ECAPP: A Process-Planning Tool Using Artificial Intelligence

Allan Fraser, Harry Sloate, and Mitchell Tseng

The electronics computer-aided process-planning (ECAPP) system is a rule- and frame- based generative process-planning system for the assembly of electronic components onto printed circuit boards (or moduless). ECAPP uses expert process-engineering knowledge, a manufacturing plant's specific process capabilities, and product information from a computer-aided design (CAD) database to generate all the feasible process routes for a product through a factory. ECAPP then recommends the best route based on the plant's process-engineering rules and generates the numeric control code, or insertion and onsertion (onsertion refers to placing surface mount components) patterns, for the automatic assembly equipment. ECAPP also checks module ease of manufacture based on a specific plant's process characterization and allows manufacturing engineers to simulate product assembly using rule-based simulation before releasing a product to the manufacturing floor.

ECAPP has been in use in Digital Equipment Corporation's Augusta, Maine, manufacturing facility since March 1989. ECAPP represents two successful transfers of technology. The first transfer was from a university research environment to the Intelligent Systems Technology Group

(ISTG) at Digital, and the second was from ISTG to the ECAPP users and system maintainers in the Augusta plant.

ECAPP has reduced the amount of time it takes a manufacturing engineer to introduce a new product into production from 1–2 days to 1–2 hours. Other benefits include consistent high-quality process plans, reduced machine setup times, and the automatic generation of insertion and onsertion patterns for the assembly machines. ECAPP is written in the Vax Lisp and CRL-OPS languages using the Knowledge Craft shell and runs under the VMS operating system on the VAX family of computers.

Prior Work

Much work has been done in using variant and generative process planning for mechanical components. However, relatively little has been done for performing process planning for electronic modules. PWA_planner is a prototype of a generative process-planning system for printed wire boards (Terwilliger 1985). It develops the mounting head sequence for a workstation and ensures no collision between components. It does not develop operation sequences or operator instructions.

Inca is an expert system for module process planning that is used by ITALTEL in Milan, Italy (Cavalloro and Cividati 1988). This system optimizes the automatic insertion of components on modules. The objective is to maximize the number of components that can automatically be inserted on the board and minimize the time used to insert them. The system does not appear to generate process routes or to deal with surface-mount components. The work by Chang and Irizarry-Lopez served as the theoretical basis for the current ECAPP tool (Chang and Wysk 1985; Irizarry-Lopez 1989; Irizarry-Gaskins and Chang 1989).

Definition of the Problem

Digital's competitive strength lies in its ability to capitalize on windows of opportunity in the international marketplace. A competitive advantage is achieved by the following: (1) reducing the time to market and the time to volume manufacturing for new products, (2) reducing product cycle times from customer order through customer receipt, (3) improving product quality and reducing product cost, (4) meeting scheduled commitments for delivering the product to customers, and (5) increasing manufacturing engineer's productivity.

As product life cycles shrink, it becomes critical that Digital's manufacturing engineers quickly and accurately produce product routings that take product similarities and the current manufacturing floor environment into account. Optimum product routings will minimize production introduction cycle times, ensure high product quality, and improve manufacturing productivity.

In 1987, in Digital's Augusta, Maine modules manufacturing plant, the process engineers responsible for introducing new products into manufacturing were finding themselves increasingly overworked. The increase in work was primarily because of the number and complexity of new products being introduced into the plant. Because of the high capital cost of their automatic assembly equipment, the insertion patterns to drive the assembly machines had to be manually developed on the production machines themselves. This work was time consuming, tedious, and error prone. In addition, the assembly machine was unavailable for regular production work during the 8 to 16 hours that it took to develop the insertion patterns for each new product.

At the same time, although design engineers were designing products that met all the functional specifications, these designs did not make the most efficient use of the new automatic assembly equipment in the plant. In general, manufacturing practice was not made visible enough to the design engineering community.

