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A framework for extending computer aided process planning to include business activities and computer aided design and manufacturing (CAD/CAM) data retrieval

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Abstract

Computer aided process planning (CAPP) systems have had limited success in integrating business functions and product manufacturing due to the inaccessibility and incompatibility of information residing in proprietary software. While large companies have developed or purchased complex order management and engineering applications, smaller manufacturers continue to use semi-automated and manual methods for managing information throughout the lifecycle of each new product and component. There is a need for reconfigurable and reprogrammable systems that combine advances in computer aided design (CAD/Computer Aided Manufacturing (CAM) technology and intelligent machining with product data management for documentation and cost control. The goal of this research is to demonstrate an architecture in which customer service, CAPP and a costing methodology known as activity based costing (ABC) are incorporated into a single system, thereby allowing companies to monitor and study how expenditures are incurred and which resources are being used by each job. The material presented in this paper is the result of a two year university and industry sponsored research project in which professors and students at the Costa Rica Institute of Technology developed a software application for FEMA Industrial S.A., a local machining and fabrication shop with sixty five employees and both conventional and CNC capabilities. The final results represent not only a significant contribution to local industry and to the students' education but, also to the continuing growth of CAPP. Implementing better decision making tools and standardizing transactions in digital format would reduce the workload on critical personnel and archive valuable knowledge for analyzing company methods and expertise.

Keywords: Capp; Activity based costing; CAD/CAM; Product data management

1. Introduction

The Costa Rica Institute of Technology (ITCR) is very conscious of its role and responsibility in contributing to the growth and modernization of the national manufacturing industry. Companies are constantly looking for new tools to optimize the use of their resources and to remove the divisions which exist between administration, engineering and production on the shop floor. While many years of experience in component and assembly fabrication have provided engineers and machinists with extensive knowledge related to processes and machines, companies continue to struggle in the areas of automation, information management and computerized design and planning techniques. The goal of this research is to develop a software framework that demonstrates how computer aided design (CAD)/computer aided process planning (CAPP)/computer aided manufacturing (CAM) technology can be combined with costing and business tools and made available to small and medium sized firms.

There are various well documented approaches that integrate cost analysis with CAPP. The first involves providing immediate feedback to designers as they work so that the economic implications of their decisions are understood at the earliest possible time and unnecessary costs can be avoided [1]. The second utilizes methods focused on optimizing process plans on the basis of time

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or cost or on some weighted combination of the two. Tool selection, process selection, tool path design, process parameter selection and operation sequencing are the most common areas for optimization in process planning. Mathematical methods such branch-and-bound for tool selection, dynamic programming for parameter selection and genetic algorithms for operation sequencing are among the examples [2].

This research proposes an activity based costing (ABC) methodology which does not optimize the process plan but, instead provides a tool for identifying the origin of each cost associated with designing, engineering and fabricating a part using company resources. ABC has proven to be very effective in product manufacturing and where automated processes are prevalent. The proposed system utilizes a Visual Basic 6 (VB6) interface that ties together customer service, process planning, a commercial 3D CAD solid modeling system, a CAM system that has built in CAPP and various business functions such as databases and document generation. This unique approach also addresses the complex problem of retrieving design and manufacturing data, critical to the overall cost of the part, using commands from the CAD/CAM Application Programming Interface (API) library of functions.

Fig. 1 outlines the specific areas of work related to the research presented in this paper. Phase one consisted of identifying the level of soft automation and CAD/CAM/CAE system usage in the local industry, specifically at component and assembly manufacturers who use CNC equipment. An evaluation of questionnaires and interviews led to the selection of a company that met the criteria of having the personnel, software capabilities and infrastructure necessary for developing a working program and a corporate vision toward automated manufacturing. A team from the university was composed of professors and students with multidisciplinary skills and backgrounds such as design and manufacturing, cost analysis and computer programming. A detailed analysis of company operations and interviews were used to determine the flow of information and specific software functionality. Program design and development, testing, presentations to representatives and documentation completed the project.

