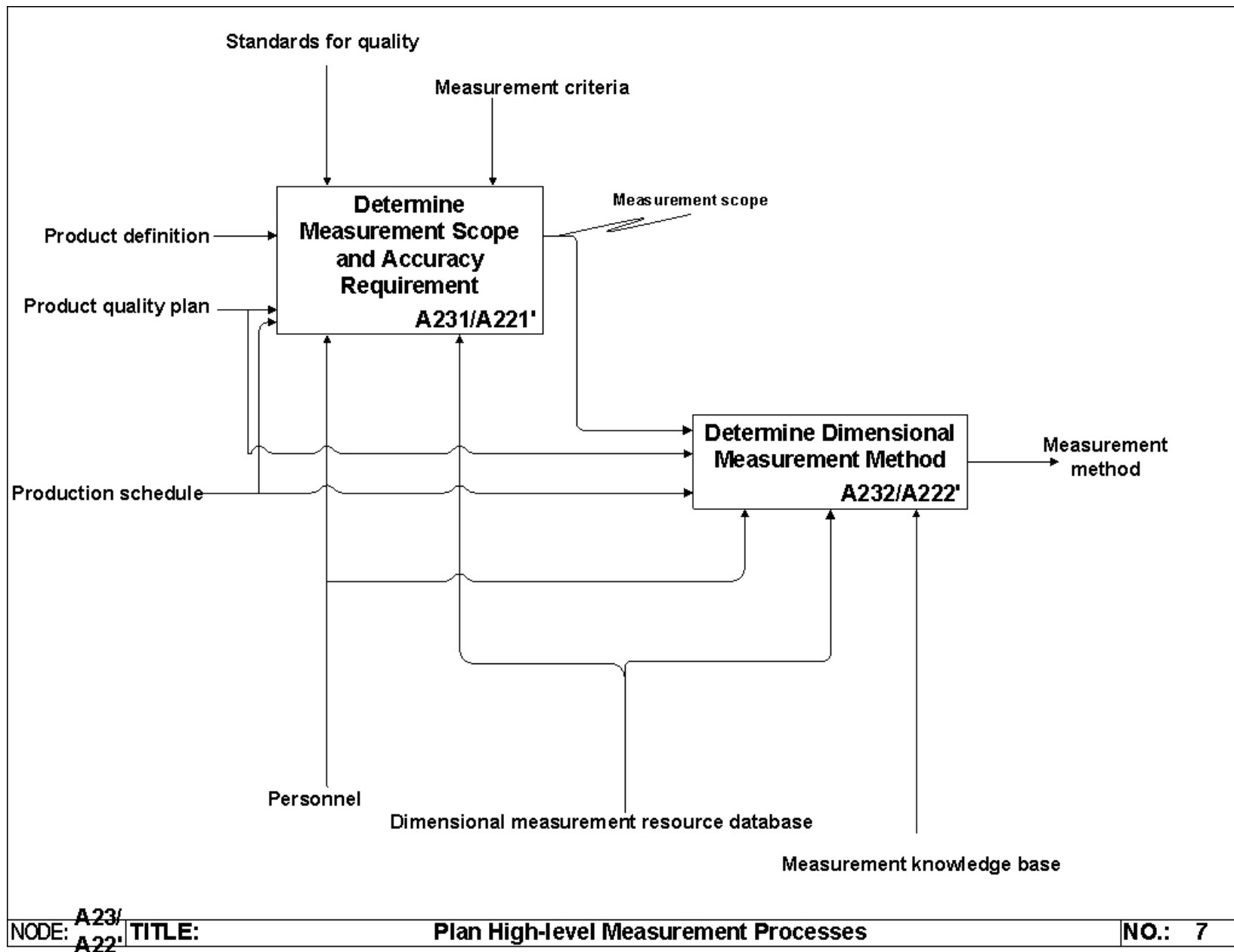


**Figure 7: A211/A211' activity – machining feature sequence generation**

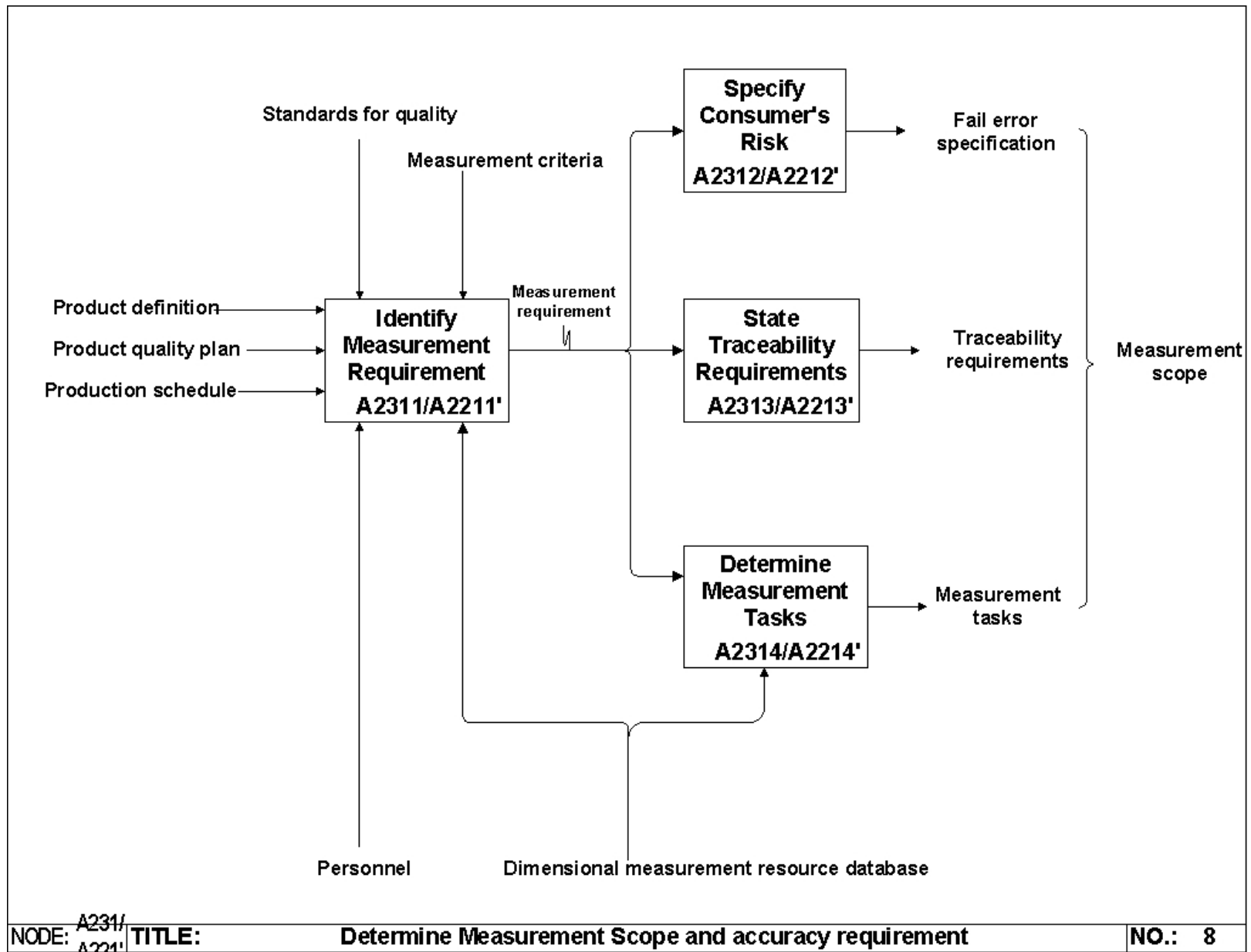




