UNIVERSITY OF BATH

This is an electronic version of an article published in Vichare, P., Nassehi, A. and Newman, S. T., 2011. Unified representation of fixtures: Clamping, locating and supporting elements in CNC manufacture. International Journal of Production Research, 49 (16), pp. 5017-5032. International Journal of Production Research is available online at: http://dx.doi.org/10.1080/00207543.2010.518992

University of Bath

Unified representation of fixtures: clamping, locating and supporting elements in CNC manufacture

Parag Vichare*, Aydin Nassehi, Stephen T. Newman

Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, UK

* Corresponding author. Email: P.Vichare@bath.ac.uk

A CNC machining operation is the outcome of the application of the integrated capabilities of various resources within the CNC machining centre. Part fixtures, clamping and other location mechanisms are essential subsets of CNC machining resources. Today, various fixturing techniques and attachments available on the market allow manufacturers to enhance their production capability without buying expensive machine tools. This technology rich fixturing domain is detached while representing and exchanging machine tool resource information for making manufacturing decisions. The research work in this paper utilizes the STEP-NC compliant Unified Manufacturing Resource Model (UMRM) for representing fixtures in conjunction with the parent CNC machining centre. Thus UMRM is enhanced in this context to represent various fixtures such as universal vises, chucks, pallets, auxiliary rotary tables among others. The major contribution of this paper is the application of the extension of the UMRM approach for representing fixturing domain, which allows generic modelling of fixtures and loading devices in addition to machine workpiece and process modelling. This would enable the stage of automated process planning and manufacturing. The universal approach in representing resource information allows the data to be utilised for making a wide variety of manufacturing decisions.

Keywords: fixture design; CNC; information model; resource modelling; STEP-NC; manufacturing systems

1. Introduction

Today, fixturing techniques allow manufacturers to increase their machining capability by holding the workpiece in orientations that are not possible with the base machine tool. Thus, the significant cost of buying expensive machine tools can be saved. In addition, the modularity and the consequential reconfigurability of these fixtures allow reuse of the manufacturing resources. These modular fixtures are considered as a major enabler for realising reconfigurable CNC manufacturing systems (Bi *et al.* 2008). As a part of CNC manufacturing system resources, fixtures have significant role in the production time and cost (Liqing and Kumar 2005, Pehlivan and Summers 2008).

Manufacturing information is one of the key factors and intensively researched domains in establishing a link among various isolated CNC manufacturing systems (Newman and Nassehi 2006) such as CAD, CAM, CNC etc. The fixtures are part of these isolated systems and their integration is of utmost importance for CNC manufacture. Traditionally manufacturing information representation has always focused on products with information relating to their design, geometry and required processes. However there is no standardized information model available to represent the equipment used to manufacture such products. This equipment includes fixtures which constitutes significant investment in setting up a CNC manufacturing facility and is considered as a major asset of the business.

The representation of the various fixturing elements of the CNC machining system resources is vital for making efficient and economic manufacturing decisions (Pehlivan and Summers 2008). Making knowledgeable decisions is dependent on the information related to manufacturing resources. The same provides the basis for manufacturing activities including process planning, resource allocation, and facility design (Bouti and Ait Kadi 1998). This basis is also essential for creating an integrated, exchangeable and data sharing manufacturing information environment for collaboration between multiple, globally dispersed organizations (Zhao *et al.* 1999).

Any state of the art CAx system can model various CNC machining system resources and stores information regarding machine tools, kinematics, configuration, cutting tools, workpieces and corresponding manufacturing process. However, very few of these systems regard fixture specific information as machining system resource information. These CAx systems can model geometric information of the fixturing elements, but preserving the context or purpose of these fixturing elements in the machining system has been underdeveloped. For example, the CAD modeller of any

CAx system can model the indexing pallet or workpiece/ tool changing arm. However, only geometric shape of such mechanical elements is stored in the system. There is no formal way of preserving the purpose (clamping, location, supporting) and configuration (clamping ranges etc) of such elements in the CAx system. The possible reason behind this limitation could be a vast variety in the fixturing resources and implementation techniques.

In addition, general purpose fixturing elements such as vises, clamps, modular jaws etc. available on the market are standardised in design. Thus, its use in component manufacture does not require any expert planning system. However, customised fixtures found in automobile and aerospace industries are more complex and designed with a variety of objectives. This design consists of a set of reconfigurable locating, clamping and supporting features, which are required to be known for changes in design, progression in work, changes in product etc. This requires a data model which can represent information regarding fixturing setup for developing an expert fixture design system.

For example, in the case of process planning with the aid of CAx systems, the manufacturing engineer has to model the fixture assembly. Various details such as clamping and location units have to be modelled for generating a collision free tool path. A manufacturing engineer's knowledge and experience is vital for planning such a fixturing setup. Generating a resource specific tool path is the next step which is well-automated using available CAM systems on the market. However, the machining setup for a different job, using the same fixturing resources requires the engineer's intervention. This is due to the fact that the configuration and capability information of these fixturing elements have not been modelled. In addition, exchanging fixture

specific information in the computing environment for the integrated product and process design is difficult due to a lack of standard constructs.

2. Fixturing elements in the CNC manufacture

Various fixture elements can be classified into standard type equipments such as vises, clamps etc and modular type fixturing elements where each element serves as a locator, supporter or clamp. Figure 1 illustrates these modular fixture elements as well as standard fixturing equipment. The final fixturing setup shown in the Figure 1 is a combination of modular elements and standard fixturing. Dai *et al.* (1997) started classifying various modular fixture elements for establishing a database for developing computer aided fixture design and assembly. The modular fixturing elements were classified according to their functions: (a) base plate elements, where all the locating, supporting and clamping elements and workpiece can be mounted; (b) locating elements, such as location pins, V-blocks, location pads etc; (c) supporting elements such as adjustable spacers, shims etc for supporting workpiece; and (d) clamping elements, used for clamping the workpiece. A set of fixturing elements can be assembled together for locating, supporting or clamping the workpiece on the machine table as shown in fixture setup pane in Figure 1. These subassemblies of modular fixture are entitled fixture towers (Dai *et al.* 1997). Another example of such fixture blocks can be found in the pallet system where multiple workpieces are clamped on a single pallet. This type of fixturing is more prevalent in the flexible manufacturing systems (FMS) due to its reconfigurable nature.

