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A production management information model for discrete manufacturing

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Abstract. The Manufacturing Systems Integration (MSI) project at the National Institute of Standards and Technology is developing a system architecture that incorporates an integrated production planning and control environment. The development of this architecture includes the definition of information models describing the information which needs to be shared among production management systems (production planning, scheduling and control systems) in order to achieve the integration of manufacturing systems. This paper presents the production management information model within the MSI project. The main focus of the model is to identify and characterize the relationships between orders and workpieces, to identify the information necessary to achieve workpiece tracking and to identify the information necessary to achieve resource requirements specifications for process plans.

1. Introduction

The nature of the state-of-the-art manufacturing shop floor has undergone many transitions in the last decade. The dramatic drop in the cost of computer technology is changing fundamental assumptions which underlaid earlier system designs. Centralized systems, based upon the need to share the sizeable investment in a single computer, are giving way to distributed systems, enabling localized, more reactive implementations. Automation, once seen as a means of increasing repeatability and reducing boredom or hazards, is no longer a luxury but an economic necessity for the survival of many industries.

Many of the early challenges for automation fell under the classification of robotics research. Information technology, in contrast, was not as much of an issue in the manufacturing domain as it was in business and financial circles. However, with the increasing levels of automation being introduced in today's manufacturing factories, the need for explicit unambiguous production information is rising dramatically. Whereas in the past much of the complexity of this information was carried in the

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manufacturing professional's head, today's applications require all the semantics to be explicitly represented. The magnitude of this challenge is perhaps best exemplified by the ongoing standardization effort under International Organization for Standardization† (ISO) Technical Committee (TC) 184–Subcommittee (SC) 4‡ known as the Standard for the Exchange of Product Model Data (STEP) (ISO 1992).

All these developments point to the need for integration of formerly separate manufacturing functions and emphasize the fact that the nature of information which must be shared by these functions is extremely complex. This paper describes work performed at the National Institute of Standards and Technology (NIST) in the area of information modelling of production management data in discrete manufacturing enterprises. In particular, the reported work addresses some of the information which must be shared between production planning, scheduling and control functions. Section 2 describes the motivation and rationale for defining such an information model. Section 3 provides some background on NIST and its role in manufacturing automation research. Section 4 presents a brief survey of related modelling efforts. Section 5 presents the actual information model. Future work planned in this area is described in Section 5, and conclusions are presented in Section 6.

2. Motivation

Despite the significant progress made in manufacturing automation research over the past decade, it is now apparent that integration is the emerging challenge for today's factories. Indeed, studies have shown that, by 1993, systems integration spending will exceed information technology spending for hardware, software, communications and service for the US Government (FED 1992). One reason for this trend is the lack of generic integration solutions, which then forces manufacturers to adopt custom non-reusable solutions to their integration problems, which tend to be extremely expensive.

2.1. *Barriers to integration*

There are at least three identifiable barriers to achieving an integrated production factory. First, most techniques and tools used to assist in the performance of production functions use specialized and often proprietary representations for the information used. These representations often force manufacturing staff to serve as human interfaces between otherwise automatable functions, with the concomitant introduction of errors, ambiguity and misinterpretation. The second barrier is the lack of support by many systems to communicate with functions outside of their scope, leading to the situation sometimes characterized as 'islands of automation'. This problem is primarily one of conflicting communication protocols. Finally, the lack of consensus on an integrating architecture which describes the behaviour of the system as a whole and thereby constrains the behaviour of supporting subsystems results in subsystems which cannot easily be interconnected even by means of information and protocol translators.

The solution to this problem has historically been to hire a systems integration company to study a given factory and to identify the various representations, protocols and business practices in use. Then, usually at considerable expense, customized approaches are designed to map representations, to translate protocols and otherwise to knit together whatever systems cannot be dispensed with, supplementing them with whatever additional modules may be necessary to achieve the level of integration desired. This approach could be avoided if accepted standards existed to address the problems commonly encountered by the systems integrators.

2.2. *Information modelling as a tool*

There are several obstacles, however, which make the definition of suitable production management information standards difficult. One problem lies in the complexity of the information being standardized. Traditional methods of standardizing such information—in terms of textual descriptions or tables—fail when applied to large, highly interconnected bodies of semantic information. It is precisely in this area that the field of information modelling can help. Nijssen's Information Analysis Methodology (NIAM) (Verheijen and VanBekkum 1982) has its roots in linguistics and strives to provide a rich and yet unambiguous representation of facts (or information). The formal practise of information modelling as a discipline supports the larger field of systems analysis, which encompasses both information and activity modelling. Modern computer-aided software engineering (CASE) tools possess both types of modelling capability, although the information modelling methodologies used by CASE tools are typically less powerful than those such as NIAM.

There are two additional requirements for an effective

† TC184 is titled 'Industrial Automation Systems and Integration'.
‡ SC4 is titled 'Industrial Data and Global Manufacturing Programming Languages'.

information modelling methodology. First, an important process in the development of information models, particularly standard manufacturing information models, is consensus building. The modelling methodology must support easy human communication and interpretation of a model. In practice, this is best accomplished by means of a graphical depiction of the model, and thus the methodology should support a graphical representation. However, the second requirement for large complex models is that the representation of the model be computer interpretable. The ability to compile directly a normative standard information model, using a computer, has proven to be invaluable in efforts such as the STEP standard mentioned earlier. Using such an approach, data dictionaries, database schemas, database access libraries, parsers and report generators can all be generated automatically. Therefore the graphical representation of semantic information should be mappable to some form of computer code which can be compiled.

The discipline of information modelling can thus be thought of as a vital tool for understanding a system, resolving complexity in an unambiguous way, reaching consensus and ultimately supporting implementation of the system, from the information perspective. The focus of this paper is to present the results of such a modelling effort in the domain of factory production management, scheduling and control, but not to describe the modelling methodology itself.

3. National Institute of Standards and Technology

Manufacturing research at NIST has been dominated by the Automated Manufacturing Research Facility (AMRF), funded by both the US Department of Commerce and the Navy Manufacturing Technology programme. It was the AMRF project which launched a serious programme of manufacturing research at the NIST.

3.1. *The automated manufacturing research facility*

The AMRF was established in 1981 to serve as a testbed factory to support research in measurement techniques and computer interface standards that are required for automated machining of parts in small lot sizes. The primary thrust of the project was to establish clear interface specifications and to support modular structures to allow plug compatibility between systems. This plug compatibility both allows a flexible manufacturing environment and offers the capability of incremental automation in existing facilities.