**Figure 8: A212/A212' activity – machining operation generation**



**Figure 9: A23/A22' activity – plan high-level measurement processes**

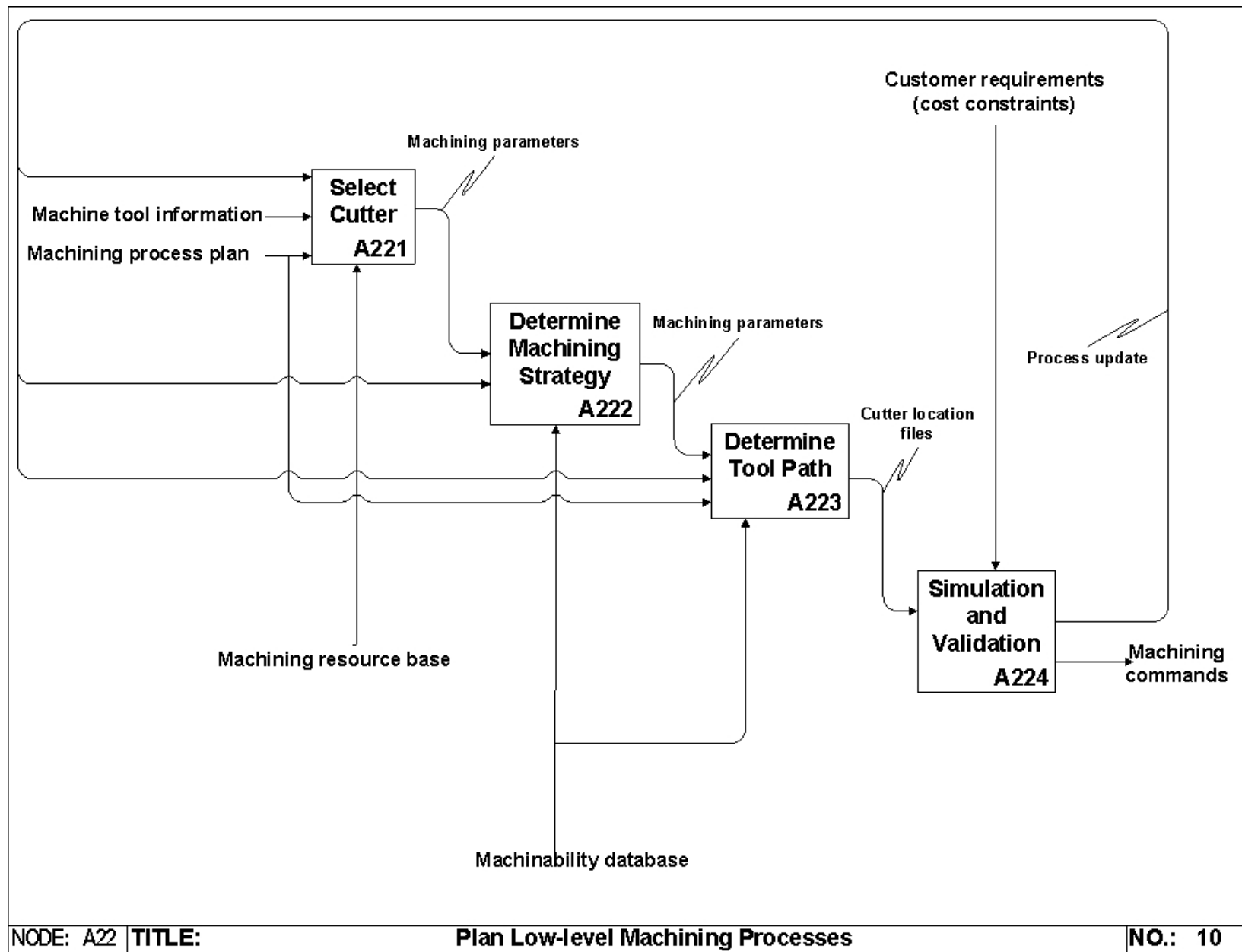