Customised fixturing equipment such as strap clamps, vises, drilling jigs are the subassemblies designed for a specific purpose. An individual item may consist of various modular fixture subassemblies along with dedicated fixturing elements suited

for the specific workpiece geometry, for example, the travelling column horizontal machining centre linked to pallet pool system used for cylinder head machining. The locating and clamping elements for these cylinder heads are customised according to the geometric and machine-ability requirements. Generally this type of fixturing can be found in the mass manufacturing scenarios where the production line is dedicated to machining a single product. In such cases, automatic fixture design is reported as a difficult task because fixture design is based on in-process, semi-finished workpiece geometry; which again depends on the available manufacturing resources (Liqing and Kumar 2005).
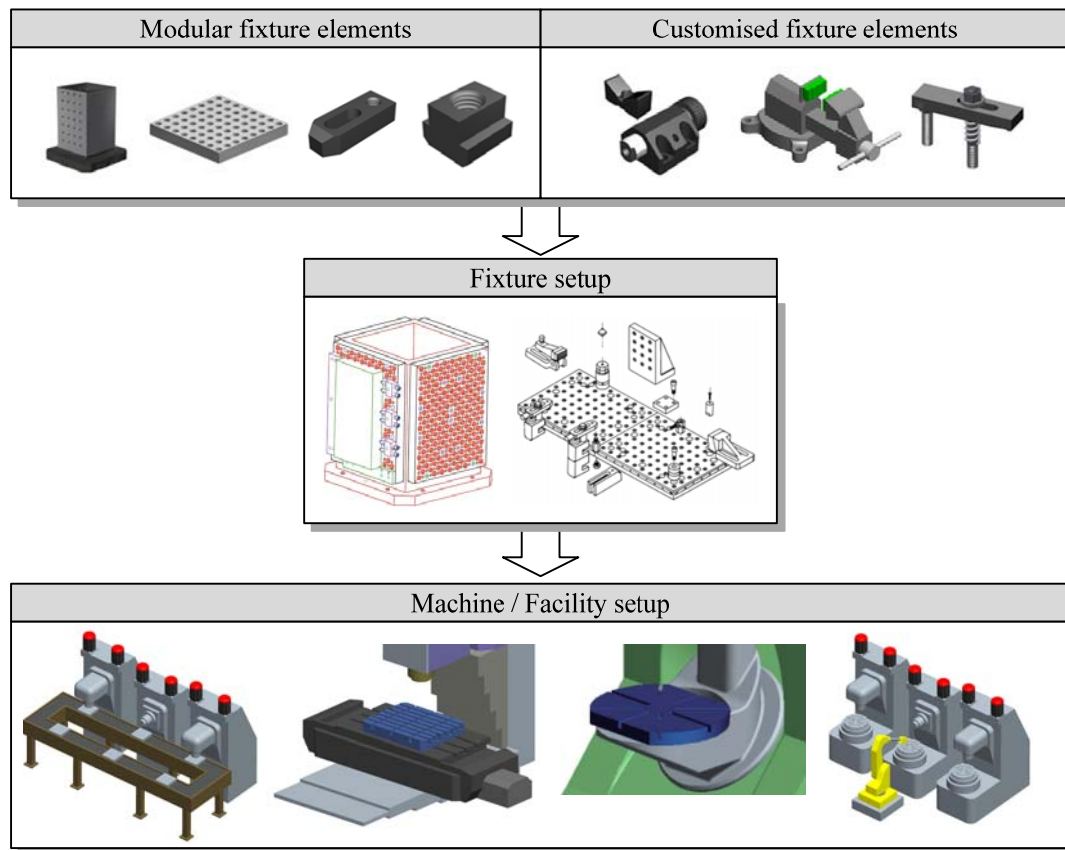

Figure 1. Use of modular and customised fixturing elements in the CNC machining operation

3. Fixture information modelling approaches

Fixturing is the mechanism that can be used for executing various functions such as locating, supporting and clamping. Theses mechanisms consist of various kinematic joints to perform required functions. A data model for representing manufacturing resources (Molina and Bell 2002) must be versatile enough to represent these kinematic links between machine elements. These kinematic joints are also a part of machine tool configuration; by virtue of which various tool and workpiece axis movements are achieved on the CNC machining centre. Hence, it is very important to have a common methodology (Cecil 2001) to represent the numerous configurations of CNC machine tools equipped with various fixturing elements in order to provide a complete representation of the CNC machining system.

The key problem of structuring the information models to support the interactions between fixture design, process planning and product design was reported by Bugtai and Young (1998). The issues related to the data structures required for verifying manufacturing knowledge were discussed and standard based framework were proposed by Cochrane *et al.* (2009). Mervyn, *et al.* (2006) developed an information model describing fixture design knowledge and specification to improve the product quality and reduce product lead-time. Yao, *et al.* (2005) divided automatic setup planning into two sub-tasks: setup planning in part level and in station level in which fixtures and machine tools were selected to machine several parts sequentially on machine tools. Kow *et al.* (2000) described a CAD based methodology for developing a tool collision free modular fixture design system using the Unigraphics (UG) solid modeller, integrated with a modular fixture element database, based on a

hole-based IMAO modular fixturing system. Liqing and Kumar (2005) and Padmanaban and Prabhaharan (2008) developed a case-based solution for design problems in the complex fixturing domain on the idea that past problem solving knowledge can be utilised in solving new problems. These approaches are well-exploited in representing a specific manufacturing resource fixturing domain. However, there has been no generic methodology for representing the enormous diversity in machine tool configurations and auxiliary devices along with fixturing domain. The commercial tools available are either machine vendor specific or limited in their scope to represent some specific machine tool resource elements; resulting in a plethora of representation methods which are bespoke and incomplete in terms of representing the entire system's resources.

A range of kinematic joints can be represented with STEP's integrated application resources (IR) (ISO 10303-105 1996). This IR specifies an information model for the kinematic aspects of the mechanical product. It also describes a methodology for representing kinematic structures. A fundamental procedure of this methodology to represent a mechanism associates all kinematic joints to the mechanism's coordinate system as shown in the Figure 2. The coordinate systems are called frames in this part of STEP. For the purpose of representing the kinematic aspect of a mechanism, a machine element is placed by the location and orientation of the associated kinematic pairs with respect to mechanism's coordinate system (ISO 10303-105 1996, Rachuri *et al.* 2005).

This methodology is capable of representing tree kinematic structures and close loop kinematic structures (Kjellberg *et al.* 2009). The objective of developing this STEP's IR was to establish a neutral file format for exchanging kinematic configuration information between CAx systems. However, its use for representing

integrated shop floor resources is debatable. For example, it can represent machine

tool structures, fixturing mechanisms, material handling systems. However, this IR

does not specify any methodology to integrate these discrete manufacturing resources.