The AMRF was designed around the concept of hierarchical control, where high-level commands were decomposed into sequences of simpler commands at the next lower level in the hierarchy. The simpler commands were in turn decomposed at yet lower levels. Protocols were established to allow command and status information to flow upwards and downwards in the hierarchy. The bulk of data transfer (such as process plans and part models) occurred directly with a distributed data administration system. A mechanism was implemented to allow any controller in the AMRF to request or store information in a generic way, regardless of which database is being used to hold that information (Libes and Barkmeyer 1988). The adoption of such an architecture avoided many potential information bottlenecks. Further, by adopting a hierarchical approach, the complexity of a task was reduced to a manageable level for each controller in the hierarchy. More details on the AMRF can be found in the papers by Simpson *et al.* (1992), Furlani *et al.* (1983), Hocken and Nanzetta (1983), McLean *et al.* (1983), McLean (1985) and Nanzetta (1984).

3.2. *The manufacturing systems integration project*

In 1990, many of the architectural and communication concepts of the AMRF were revisited under the auspices of the manufacturing systems integration (MSI) project. In particular, attention was focussed on how to address error handling and production management in a hierarchical control system. These two topics were understood to be closely related, since errors and other unanticipated events generally affect the production schedule. Some of the results of the MSI work can be found in the papers by Senehi (1991a, b) and Ray (1992).

3.3. *Manufacturing systems integration project goals*

The approach taken within the MSI project was to address three principal goals to enable flexible integration of manufacturing systems. These three goals were the definition of an open architecture which supports both hierarchical control and production management functions, the identification or definition of candidate standard information models needed by all the functions within the scope of the architecture, and the identification or definition of candidate standard communication interfaces among the modules used to carry out the above functions. Thus, rather than attempting to resolve how best to carry out many of these manufacturing functions, the aim of the MSI project was to specify how to integrate these functions. For an overview of the MSI project, see Senehi *et al.* (1992).

This paper addresses one part of the second goal, namely the definition of a candidate standard production management information model, which structures the information needed to support the production functions on a factory shop floor. A complete discussion of the information models developed as part of the MSI project has been given by Barkmeyer *et al.* (1993).

4. Prior and related work

The challenge of defining the information models to support manufacturing production is receiving increasing attention from the manufacturing research and development community. Much of this is due to the increasingly apparent need for such standardized structures as a precursor to integrated manufacturing. Unfortunately, relatively little information is available in the public literature describing the detailed information models which have been developed. One of the motivations of this publication is to address this situation by placing this information model in the public domain.

There is at least some evidence in the literature that work is going on in the information modelling arena, either for its own sake or to support the development of a new manufacturing system or method. Researchers at the University of Massachusetts (Ketcham *et al.* 1988) describe a 'database-centred modelling environment' which '... holds facilities configurations, production requirements, and manufacturing parameters that can be accessed and updated by several planning and control models', Talavage and Barash (1977) at Purdue University worked on explicitly defining both the 'system description' and the 'status vector' for a manufacturing environment. Canzi *et al.* (1989) described both a manufacturing resource categorization and an AND/OR representation for processes, in support of a knowledge-based scheduling system that they developed. Moyne *et al.* (1989) developed an abstract generic entity–relationship information model for process recipe information flow. Chryssolouris and Gruenig (1988) published one of the few explicit manufacturing production models, using the IDEF1X methodology (defined in ICAM (1985)), with a scope similar to that described in this paper. We feel that the current work extends the amount of detail which is modelled and supports additional manufacturing functions such as scheduling, routeing and resource maintenance.

Computer Aided Manufacturing—International, Inc. (CAM-I) is an international industrial consortium long associated with the development of computer integrated manufacturing (CIM) technology. In the early 1980s, CAM-I sponsored a research programme now known as the Intelligent Manufacturing Management Program (IMMP) which also covered some of these areas. Further information can be found in the report by CAMI (1985).

In the national and international standards arena, the need to model manufacturing production information is also coming into the spotlight. ISO TC184/SC4/WG8 is a new Working Group, (WG), colloquially known as 'Industrial Manufacturing Management Data', The charter of this group is to address the 'model, form, and attributes of data exchanged between an industrial manufacturing company and its environment,' data 'to be used by the manufacturing management for the purposes of managing the manufacturing company,' and 'data controlling and monitoring the flow of materials within the ... company from a manufacturing management viewpoint' (ISO 1991). The work reported in this paper will be submitted to WG8.

Finally, a number of commercial production management systems are available, each of which contains some sort of embedded data model to support work and order tracking, etc. It is the hope of the present authors that ultimately a standard model will be adopted by the various commercial vendors and thus one of the major barriers to plug compatibility between such systems will be overcome. It should be noted that a significant fraction of the information appearing in the model presented here is already supported in one form or another within most commercial production management systems. Thus, for that portion of the information, the adoption of a standard model would only require a mapping of previous representations to the standard representation, without altering the functionality of the system.

5. The manufacturing systems integration production management information model

The intention of the model presented in this paper is to capture all shared information necessary to support production management functions—order entry, planning (batching, resource allocation and scheduling), factory configuration and control—in the context of discrete part manufacturing. The model attempts to merge the viewpoints of the functions listed above to provide a neutral perspective, at least with respect to those functions. This section presents a detailed walk through of the production management information model that supports the MSI architecture. Each entity is defined, its attributes are enumerated and defined, and its relationships with other entities in the model are discussed.

The model's focus on shared information neither precludes the existence of private data that may be necessary to perform any of the production management functions

