Journal of Manufacturing Systems
Vol. 21/No. 1
2002

Trends and Perspectives

Computer Aided Fixture Design: Using Information Intensive Function Models in the Development of Automated Fixture Design Systems

J. Cecil, Assistant Professor, Virtual Enterprise Engineering Lab (VEEL), Industrial Engineering Dept.,
New Mexico State University, Las Cruces, New Mexico, USA

Abstract

In this paper, the development of an Information Intensive Function Model (IIFM) of fixture design activities is discussed. This function model was developed using the IDEF-0 (Integrated Definition) methodology and was built primarily after interacting with expert fixture designers. In addition, knowledge from fixture design, tool design, and metalcutting handbooks and from journal papers was used to lend a holistic flavor to the developed IDEF-0 model. An IDEF-0 modeling software tool, AI0 Win®, was used to build this model at various levels of decomposition. This paper also discusses the importance of IIFMs in the current and future design of Computer Aided Fixture Design (CAFD) systems.

Keywords: *Fixture Design, Computer Aided Fixture Design, Function Modeling, CAD/CAM, Information Intensive Function Models*

Introduction

Fixture design is a complex task that has been viewed by industrial practitioners and researchers as a vital link between design and manufacturing activities (Sakurai 1990; Senthil Kumar, Subramaniam, Seow 1997). Computer Aided Fixture Design (CAFD) is a crucial task whose realization will enable the integrated accomplishment of computer-aided design (CAD) and computer-aided manufacturing (CAM) activities in modern manufacturing environments. There have been numerous efforts to automate fixture design activities and develop CAFD methods for rotational and prismatic parts manufacturing (see references 1-22, 24-39, 41, 42, 45, 46). However, there has been a lack of effective CAFD techniques to fill the void between CAD and CAM, and automated fixture design techniques continue to be the focus of manufacturing research efforts. There is a need to better understand the complex tasks and subtasks within the fixture design activity by developing a function model of overall activities. Such a model would not only help the understanding of the complex functions and task accomplishments within fixture design but would result in a model of what was being accomplished by the various functions. In general, a function model can be described as a representation of activities (within a target focus area or system) and the relationships between them. A function model can also enable understanding of the impact and role of various information inputs and controls in the accomplishment of activities.

Past efforts have not emphasized the use of formal models or representations as a basis for designing and developing CAFD systems. The research activity discussed here explores the role of information intensive function models (IIFM), which can be a valuable tool in obtaining a better understanding of complex activities and tasks in a domain such as fixture design. Further, these models provide a structured basis of communication to concurrent engineering (CE) teams, who will be impacted by (and who impact) the activities within fixture design. Function models can also be used as a requirements definition map by software engineers who support the implementation of software systems that accomplish CAFD. A formally structured model can more effectively convey the complex relationships and dependencies among subactivities. Other engineers (such as product designers or machinists) involved in the life cycle of a product, and who are not familiar with fixture design activities, can get a better understanding of the interrelationships and the need for feedback (and timely communication) among their respective CE teams before an infeasible design idea progresses toward other downstream activities. The power of IIFMs lies in their ability to describe what can or will be accomplished by a system, human team members, and other resources. IIFMs explicitly capture intricate relationships between information sources, bottleneck-oriented constraints (for example, availability of data or some other internal attribute), and the software or hardware mechanisms that work together to accomplish a given activity. In today's information technology oriented manufacturing environment, the design of manufacturing-related software systems must be accomplished taking into consideration such information attributes (that are captured in IIFMs). Fixture design is a complex task , and understanding the relationships explicitly and building an IIFM of these attributes lays the foundation for implementing effective CAFD approaches. It also provides a common language for reasoning a specific approach, enables CE team members to understand and communicate potential problems (in information availability) more effectively, and proposes ways to accomplish a core set of activities in a more integrated manner. Using the function model of fixture design activities, a preliminary version of a CAFD system called TAMIL (Towards A Manufacturing Integration Link) has been developed (Cecil 2001). The IIFM provided a fundamental basis to understand and map complex relationships, study information flow, and then design and build a system to automate fixture design activities.

IDEF-0 methodology was used to build the IIFM. The IDEF-0 model resulting from the use of this methodology provided a foundation for understanding the complex activities in fixture design and facilitated the definition of activities and information surrounding these functions. In other initiatives, the IDEF-0 method has been used as a powerful modeling tool for analysis, specification, and design of manufacturing and other systems (Cecil 1995; Mayer, Keen, Blinn 1990). The four basic attributes modeled for each activity (and subtasks) include inputs, controls, outputs, and mechanisms (termed ICOMs, see *Figure 1*). The IDEF-0 method includes a graphical language that enables the user to describe the activities being modeled in a powerful hierarchical manner. The root or highest level in this hierarchical structure has lower level, or children, nodes that detail the functional activity being modeled. A traversal of this hierarchy unfolds the details of the children activities and the objects that form the relations between these activities.

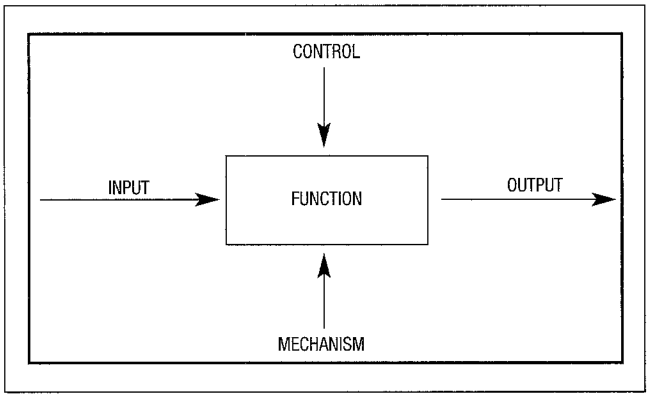


Figure 1
ICOM Attributes Illustrated in an IDEF-0 Model

Function Model Development and Descriptions

The IDEF-0 function model discussed was built after studying the accomplishment of fixture design activities by expert fixture designers and process planners. Knowledge and information from fixture design, tool design, and metalcutting handbooks and from journal papers has also been used to develop a more holistic IDEF-0 model. Additional discussion of the information represented in an IDEF-0 model is provided in the section entitled IDEF-0 Function Model of Fixture Design.

Domain experts included a process planner (expert A), a tool engineer (expert B), and an engineering instructor (expert C). Expert A works in a machine shop and has more than 20 years of experience performing process planning, fixture design, and machining in a job shop, which produces both rotational and prismatic parts. Expert B is a tool engineer in the automobile industry with a decade of industrial experience who designs jigs and fixtures for parts used in the production of cars and trucks. Expert C is a mechanical engineering instructor who teaches fixture design-related courses and had previously worked as a fixture designer in the automobile industry.

Verbal Protocol Analysis was used as the method of acquiring detailed knowledge from the domain experts. After being given a product design and designing the fixture, each expert provided explanations of a list of possible designs (or conclusions). After the experts completed the necessary explanations, the model developer reviewed the description of the protocol (or steps used to arrive at the fixture designs) and added more details if necessary (Cecil 2000).

Another protocol used in knowledge acquisition for the fixture design activity was blind problem discussion (Tuthill 1990). Fixture designs from another knowledge expert, as well as from books and papers, were used in the discussion. Each fixture design expert was presented with a part design (design A) and asked to design a fixture for that part design. Each expert's organization of knowledge, the hypotheses considered, the influence of various factors during analysis, and the determination of the overall detailed design were recorded. This recorded approach was compared with the approach described by other fixture design experts for the same part design. By comparing and contrasting the approaches of these fixture designers, a better understanding of the fixture design activity was obtained. This technique was repeated with approaches detailed in books and manuals. Numerous questions were asked to clarify why certain tasks were performed and what role specific factors or inputs played in the fixture design. The intent was to obtain an understanding of analysis criteria in fixture design. Typical questions explored by the model developer included: what types of information were required to determine problem boundaries; what level of detail in the solution (or design) was required; how to decompose a problem into subproblems; and what types of analytical and heuristic rules were typically used or required to validate the final design solution (without having to build an actual fixture of the developed fixture design).

The domain experts' conclusions were analyzed further by posing 'what-if' scenarios to understand more about the problem solution. A follow-up post-session discussion helped explore each factor and attribute that seemed to influence development of the problem solution. This discussion helped establish individual contributions of the various inputs or factors (such as tolerances, feature attributes, etc.) to the overall fixture design activity.