In addition, it has not been utilised for constructing kinematic pairs by mapping
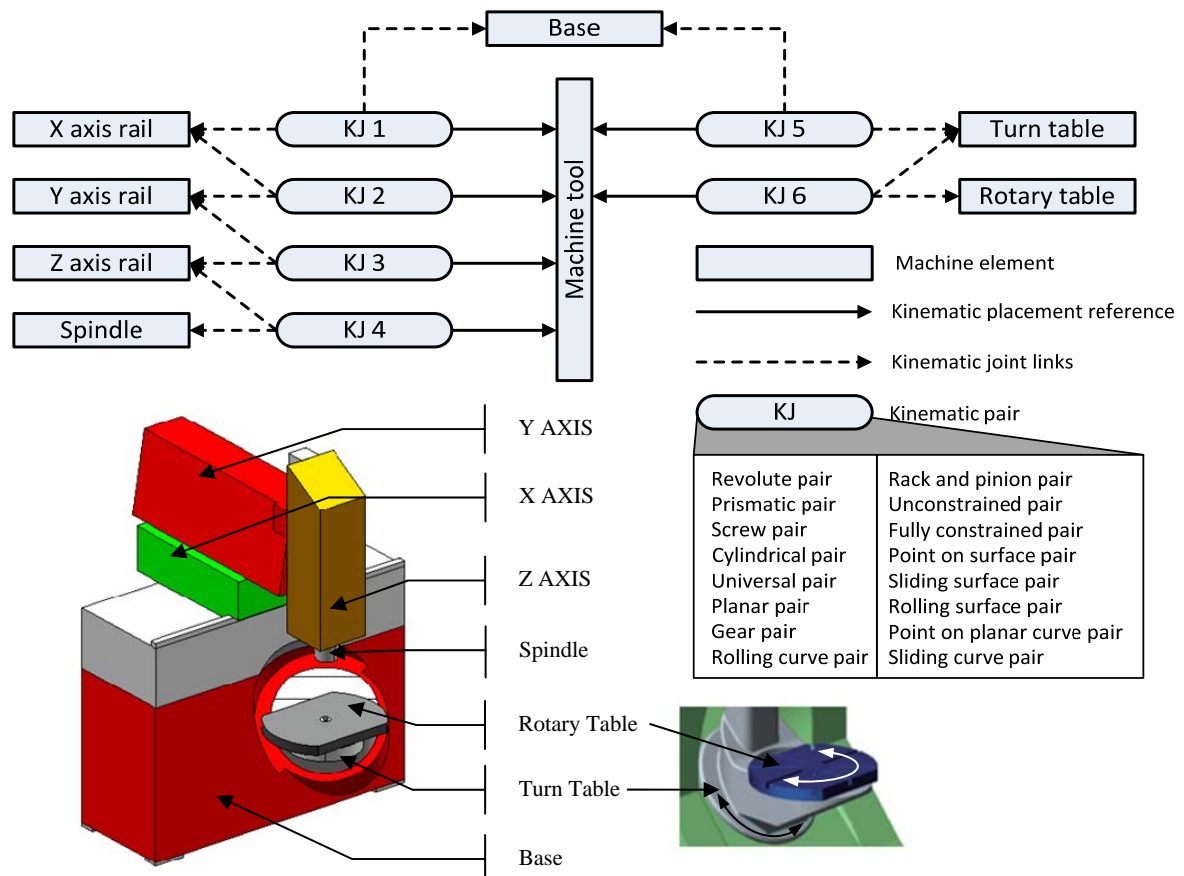
assembly features.

Figure 2. Machine tool configuration and corresponding kinematic representation
using STEP's IR 105 (ISO 10303-105 1996)

Vichare *et al.* (2009b) proposed a unified resource information modelling

approach called Unified Manufacturing Data Model (UMRM) for representing

information regarding a variety of manufacturing resources in decision making

process. The UMRM has been utilized to represent various configurations of

conventional CNC machine tools. It has been verified for modelling various

configurations (at least 256 configurations) of the 5 axis vertical machining centres

reported by Sato (Sato 2006). It has been utilised for representing various Turning centres and multitasking turn-mill centres (Vichare *et al.* 2009b) along with various auxiliary devices and material handling system configurations prevalent in the manufacturing industry (Vichare *et al.* 2009a). In addition, UMRM has also been exploited for verifying the fitness of the available manufacturing resources against STEP-NC (ISO 14649-1 2002) compliant process plans (Nassehi and Vichare 2008).

Figure 3 depicts the reach of UMRM in representing manufacturing resource domains. The scope of the last version of the UMRM (Nassehi and Vichare 2009) was limited to representing machine tool axes movements required for the postprocessor development. However, looking at the growing application of the modular fixtures, reconfigurable setups this research work extends the scope of UMRM for representing various kinematic aspects of the fixturing system by exploiting rich information constructs of ISO 10303-105 (ISO 10303-105 1996).

4. An Information model

4.1. Fixturing setup: A type of manufacturing resource

A machine tool is an assembly of a various mechanical elements intended to convert a workpiece into the finished product. Thus fixturing domain, as a part of manufacturing resource is considered as an assembly of mechanical machine elements with different kinematic joints to facilitate constrained movements. Figure 3 illustrates entity "manufacturing_resources". This entity has been exploited for representing various CNC machining system resource such as machine tools (Vichare *et al.* 2009b), material handling systems etc (Vichare *et al.* 2009a). However, fixture specific information in the CNC manufacture environment is as important as other manufacturing resources. Thus, fixture specific information has been represented in

this paper by escalating the scope of UMRM through an entity "fixturing_setup"