Several attempts had been made to solve this problem using conventional programming techniques. In each case, the conventional solution required the manufacturing engineer to make the decisions regarding the best route for each product. These systems also did not take product and process variables into account when selecting a route, and they still required that the engineer spend a significant amount of time translating and reformatting data to make optimum use of the automatic assembly equipment in the plant. In summary, product and process changes still created considerable work for a manufacturing engineer.

Description of the ECAPP Application

ECAPP is a generative process-planning system for the assembly of electronic components onto modules. ECAPP is designed to (1) reduce the time to market for new products, (2) consistently produce process plans of the highest quality, (3) reduce insertion machine setup time, (4) increase process engineers' productivity and minimize fire fighting, (5) reduce product cycle time by using process flexibility, (6) provide input to a daily scheduler or other plant systems, and (7) develop a process-planning knowledge base.

The ECAPP system makes use of product information provided by CAD systems, a manufacturing plant's specific process capabilities, and heuristics acquired from process- engineering experts to produce a

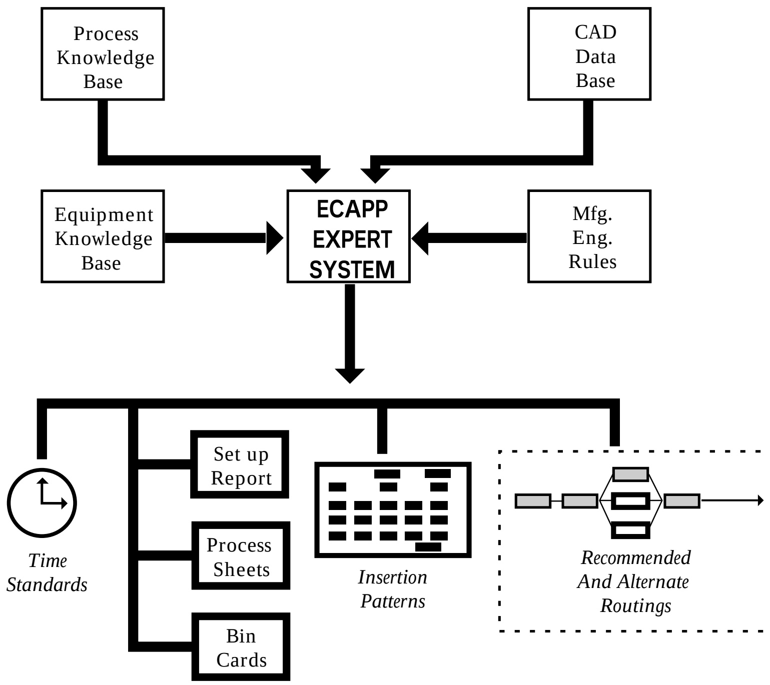


Figure 1. ECAPP System Architecture.

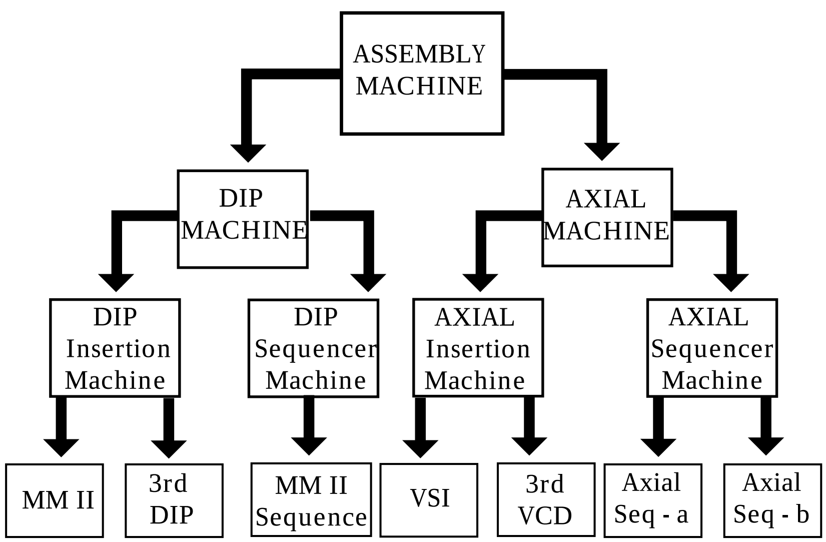


Figure 2. Equipment Knowledge Base.