2. Background information

Process planning is defined by the society of manufacturing engineers as the 'systematic determination of the methods by which a product is to be manufactured economically and competitively' [1]. It is the bridge which connects the engineering department to the shop floor and includes all of the steps required to convert design specifications into detailed manufacturing instructions [3]. Process planning is defined by Chang and Wysk [4] as the function within the manufacturing facility that establishes which processes and parameters are to be used (as well as those machines capable of performing these processes) to convert a work piece to a finished part from its initial form to the final one predetermined in a engineering drawing. A typical plan includes detailed drawings, routing sheets, material, tooling, fixtures, part programs and cost data [5]. Process planning is difficult to automate because of the practical experience required to make technical decisions and the company specific knowledge utilized by planners to produce and optimize final plans.

2.1. Review of existing work in computer aided process planning (CAPP)

CAPP systems automate some or all of the manual process planning areas mentioned above, thus minimizing user interaction and drastically reducing the time to produce usable plans. CAPP optimizes and computerizes process planning by using software programs and optimization techniques. Due to the disappearance of experienced process planners in industry, shorter product life cycles and the importance of CAD/CAM integration, research in areas related to CAPP is receiving widespread attention and growing more than ever before [2]. Significant benefits can result from the implementation of CAPP. In a detailed survey of twenty-two large and small companies using CAPP systems, the following estimated cost savings were achieved: 58% reduction in process planning effort, 10% saving in direct labor, 4% in material, 10% in scrap, 12% in tooling and a 6% reduction in work-in-process [6]. Other benefits include the standardization of company practices, increased productivity for planners and better interfaces to related programs [3].

Traditional CAPP systems were classified as either variant or generative. Variant systems follow the principle that similar parts require similar plans. Therefore, the process requires a human operator to classify a part, input part information, retrieve a similar process plan from a database (which contains a library of previous process plans), and edit the plan to produce a new variation of the pre-existing plan. Planning for a new part involves retrieving an existing plan and modifying it based on the new conditions. In some variant systems, parts are grouped into a number of part families, characterized by similarities in manufacturing methods and thus related to group technology [2]. Generative process plans utilize decision logic, mathematical formulas, manufacturing rules and geometric data to determine the processes required to convert the raw material into a finished part. This type of system develops a new plan for each part based on input about the part's features and attributes. Due to the complexity of this approach a generative CAPP system is more difficult to design and implement than a system based on the variant approach. But, a generative CAPP system does not rely so much on the aid of a human planner, and can produce plans not belonging to an existing part family [2].

Different researchers distinguish dynamic process planning from static one in different ways. Usher and Fernandez [7] proposed that the static process plan is

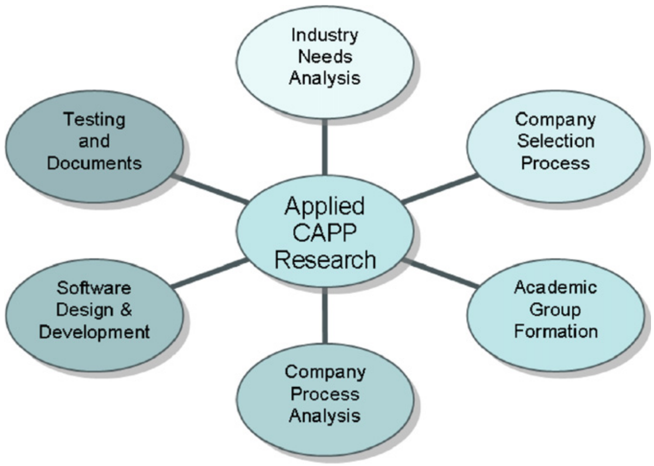


Fig. 1. Areas related to research development.

concerned with the generation of alternative plans that are generic in that they do not take into account the specifics with respect to the operational status of the shop floor resources. This planning involves the selection, assignment, and sequencing of the processes and machines that could be. Dynamic planning takes place when a job is released for production to the shop floor. At this time, the macro level plans are retrieved and planning is finished, considering the availability of the shop floor resources and the objectives specified by the scheduler [7]. One CAD system, MAPS-1, is use for suggesting candidate manufacturing processes for a part that has been developed. It takes batch size, bulk shape, part shape, tolerance, surface roughness, etc. into account to select processes and materials [8]. Computer oriented materials, processes, and apparatus selection system (COMPASS) has been designed as a tool to assist designers in identifying potential problems early in the design process [9]. An enabling technology for flexible integration using computer sockets or Common Object Request Broker Architecture (CORBA) provides developers with methods and tools to link together agents and various engineering software applications, including CAD/CAM, expert systems, math tools and database management systems [10]. CORBA has been utilized to teach students about Internet-based product development in a distributed environment and obtain real-time process plans based on availability of machines and tools [11]. Another system, MetCAPP® serves as a link between the design and manufacturing floor. It provides the ability to take CAD generated solid models and use them to generate process plans based on the best: machines tools, sequence of steps, timing routing/cost combinations. MetCAPP is a modular system which includes feature recognition from the 3D solid model, a technology manager, report writer and a cost estimator [12].