shown in the Figure 3. EXPRESS-G diagram illustrates this entity as a type of

mechanical resource, which uses a kinematic joint to be able to connect it with the
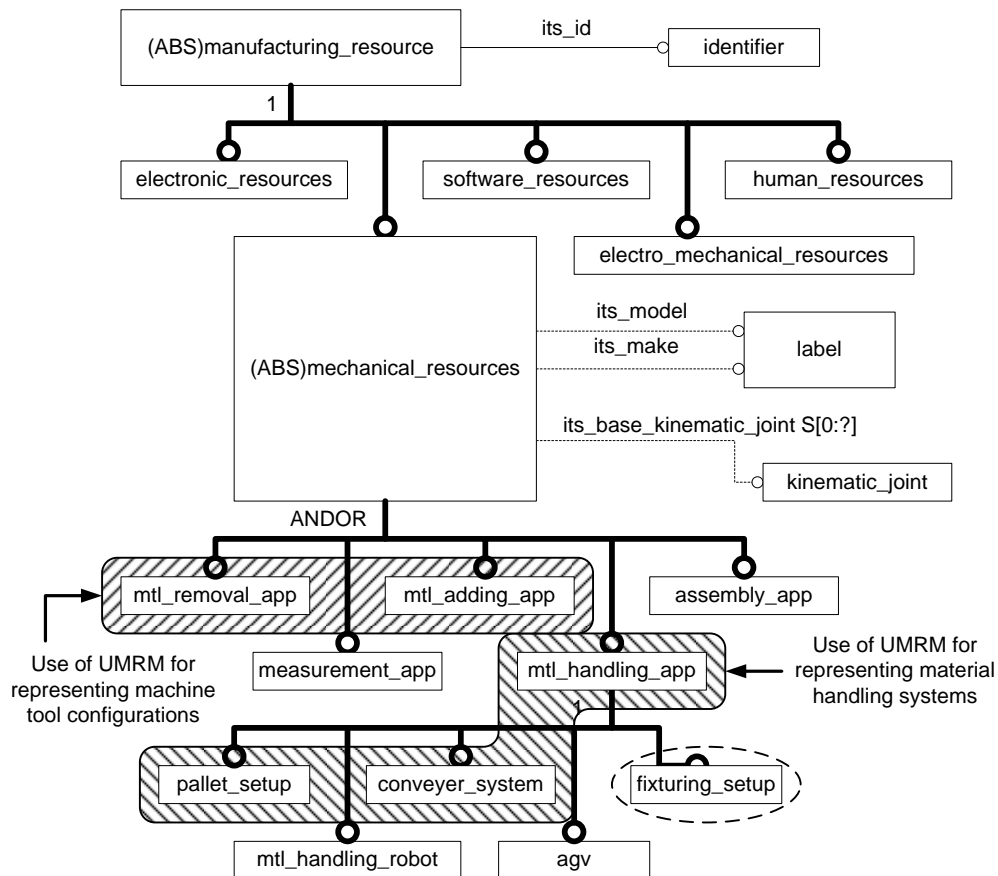
parent machine tool.

Figure 3. EXPRESS-G representation of UMRM entity "manufacturing_resource" for representing fixturing setup

4.2. Representation of kinematic joint information for describing fixturing setup

The kinematic aspects between two fixture elements or between fixture and the

machine tool can be rendered with the attributes of the entity "kinematic_joint". This

entity inherits various kinematic pairs described in ISO 10303-105 (ISO 10303-105

1996) and has illustrated in the Figure 4. Each kinematic pair has distinct properties,

by virtue of which kinematic movements in the fixture assembly can be presented.

Entity "kinematic_joint" may have some axes of movement attached to it. Attaching individual axis to kinematic joint represents their degrees of freedom. The entity, axis has two subtypes: "linear_axis" and "rotary_axis". When several axes are attached to the kinematic joint, it represents a mechanical machine element (of the fixture assembly) capable of moving in different directions. The kinematic linkage between a kinematic joint and the machine element can be represented with the attribute "kinematic_link". Thus, a kinematic joint can be attached to the set of machine elements using this attribute. It has a unique identifier and distinct transfer placements for referencing it from the previous machine element's kinematic joints. Thus, every kind of manufacturing resource has a kinematic joint; and every kinematic joint is connected to the mechanical machine element.
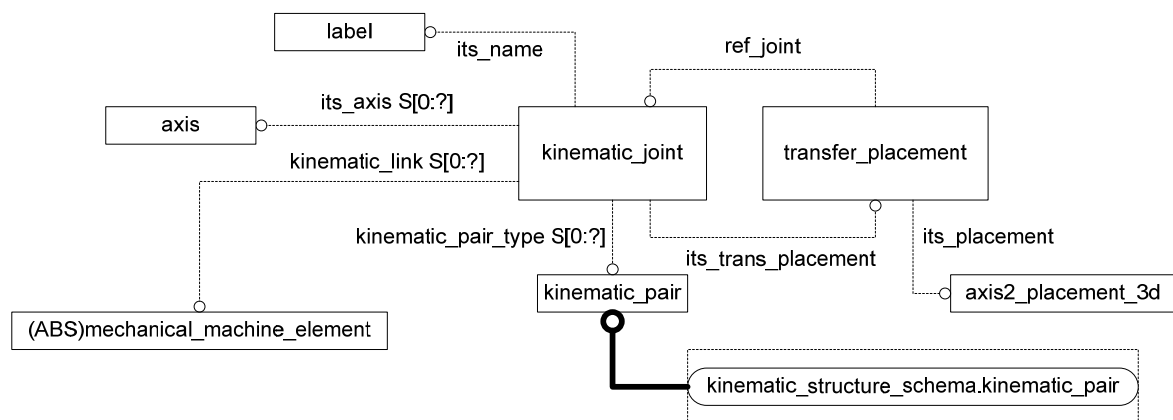

Figure 4. EXPRESS-G representation of UMRM entity "kinematic_joint"

4.3. Representation of fixturing configuration information

Every mechanical machine element modelled using UMRM has a capability of representing information regarding the fixturing configuration to be able to assemble it with another machine element. For example, a typical machine tool table is a mechanical machine element, which has T-slots for accommodating other fixtures.

Thus, T-slots can be represented by exploiting various attributes of the entity "fixturing_config". This entity (Figure 5) is abstracting various types of fixturing configurations that could be available on the mechanical machine element and can represent placement and pattern information of the fixturing feature by using entity "placement_pattern". Thus, it is possible to construct a kinematic joint by mapping various fixturing features as shown in Figure 6.
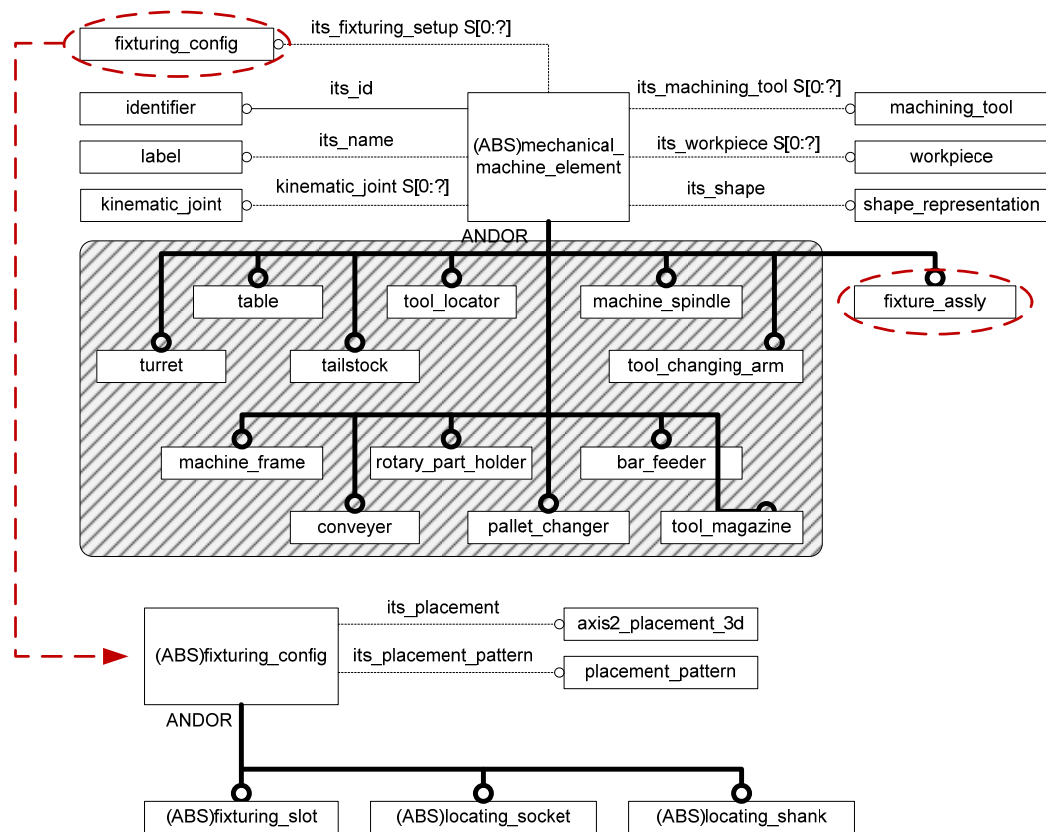