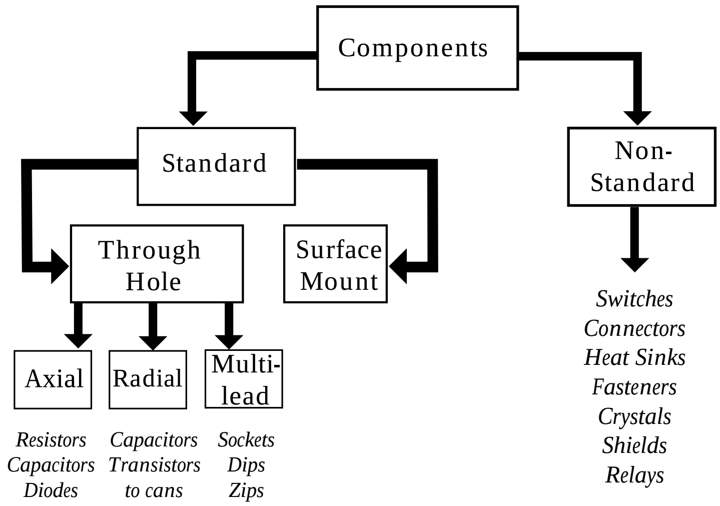


Figure 3. Computer-Aided Design Database.

network of feasible product routes through the manufacturing process. ECAPP then uses process-engineering rules to select the best route.

Process-engineering rules are also used to check component placement to ensure that tooling and machine constraints are not violated. A graphic display of the board is produced, showing the sequence in which the components are placed on the board. Each component is color coded to show which machine type is used to place it. Components that exceed constraints are colored red. Polarized components with the wrong orientation are highlighted in yellow. This color coding greatly reduces the need for dry runs on production machines to test new insertion patterns because problems can be eliminated before the patterns are generated.

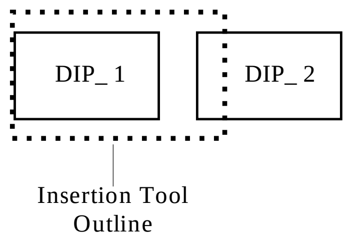
Figure 1 shows the ECAPP system's modular architecture. The equipment knowledge base contains the descriptions of the assembly machines in the plant (figure 2). The process knowledge base contains the descriptions of the process operations in the plant. The CAD database contains the feature-based product description (figure 3). The manufacturing engineering rules are the process engineer's heuristics for route selection and ease-of-manufacture checking (figure 4).

ECAPP generates all the feasible process routes for a product through the factory as well as recommends the best route based on the process-engineering heuristics. ECAPP also generates setup reports and bin cards showing how the assembly machine's configuration needs to be changed to assemble the current product, process sheets that detail all

PROCESS RELATED:

IF PRODUCT contains a DIODE
THEN AXIAL OPERATIONS are REQUIRED

MANUFACTURING CONFLICT RELATED:



IF there exists a DIP_1 with boundary box B!
AND there exists a DIP_2 with boundary box B2
AND DISTANCE from B1 to B2 < MIN_DIP_DIST
THEN mark DIP_1 and DIP_2 as a CONFLICT

Figure 4. Examples of Expert's Heuristics.

the process steps required to assemble the product, product time standards based on the rate of the assembly machine and the number of operations to be performed by the machine, and the actual insertion-onsertion patterns that drive the assembly machines in the selected process route.

Figures 5, 6, and 7 are black-and-white images of the ECAPP user interface. ECAPP runs in color both on VAX workstations and VT340 terminals connected to a computer. The former environment is used by the ECAPP development team, the latter by the manufacturing engineers in the plant. The terminals have lower capital cost and better performance because of a more powerful central processing unit when operating in a local area network environment. In either case, the operation of the ECAPP system is the same.