IDEF-0 Function Model of Fixture Design

In this section, the IDEF-0 model of fixture design is presented and a brief discussion of each activity performed in fixture design is provided. In general, an IDEF-0 model includes a summary (purpose, viewpoint, context), decomposition diagrams, descriptions of the modeled activities, and a glossary of the ICOM attributes captured in the model. In this paper, the top level and decomposition diagrams are illustrated in *Figures 2, 3, 4, 6, 8, 9,* and *13.*

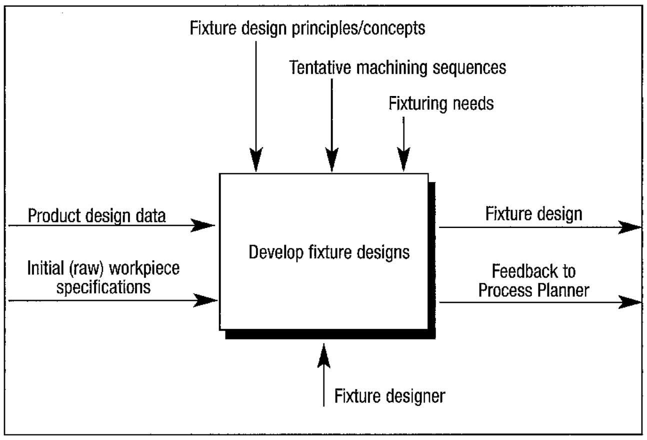


Figure 2
A-0 Level Diagram of Fixture Design Activity

The purpose of building this IDEF-0 model was to provide a better understanding of the various activities (and subactivities and tasks) performed within fixture design and capture the complex interrelationships among these activities and their decompositions. This function model was used to build an automated fixture design system to serve as a link between CAD and CAM activities. The modeling viewpoint was from an industrial engineer with a strong background in both design and manufacturing who has performed fixture design activities and is familiar with fundamental fixture design tasks. The context for building any IDEF-0 function model is provided in a diagram referred to as a context diagram (shown in *Figure 1*). The specific context-level diagram for the modeled fixture design activities is shown in *Figure 2*. For the fixture design activities, inputs assumed to be available to the fixture designer include product design information (such as design drawings/CAD models, tolerance specifications, etc.) and workpiece material. Inputs can be real objects or data needed to perform a function. Information such as the process sequence, machining tool path information, and manufacturing resources capabilities (that influence the fixture design task) are modeled as controls. The fixture designer begins the fixture design task with a tentative process plan. Outputs from the fixture design task include the validated fixture design and feedback to the process planner and the designer. The complete model, along with illustrated examples, is discussed in the following sections.

Context Diagram for 'Develop Fixture Designs'

The A0 level diagram, which served as the context diagram for the modeling task (pertaining to developing fixture designs), is shown as *Figure 2*. This activity has five major subactivities (A1, A2, A3, A4, and A5) (*Figure 3*). Each of these activities is described in detail in the following sections.

Study the Product Design (A1)

The first activity (A1 in *Figure 3*) performed by fixture designers is to study the part drawing. This is a crucial activity that enables the fixture designer to understand the design. This understanding has a major influence on each of the remaining activities performed by the fixture designer.

Analyze the Machining Requirements (A2)

Using the assimilated information about the given product design, the fixture designer then proceeds to analyze the machining requirements involved (activity A2 in *Figure 3*). This enables the fixture designer to identify machining constraints, such as special chip removal considerations and aspects related to support and locator design. Another output from this activity is the generation of setups to machine the given part design, taking into consideration its design, process sequence, and the available machining capabilities.

Develop Skeletal Fixture Design (A3)

The third activity (A3) is the evolution of the skeletal fixture design where the fixture designer produces an outline of the overall fixture design (*Figure 3*). Such an outline includes tentative support, location, and clamping approaches. Any conflicts between these three approaches are resolved before the next activity (detailing and consolidating the fixture design) is performed. Interestingly, some experienced fixture designers occasionally skip this task (performing preliminary fixture design). Their experience enables them to perform detailed support, location, and clamping designs that are usually feasible.

Detail and Consolidate Fixture Design (A4)

In this activity (*Figure 3*), the fixture designer

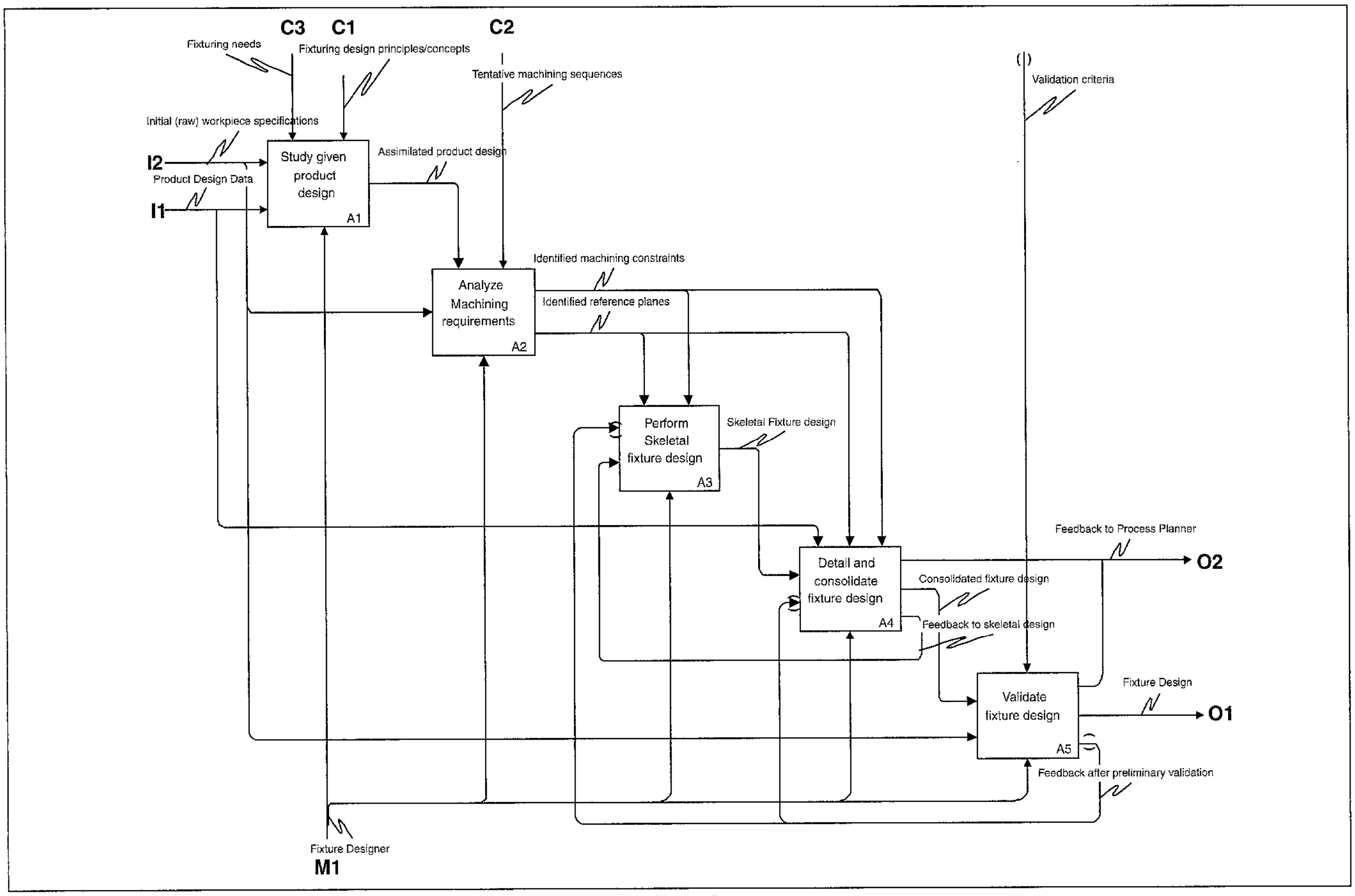


Figure 3
Decomposition of 'Develop Fixture Designs' Activity

performs the support, locator, and clamp design. At the completion of this activity, the support, location, and clamping faces on the workpiece are determined. The associated support, location, and clamping devices selected to perform their respective functions are identified (including the material and dimensions of each of the selected devices). Finally, the fixture designer performs a cursory check to ensure that the overall design of the support, locators, and clamps are compatible. This latter activity is performed to identify and rectify situations such as when a clamp is positioned over a flat plate locator butting against an additional locating face, etc. The fixture designer also ensures that for every locator used against the primary (plf) and secondary locating faces (slf), there is a clamp or locator used on another face (called the additional location face and is parallel to the locating face [lf]) to ensure that the workpiece is restrained along the *x, y,* and *z* axes.