Figure 5. EXPRESS-G representation of the UMRM entities "mechanical_machine_element" and "fixturing_feature"
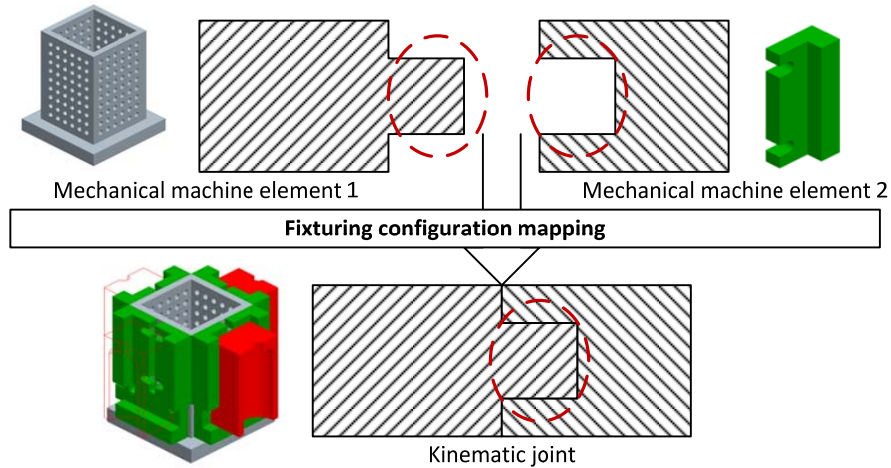
Figure 6. Fixturing features and corresponding mapping for constructing kinematic joints

The majority of fixturing equipment has an array of fixturing features such as slots, sockets etc. This enables reconfigurability with fixturing elements. The information regarding such a fixturing configuration has to be stored to be able to be used for change in work setup, progression in work etc. The placement pattern of the fixturing configuration is described with UMRM's entity "placement_pattern". Two placement patterns, namely circular pattern and rectangular pattern can be presented using this entity. Thus, any fixturing feature such as location hole or fixturing slot can be described once and used again for representing its progressive placement as shown on Figure 7. The pattern placement has a distinct reference which can be presented using an attribute "pattern_placement_reference".

Fixturing features such as fixturing slots are utilised for holding and/or clamping a workpiece and/or cutting. They can also be utilised for assembling one mechanical machine element to another. There are standard slot profiles such as vee profile, tee profile, rectangular profile utilised in most common fixturing devices. UMRM unifies a variety of such slot profile under an abstract entity "fixturing_slot". Customised slot information can be represented by defining a trajectory and cut

section using a STEP entity "shape_representation". In addition, it is possible to represent information regarding slot end condition using a STEP entity "end_condition".

Similarly, machine tool manufacturers use customised elements for holding tools and workpieces. Though there is an abundant diversity in the design of tool or workpiece holders, the common element among these units is their purpose, namely to hold either a workpiece or a tool. The proposed model for machine tool resources emphasises the role of these elements. Hence, abstract entities, namely "location_socket" and "location_shank" are designed within UMRM for generalising and representing fixturing features.
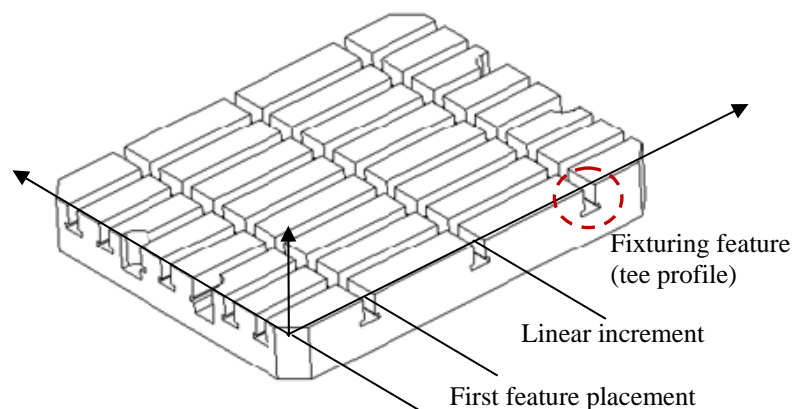

Figure 7. Example of rectangular patterned fixturing features (tee profile slot) on the table

The recursive nature of the entity "mechanical_machine_element" (Vichare *et al.* 2009b) for representing CNC machining system resources has a capability of representing functional details of the various sub systems of the parent CNC machining system. For example, a machine tool is attached with the robotic arm. This robotic arm has a capability of handling workpieces as well as cutting tool. This case can be represented with attaching two "fixture_assly" entities to the robotic arm head. One of which holds fixture setup for holding workpiece and other "fixture_assly"

holds another fixture setup for holding cutting tool. This has only been possible due to the flexibility of mechanical machine element to hold a set of another mechanical machine element, workpiece or cutting tool.