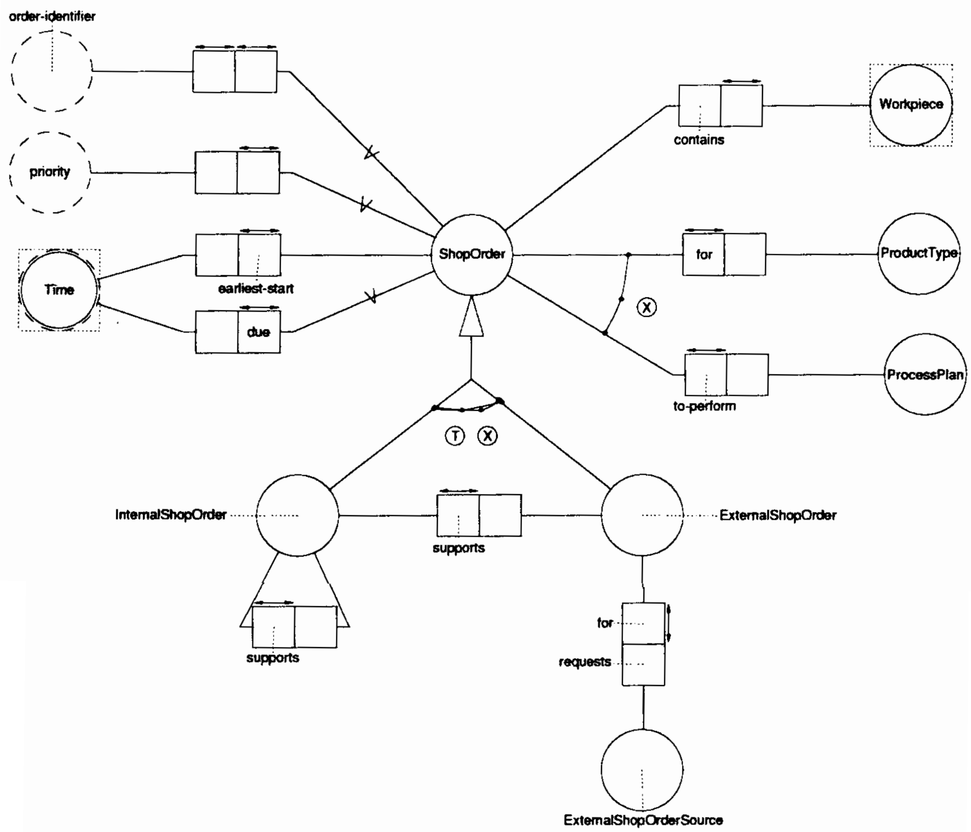

Figure 1. Shop orders.

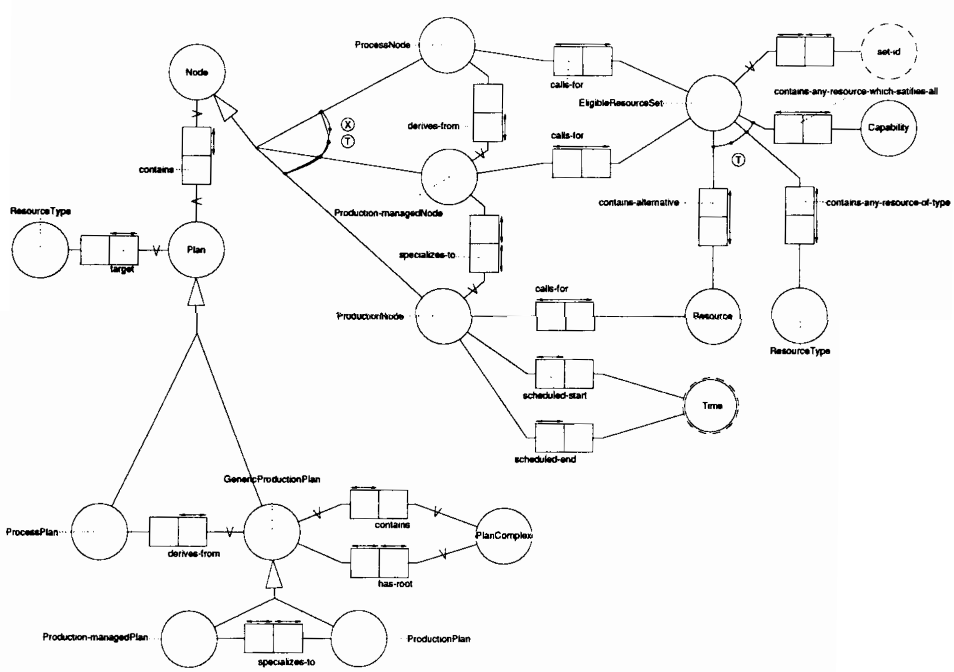

Figure 2. Plans and nodes.

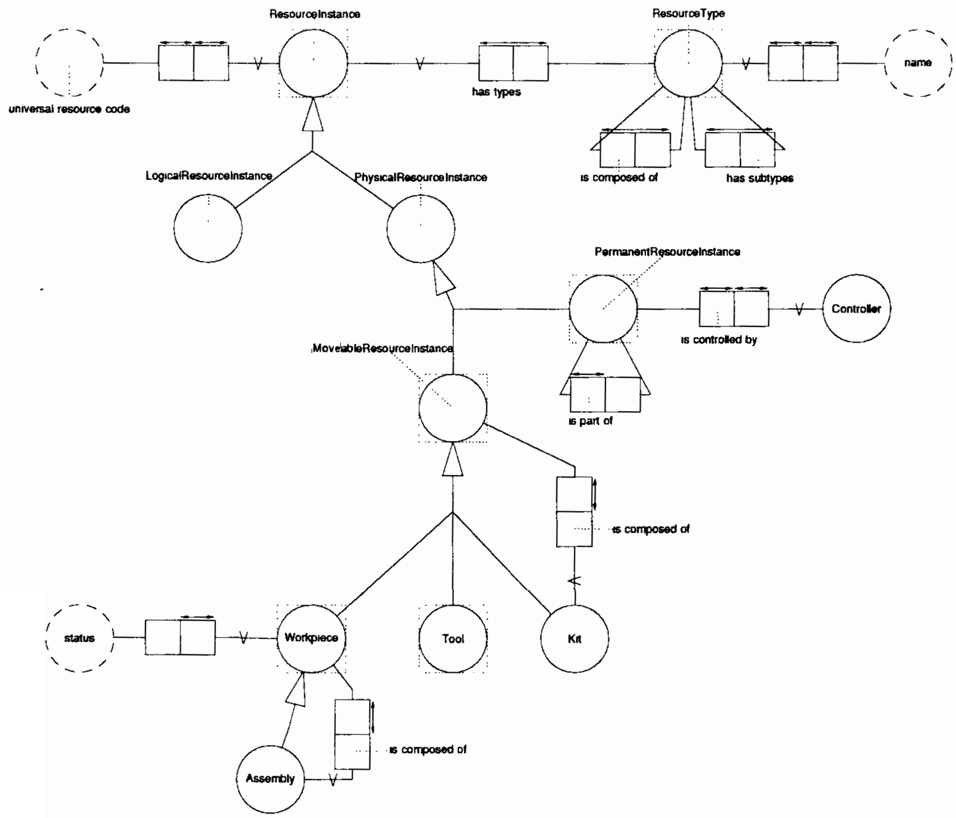

Figure 3. Resources.