Validation of Fixture Design (A5)

The fixture design is reviewed in this final activity of validation (A5 in *Figure 3*). The issues addressed include ensuring feasibility of the location surfaces used, ensuring that chip accumulation does not affect the stability of the workpiece, and making sure the machine tool path does not intersect with the clamps used in the fixture during the actual manufacture of the part, etc. If the fixture design is invalid, the factor (or aspect of the design) causing the invalidation must be addressed (this is modeled as a feedback loop to A3 and A4). Based on the nature of the invalidation, an alternate design may be produced. If an alternate design cannot be produced, the fixture designer informs the process planner about the problem (for example, being unable to perform location, or unable to identify a feasible clamping point on the workpiece, etc.)

Decomposition of Activity A1 ('Study given product design')

In this activity, 'study given product design' (*Figure 4*), the geometry and topology of the part design are studied (A11), the features occurring on the part design are identified (A12), and toler-

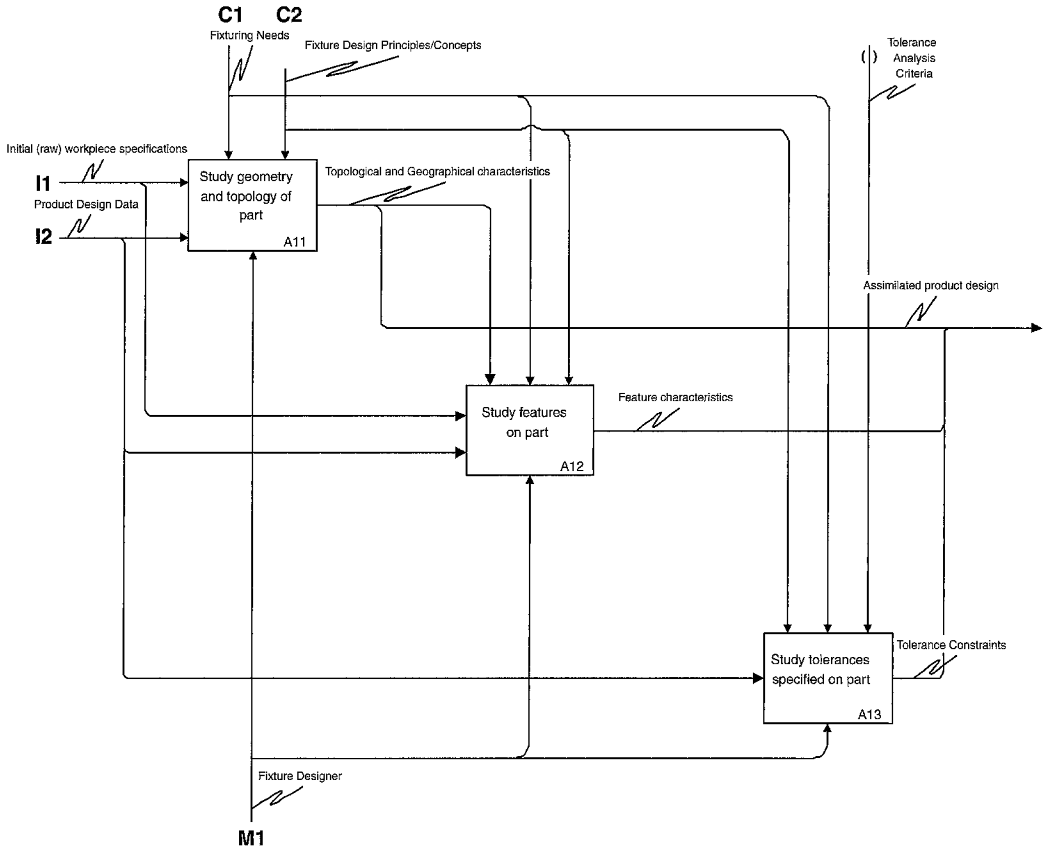


Figure 4: Decomposition of 'Study Given Product Design (A1)

Figure 4
Decomposition of 'Study Given Product Design' Activity A1

ance specifications are analyzed (A13). The general shape and size of the part design are reviewed, and the fixture designer forms a mental picture of the difficulty or ease of the fixture design task ahead. The types of features on the part design are then identified and the physical occurrence (or geometrical positions) of the various features on different faces of the part design is carefully observed. Occurrences of feature intersections are also noted (mentally). Next, the fixture designer studies the given tolerance specifications for various features on the part design; the fixture designer identifies the tolerance planes or datum reference planes for each feature. (This activity is a precursor to identifying the datum or reference planes in each setup, which is performed later.) *Figure 5* illustrates an example of a part design with tolerances (units in mm) and two features—step and a blind hole. The datum planes given are faces f5, f7, and f1.

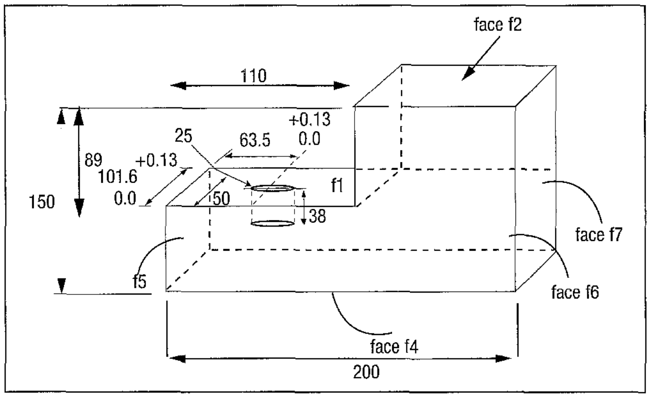


Figure 5
Example of a Part Design

Decomposition of Activity A2 ('Analyze machining requirements')

Under the category 'Analyze Machining Requirements' (*Figure 6*), the first activity involves identifying machining requirements (A21). The fixture designer studies the machining requirements of each feature in the given part design. Any machining

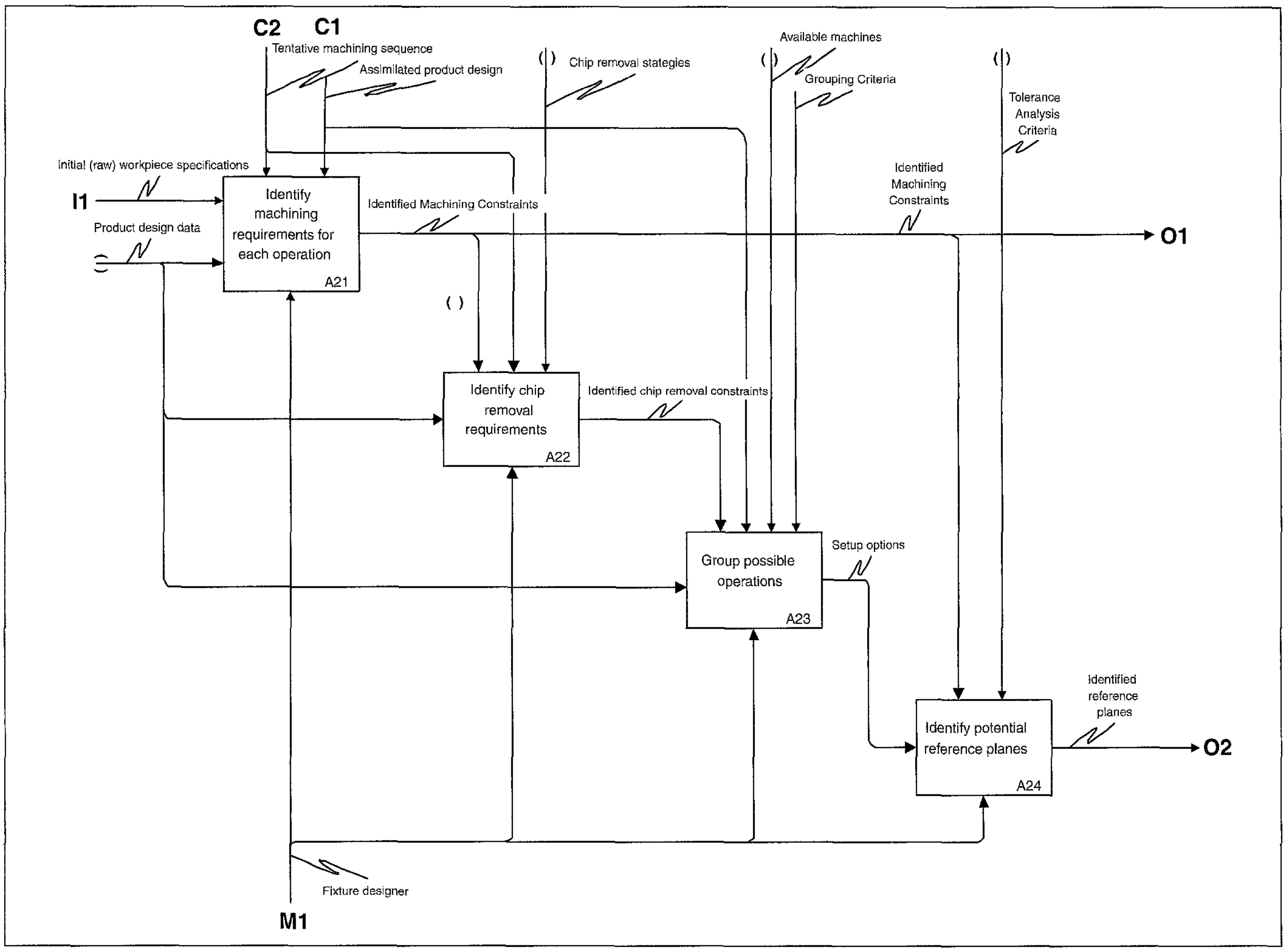
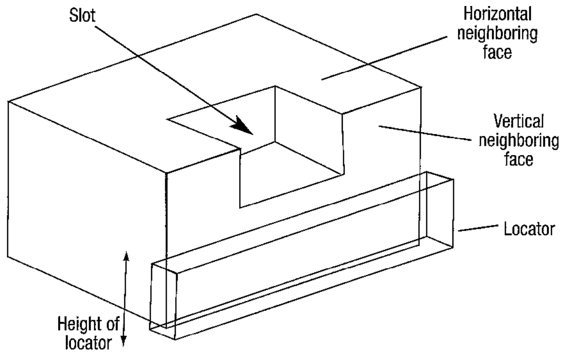