An entity "fixture_assly" shown in Figure 8 addresses locating, clamping and supporting elements available in the fixture assembly. The fixture assembly can either be modelled by using an entity "std_fixture_assly" for representing standard fixturing devices such as a vise or the entity "modular_fixture_elements" for modelling a reconfigurable fixture tower. For example, a V block vise can be modelled by associating entity "fixturing_slot" to each vise jaw.
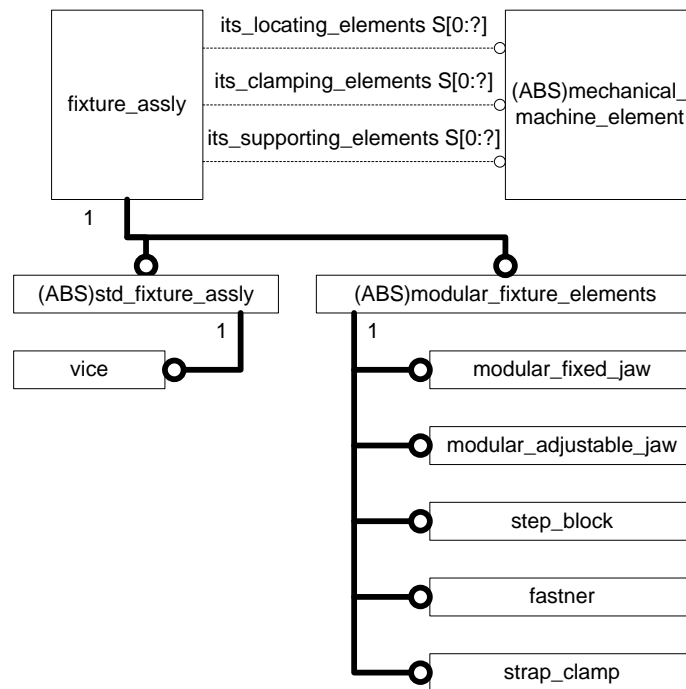

Figure 8. EXPRESS-G representation of the UMRM entity "fixture_assly"

5. Representation of fixture specific information: a case study

5.1. Vertical indexing pallet setup

A typical horizontal machining centre shown in the Figure 9 has a vertical indexing pallet mounted on the C axis rotary table. The operation under consideration is machining of blow mould for a bottle production. In the regular process planning

scenario with the aid of CAx systems, the manufacturing engineer has to model a vertical indexing pallet assembly. Various details such as clamping and location units have to be modelled for generating a collision free tool path. Manufacturing engineer's knowledge and experience is vital for planning such a fixturing setup. Generating a resource specific tool path is the next step which is well-automated using available CAM systems on the market. However, the machining setup for a different job, using the same fixturing resources requires the engineer's intervention. This is due to the fact that the configuration and capability information of these fixturing elements have not been modelled. In addition, exchanging fixture specific information in the computing environment for integrated product and process design is difficult due to lack of standard constructs.

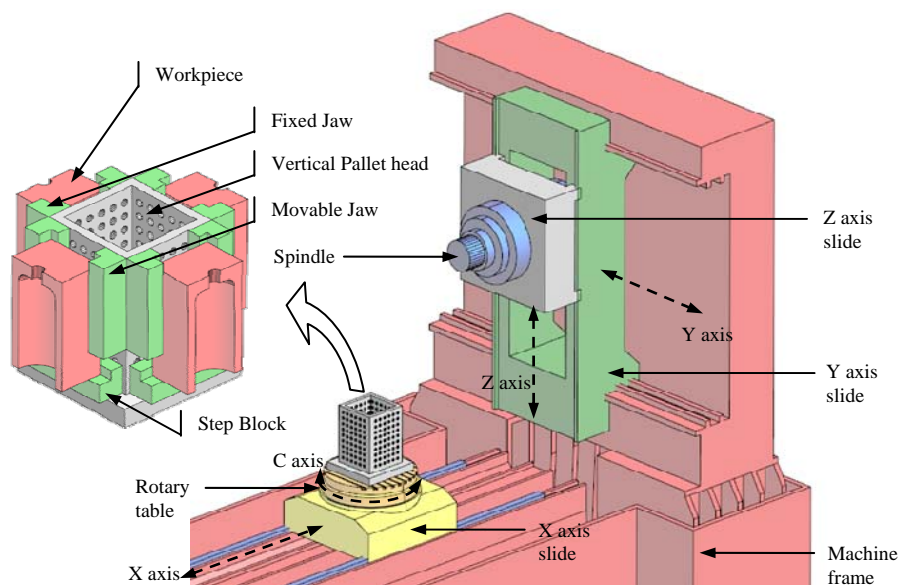Figure 9. A typical 4 axes horizontal machining centre with vertical indexing pallet

Thus, by using UMRM, the fixture specific information can be coupled with the machine tool specific information. Every mechanical machine element modelled using UMRM carries fixturing features. Table 1 illustrates various mechanical machine elements and corresponding fixturing features for modelling horizontal

machining centre with vertical indexing pallet. Representation of the fixture element and corresponding fixturing features for constructing kinematic pair are illustrated in the table. For example, a rotary table of the machine is a mechanical machine element which has T-slots; and vertical indexing pallet's base has location sockets. Thus, these two fixturing features can be mapped on each other for constructing rigid kinematic joint. Standard fastener library can be utilised to select required fasteners for constructing a kinematic joint. The fixturing feature represents available provisions i.e. slots, locating sockets, locating shanks of the mechanical machine element for assembling it with another machine element. For example, four vertical walls of the pallet have a grid of locating holes as shown in the Figure 9; few of them are utilised for assembling fixed jaw, movable jaw and a step block. However, by using an entity "placement_pattern", the placement of the every location hole can be stored and utilised in the fixture reconfiguration.

5.2. Fixturing setup representation using a STEP part 21 file

A part 21 file (also known as .stp or .step file) can represent geometry of the assembly by using ASCII clear text encoding format (ISO 10303-21 1994). The STEP application protocol (AP) for generating this part 21 file has a mechanism to display geometric entities of the assembly. However, this AP does not preserve the context of such geometric entities in the part 21 file. Thus, UMRM provides a mechanism to store the functionality information of such geometric entities by using a data model explained in section 4.

The vertical indexing pallet and available fixturing features can be represented with the UMRM's entity "fixturing_config". The machine table is a circular type and has T-slots which are represented by using entities "tee_slot" and

"placement_pattern". The vertical indexing pallet has a grid of location holes that can be used for assembling various fixturing elements such as reconfigurable clamps, supporting plate etc. Finally, the entity "fixture_assly", a subtype of "mechanical_machine_element" addresses elements required for clamping, locating and supporting the workpiece. Thus, configuration of the vertical indexing pallet, reconfigurable clamp and supporting plate can be represented by using UMRM entities for enhancing the automated process planning capability. Thus, specific fixturing setup details such as location configuration, clamping points, location elements can be represented using a UMRM's data model with part 21 file as shown in the Figure 10. This Part 21 file based on the existing STEP, STEP-NC and UMRM information constructs can be used by a variety of manufacturing application shown in Figure 11.