Ecapp Impact

The following beneficial effects of ECAPP have been observed in the plant: ECAPP shortens product introduction times by automatically generating consistent, high-quality, process plans for module assembly (insertion and onsertion patterns, bin cards, documentation); reduces lost time on assembly machines because of the testing of new insertion and onsertion patterns; reduces setup time on insertion and onsertion machines by using existing setups; reduces design time by checking module ease of manufacture; and allows production to change routings in response to demand changes or machine outages. The tooling-conflict and polarity-checking features of ECAPP can be used by design engineers to correct board layout problems before a new module is issued to manufacturing. If the design engineer knows in which manufacturing plant their new product will be produced, they can utilize the plant's process characterization in ECAPP to perform these up-front ease-of-manufacture checks prior to releasing the design to manufacturing. This approach reduces both the time to market and the cost of producing this module.

Input to ECAPP

Both process and product information are used to generate the routings for the product.

Plant Configuration

This option allows the user to see the current plant configuration by looking at the assembly machines and the process operations knowledge bases. Both of these knowledge bases are frame based and contain all the information used by the program pertaining to the assembly machines and the process steps that take place on the manufacturing floor.

In the knowledge base for the assembly machines, we find information about the number of component channels and the various types of tooling heads on each machine. There are seven levels in the current knowledge base, with the frames at the lowest level corresponding to each physical machine on the production floor.

In the process operations knowledge base, we find the information about each process operation. For example, the surface-mount screen-and-paste operation has a certain operation code and takes place in a certain work cell. To update either of these knowledge bases, the user calls up a forms editor that performs some local security functions and error checking before transmitting the updated information through a

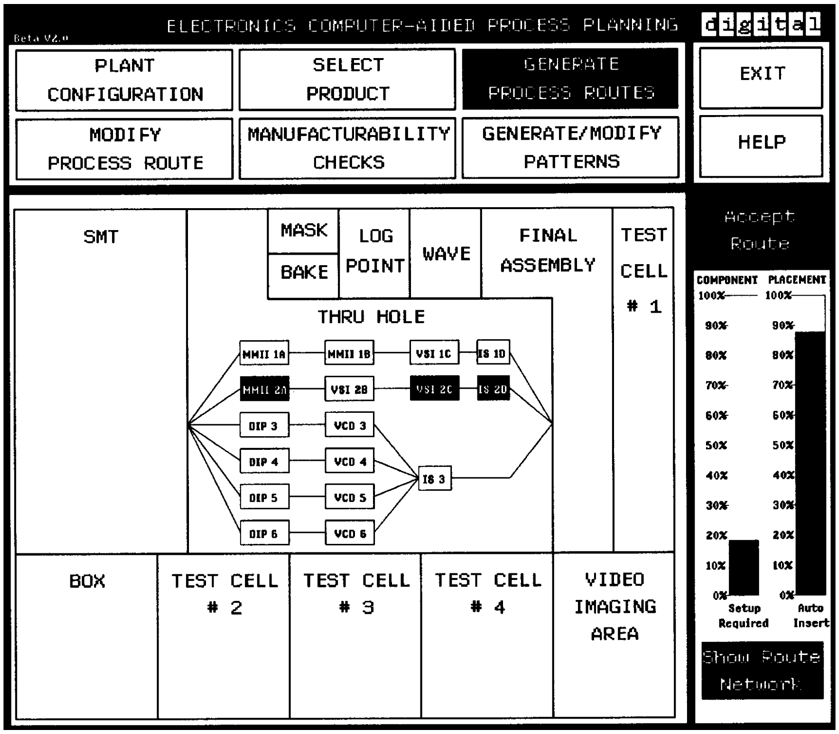


Figure 5. Recommended Route, Factory Layout Format.

message bus to a relational database that contains all the manufacturing data for the plant.

Select Product

This option allows users to select the product that they wish to process using the ECAPP system. Once identified, the product's CAD data are automatically transferred over the network to the local work area and preprocessed for use in ECAPP. Product data are also stored in frames. There are several levels in the product knowledge base hierarchy. The lowest- level frame represents one physical component on a board. The types of information stored in the frame for a component are part number, reference designator, x and y coordinates, and the side of the board on which to assemble the component.