Figure 6
Decomposition of 'Analyze Machining Requirements' Activity A2

constraint that may influence the design of the fixture is identified. The machining constraints influencing fixture design depend on the type of feature being machined. An example of this would be whether the machining of a feature (such as a through-hole or slot) influences the design of a support or locator. Machining a through-hole requires that care be taken while designing a support. A key aspect to be addressed is ensuring that the machine cutting tool (such as a drill) is able to drill through the bottom face (and 'clear' the bottom face in reference). This would require that the support device used be designed to provide a relief for the drill tool to clear the bottom face while machining the through-hole in reference. The machining of a slot or any other feature that straddles two faces (or occurs across two faces) also needs to be studied. Machining of slots necessitates a side height clearance to allow the milling cutter to machine the entrance of the slot. The face possessing the entrance of a slot can be used as a locating or additional locating surface as long as the locating device does not obstruct the machining of the slot (*Figure 7*). Issues related to the machining of features are identified in this activity and are useful when the fixture designer performs detailed locator, support, and clamp design in the later stages.

The next activity, 'Identify chip removal requirements' (as indicated in *Figure 6*), is closely related to activity A21. The accumulation of chips during machining of features such as through-holes needs to be addressed. The type of machine tool used also influences the chip accumulation problem. For example, if a machine tool such as a gun drill is used, chip accumulation is not a problem because a gun drill collects the chips with the used coolant during drilling and disposes them using a suction mechanism. When other drill tools are used, the fixture designer has to incorporate a relief design in the support device to minimize the accumulation of chips during machining.

Another activity relates to grouping possible operations (A23 in *Figure 6*). The major machining constraint addressed by the fixture designer is in the generation of setups; the goal in this activity is to enable the machining of as many features as possible in a setup. The major constraint is the capability of the machines available on the shop floor (tentatively specified by the process planner; see *Figure 2*). Various setups to machine the features on the given part design are generated based on the direction of machining, the process sequence, and the machining capabilities of available machines on the shop floor. The fixture designer identifies the machining directions to produce each of the features on a given part design. Features that possess the same machining direction (that can be machined on an assigned machine per the process sequence provided) are grouped together and form one setup. For the part design shown in *Figure 5*, both of the features can be machined in the same setup.



Dimensions of locator should allow for machine tool clearance to machine the slot.

Figure 7
Analyzing Machining Requirements

The last activity of A2 (see *Figure 6*) is to identify potential reference planes (A24). After determining the various machining setups, the fixture designer attempts to identify reference planes (or features) for each setup. The guiding theme in this activity is to accurately locate various features to be machined in a setup. In general, fixture designers prefer the use of pre-machined (or pre-existing) through-holes and a pair of adjacent perpendicular faces. Dowel pins inserted into through-holes position the workpiece accurately and hold that position well during machining. A pair of flat plate locators butting against a corresponding pair of right-angled surfaces rigidly ensures accurate workpiece location during machining. For the features to be machined in *Figure 5*, faces 1, 5, and 7 can serve as potential reference planes.

Decomposition of Activity A3 ('Perform skeletal fixture design')

The activity 'performing a skeletal fixture design' (activity A3 in *Figure 3*) can be decomposed as shown in *Figure 8*. The term 'skeletal fixture design' refers to the general design idea to support, locate, and clamp a workpiece in a setup. For instance, a fixture designer

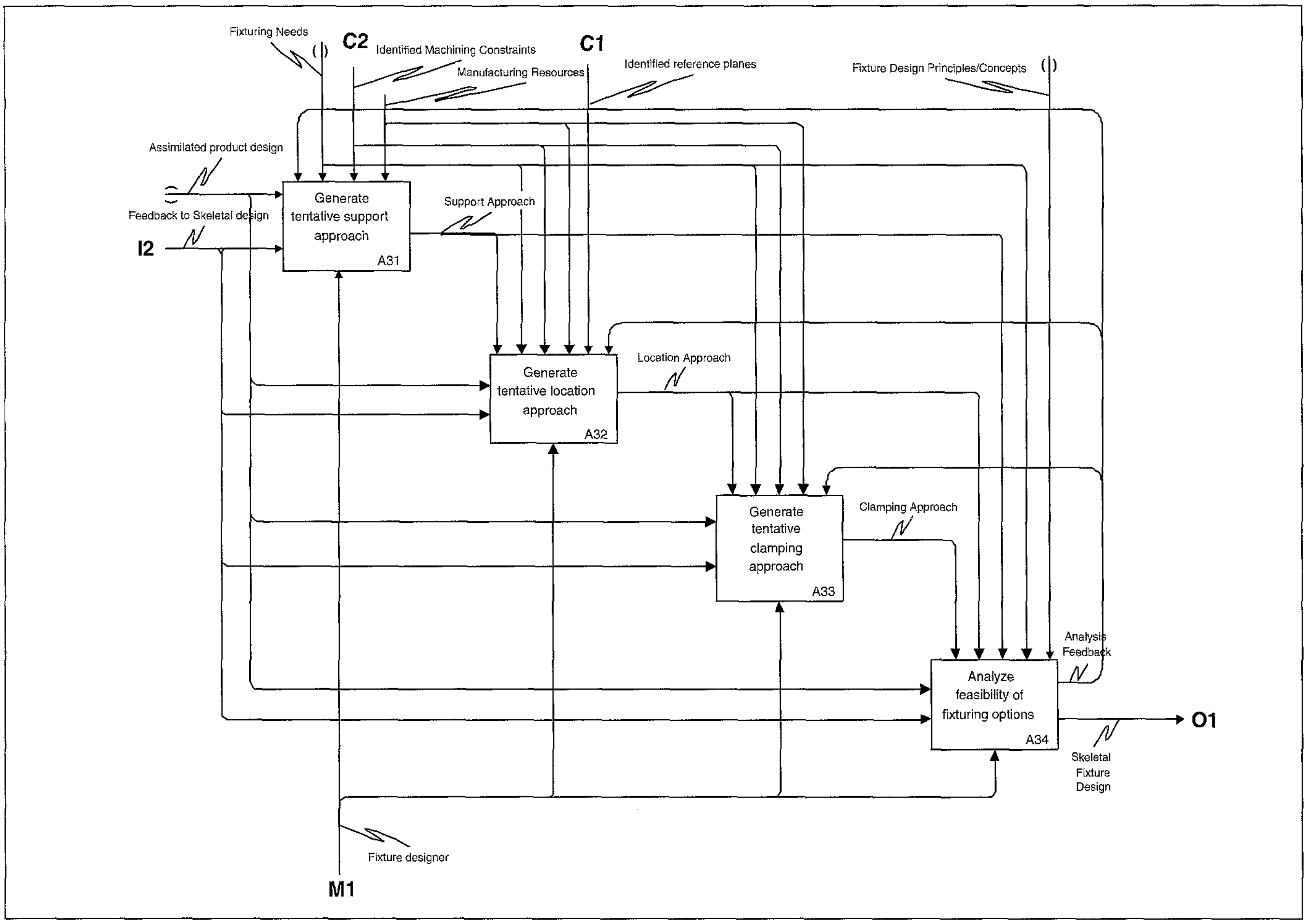


Figure 8
Decomposition of 'Perform Skeletal Fixture Design' (A3)

may initially decide on: (1) using a support against the bottom face of a part; (2) using a pre-machined hole to locate all features to be machined in that setup; and (3) adopting a side clamping method to hold a workpiece. This initial design is based on the fixture designer's understanding of the features to be produced, the datum planes in that setup, and the nature of the base and side faces (that is, are they planar and do they possess enough area for a clamp to be used, among other issues). As mentioned earlier, experienced fixture designers usually focus on the detailed fixture design without developing a skeletal fixture design. The domain experts opined that during their initial years they performed skeletal fixture design before detailing the design; however, as their experience increased, they became more skilled at producing a feasible fixture during their first attempt and gradually stopped developing the skeletal fixture design altogether.