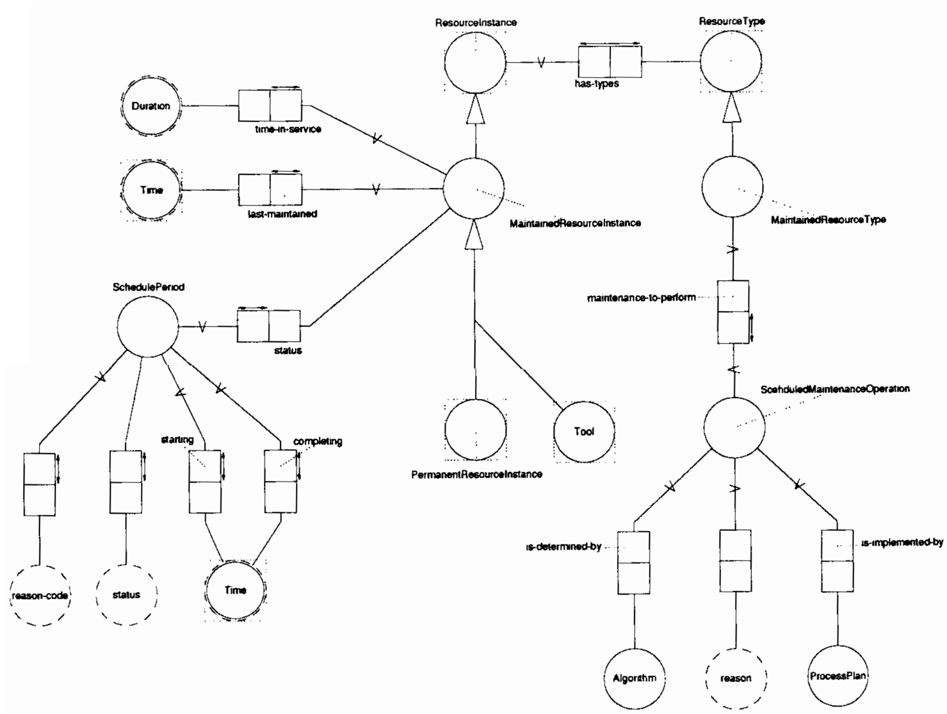

Figure 4. Maintained resources.

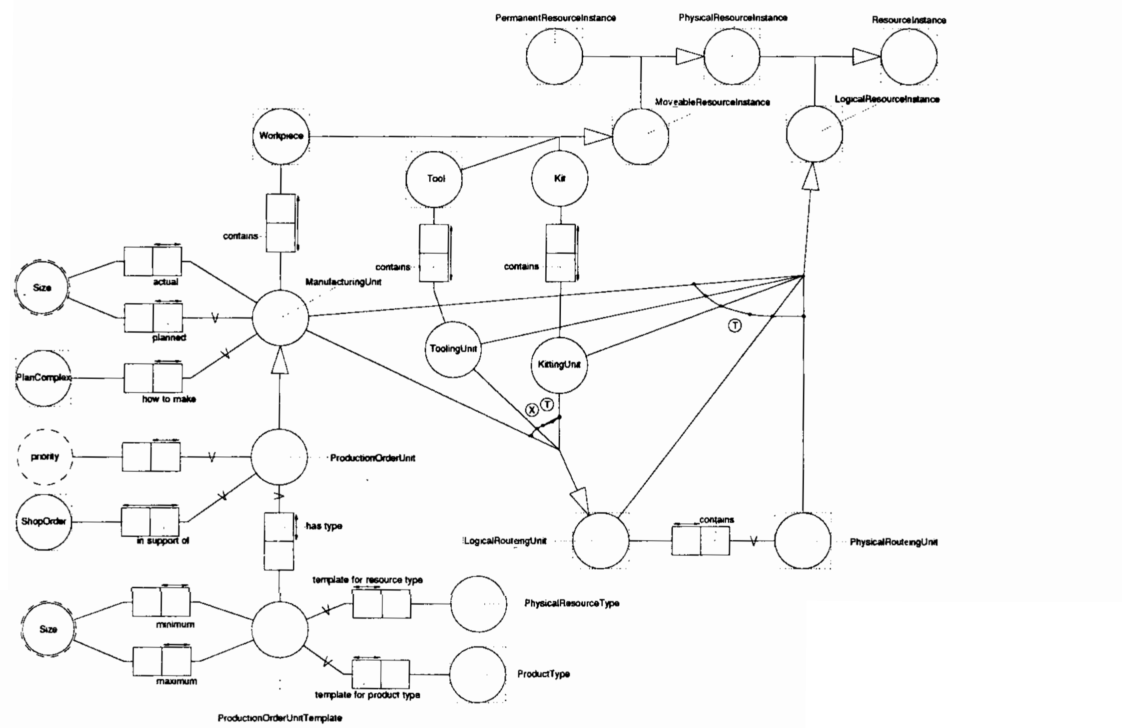

Figure 5. Logical resources.

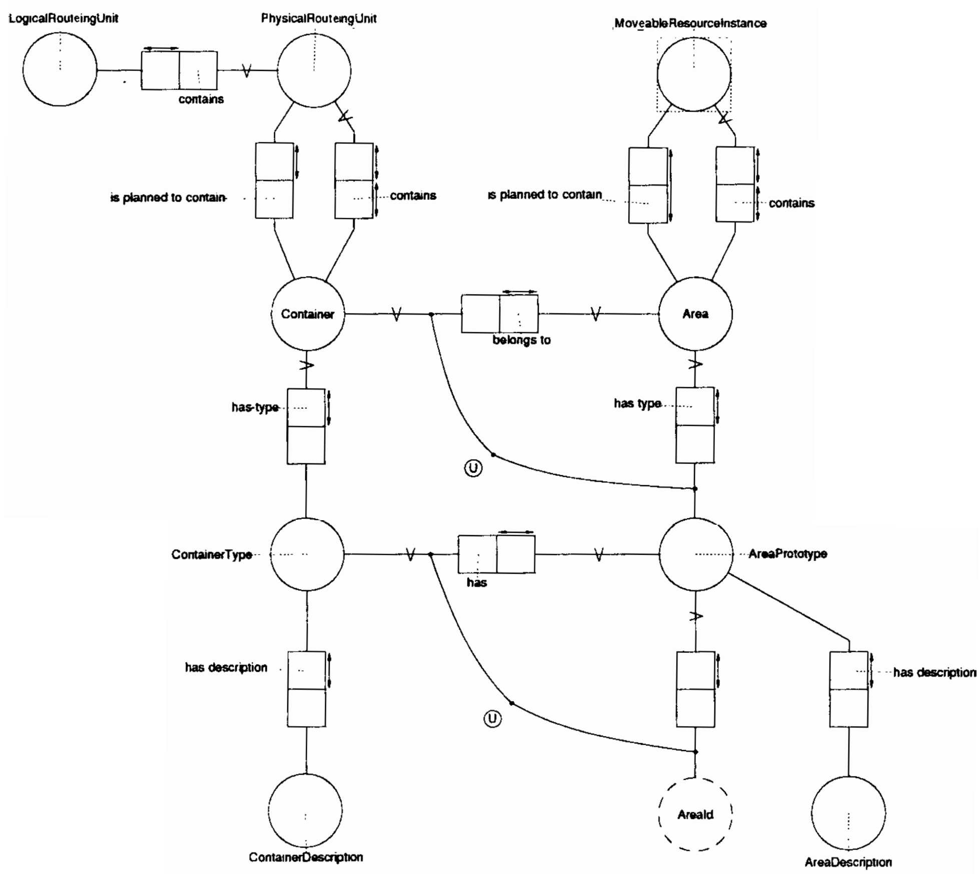

Figure 6. Material handling resources.

nor implies or specifies any policy or procedures on when this information is generated or used. Section 5.2 discusses a few scenarios describing when and how the information presented in this information model might be used.