Output from ECAPP

Outputs are automatically provided for the user. They can be customized for particular plants.

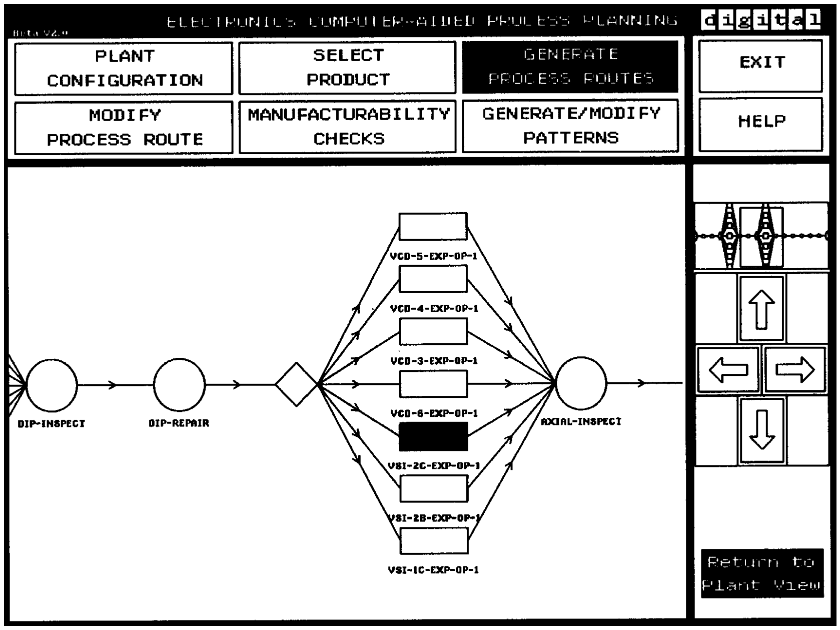


Figure 6. Recommended Route, Process Operation Format.

Generate Process Routes

By clicking on this function, the user activates the CRL-OPS rules portion of the ECAPP system. These CRL-OPS rules match product characteristics (for example, dual inline package [Dip] components) to one or more process operations. If there are Dip components on a board, then Dip Insert, Dip Inspect, and, possibly, Dip Repair operations are necessary. ECAPP then matches the required process operations with the machines required to perform these operations. If a Dip Insert operation is needed, then a resource on which to perform this Dip Insert operation must be found.

ECAPP generates all the feasible process routes by which a product can be assembled. ECAPP also recommends the best route for a product based on a manufacturing plant's process-engineering rules. In the Augusta plant, ECAPP mimics the process engineers' behavior by recommending the route that assigns products to work cells according to group technology rules, minimizes setup to provide the flexibility to build small lot sizes, and maximizes the automatic assembly of components to minimize process cycle time and assembly cost (figures 5 and 6). The user can elect to ignore the recommendation provided by ECAPP by using a manual override. The user simply changes ECAPP's

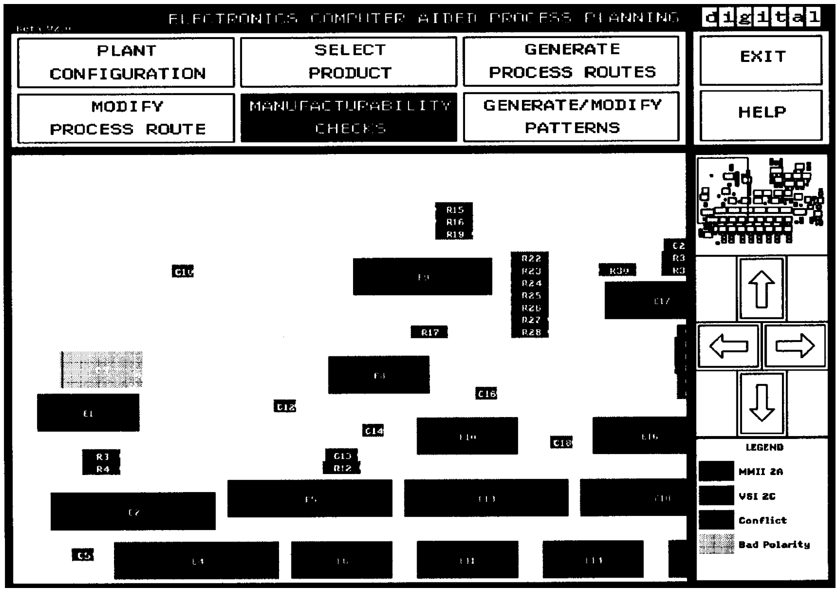


Figure 7. Screen for Ease-of-Manufacture Checks.