As indicated by activities A31, A32, and A33 in *Figure 8*, other fixture designers prefer a more organized approach. They initially form a mental picture of each of the supporting, locating, and clamping techniques they think are feasible to hold, support, and locate the workpiece during machining (Cecil 2000, Cecil 1995). A general outline of the fixture is produced after discarding infeasible designs or resolving conflicting design problems (as in A34). Conflicting design problems include issues such as determining whether the tentatively selected down clamping method (in A33) agrees with the location approach (in A32), such as using a radial location technique. If they are infeasible, then this conflict is resolved iteratively as indicated by the feedback loop ('analysis feedback') from activity A34. As indicated in activity A3, one of the controlling influences is the term 'fixturing design principles'. This refers to the embedded fixturing knowledge of the designer (including heuristics and expertise gained in this area) when performing the fixture design task. Knowledge of the fundamentals of fixture design, coupled with the heuristic base, is an important influence (or controlling factor) during the

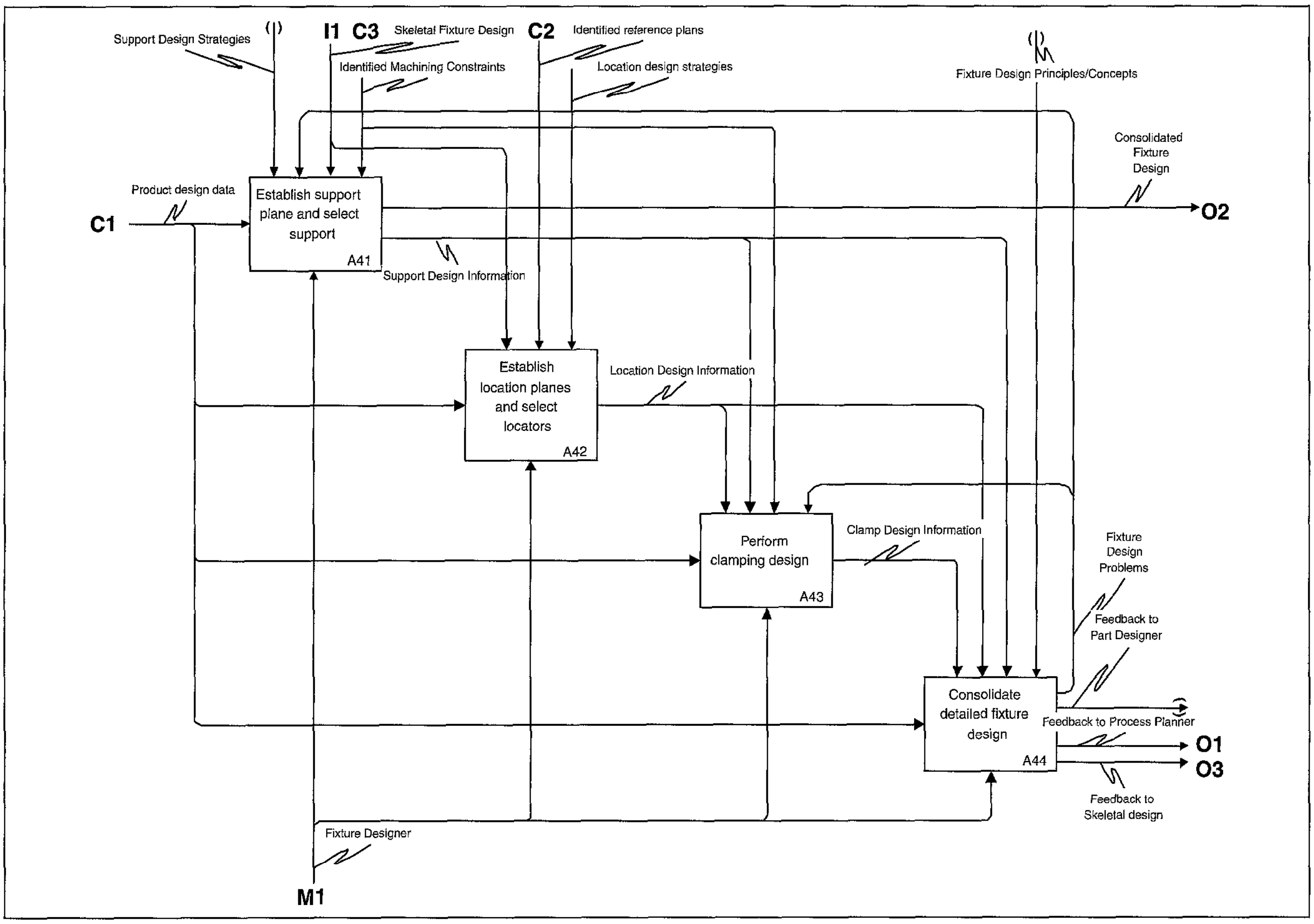


Figure 9
Decomposition of 'Detail and Consolidate Fixture Design' (A4)

accomplishment of the fixture design. Such knowledge includes identifying the preferred choice of locating surfaces and whether there is a need for radial location, familiarity with different clamping methods (ranging from down clamping to side clamping), and so on.

Decomposition of Activity A4 ('Detail and consolidate fixture design')

Activity A4, which is to detail and consolidate the fixture design, is decomposed into four subactivities (as in *Figure 9*).

Perform Support Design

In the first subactivity (establish support plane and select support [A41]), the fixture designer determines the support face in each setup and selects the type of support device to be used in the fixture. Influences on this activity include part design, type of feature to be machined in that setup, and machining constraints. If machining is to be performed along a *z*-axis, then the fixture designer prefers to use a flat surface whose outer geometrical envelope along the *x*-*y* axis contains geometrical profiles of the features to be machined in that setup (*Figure 10*). This increases the stability of the workpiece during machining (which is a support design heuristic). If a through-hole needs to be drilled in that setup, then the machining constraints information will influence the fixture designer to select a flat plate with a relief incorporated in it. In *Figure 10*, a support block with a relief enables tool clearance during the drilling of a through-hole.

Perform Locator Design

The second subactivity in A4 (*Figure 9*) is to establish location planes and select locators (A42). The fixture designer uses the identified reference plane, part design information, and location design heuristics (gained from his or her experience) to determine a feasible location face on the workpiece. The location device is then selected based on the