Figures 1–6 depict the information model using the NIAM representation. The reader is referred to the Appendix for assistance in reading NIAM information models. To aid the reader in correlating the textual description of the information model with the NIAM diagram, entities which appear in the information model are capitalized (e.g. Shop Order). Table 1 lists each entity contained in the model, which figure(s) it is contained in, and what subsection within Section 5.1 defines and discusses it.

Table 1. Entities within the production management model.

Entity name	Relevant figure	Section defined in
Area	Figure 6	5.1.6
Area Prototype	Figure 6	5.1.6
Assembly	Figure 3	5.1.3
Container	Figure 6	5.1.6
Container Type	Figure 6	5.1.6
Controller	Figure 3	5.1.3
Eligible Resource Set	Figure 2	5.1.2
External Shop Order	Figure 1	5.1.1
External Shop Order Source	Figure 1	5.1.1
Generic Production Plan	Figure 2	5.1.2
Internal Shop Order	Figure 1	5.1.1
Kit	Figures 3 and 5	5.1.3
Kitting Unit	Figure 5	5.1.6
Logical Resource Instance	Figures 3 and 5	5.1.5
Logical Routeing Unit	Figures 5 and 6	5.1.6
Maintained Resource Instance	Figure 4	5.1.4
Maintained Resource Type	Figure 4	5.1.4
Manufacturing Unit	Figure 5	5.1.5
Moveable Resource Instance	Figures 3, 5 and 6	5.1.3
Node	Figure 2	5.1.2
Permanent Resource Instance	Figures 3–5	5.1.3
Physical Resource Instance	Figures 3 and 5	5.1.3
Physical Routeing Unit	Figures 5 and 6	5.1.6
Plan	Figures 2	5.1.2
Plan Complex	Figures 2 and 5	5.1.2
Process Node	Figure 2	5.1.2
Process Plan	Figures 1, 2 and 4	5.1.2
Product Type	Figures 1 and 5	(ISO 1992)
Production Node	Figure 2	5.1.2
Production Order Unit	Figure 5	5.1.5
Production Order Unit Template	Figure 5	5.1.5
Production Plan	Figure 2	5.1.2
Production-managed Node	Figure 2	5.1.2
Production-managed Plan	Figure 2	5.1.2
Resource Instance	Figures 2–5	5.1.3
Resource Type	Figures 2–4	5.1.3
Scheduled Maintenance Operation	Figure 4	5.1.4
Schedule Period	Figure 4	5.1.4
Shop Order	Figures 1 and 5	5.1.1
Tool	Figures 3–5	5.1.3
Tooling Unit	Figure 5	5.1.6
Workpiece	Figures 1, 3 and 5	5.1.3

5.1. *Presentation of the manufacturing systems integration production management information model*

The production management information model addresses two major areas of production management information requirements: the information necessary for workpiece tracking, and the information necessary to specify resource requirements within process plans. As a result, a large portion of the information model centres around the attributes of and relationships between Shop Orders, Plans and Nodes, Resources, Maintained Resources, Logical Resources and Material-handling Resources.

5.1.1. *Shop Orders*

A Shop Order is any order that causes activity to occur within a shop; most Shop Orders will cause manufacturing to occur. There are two types of Shop Order: Internal Shop Orders and External Shop Orders. An External Shop Order is an order that originates outside the shop and, as such, has an External Shop Order Source associated with it. An External Shop Order Source designates the external entity which causes the existence of an External Shop Order (e.g. a customer, or another shop within the factory). An Internal Shop Order is an order that originates from either an External Shop Order or another Internal Shop Order (e.g. an order to make a fixture in support of some other order). The information that is needed for each Shop Order (Internal and External) is an order identifier to identify uniquely each order within the shop, the priority of the order, a due date specifying when that order should be completed, and an earliest start time for initiating the order. In addition, each Shop Order that causes manufacturing to occur within the shop needs to specify the Product Type to manufacture, the quantity to manufacture, and the set of Workpieces (ultimately to become Final Products) associated with the order. It is not necessary (but possible) to associate specific Workpieces with each Shop Order prior to or during the manufacturing process; that relationship can be determined after manufacturing has completed.

5.1.2. *Plans and Nodes*

A Plan is a recipe for performing a procedure; it contains a set of Nodes (or steps) which provide sequencing information and detail how to perform each operation. Every Plan has an associated target Resource Type which specifies the Resource Instance(s) which may execute that Plan. There are three types of Plan: Process Plans, Production-managed Plans and Production Plans. A Process Plan is a generic recipe describing how to carry out some procedure in support of the production of some number (usually one) of Products defined by a Product Type. A Production-managed Plan is an expansion of a Process Plan which supports the production of a required number of products using a given factory configuration. A Production Plan is a refinement of a Production-managed Plan which adds resource allocation and scheduling information. A Plan Complex is a collection of Production-managed or Production Plans, one of which is labelled the root Plan; all other Plans in the Plan Complex are referenced directly or indirectly by the root Plan. In addition, all Plans in a Plan Complex refer to the same target Resource Instance or Resource Type.

There are three types of Node which parallel the three types of Plan: Process Plan Nodes, Production-managed Plan Nodes and Production Plan Nodes. A Process Plan contains only Process Plan Nodes. A Production-managed Plan contains only Production-managed Plan Nodes. A Production Plan may contain any combination of Production-managed Plan Nodes and Production Plan Nodes (depending on whether scheduling or rescheduling is currently being performed). Since a Production Plan contains resource allocation and scheduling information, Production Plan Nodes may have a scheduled start and completion time and may refer to specific Resource Instances.