**Figure 10: A231/A221' activity – determine measurement scope and accuracy requirement**



**Figure 11: A232/A222' activity – determine dimensional measurement method**

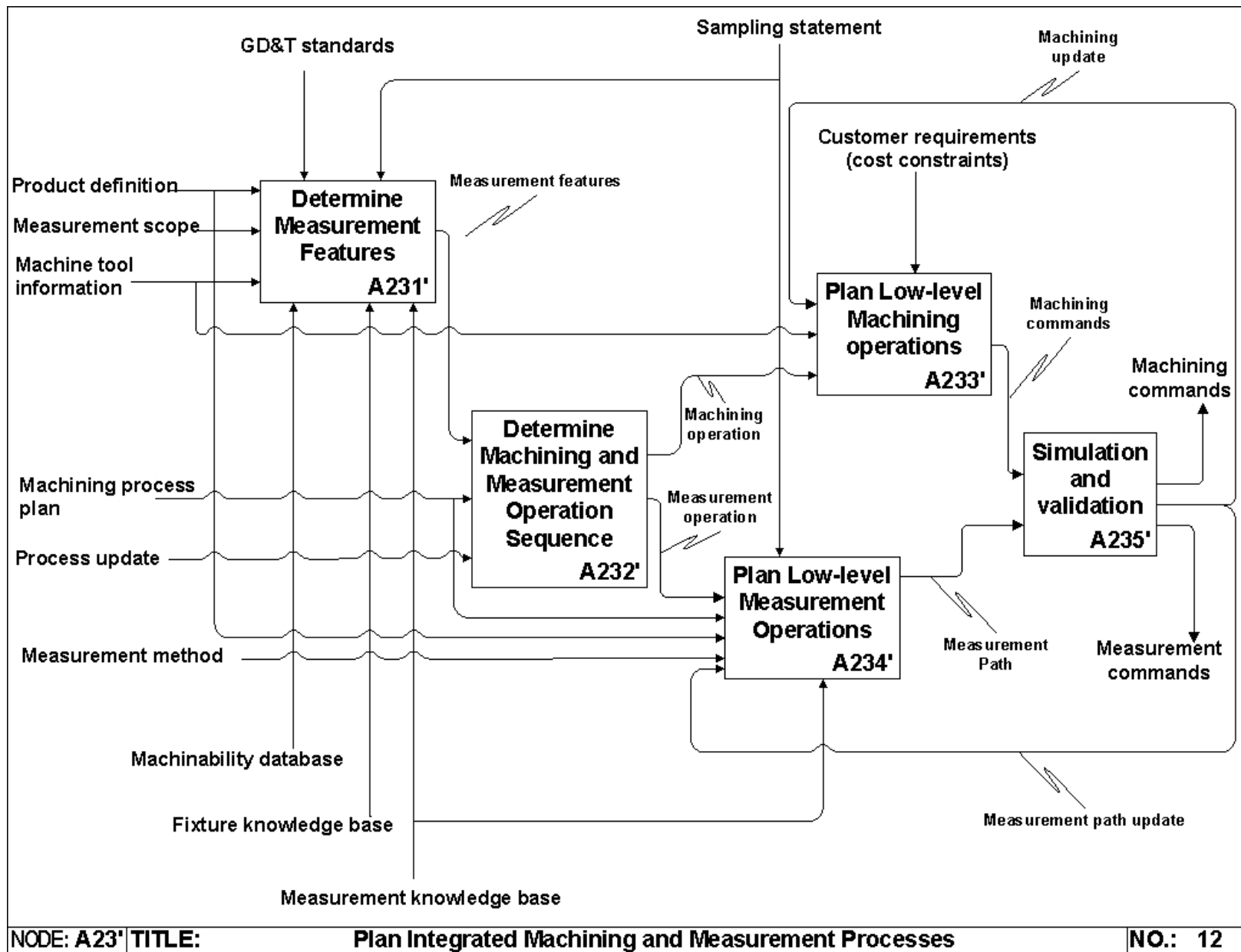




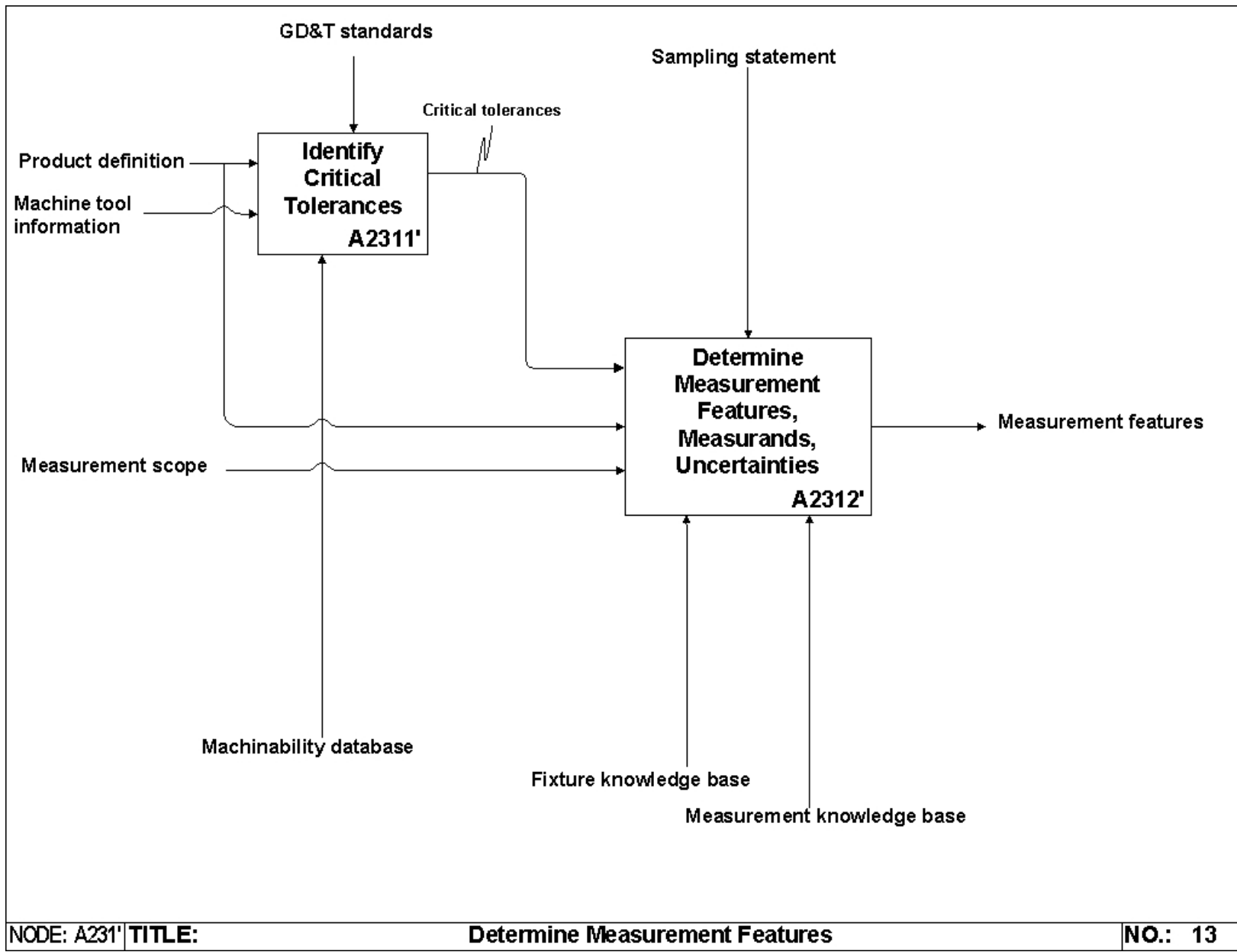
**Figure 12: A22 activity – low-level machining process planning**