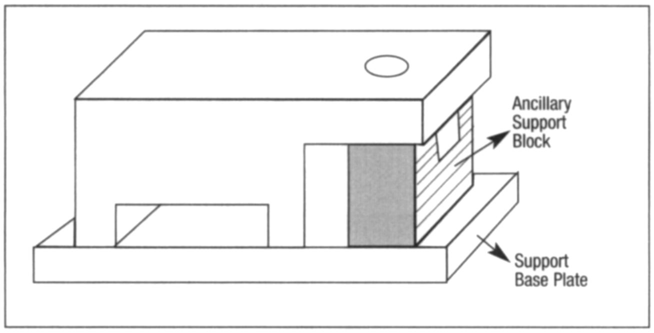


Figure 10
Machining Constraints Taken into Consideration

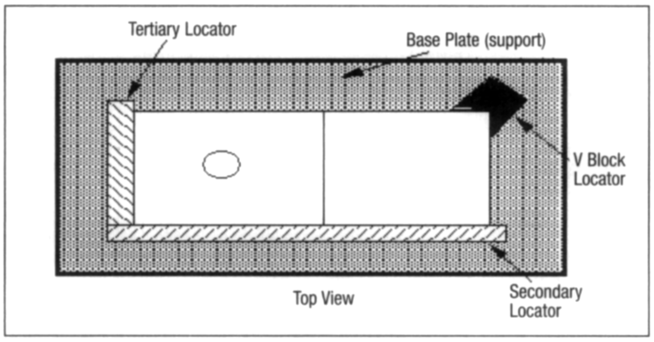


Figure 11
Using Locators for Part Design Shown in *Figure 5*

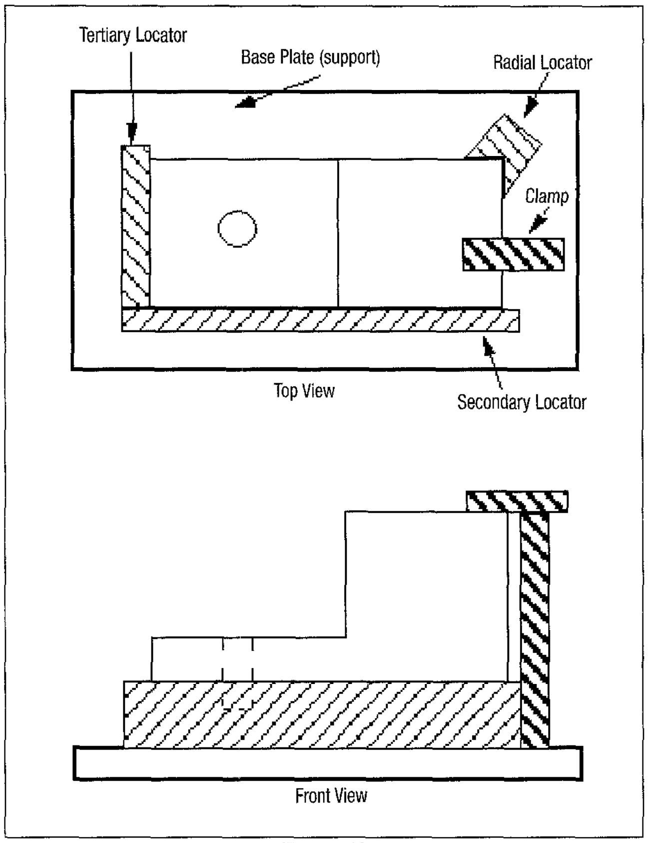


Figure 12
Clamp Positions with Respect to Locator Positions and Feature Occurrences

nature of the locating faces, features to be machined, and material of the workpiece. Flat plates (or three locating pins) are usually selected to serve as secondary and tertiary locating faces. If any machining constraints exist for features such as blind slots, the flat plate size must not hinder the path of the cutting tool. By selecting a flat plate whose height does not overlap the entrance of the slot (to be machined), collision of the machine tool against the locator is prevented (see *Figure 7*). A V-block is commonly used when a pair of adjacent, perpendicular faces are identified as additional locating faces. For the part design shown in *Figure 5,* a V-block can be used to perform location as indicated in *Figure 11.*

Perform Clamp Design

The third subactivity in A4 is to perform the clamping design (A43 in *Figure 9*). In this step, the machining forces involved are considered and a clamping face is selected to apply clamping force. The fixture designer's goal for this activity is to ensure that the machining forces do not lift or move the workpiece from its position with respect to the cutting tool. Clamping assists in the location task. In general, the fixture designer uses a clamp on a face that is parallel to a location or support face. The intention is to hold the workpiece against the locator. The workpiece position, with respect to the machine tool, is maintained by holding the workpiece against fixed solid supports. The part design is analyzed to ensure that the clamping region on the clamping face neither contains nor overlaps any features. This ensures that the machine tool does not collide with the clamp on the fixture. In *Figure 12,* the clamp face is parallel to the support face and the clamp position does not overlap any feature locations. The size of the clamp depends on the magnitude of the machining force and the type of clamp material. Different clamp materials have different tensile strength values to withstand cutting forces.

Consolidate Detailed Fixture Design

The last subactivity (indicated in *Figure 9*) is to consolidate the detailed fixture design (A44). The fixture designer reviews the design generated after the detailed support, locator, and clamp design have been completed. Fixture designers (like most humans) are prone to committing mistakes. For instance, the selected support plate may not be large enough to also position the clamps and locators; thus, a support plate of a larger size would be required. In

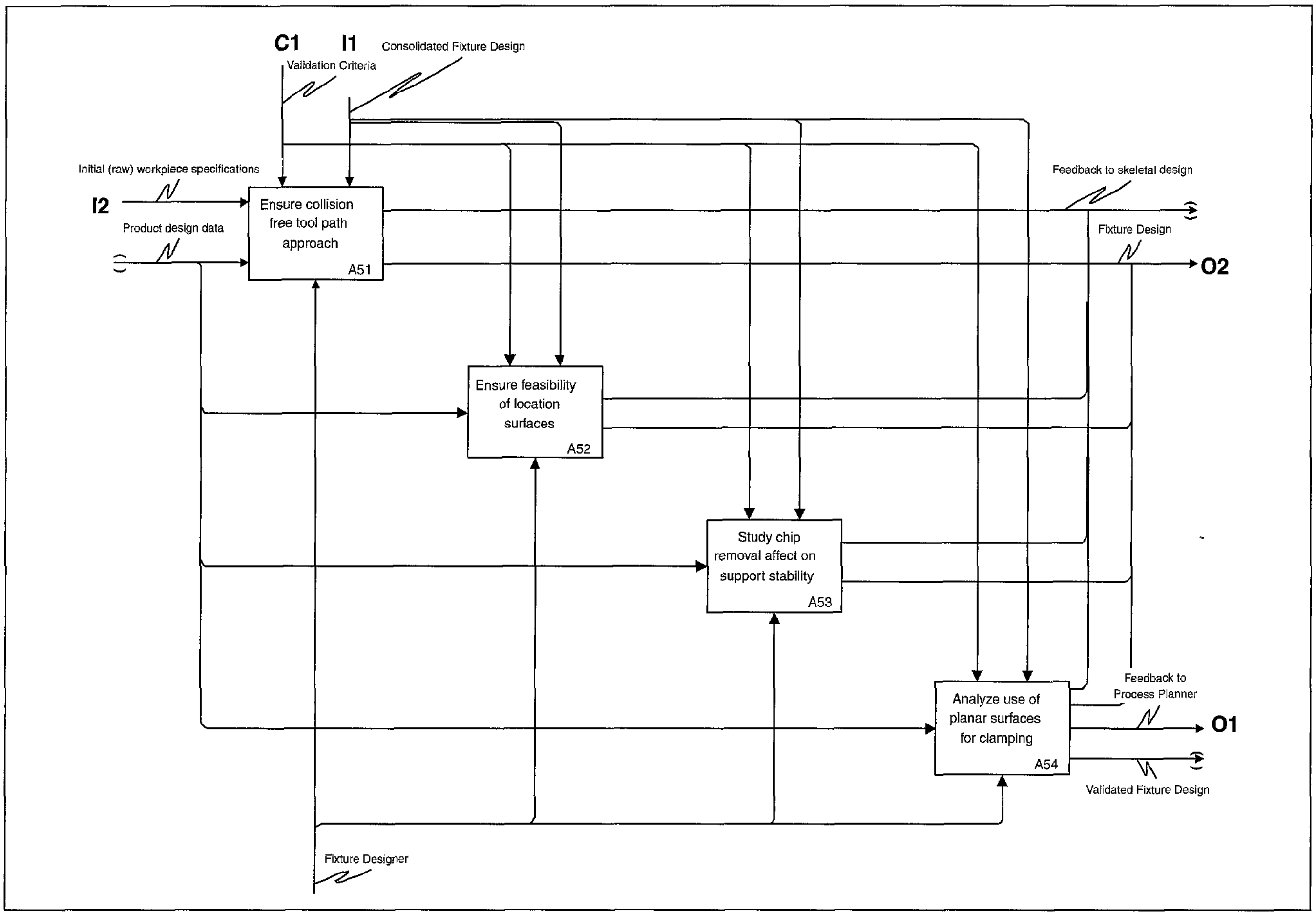


Figure 13
Decomposition of 'Validate Fixture Design' Activity A5

certain cases (where the part size is small and there is not enough region to use a clamp), the fixture designer may change the type of clamping approach. For example, side clamping may be preferred to the (original) down clamping design. The feedback loop 'design conflicts' (in A44) reflects this occurrence. Based on such feedback, changes to the overall fixture design can be performed.