A Node must detail not only how to perform a specific operation but also the resources necessary to perform that operation. Any given operation may require Resource Instances with a specific Capability (e.g. three-axis milling), Resource Instances of a specific Resource Type (e.g. three-axis milling machine), specific Resource Instances (e.g. three-axis milling machine 076X3A), or any combination. Production Plan Nodes necessarily refer to Resource Instances since resource allocation has already been performed. Process Plan Nodes and Production-managed Plan Nodes refer to some number of Eligible Resource Sets. The number of Eligible Resource Sets that are associated with a Node is the same as the number of Resource Instances that are to be associated with the corresponding Production Plan Node; each Eligible Resource Set abstractly or concretely describes a single required Resource Instance. An Eligible Resource Set may abstractly describe a Resource Instance by specifying a set of Capabilities, *all* of which the Resource Instance must satisfy, or by specifying any number of Resource Types, at least *one* of which the Resource Instance must be a member of. An Eligible Resource Set may concretely describe a Resource Instance by specifically identifying a set of Resource Instances, *one* of which must be chosen. An Eligible Resource Set has a unique identifier and may be referred to by any number of Nodes in any number of Plans.

5.1.3. *Resources*

A Resource Instance is characterized by membership in some number of Resource Types. The modelling of Resource Types is outside the scope of this paper. A first step in characterizing a resource taxonomy and resource aggregation is provided via the relationships 'has subtypes' and 'is composed of' (see Figure 3.). Future work will address a more complete characterization of Resource Types including their behaviour and constraints.

Each Resource Instance has a universal resource code which uniquely identifies it. Resource Instances have additional characteristics which may be necessary for non-production management functions (e.g. process planning or maintenance); such information is beyond the scope of this paper. Resource Instances can be categorized into two major types: Logical Resource Instances and Physical Resource Instances. Logical Resource Instances are pieces of information that are created to aid and assist the production management and control functions; in general, they represent collections of Physical Resource Instances. All other Resource Instances are Physical Resource Instances and have some type of physical realization (e.g. trays, milling machines, sand and electricity). There are two types of Physical Resource Instance: Permanent Resource Instances and Moveable Resource Instances. Permanent Resource Instances are either resources that are not expected to change locations during manufacturing processes (e.g. workstations on the shop floor such as machine tools, fixed robots and storage devices), or resources that do not require assistance to change their location (e.g. automated guided vehicles, and humans). Some Permanent Resource Instances are automated and may have a Controller associated with them.

Moveable Resource Instances include all Physical Resource Instances that are not permanent and include such resources as Tools, Kits, Workpieces and Assemblies. Tools are Resource Instances that do not become part of the Final Product. Kits are groupings of *related* Tools and Workpieces (e.g. fixtured Workpiece, a group of Workpieces and the Tools necessary to perform a specific operation on those Workpieces). Workpieces are Resource Instances that become part of the Final Product. Each Workpiece has status information which denotes the state of the Workpiece. This status is modified by controllers during the manufacturing process if the Workpiece is damaged or its status is unknown (needs to be inspected to determine its status). Assemblies are complex Workpieces which are composed of other Workpieces.

5.1.4. *Maintained Resources*

All Permanent Resource Instances and Tools are also Maintained Resource Instances. A Maintained Resource Instance is a resource for which availability and maintenance information is needed. For each Maintained Resource Instance, information is needed about when that Resource last underwent maintenance, and how long that resource has been in service. For example, a machine tool may have undergone maintenance 2 months ago, and its time in service (actual processing time) may be 200 h. Both pieces of information are useful for determining when that resource should undergo further maintenance. For each Maintained Resource Instance it is necessary to capture both its current and future status (classified by 'reason code') and the interval for which that status is valid. In the information model this is represented as a Schedule Period. Maintained Resource Instances have a corresponding Maintained Resource Type. A Maintained Resource Type will have an associated set of Scheduled Maintenance Operations. Each Scheduled Maintenance Operation will specify not only the type of maintenance that will need to be performed on every instance of that type but also an algorithm for determining when that type of maintenance will need to be performed and a Process Plan detailing how to perform the maintenance.

5.1.5. *Logical Resources*

A Logical Resource Instance is a piece of information that is created to aid and assist the production management and control functions. A Logical Resource Instance is associated with a set of Moveable Resource Instances that are grouped together during some portion of a manufacturing process. There are six types of Logical Resource Instance: Manufacturing Units, Production Order Units, Tooling Units, Kitting Units, Logical Routeing Units and Physical Routeing Units. Logical Resource Instances may exist for all controllers in a control hierarchy.

A Manufacturing Unit is associated with a set of Workpieces that are logically grouped for manufacturing purposes for some portion of the total manufacturing life cycle. Each Manufacturing Unit has a planned and actual size (number of Workpieces in that Manufacturing Unit) and refers to each Workpiece instance that is contained in the Manufacturing Unit. In addition, each Manufacturing Unit is associated with a Plan Complex which details, at a given level of control, the steps to manufacture the planned quantity of Workpieces in that Manufacturing Unit.

A Production Order Unit is a type of Manufacturing Unit and therefore also has a planned and actual size, refers to each Workpiece instance that is contained in the Production Order Unit and is associated with a Plan Complex which details the steps to manufacture the planned quantity of Workpieces in that Production Order Unit. In addition, a Production Order Unit has an associated priority which is used during scheduling. A shop Production Order Unit is, logically, the set of all Workpieces of a given Product Type which will be tracked as a group throughout its *entire* manufacturing life cycle. A shop Production Order Unit partially or completely fulfils one or more Shop Orders.† A work cell (or equipment) Production Order Unit is, logically, the set of all Workpieces of a given Product Type which will be tracked as a group during a contiguous portion of manufacturing by a given work cell (or equipment). In general, the size of Production Order Units and Manufacturing Units is constrained by resource capacity (e.g. physical buffer size) of the different machines in the factory that must operate on the Workpieces contained in the Production Order Units and Manufacturing Units. Each Production Order Unit has a corresponding Production Order Unit Template which takes into consideration these constraints. A Production Order Unit Template exists for each combination of Physical Resource Type and Product Type. A Production Order Unit Template specifies the minimum and maximum number of Workpieces (of a given Product Type) that a Production Order Unit (for a given Physical Resource Type) may contain. Future work will generalize this concept to include other resource constraints which depend on the Product Type.