**Figure 13: A24 activity – low-level measurement process planning**

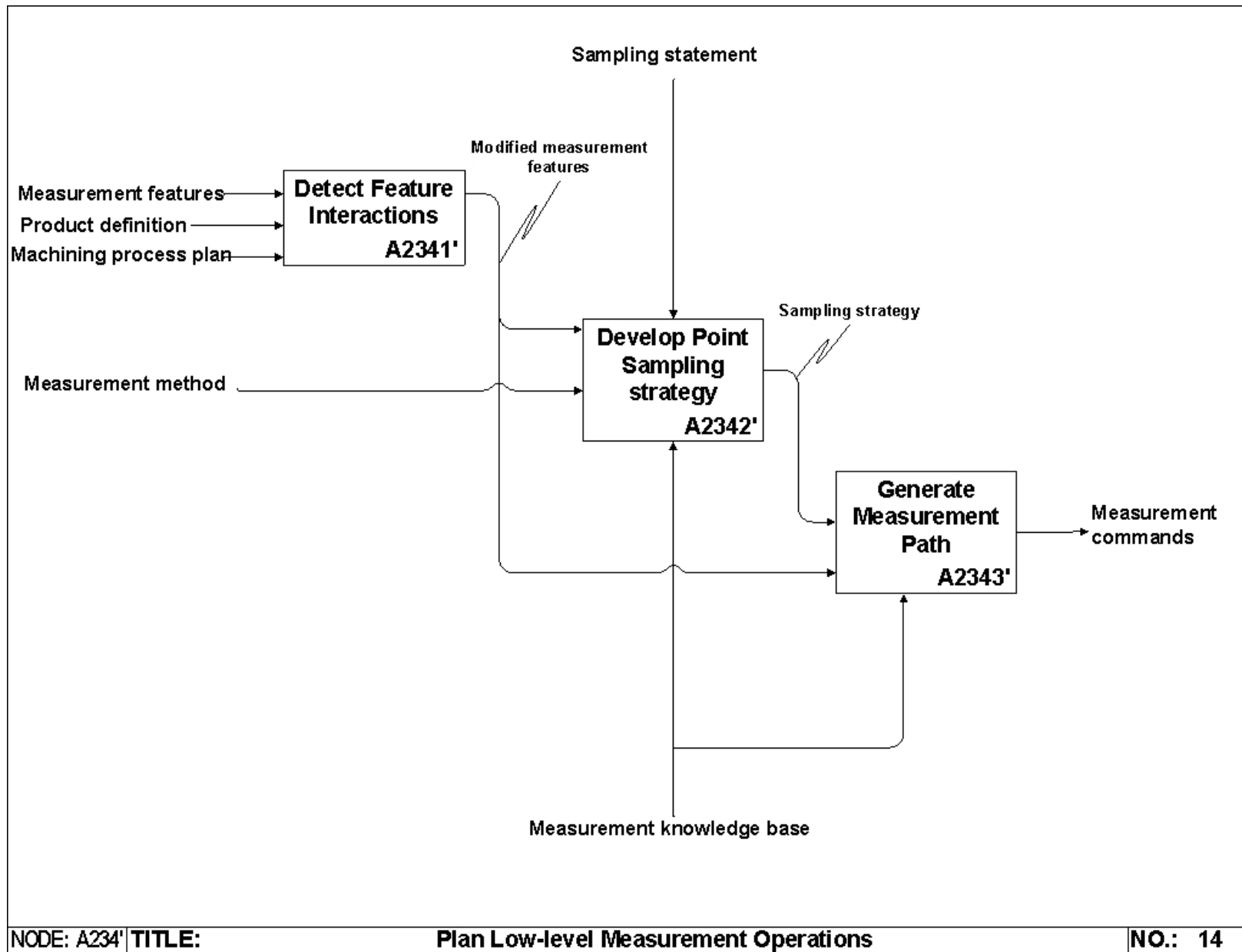


**Figure 14: A23' activity – integrated machining and measurement process planning**



**Figure 15: A231' activity – determine measurement features**



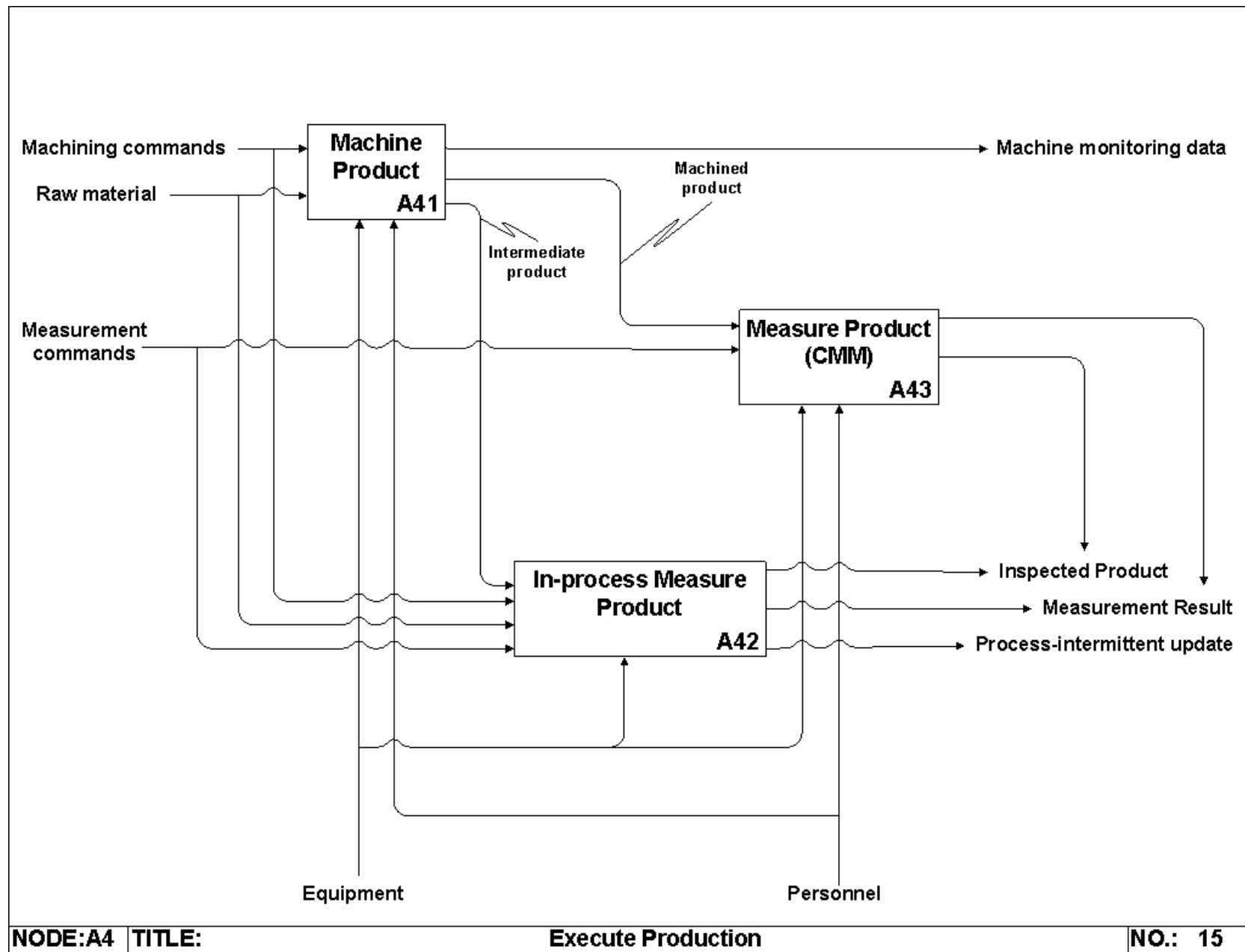


**Figure 16: A234' activity – low-level measurement operation planning**

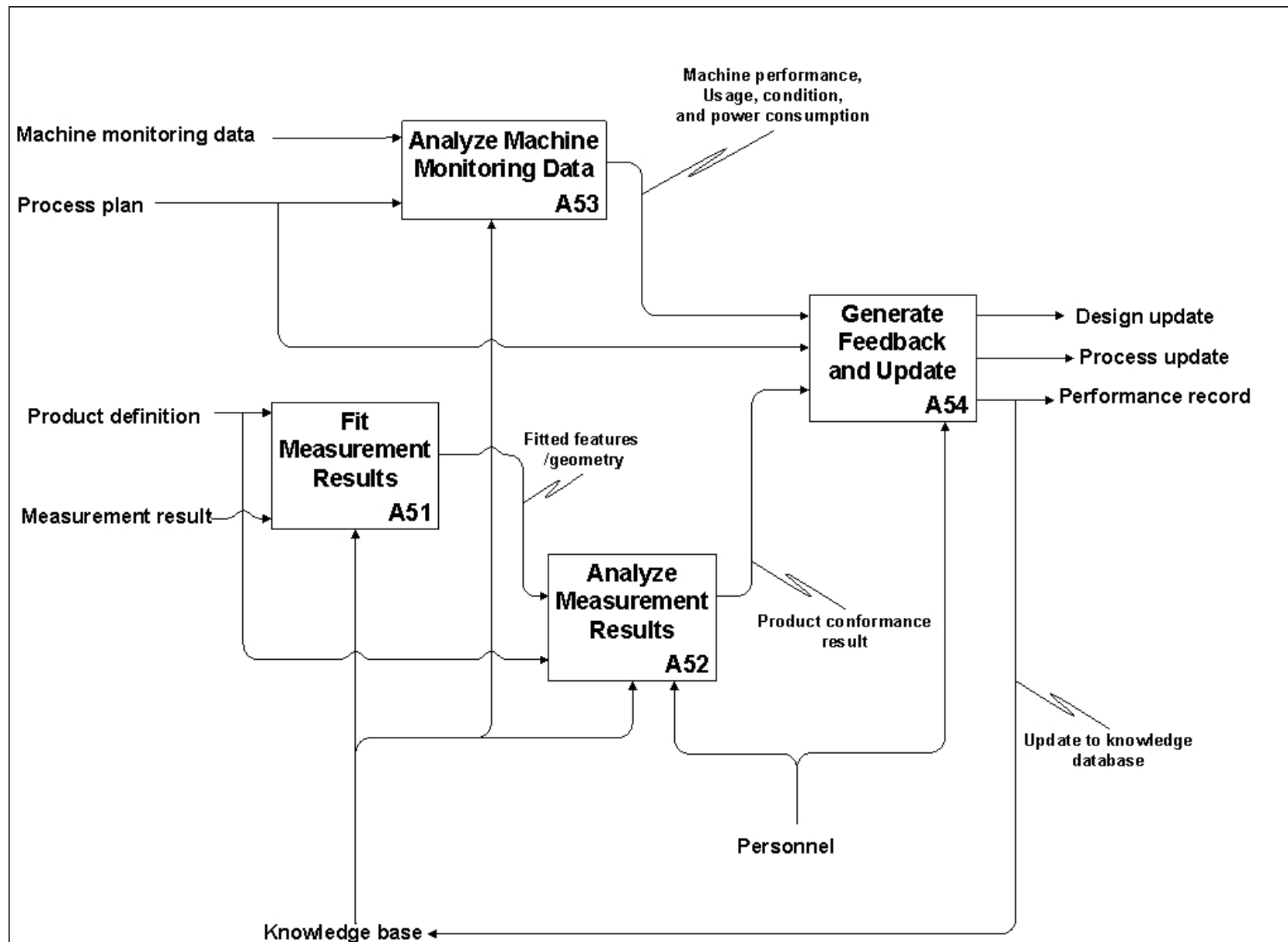
### ***3.3 Execution and Analysis and Reporting Activity Model***

After machining and measurement commands are generated, the execute production activity (A4) is carried out as shown in Figure 17. Machining commands are loaded to a machining center for machining operation in activity A41. If the process planning is carried out through activity A2, CMMs are used for measurement in activity A43. If the process planning is carried out through activity A2', in-process measurement using on-machine probing or portable measuring devices are used for measurement in activity A42.

Activity A5 shown in Figure 18 processes machine monitoring information and measurement results to generate process update, design update, and performance record. It consists of four sub-activities A51 through A54. The measurement results are first processed through a data fitting activity (A51) to generate fitted geometry. Then, measurement results analysis activity (A52) is carried out to generate product conformance information. Machining monitoring data is also analyzed to generate machine performance, machine usage, machine conditions, and power consumption information in activity A53. The results from these above activities are processed through activity A54 for feedback and update.