Decomposition of Activity A5 ('Validate fixture design')

After the detailed fixture design has been produced, the fixture designer critically evaluates and validates the generated design (A5 in *Figure 3*); the decompositions of this activity are shown in *Figure 13*. The first issue addressed is to ensure that the tool path approach does not intersect or overlap with clamp and locator positions (A51). The feasibility of location surfaces (or features) is analyzed with respect to the features to be machined in each setup (52). The fixture designer studies the tolerance specification of each feature to determine whether it can be located accurately in relation to locating surfaces. In activity A53, the support design is studied to ensure relief designs have been incorporated, especially when multiple through holes need to be machined in a given setup (Cecil 2000). The clamping faces are studied to ensure they are planar in nature and do not overlap any features to be machined in that setup (A54 in *Figure 13*). If any validation criteria are not satisfied, the fixture designer reexamines the design problem for the associated criteria and makes the necessary design changes. The feedback loop to skeletal design and detailed design activities from each activity in A5 reflect this action. Based on the redesign, the validation task is performed again until all validation criteria are satisfied. The final output is a validated fixture design (the fixture shown in *Figure 12*). If the fixture designer is unable to determine a feasible clamping or locating face despite repeated attempts, the process planner is informed of this predicament. The resolution of such problems is beyond the scope of this model and is not addressed in this paper.

Conclusion

In this paper, an IDEF-0 model was discussed that describes the major activities performed by expert fixture designers while designing a fixture for a given part design. The developed function model illuminates the complex activity of fixture design and provides a better understanding of the functional activities accomplished during fixture design. Further research efforts can extend the findings described herein by building more detailed decompositions of the fixture design activity that were not addressed in this research effort. In addition, while the IDEF-0 model provides an understanding of what was being accomplished, it would be beneficial to develop other models that focus more on the temporal precedence of tasks and activities within fixture design (which cannot be explicitly captured in an IDEF-0 model). The use of languages such as the Enterprise Modeling Language (EML)® will help facilitate the capture of such time-based sequences of tasks and subtasks being modeled as well as provide an information-rich functional description of tasks and activities (VETI 2001).

Based on the developed function model, some important observations can be concluded. The given product design and related machining requirements must be analyzed prior to performing the actual fixture design. These activities can be viewed as a set of preliminary design tasks performed by fixture designers (see *Figures 3* and *4*). Activities such as machining analysis (which have not been adequately addressed by most CAFD-based techniques) are important activities performed by fixture designers to ensure that proper allowance is given for tool clearance and approach. To help facilitate early identification and communication of such issues and problems in a CAFD context, virtual prototyping based analysis techniques can be beneficial. Using virtual prototyping, automated fixture design techniques (employed by cross-functional product /process design teams in a factory) can highlight problems long before a fixture design/process plan is released to downstream operations, such as machining or fixture assembly. Virtual prototyping will enable the identification of collisions between tool and fixture components, enable better understanding of tool path issues, and identify the need for tool clearances during machining (which may otherwise be overlooked). Geometric reasoning methods, automated feature extraction techniques, and tool path generation techniques can support the design of such virtual prototyping based approaches, which can be viewed as the next generation of CAFD techniques.

After the product design and associated machining requirements are analyzed in preliminary design tasks, the second major activity is performing the support, locator, and clamp design for the fixture. The design of supports, locators, and clamps can be automated by using vector calculus, studying (cutting) force-balancing relationships (especially for clamp design), and using geometric reasoning methods (to identify the most feasible areas to clamp, support, and locate a workpiece). Other researchers have also arrived at similar conclusions regarding the role of tolerances (Nee et al. 1992; Sakurai 1990; Senthil Kumar, Subramaniam, Seow 1999). Tolerances play an important and strategic role in locator design. The identification of datum surfaces and features for locating workpieces during machining is critical. This task can be automated using a variety of techniques that enable analysis of relationships between features to be machined and the existence of datum planes in each setup.

Based on the model developed, the third major theme-oriented activity is the validation of the designed fixture (prior to handing it over to the process planner or chief process engineer, in some cases, for review). Detection of profile intersections of clamp areas and feature locations, validation of the feasibility of location faces, and other issues can be automated using geometric reasoning algorithms and analysis techniques (to perform tasks that answer questions such as "does the clamp area profile overlap with the tool path profile?" and others).

In conclusion, the fixture design task can comprise several phases, namely: a preliminary phase in which the focus is on studying the given product design; a functional analysis phase in which the support, locator, and clamp design is performed; and a final phase whereby the designed fixture is validated. Based on the understanding of fixture design activities from studying this model, a preliminary system TAMIL (Towards A Manufacturing Integration Link) has been implemented that accomplishes the fixture design tasks in distinct phases (Cecil 2001).

Information intensive function modeling (IIFM) will continue to play an important role in understanding complex manufacturing-related domains, as well as

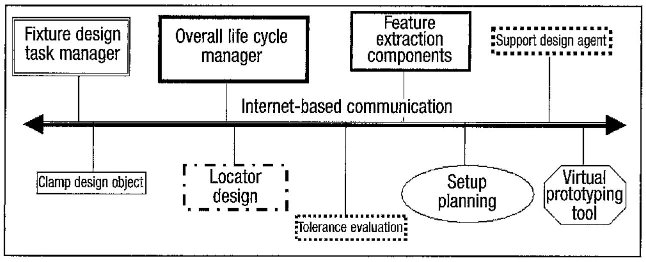


Figure 14
Internet-Based Framework for Distributed Fixture Design

serving as a basis for communication among concurrent engineering teams who may be collocated or distributed. In the rapidly emerging scenario of distributed virtual manufacturing, the need to build IIFMs for all life cycle activities at various levels of abstraction will become a necessity. Computer-aided fixture design may no longer be performed by a single system; rather, the various activities and subactivities will be performed by distributed resources or modules that are heterogeneous (implemented in a variety of programming languages) and running on heterogeneous computing platforms (ranging from Unix® to Windows®). The Internet can be a communication mechanism to link various functions (and the associated software entities accomplishing those functions) at geographically distributed locations around the world. *Figure 14* illustrates a distributed framework in which heterogeneous software and information resources will collaborate with each other in an integrated manner. A software-based fixture design manager will interact with a software-based life cycle product development manager to guide the accomplishment of fixture designs for proposed part designs. Then, this fixture design manager communicates those results to the distributed enterprise team members and other associated software components. In such an evolving virtual scenario, IIFMs will serve as a communication map that enables distributed teams to functionally model:

- what activities will be accomplished by which software entity (or concurrent engineering team member);
- the influencing constraints to accomplishing a certain subtask. Some issues will become critical to developing the overall approach. For instance, access to information relating to the availability of fixture components, such as clamps or locators, by a virtual customer located in a distant country will become important, as will the nature of the data format in which this information is available;
- which outcomes or decisions need to be communicated to which software entity or team member, among others.

IIFMs can then be viewed as a basis to conceptualize and detail 'AS IS' or 'TO BE' collaborative activities involving distributed teams and their resources. IIFMs also can be used for modeling other life cycle activities ranging from product design, process planning, and manufacturing control (among others), which can be used as a basis for accomplishing virtual enterprise oriented activities.

To support better communication and cross-functional understanding among fixture designers, tool designers, process planners, and other manufacturing personnel, virtual prototyping based techniques can be developed that allow candidate fixture designs to be proposed, analyzed, modified (if necessary), and validated. This will enable earlier identification of problems before a part design is released to downstream operations. It is important to realize that for CAFD to serve as an integrator between CAD and CAM it must be performed in a manner where upstream and downstream participants can understand problems and communicate effectively; the use of visualization and immersive virtual reality based environments (supported by virtual prototyping techniques) will facilitate effective communication among distributed cross-functional team members.

Insights gained from the function model described in this paper can be used to explore the design and development of future CAFD methodologies. This model can serve as a basis for building advanced fixture design systems in the context of today's evolving distributed manufacturing environments.

Acknowledgment

The author would like to acknowledge the contribution of the fixture design experts (especially Umesh Hari) for their time and interest in sharing their expertise during this modeling study. Dr. R. Mayer (Texas A&M University) was helpful in reviewing the function model and suggesting modifications.

References

1. Asada, H. and By, A. (1984). "Kinematic analysis of workpart fixturing for flexible assembly with automatically reconfigurable fixtures." *IEEE Journal of Robotics Automation*, pp86-93.
2. Bausch, J.J. and Youcef-Toumi, K. (1990). "Computer planning methods for automated fixture layout synthesis." *Proc.* of Mfg. Int'l (v1), pp225-232.
3. Bidanda, B. and Cohen, P.H. (1990). "Development of a computer-aided fixture selection system for concentric rotational parts, advances

in integrated design and manufacturing." *Proc.* of 1990 ASME Winter Annual Meeting, San Francisco (v23, n1), pp151-162.