5.1.6. *Material-handling resouces*

Logical Routeing Units and Physical Routing Units relate to material-handling processes. A Physical Route-

† It should be noted that the mapping from Shop Orders (which represent external tracking of manufacturing requests) and Production Order Units (which represent internal tracking of manufacturing requests) may include aggregation or disaggregation. In other words, several Shop Orders may be fulfilled by the manufacturing of a single shop Production Order Unit (aggregation), a single Shop Order may be fulfilled by the manufacturing of several shop Production Order Units (disaggregation), or several Shop Orders may be partially fulfilled by the manufacturing of a single shop Production Order Unit (aggregation *and* disaggregation).

ing Unit is a Logical Resource Instance that represents the set of Moveable Resource Instances that make up the contents of some Container. The Moveable Resource Instances that the Physical Routeing Unit represent may be related (i.e. part of the same material-handling request) or not (i.e. not part of the same material-handling request, but coincidentally collocated). A Logical Routeing Unit is a Logical Resource Instance which is associated with a set of *related* Moveable Resource Instances that are to be routed as a group through some portion of the shop. A Physical Routeing Unit contains one or more Logical Routeing Units and a Logical Routeing Unit is part of no more than one Physical Routeing Unit. For example, a tray (type of Container) may contain three widgets and five gadgets. The three widgets may be *en route* to a specific cleaning and deburring workstation to be deburred and the five gadgets may be *en route* to the same cleaning and deburring machine to be washed. All these workpieces are in the same tray because it is convenient for the material-handling system to deliver them to the workstation at the same time. The Physical Routeing Unit is the collection of the three widgets *and* the five gadgets, because all eight Moveable Resource Instances are physically in the tray at the same time. There are two Logical Routeing Units; the three widgets comprise one Logical Routeing Unit and the five gadgets comprise another Logical Routeing Unit.

To understand better the relationships between Production Order Units, Manufacturing Units and Logical Routeing Units, consider the following example (Figure 7). There is a Shop Order to make 24 widgets. A widget is designed to be a part blank with a hole in the middle. The Process Plan for making a single widget contains the following sequence of manufacturing steps: deliver to mill, mill hole, deliver to deburr, deburr hole, and deliver to inventory. The milling work cell has a buffer capacity of eight widgets. The deburring work cell has a buffer capacity of four widgets. The material-handling work cell uses an automated guided vehicle (AGV), and a tray with a capacity of ten widgets. Given this factory configuration, there will be a single shop Production Order Unit for this Shop Order which will contain the set of all 24 Workpieces (widgets). Because of the buffer capacity of the milling work cell, there will be three shop Logical Routeing Units for the first material-handling operation, each containing eight Workpieces (because the material-handling work cell has a capacity greater than eight Workpieces, it may choose to put additional Workpieces from other jobs on the tray). There will be three shop Manufacturing Units for the milling operation, each containing eight Workpieces; each shop Manufacturing Unit will correspond exactly to a Production Order Unit of the milling work cell. There will be six

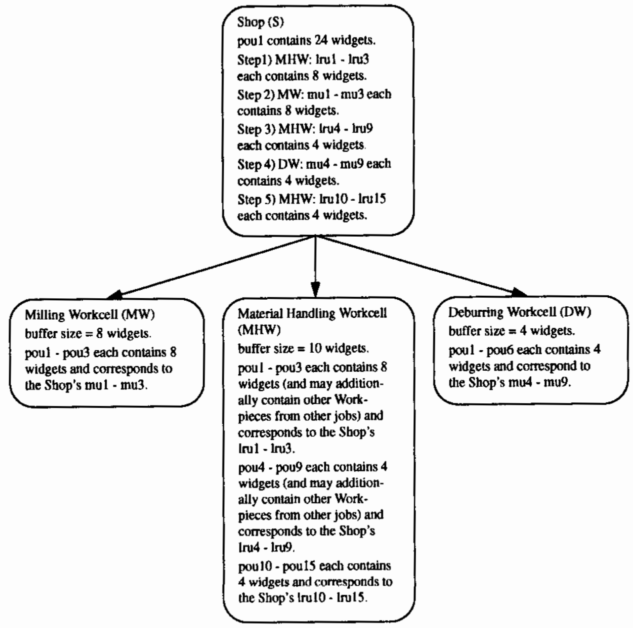

Figure 7. Example of the manufacture of 24 widgets. The Process Plan to manufacture one widget is as follows.

Step 1 Deliver to milling work cell.
Step 2 Mill hole.
Step 3 Deliver to deburring work cell.
Step 4 Deburr hole.
Step 5 Deliver to inventory.

shop Logical Routeing Units for the second material-handling operation, each containing four Workpieces (because the material-handling work cell has a capacity greater than four Workpieces, it may choose to put additional Workpieces from other jobs on the tray). There will be six shop Manufacturing Units for the deburring operation, each containing four Workpieces; each shop Manufacturing Unit will correspond exactly to a Production Order Unit of the deburring work cell. There will be six Logical Routeing Units for the final material-handling operation, each containing four Workpieces.

A Tooling Unit is associated with a set of Tools which are required to perform a manufacturing step on at least one instance of a given Product Type. A Kitting Unit is associated with a set of Kits which are logically grouped together for manufacturing purposes for some portion of the total manufacturing life cycle.

The key to workpiece tracking is not only knowing which Workpieces belong to which Shop Orders, but also *where* the Workpieces are at all times. Each Moveable Resource Instance (e.g. Workpiece) is logically contained in some Container. Examples of Containers include trays, robot grippers and machine tool vises. Each Container is subdivided into one or more Areas. Each Area

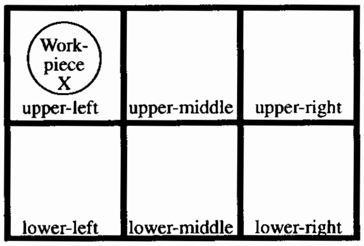

Figure 8. Tray 93382 is a Container having a Container Type of 3 ft by 2 ft Tray.

is defined to contain no more than a single Moveable Resource Instance. The subdivisions of a Container may be physical or conceptual. For example, a tray may be physically partitioned to have nine Areas, or it may be conceptually partitioned with no physical barriers. Furthermore, a Container may have several different conceptual partitionings. Some Containers may have only a single Area (e.g. robot gripper). Each Container belongs to a Container Type. Each Container Type is associated with some number of Area Prototypes which identify and describe the different partitions of Containers of that type. A specific Area Prototype of a given Container Type will uniquely identify the corresponding Area of a Container of that Container Type. For example, there is a Container Type called a '3 ft by 2 ft Tray' (Figure 8), It has six associated Area Prototypes, identified as follows: upper left, upper middle, upper right, lower left, lower middle and lower right. Tray 93382 is a 3 ft by 2 ft Tray. Therefore it has six Areas, each of which is identifiable by the Tray and the Area Prototype Identifier. The location of a given Workpiece X could be 'the upper left Area of Tray 93382'.