process route by graphically manipulating the icons corresponding to the assembly machines. The rules in the ECAPP system are continuously being added to and modified by Augusta's process engineers. ECAPP's process-engineering rules can also easily be changed to coincide with another plant's objectives for assembling modules.

Ease-of-Manufacture Checks

When this function is selected, a scaled, color-coded diagram of the module is displayed. ECAPP displays each component on the screen in the exact order that it will be assembled on the board during the assembly process. Components are colored to indicate which machine did the placement and whether a tooling conflict or polarity inconsistency occurred with a component on the module. See figure 7 for the display of an actual board as shown in ECAPP. Because of the size of a full module, only a portion of the module can be shown in the viewing window of the ECAPP screen at a time. A miniature characterization of the complete module is shown in the upper right-hand corner on the screen. The viewing window can be moved over the full module by clicking on the arrow icons.

Tooling conflicts can occur when components are placed too close together. For example, while a Dip insertion machine is inserting a small integrated circuit (IC), the machine-insertion head will overhang the component. If adjacent components are too close, the machine-insertion head will damage surrounding components when it attempts to insert this IC (figure 4).

ECAPP uses CRL-OPS rules in conjunction with its model of the board as it is being assembled to check whether a Dip component comes into conflict with a previously mounted surface mount or Dip component. If ECAPP locates a tooling conflict, the components will be colored red on the screen to alert the manufacturing engineer of a potential problem before it occurs on the production floor. At this time, the manufacturing engineer needs to assess whether changing the order of component placement will alleviate this problem. ECAPP displays components with polarity inconsistencies in yellow. ECAPP decides which axial components have polarity inconsistencies by using what we call the *rule of majority.* If an axial component is displayed in yellow, it does not mean the component has the wrong polarity. It simply means that the component's polarity is different from the majority of polarity-sensitive components of the same type that are to be assembled on the module.

The dual polarity of components requires the assembly machine to make 90-degree index steps to place these components. Because of the high rates of assembly using the newer automatic assembly equipment (for example, an axial machine can assemble 7500 parts each hour), additional index steps can significantly increase assembly time and adversely affect product yield. If a product is only spending two minutes on a machine, and you add two index steps at 15 seconds each (to rotate the table and check the alignment), then you just increased the assembly time for this product by 25 percent!

Generate-Modify Patterns

This function is utilized to create the insertion patterns for all the machines in the selected process route. ECAPP currently supports several automatic insertion machines, including Universal Instruments Corporation Dip insertion machines, axial insertion machines, surface-mount onsertion machines, and Fuji surface-mount onsertion machines. ECAPP's pattern generators are implemented using object-oriented programming techniques. All that is required to generate a pattern for a machine is to send a message to the generate-pattern slot of that machine. The contents of this slot are a method of how to generate the pattern for that machine. A pattern to assemble the Dip insertion on a module on a Universal Multi-Mod II machine is shown in figure 8. Included in the pattern are the x and y coordinates for each component in the machines coordinate system, the channel number in which the