4. Boerma, J.R. and Kals, H.J.J. (1988). "Fixture design with FIXES." *Annals of the CIRP* (v38), pp399-402.
5. Cecil, J.A. (1995). "Fixture design in a CIM environment." PhD dissertation. College Station, TX: Dept. of Industrial Engg., Texas A&M Univ.
6. Cecil, J.A. (2000). "Developing function models of fixture design." Research Report. Virtual Enterprise Engg. Lab, Mechanical and Aerospace Engg. Dept., Utah State Univ.
7. Cecil, J.A. (2001). "A clamping design approach for automated fixture design." *Int'l Journal of Advanced Mfg. Technology* (v18), pp784-789.
8. Chang, T.C. (1990). *Expert Process Planning for Manufacturing.* Reading, MA: Addison Wesley Publishing Co.
9. Dai, J.; Nee, A.Y.C.; and Fuh, J.Y.H. (1997). "An approach to automating modular fixture design and assembly." Proc. of the Institution of Mechanical Engineers, Part B, *Journal of Engg. Manufacture* (v211), pp509-521.
10. Darvishi, A.R. and Gill, K.F. (1988). "Knowledge representation database for the development of a fixture design expert system." *Proc.* of the Institution of Mechanical Engineers (v202), pp37-49.
11. DeVor, R.E.; Chandrasekharan, V.; and Kapoor, S.G. (1998). "Mechanistic model to predict the cutting force system for arbitrary drill point geometry." *ASME Journal of Mfg. Science and Engg.* (v120), pp563-570.
12. Dong, X.; Gilman, C.; Wozny, M. (1994). *Feature-based Fixture Design and Set-up Planning Artificial Intelligence in Optimal Design and Manufacturing.* Englewood Cliffs, NJ: Prentice-Hall, Inc.
13. Ferreira, P.M. and Liu, C.R. (1988). "Generation of work piece orientations for machining using a rule based system. *Robotics and Computer Integrated Mfg.* (v4, n3/4), pp545-555.
14. Gandhi, M.V. and Thompson, B.S. (1987). "Automated design of modular fixtures for flexible manufacturing systems." *Journal of Manufacturing Systems* (v5, n4), pp243-252.
15. Kang, Y.; Rong, Y.; and Sun, M. (1998). "Constraint based modular fixture assembly modelling and automated design." *Proc.* of ASME Mfg. Science and Engg. Div. (v8), pp901-908.
16. Kow, T.S.; Senthil Kumar, A.; and Fuh, J.Y.H. (1998). "An integrated computer aided modular fixture design system for interference free design." *Proc.* of ASME Mfg. Science and Engg. Div. (v8), pp909-916.
17. Latombe, J. and Ingrand, F. (1980). "Functional reasoning for automatic fixture reasoning." *Lifia IMAG* (v6), pp35-39.
18. Liu, C. (1994). "Systematic conceptual design of modular fixtures." *Int'l Journal of Advanced Mfg. Technology* (v9), pp217-224.
19. Ma, W.; Li, J.; and Rong, Y. (1999). "Development of automated fixture planning systems." *Int'l Journal of Advanced Mfg. Technology* (v15, n3), pp171-181.
20. Mani, M. and Wilson, W.R.D. (1988). "Automated design of workholding fixtures using kinematic constraint synthesis." *Transactions of the North American Manufacturing Research Institution of the Society of Manufacturing Engineers* (Vol. XVI), pp437-444.
21. Mantyla, M. (1988). *An Introduction to Solid Modeling.* Rockwell, MD: United States Press.
22. Markus, A. (1984). "Fixture design using PROLOG: An expert system." *Robotics and Computer Integrated Mfg.* (v1, n2), pp195-201.
23. Mayer, R.J.; Su, C.J.; Mayer, P.S.D.; Keen, A.; and Blinn, T. (1990). "Design knowledge management system." DKMS Report, AFHRL-TP-90-81. College Station, TX: Knowledge Based Systems Inc.
24. Menassa, R.J. and DeVries, W.R. (1991). "Optimization methods applied to selecting support positions in fixture design." Trans. of ASME, *Journal of Engg. for Industry*, pp412-418.
25. Miller, A.S. and Hannam, R.G. (1985). "Computer aided design using a knowledge base approach and its application to the design of jigs and fixtures." *Proc.* of the Institution of Mechanical Engineers, B4, p199.
26. Nee, A.Y.C.; Bhattacharya, N.; and Poo, A.N. (1987). "Applying AI in jigs and fixture design." *Robotics and Computer Integrated Mfg.* (v3, n2), pp195-201.
27. Nee, A.Y.C.; Whybrew, K.; and Senthil Kumar, A. (1995). *Advanced Fixture Design for FMS:* Springer Verlag.
28. Nee, A.Y.C.; Senthil Kumar, A.; Prombanpong, S.; and Puah, K.Y. (1992). "A feature based classification scheme for fixtures." *Annals of the CIRP* (v41, n1), pp189-192.
29. Nnaji, B.O. and Liu, H.C. (1990). "Feature reasoning for automatic robotic assembly and machining in polyhedral representation." *Int'l Journal of Production Research* (v28), pp517-540.
30. Pham, D.T. and De Sam Lazaro, A. (1990). "Auto-fix—An expert CAD system for jigs and fixtures." *International Journal of Machine Tools and Manufacture* (v30, n3), pp403-411.
31. Rong, Y. and Zhu, J. (1993). "Fixturing feature analysis for computer aided fixture design." *Intelligent Design and Manufacturing.* ASME Winter Annual Meeting, New Orleans, LA, pp267-271.
32. Rong, Y. and Wu, S. (1994). "Automated verification of clamping stability in computer aided fixture design." *Computers in Engg., Proc.* of ASME Int'l Conf. and Exhibition, pp421-426.
33. Rong, Y. and Bai, Y. (1997). "Automated generation of modular fixture configuration design." *Journal of Mfg. Science and Engg.* (v119), pp208-219.
34. Rong, Y.; Wu, Y.; Ma, W.; and LeClair, S. (1997). "Automated modular fixture design: Accuracy analysis and clamping design." *Robotics and Computer Integrated Mfg.* (v14), pp1-15.
35. Rong, Y.; Ma, W.; and Lei, Z. (1997). "Fix-des: A computer aided modular fixture configuration design system." *Int'l Journal of Advanced Mfg. Technology* (partially presented at ASME Computers in Engg. Conf., Sacramento, CA).
36. Sakurai, H. (1990). "Automatic setup planning and fixture design for machining." *Journal of Manufacturing Systems* (v11, n1), pp30-37.
37. Senthil Kumar, A.; Subramaniam, V.; and Seow, K.C. (1999). "Conceptual design of fixtures using genetic algorithms." *Int'l Journal of Mfg. Technology* (v15, n2), pp79-84.
38. Senthil Kumar, A.; Nee, A.Y.C.; and Prombanpong, S. (1992). "Expert fixture design system for an automated manufacturing environment." *Journal of Computer Aided Design* (v24), pp316-326.
39. Slocum, A.H.; Peris, J.; and Donmez, A. (1985). "Development of a flexible automated fixturing system." Progress Report: U.S. National Bureau of Standards, Automated Production Technology Div.
40. Sun, Shu Huang and Chen, J.L. (1995). "Modular fixture design system based on case based reasoning." *Int'l Journal of Production Research* (v34), pp3487-3497.
41. Thompson, B.S.; and Gandhi, M.V. (1985). "A literature survey of fixture design automation." *Int'l Journal of Advanced Mfg. Technology,* pp240-255.
42. Tuthill, G.S. (1990). *Knowledge Engineering.* Blue Ridge Summit, PA: TAB Books, Inc.
43. Trappey, A.J.C. and Liu, C.R. (1993). "Automated fixture configuration using projective geometry approach." *Int'l Journal of Advanced Mfg. Technology* (v8), pp297-304.
44. VETI Project Report (2001). "Design of an Enterprise Modeling Language (EML) for virtual enterprise applications." Las Cruces, NM: Virtual Enterprises Technologies, Inc.
45. Wu, Y.; Rong, Y.; and Ma, W. (1998). "Automated modular fixture planning: Geometric analysis." *Robotics and Computer Integrated Mfg.* (v14), pp1-15.
46. Wu, Y.; Rong, Y.; and Ma, W. (1998). "Automated modular fixture planning: Accuracy, clamping, and accessibility analysis." *Robotics and Computer Integrated Mfg.* (v14), pp17-26.

Author's Biography

J. Cecil is an assistant professor in the Dept. of Industrial Engineering at New Mexico State University. He completed his bachelor of engineering studies in mechanical engineering at Anna University (Madras, India). His graduate degrees are in industrial engineering, including an MS from the State University of New York and a PhD from Texas A&M University. His teaching and research interests include distributed manufacturing, information-oriented enterprise modeling, virtual manufacturing, simulation-based design, CAD/CAM, and electronic commerce, among other areas. Dr. Cecil is interested in a wide range of domains, including prismatic parts manufacturing, electronics assembly, satellite manufacturing, and microelectromechanical systems (MEMS).