5.2. *Information model flexibility*

Although the production management information model rigidly defines the information that is shared between production management systems, it remains flexible by not only allowing organizations to extend the information model to incorporate domain specific and policy- or procedure-related information but also allowing the organization to determine *when* the relationships between different entities in the information model are established.

In particular, this allows flexibility in supporting external workpiece tracking (which Workpieces belong to which Shop Orders). External Workpiece tracking is achieved by establishing the relationships between Shop Orders, Production Order Units and Workpieces; *when* these relationships are established determines the accuracy of external workpiece tracking. Some organizations require that Workpieces always be associated with a Shop Order and that Workpieces cannot switch between Shop Orders. In this case, the relationships between Shop Orders, Production Order Units and Workpieces need to be established early in the manufacturing life cycle and will undergo few, if any, changes. Other organizations may require that Workpieces always be associated with a Shop Order, but that Workpieces can switch between Shop Orders in order to meet deadlines. In this case, the relationship between Shop Orders and Production Order Units needs to be established early in the manufacturing life cycle, but the relationships between Shop Orders and Workpieces may be deferred. Other organizations may have absolutely no requirements about tying Workpieces to Shop Orders during the manufacturing life cycle but require that knowledge after the manufacturing is complete. In this case, the relationships between Shop Orders, Production Order Units and Workpieces may be deferred until the end of the manufacturing life cycle, when a Workpiece would be assigned to a given Shop Order.

6. Future work

The production management information model presented in this paper is an initial attempt at modelling the information necessary on the factory shop floor during manufacturing. Because of the highly interconnected nature of this information, however, a few portions only of the information model have been identified. These include the resource class (Resource Type) and instance (Resource Instance) taxonomy, configuration definition and status information (Controller), design information needed during manufacturing (Product Type and Product Aspect), and a process plan information model (Plan and Node).

The resource class information model will provide a taxonomy of fixed resources (e.g. the workstations and equipment on the shop floor), moveable resources (e.g. workpieces, tooling and fixtures), raw stock (e.g. part blanks) and logical resource templates (e.g. templates for logical groupings of physical resources). Information included in this information model will allow for the specification of physical characteristics of all resource classes (e.g. dimensions, weight and manufacturer), capability information needed for process planning, and physical constraint information needed for production planning and scheduling (e.g. maximum buffer size, and number of spindles).

The resource instance information model will contain the resource instance information which differs from instance to instance (e.g. physical location on the shop floor for fixed resource instances, location for moveable resource instances, availability information, and remaining life for consumable resource instances).

The process plan information model will contain the necessary information for specifying process plans, including support for task decomposition, synchronization, alternatives, iteration, sequencing, concurrency and parallelism. Several efforts are currently under way to develop a process plan information model, including the ISO process plan model being worked on within ISO TC184 SC4/WG3/P11, and ALPS (Catron and Ray 1991, Ray 1992).

The configuration definition information model will contain the information necessary to define a control hierarchy and static controller information. The configuration status information model will contain the current status information about controllers which are in an instantiated control hierarchy.

Some design information is necessary during manufacturing, such as geometries, dimensions, shape, weight and tolerance information. This information is necessary for material handling (e.g. dynamic path planning, collision avoidance, and for determining grasp locations and orientations) and quality assurance applications during manufacturing (e.g. in-process monitoring, post-process gauging, tolerancing and inspection). The primary effort currently addressing this information is STEP (ISO 1992).

The information modelling effort within the MSI project is an ongoing process. Current areas of focus include refining ALPS, defining the configuration definition and status information model and integrating both into the production management information model.

7. Conclusion

The MSI production management information model is our first attempt at identifying the information that is needed by production management systems (order entry, planning and control). Its main focus is identifying and characterizing the relationships between orders and workpieces, identifying the information necessary to achieve workpiece tracking and identifying the information necessary to achieve resource requirements specifications for process plans. There is still much work to be done in the information modelling of manufacturing information in order to achieve a generic solution to the integration of production management systems and offer the hope of truly plug-compatible systems.

Acknowledgement

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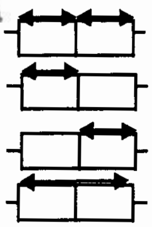
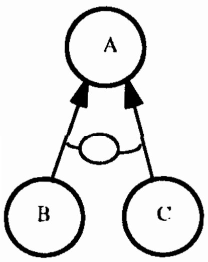
Appendix. Nijssen's information analysis methodology representation

This appendix provides a key for reading information models represented in NIAM in tabular form.

Symbol	Meaning
	A *non-lexical object type* (NOLOT) with name 'nolot name' represents a class of real world entities each of which is represented in the system (e.g. *Person* is a NOLOT)
	A NOLOT which appears in multiple places with an information model
	A *lexical object type* (LOT) with name 'lot name' represents a class of characters, strings, numbers, etc., used to name or describe some aspect of an object (NOLOT) (e.g. *Social Security Number* is a LOT)
	A LOT–NOLOT with name 'lot–nolot name' represents an abstract class of characters, strings, numbers, etc., which has internal form but is only used to name or describe some aspect of an object (NOLOT) (e.g. *Date* could be a LOT–NOLOT, used to denote a *person's* date of birth)
	A LOT–NOLOT which appears in multiple places within an information model.

(*continued*)

Symbol	Meaning
 one-to-one; many-to-one; one-to-many; many-to-many	Represents a relationship between two NOLOTS, a NOLOT and a LOT–NOLOT, or between a NOLOT and a LOT. Each half of the box is referred to as a *role*. Each role can have a multiplicity factor, represented as an optional arrow over the role. The arrow indicates uniqueness. An arrow over each of the roles designates a one-to-one relationship between the two objects participating in the relationship. An arrow over only a single role designates a one-to-many relationship between the two objects participating in the relationship. A single arrow over both roles designates a many-to-many relationship
	Subtype. This special symbol for a binary relationship type—called an 'is a' or subtype link—is used whenever a NOLOT 'is a' subtype of another NOLOT: A 'is a' subtype of B. For example, a *male* 'is a' (subtype of a) *person*. In the diagram, every B 'is a' A
 Ⓣ	Totality. Any instance of NOLOT A must also be an instance of either NOLOT B or NOLOT C. For example, every *person* must be either a *male* or a *female*. Therefore there is a totality constraint between *male* and *female* and *person*
Ⓧ	Exclusion. If an instance of NOLOT B 'is a' instance of NOLOT A, it cannot be an instance of NOLOT C. Equivalently, if an instance of NOLOT C 'is a' instance of NOLOT A, it cannot be an instance of NOLOT B. For example, if a *person* is a *male*, that *person* cannot be a *female* also and, if a *person* is a *female*, that *person* cannot be *male* also. Therefore there is an exclusion constraint between *male* and *female*