**Figure 17: A4 activity – execute production**



NODE:A5 TITLE:

Analyze and Report

NO.: 16

**Figure 18: A5 activity – analyze and report**

### ***3.4 Glossary for the Data in the Activity Model***

#### ***Input data:***

**Design specifications:** precise and explicit information for a product design including functional and non-functional design requirements, material requirements, functional constraints, product performance requirements, dimensions, etc. It provides the product designer with all the information and references that are necessary to produce the computer-interpretable representation of a part.

**Product quality plan:** a plan defining the quality requirements for a specific product, such as surface finishing, shininess, roughness, etc.

**Functionality requirements:** functional requirement of the product.

#### ***Control and constraint data:***

**Customer requirements:** the limitation required by customers. It includes acceptable machining cost and machining time imposed by product planners' and company's decisions.

**Standards for quality:** international standards on quality assurance, such as standards in the ISO 9000 series.

**GD&T standards:** national and international standards on dimensioning and geometric and statistical tolerancing.

#### ***Mechanism and resource data:***

**Personnel:** persons that are involved in product manufacturing processes, such as product designer, process planer, CNC machine operator, product quality inspector, etc.

**Equipment:** equipment that are involved in product manufacturing processes, such as computers, CNC machines, measurement probes and machines, etc.

**Resource database:** databases that provides resources for product manufacturing processes, such as material resource database, machining resource database, dimensional measurement resource database, machinability database, standard process.

**Knowledge base:** databases that provide knowledge for decision making in product manufacturing processes, such as standard process knowledge, measurement knowledge, fixture knowledge, etc.



### ***Output data:***

**Design update:** information fed back to design activities for changes to the product model to improve the part's manufacturability and cost effectiveness of the manufacturing process.

**Product:** manufactured product.

**Performance record:** machining centre performance record showing the accuracy, stability, repeatability record.

### ***Internally used data:***

**Coordinate metrology specification:** a document that contains specific and/or classes of coordinate measuring machines that are needed to perform measurement.

**Critical tolerances:** a document that specifies the tolerances that need to be monitored during machining processes.

**Cutter location files:** files that contain lists of cutter paths for machining operations.

**Fail error specification:** a document that defines the specifications of failure status and error status during measurement.

**Fitted features/geometry:** the calculated feature/geometry generated through a data fitting activity based on collected measurement points.

**Gage specifications:** a document that contains specific and/or classes of gages that are needed to perform measurement.

**Inspected product:** the part that is measured through measurement processes. The inspected product may or may not meet the quality requirements.

**Intermediate machining features:** the features and geometries that define the intermediate shapes at stages of machining.

**Intermediate product:** the part produced at different stages of machining processes before the final part is machined.

**Machine performance, usage condition, and power consumption:** information describing machine performance, usage and condition, and power consumption (refer to each terminology for its definition).

**Machine performance:** a document that records machine performance information such as machine accuracy, repeatability, stability, etc.

**Machine usage and condition:** a document that records machine usage and machine condition information such as machine usage time, spindle revolutions, coolant level, overheating level, etc.

**Machine power consumption:** a record of machine power consumption information.

**Machine tool information:** information on the selected machine tool/machining center such as identification of the machine, its accuracy, stability, repeatability, etc.

**Machine tool selection:** the information describing a class of machine tool that is capable of performing generated machining operations including machine controller types, machine accuracy information, machining volume, maximum federate and spindle speed, etc.

**Machined product:** the final part produced after machining processes.

**Machining commands:** computer-interpretable codes that control machining centers.

**Machining features:** zones in the material stock to be removed during machining processes. The zones have specific geometries, locations, and orientations relative to the stock.

**Machining feature sequence:** the sequence of features to be machined during the machining process.

**Machining monitoring results:** data collected through machining monitoring devices including machine usage time, spindle speed, coolant level, excessive vibration, overheating, etc.

**Machining operation:** a set of actions that machine tool does to remove material from the stock, e.g. milling, drilling, rough milling, finish milling, etc.

**Machining path:** the path/route that cutters follow during machining.

**Machining parameter:** parametric information of chosen machine tool, cutter, machining strategy including cutter dimensions, machining speed, feed rate, cutting depth, etc.

**Machining process plan:** the detailed plan for a machining process. It may include high-level machining information such as machining operation sequence and cutter information and/or low-level machining information such as cutting path, spindle speed, feed rate, etc.

**Machining process sequence:** a document that defines the sequence of machining operations or the sequence of machining features to be machined.

**Machining resources and part setups:** documents that contain the following information: 1) form and functional information of available machine and tooling equipment including dimensions and shape of the equipment, dimensional variation distributions of machined features, machine speeds versus powers, work volume, fixture rigidity and versatility, machine controller descriptions, cutter descriptions, adapter descriptions, etc. 2) a specification of locations and orientations of the part relative to the machine coordinates and the means of fixing the part on the machine table during the machining process.

**Machining tolerance specifications:** tolerances defined in process planning for the intermediate features. These are derived from target tolerances for the part features by the process planners.

**Material stock specifications:** a document that specifies the form and properties of chosen material stock.

**Measurand:** a quantity intended to be measured.

**Measurement accuracy requirements:** a document that specifies the process-dependent requirements of measurement accuracy. Measurement accuracy is the closeness of agreement between a value obtained by measurement and the true value of the measurand.