Table 1. Fixturing features and corresponding mapping for constructing kinematic joints

```
ISO-10303-21;
HEADER;                                                      Header
FILE_DESCRIPTION(('MCM PALLET CHANGER','MCM'),'1');
FILE_NAME('MCM_PALLET_CHANGER.STP','2009-02-04',('PARAG VICHARE','AYDIN
NASSEHI','STHEPHEN NEWMAN'),('UNIVERSITY OF BATH'),$,'ISO14649',$);
FILE_SCHEMA(('MACHINING_SCHEMA','TURNING_SCHEMA','MILLING_SCHEMA','MILLING_TO
OL_SCHEMA','TURNING_MACHINE_TOOL_SCHEMA','UMRM_SCHEMA','AUTOMOTIVE_DESIGN'));
ENDSEC;

DATA;
#1 = MECHANICAL_DESIGN_GEOMETRIC_PRESENTATION_REPRESENTATION('',
(#73,#74,#75,#76,#77,#78,#79,#80),#105);
#2 = PRODUCT_DEFINITION_CONTEXT('',#100,'PART DEFINITION');
#3 = APPLICATION_PROTOCOL_DEFINITION('INTERNATIONAL STANDARD','',,#100);
#4 = SHAPE_DEFINITION_REPRESENTATION(#101,#102);
.                                                Geometry description
.
#101 = PRODUCT_DEFINITION_SHAPE('NONE','NONE',#372);
#102 =
ADVANCED_BREP_SHAPE_REPRESENTATION('BED_ASSLY',(#420,#421,#422,...),#105);
.

#1526 = WORK_STATION('MCM PALLET CHANGER',#1520,(#1628,#1629);
#1628 = MACHINE_TOOL('MCM HMC','','MCM',#1        Manufacturing resources
#1629 = FIXTURING_SETUP('PALLET CHANGER','

#2346 = MODULAR_FIXED_JAW(....);
#2347 = MODULAR_ADJUSTABLE_JAW(....);            Fixture assembly elements
#2348 = STEP_BLOCK(.....)

#2543 = TEE_PROFILE(#2544,#2549,#2568,#....);
#2549 = PLACEMENT_PATTERN(#2570,#2550);
#2550 = RECT_PATTERN(#2551,);
#2551 = ROW_CONFIG(#2552);                       Fixturing features
#2552 = FEATURE_PLACEMENT(80.000,50.000,8);

.
#2589 = LOCATION_HOLE_SOCKET(#2621,#2626,15.000,10.000,'');
.
.                                                Location holes on the pallet
#3521 = FIXTURE_ASSLY((),(#2346,#2347),(#2348));
```

Figure 10. An extract of the part 21 file for representing manufacturing resources

5.3. *Fixturing knowledge generation and preservation for developing large volume build philosophies*

Fixturing setup in aerospace and automotive manufacturing sectors is also known by

the term "tooling". Tooling in these manufacturing sectors constitutes large

mechanical structures such as assembly jigs, component handling frames, transfer line

jigs, large sheet metal dies etc. The design of these tooling components is well

researched through the feasibility studies before releasing for the production

environment. Significant amount of knowledge regarding fixture design is generated

in these feasibility studies, which became an asset of the business for excelling key competencies. However key challenges in fixturing knowledge representation are rooted through the basic questions such as: What information regarding fixturing setup is needed for representing fixturing knowledge, How this information can be modelled, utilised throughout the product manufacture and preserved for designing next generation of the product manufacturing philosophies.

UMRM has been utilised as a fixturing information generation template for representing fixtuing setup information in the form of part 21 file as described in section 5.2. Figure 11 illustrates UMRM's framework for generating fixturing setup information and utilising it in various manufacturing applications used in product design and development. UMRM's EXPRESS schema can be acquired for further development by contacting corresponding author.
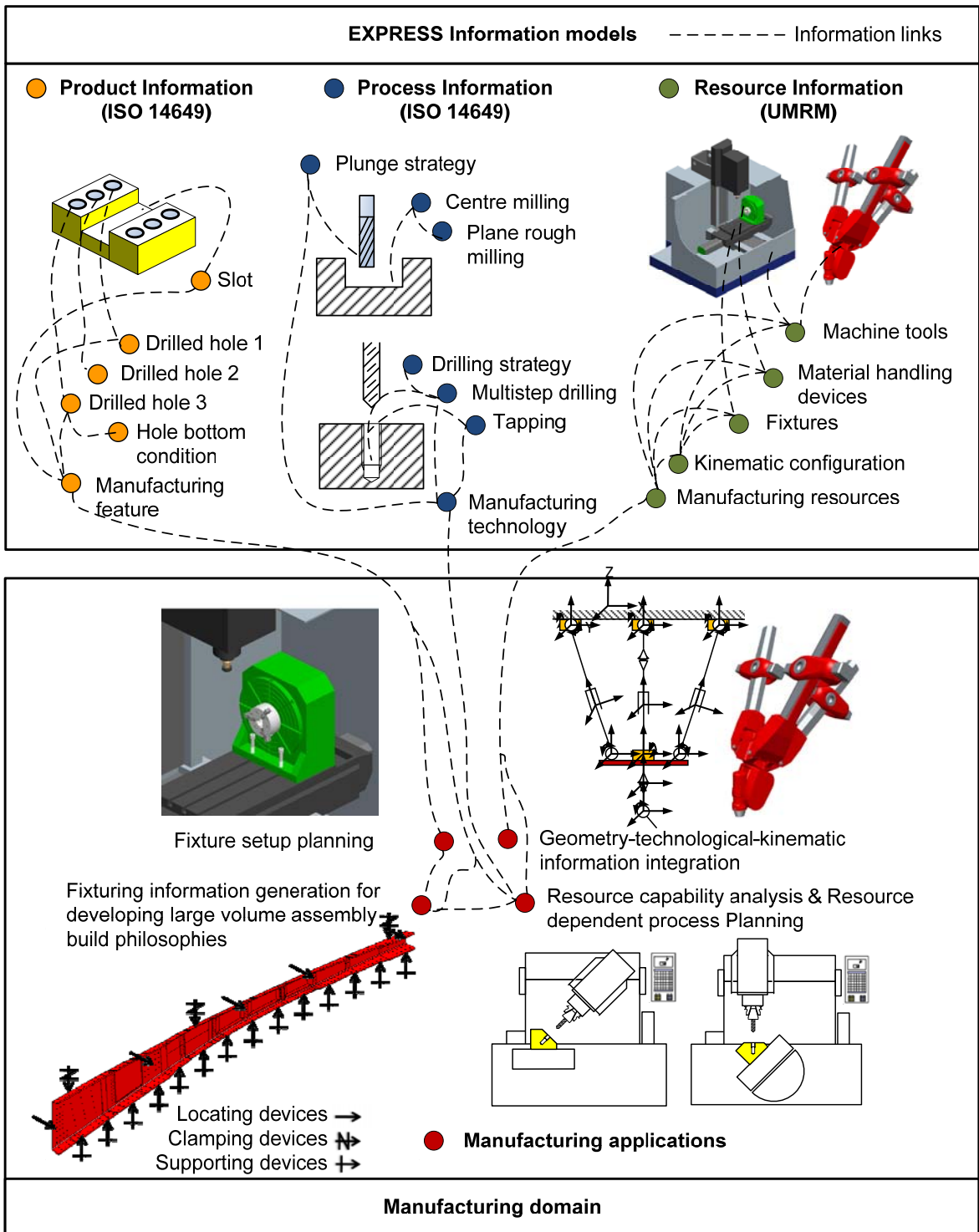
Figure 11. UMRM's framework for generating fixturing setup information and utilising it in various manufacturing applications used in product design and development.