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        1B_M3127PA-A1-000-000-00.PUT
0001> +00000 +00000 -00004 +00001 +00000 +00225 +00000 O O
0002> +11000 +09000 -00004 +00001 +00000 +00225 +00000 O I
0003> +10175 +07400 -00004 +00001 +00000 +00025 +00000 O O
0004> +02375 +02250 -00004 +00001 +00000 +00002 +00000 O B
0005> +02225 +02250 -00004 +00001 +00341 +00025 +00000 O C
0006> +01125 +02450 -00004 +00001 +00318 +00025 +00000 O C
0007> +01625 +06250 -00004 +00001 +00327 +00326 +00000 O C
```

Figure 8. Dip Insertion Pattern.

component is located, and the step and repeat information for each circuit on the panel. Because all the process-planning knowledge is already contained within ECAPP, it is estimated that writing a pattern generator for an additional assembly machine will require only one month of programming effort, including time to field test the pattern generators and take care of all the programming intricacies of the particular assembly machine.

Once a pattern has been generated for a particular machine, then it can be downloaded over a network link directly to the assembly machines and kept in a pattern library where it is available to the machine operators.

Setup Reports

Setup reports are automatically generated for each module and are created along with the insertion patterns. A setup report is generated for each machine used in the assembly process. Setup reports contain a list of part numbers for all the components that the specified machine will need to insert for the selected module. In addition, the setup report informs the user of the number and type of components not currently in the machine that need to be added before the module can be fully assembled.

During pattern generation, ECAPP automatically assigns channels for each component that is not already on the target assembly machine. The channels are assigned using the Augusta plant's process-engineering rules. An example is, "Assign a .300 Dip first to the front of the machine, as close to the middle of the machine as possible. If none of the channels on the front of the machine are free, then assign it to a free channel on the back of the machine. Otherwise, assign that component to hand assembly and flag the user."

Users can edit the patterns or setup reports if they so desire by clicking on the appropriate icon in the generate patterns menu. Usually, no pattern editing is required, although the user must have this capability if a problem is found with the ECAPP-generated pattern.

Development and Technology Transfer Strategy

ECAPP was developed by ISTG and implemented in the Augusta plant during a 2-1/2-year period. First, research at Purdue University in generative process planning was initiated (Irizarry-Lopez 1989; Irizarry-Gaskins and Chang 1989). University researchers spent time at the Augusta plant during the summer of 1987 learning about process planning and Augusta's electronic modules assembly process. A research prototype was developed at Purdue from September 1987 to September 1988. This prototype was then transferred to Digital, where knowledge engineers began working with the manufacturing personnel in the Augusta plant to develop a project plan based on plant needs. It should be noted that it was critical to ECAPP's success that the project be structured to be able to show demonstrable effects on Augusta's business operations within the time horizon of Augusta's budgeting cycle. In other words, although Augusta was interested in acquiring AI technology, they didn't want to have to wait a long time before seeing some results that would improve their operating practices. The ECAPP developers then worked to develop an initial ECAPP prototype that would address some immediate plant needs. The first ECAPP prototype was completed in March 1989 and field tested in the plant. ECAPP was installed in limited production use in the Augusta plant in July 1989 and has been successively refined ever since while it still supports production operations in the plant. ECAPP has been used on over 40 products in the Augusta plant since March 1989. ECAPP is currently used on every new product being introduced in the plant as well as on older products that can be transferred to the newer automatic insertion equipment.

During ECAPP prototype development, credibility was established with the user community by providing them with a graphic representation of the plant layout, something the users were intimately familiar with. Also provided was an intuitive, easy-to-understand graphic user interface, which contained a control panel of main menu items, pop-up menus, and messages. A good user interface helped to promote the use of the system at an early stage in its development. Putting in the display of the board layout to show component placement and the use of color coding to highlight tooling conflicts and polarity inconsistencies also gave the users a graphic overview of the module assembly process and quickly highlighted potential problem areas. The ability to quickly respond to user requests for changes to the ECAPP system proved to be invaluable when introducing ECAPP to the plant user community.

Future Improvements

The ECAPP environment provides a framework in which many other functions can be included. The rules addressing product ease of manufacture can be expanded to include company standard practices for component placement and other process-related practices. It is also planned to interface with other systems relating to the automatic generation of process sheets. ECAPP's expertise could be extended to other parts of the manufacturing operation such as test. ECAPP could also be adapted to run in other manufacturing plants by customizing the equipment and process knowledge bases for the plant and incorporating their rules for product ease of manufacture into the system.

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