**Measurement commands:** computer-interpretable codes that control measurement machines or a measurement device that is linked with a machining centre.

**Measurement features, measurands, and uncertainties:** a document that specifies measurement features, measurands, and measurement uncertainties (refer to each of the terminology definitions).

**Measurement features:** zones on the part to be measured. The zones have specific geometries, locations, and orientations relative to the part.

**Measurement fixture and setup information:** a specification of setups needed to inspect all the tolerances and dimensions within the measurement scope and all the clamping devices that are needed in all the setups.

**Measurement method:** a document that specifies the methods that will be used to fulfill the requirements in measuring a part.

**Measurement operations:** a set of actions that a measurement tool/device does to measure the part during measurement processes.

**Measurement path:** a document that specifies the path/route that the measurement sensor or gages follow during measurement processes.

**Measurement plan:** a document that defines the sequence of operations for measurement based on the product model and measurement scope.

**Measurement process plan:** a document that defines detailed plan for a measurement process. It may include high-level measurement information such as measurement feature and operation sequence and/or low-level measurement information such as measurement device information, measurement points and path, etc.

**Measurement requirement:** required instructions for inspecting manufactured parts including tolerances and dimensions to be verified and acceptable pass/fail errors.

**Measurement results:** data collected through measurement process including at least raw data points and possibly some preliminary results of analysis.

**Measurement scope:** a document that specifies the tolerances and dimensions on a manufactured part that need to be verified by measurement. It includes fail error specifications, traceability requirements and measurement tasks (refer to definitions of these terminologies).

**Measurement uncertainty:** parameter that characterizes the dispersion of the quantity values that are being attributed to a measurand.

**Measurement tasks:** a document that contains specific measurands to verify tolerances/parameters or establish datum features. It also specifies tasks that are to be performed to evaluate each measurement requirement.

**Modified measurement features:** measurement features that are modified after feature interaction detection.

**Process plan:** documents that define the sequences of operations for machining and measuring the part based on the product model.

**Process plan update:** information fed back to process planning activities to improve the machining and measurement process.

**Process-intermittent update:** the updates generated after in-process measurement that are fed back to machining process planning activities requesting changes to the subsequent process/operation plans.

**Process schedule and adjustment:** information fed back from production planning and scheduling activities requesting changes or adjustments to the current machining and/or measurement plan. The requests can be modifications of machine and tooling specifications, procedural changes, etc.

**Product conformance result:** the result obtained after measurement result analysis activity that records whether the product meets specified quality and/or functional requirements.

**Product definition:** computer-interpretable representation of a part. The representation provides the following information about the part: geometry, topology, features, dimensions, tolerances, datum references, material, surface roughness, hardness, coatings, screw threads, and notes on special processing and quality control procedures.

**Production schedule:** documents that specify the production schedule to maximize the efficiency of manufacturing operations and reduce costs. It includes information such as when to make the product, on what machining center, how many parts to make, etc.

**Raw materials:** raw stock material selected for the current manufacturing process.

**Sampling plan:** a document that specifies point locations and densities for measuring all the measurement features. On the part level, a sampling plan describes the frequency of measuring manufactured parts or the quantity of parts to be measured in a batch.

**Sampling statement:** a qualitative statement that specifies sampling rate and sampling size.

**Sampling strategy:** a document that specifies the number of points, point distributions and densities for measuring different types of measurement features.

**Sensor specifications:** a document that contains specific and/or classes of sensors that are needed to perform measurement

**Traceability requirements:** a document that specifies traceability requirements for measurement processes. Traceability is a property of a measurement result relating the result to a stated metrological reference through an unbroken chain of calibrations of a measuring system or comparisons, each contributing to the stated measurement uncertainty.

## 4. Conclusions

The machining and measurement activity model described in this paper has been developed as part of an effort to improve interoperability in manufacturing systems. The effort is on identifying common activities in machining and measurement process planning systems as well as manufacturing execution, analysis and reporting systems. The purpose is to capture the information required for each activity and the information exchange between these activities. This activity model was specially developed to provide a broad view for standards developers and industry experts. Ideally, measurement process planning should be carried out as an integrated element in manufacturing systems and should be connected with machining process planning systems so that measurement

operations can be planned at desirable stages during a machining process. In this way, machining processes are closely monitored through in-process measurement. Measurement results can, therefore, be analyzed in a real-time fashion and updates can be fed back to improve machining processes.

However, today's machining and measurement process planning are largely carried out separately in industry. Machining process planning departments are not getting quick response or feedback from quality control department. The information exchanges are mostly manual and on paper. The main reason for this situation is that there is no standardized data model to provide sufficient information for machining and measurement process planning systems. Standards committees that are in charge of developing standards for machining and measurement are working in their own area with very limited communication with each other. Through this activity model, it can be seen that a lot of information is shared among process planning (including both machining and measurement process planning systems), execution, analyzing and reporting systems. However, the common information is defined differently in multiple standards and/or proprietary specifications. In order to improve interoperability in manufacturing systems, especially between software systems, these common information definitions need to be harmonized. This paper summarized existing standards and/or specifications for the information exchange at different stages of manufacturing processes.

The next phase to improve manufacturing systems interoperability is to harmonize existing standards and data models for the common information identified in this activity model. Work such as defining a common data model for the entire dimensional metrology process including measurement process plan, measurement execution, measurement result collection and analysis is under way.

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