6. Conclusions and future work

In this paper, authors have proposed a UMRM for representing fixture specific information for CNC manufacture. The UMRM has a rich data model which has a promising potential for representing manufacturing resource domains such as machine tools, material handling systems including fixturing setup. A case study is presented, in which vertical pallet setup has been represented with the part 21 file. Thus, UMRM can represent the kinematic chain between tool and workpiece considering fixture configurations. In addition to geometric entities, unlike commercially available tools, UMRM can represent logical purpose of the available manufacturing resources. At present, UMRM's data model can represent the information required for tool path verification. However, adding fixture specific information has enabled UMRM to be used for developing reconfigurable process plans. It utilised pre-established standardised information constructs for representing information regarding a range of kinematic joints; thus, it can be utilised to establish a neutral file format for exchanging resource information including fixturing information in the CAx chain.

Further developments, especially for modelling the application oriented behaviour of the resource elements, are aimed at the extension for representing CNC machining system. UMRM's Resource information can be considered as a focal aspect for developing solutions for ever-challenged research areas such as design of interoperable and reconfigurable manufacturing environment, intelligent controller, resource integration in the supply chain etc due to its wide scope.

7. Acknowledgement

References

Bi, Z.M., Lang, Y.T., Verner, M. & Orban, P., 2008. Development of reconfigurable machines. *Int J Adv Manuf Technol,* 39 (11-12), 1227-1251.

Bouti, A. & Ait Kadi, D., 1998. Capturing manufacturing systems knowledge using multi-view modelling. *International Journal of Computer Integrated Manufacturing,* 11 (1), 77-93.

Bugtai, N. & Young, R.I.M., 1998. Information models in an integrated fixture decision support tool. *Journal of Materials processing Technology,* 76, 29-35.

Cecil, J., 2001. Computer-aided fixture design - a review and future trends *Int J Adv Manuf Technol,* 18, 790-793.

Cochrane, S., Young, R., Case, K., Harding, J., Gao, J., Dani, S. & Baxter, D., 2009. Manufacturing knowledge verification in design support systems. *International Journal of Production Research,* 47 (12), 3179-3204.

Dai, J.R., Nee, A.Y.C., Fuh, J.Y.H. & Kumar, A.S., 1997. An approach to automating modular fixture design and assembly. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* 211, 509-521.

ISO 10303-21, Industrial automation systems and integration — product data representation and exchange, part 21: Implementation methods: STEP-file clear text encoding of the exchange structure 1994.

ISO 10303-105, Industrial automation systems and integration — product data representation and exchange, part 105: Integrated application resources: Kinematics 1996.

ISO 14649-1, Industrial automation systems and integration — physical device control — data model for computerized numerical controllers, part 1: Overview and fundamental principles 2002.

Kjellberg, T., Von Euler-Chelpin, A., Hedlind, M., Lundgren, M., Sivard, G. & Chen, D., 2009. The machine tool model—a core part of the digital factory. *Annals of the CIRP,* 58 (1), 425-428.

Kow, T.S., Kumar, A.S. & Fuh, J.Y.H., 2000. An integrated approach to collision-free computer-aided modular fixture design. *Int J Adv Manuf Technol,* 16, 233-242.

Liqing, F. & Kumar, A.S., 2005. XML-based representation in a CBR system for fixture design. *Computer-Aided Design & Applications,* 2 (1-4), 339.

Mervyn, F., Kumar, A.S. & Nee, A.Y.C., 2006. Fixture design information support for integrated design and manufacturing. *International Journal of Production Research,* 44 (11), 2205-2219.

Molina, A. & Bell, R., 2002. Reference models for the computer aided support of simultaneous engineering. *international Journal of Computer Integrated Manufacturing,* 15 (3), 193-213.

Nassehi, A. & Vichare, P., 2008. Determination of component machineability in CNC manufacture *Proceedings of the FAIM2008*, Skövde, Sweden, 23-30.

Nassehi, A. & Vichare, P., 2009. A STEP-NC compliant methodology for modelling manufacturing resources. *In* Xu, X.W. & Nee, A.Y.C. eds. *Advanced design and manufacturing based on STEP.* Springer London, 261-281.

Newman, S.T. & Nassehi, A., 2006. Universal manufacturing platform for CNC machining. *Annals of the CIRP,* 56 (1), 459-462.

Padmanaban, K.P. & Prabhaharan, G., 2008. Dynamic analysis on optimal placement of fixturing elements using evolutionary techniques. *International Journal of Production Research,* 46 (15), 4177-4214.

Pehlivan, S. & Summers, J.D., 2008. A review of computer-aided fixture design with respect to information support requirements. *International Journal of Production Research,* 46 (4), 929-947.

Rachuri, S., Baysal, M., Roy, U., Foufou, S., Bock, C., Fenves, S., Subrahmanian, E., Lyons, K. & Sriram, R., 2005. Information models for product representation: Core and assembly models. *International Journal of Product Development* 2(3), 207-235.

Sato, M., 2006. Design and performance of 5 axis machines in japan *Proceedings of the 12th International Machine Tool Engineer's Conference*, Tokyo, Japan, 167-189.

Vichare, P., Nassehi, A., Kumar, S. & Newman, S.T., 2009a. A unified manufacturing resource model for representation of CNC machining systems elements. *Robotics and Computer Integrated Manufacturing,* 25 (6), 999-1007.

Vichare, P., Nassehi, A. & Newman, S.T., 2009b. A unified manufacturing resource model for representation of CNC machine tools. *Proc. IMechE, Part B: J. Engineering Manufacture,* 223 (5), 463-483.

Yao, Y., Liu, C. & Li, J., 2005. Web-based virtual machining and measuring cell *Proceedings of the 9th International Conference on Computer Supported Cooperative Work in Design*, 673-678.

Zhao, J., Cheung, W.M. & Young, R.I.M., 1999. A consistent manufacturing data model to support virtual enterprises. *International Journal of Agile Management Systems,* 1-3, 150-158.