Extensive work is now being done to improve and standardize data exchange, integrate design for manufacturing tools and utilize software agents to create a collaborative, web based platform for sharing information [13]. CAPP technology is continuously evolving and merging with areas of Computer Integrated Manufacturing (CIM), including business automation, cost control, resource allocation and internet based product development [6]. Many existing CAPP systems developed the rule based technology and functionality that has subsequently been implemented in commercially available CAD/CAM interfaces. These include feature based design and manufacturing, determination of cutting conditions and automatic selection of machining strategies which are stored in libraries and made available for modification according to personal preference.

2.2. Activity based costing (ABC) methodology

ABC, pioneered by Robin Cooper [14,15], Robert Kaplan [15], and Thomas Johnson [16], is a costing methodology used to trace overhead costs directly to cost objects (i.e. products, processes or services) and helps managers to make the right decisions regarding product mix and competitive strategies [17]. In the first stage of ABC, costs are assigned to activities based on a cost driver, for example, quote preparation utilizes salaries, rent, and office supplies. The cost driver for salary is the time spent by the employee whereas rent is driven by square feet. In the second stage, costs are allocated from the activities to a product based on the product's consumption of resources during the activities. Fig. 2 illustrates how cost drivers relate expenses, activities and products throughout the first and second stages. This figure will also help the reader understand the steps of the procedure (steps 1–8) outlined below and the creation of the expense-activity-dependence and activity-product-dependence matrices which are fundamental to applying the technique.

Two of the difficult parts of using ABC in small companies are the high costs associated with data collection and the assignment of overhead costs to activities. A summary of the procedure as defined by Roztocki and Valenzuela [18] is shown below.

Step 1: Identify the expense categories. The initial step is to examine the expense categories in the income statement

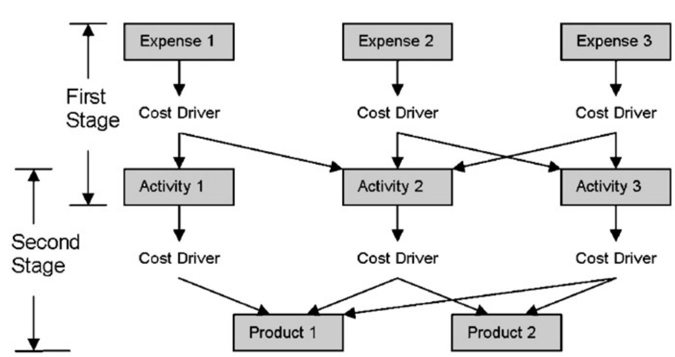


Fig. 2. Relationship between expense categories, activities and products.

Table 1
Expense activity dependence matrix

Activities Expense Category	Administration	Depreciation	Rent and utilities	Office expenses	Transport	Interest	Product shipment	Business travel	Insurance and legal	Advertising	Entertainment	Miscellaneous expenses
Customer contact	0.06		0.01	0.24				0.63		0.64	0.58	0.09
Quote preparation	0.1		0.05	0.14								0.09
Engineering work	0.1	0.7	0.12	0.08				0.14				0.09
Material purchasing	0.08		0.09	0.09		0.8						0.09
Production prep.	0.04		0.11	0.03								0.09
Material rec./hand.	0.05		0.09	0.06	0.4				0.11			0.09
Production mgt.	0.2		0.13	0.01								0.09
Quality assurance	0.1	0.3	0.2	0.02								0.09
Product shipment	0.05		0.12	0.05	0.6		1		0.23			0.09
Customer payment	0.04		0.01	0.08					0.46			0.09
General management	0.18		0.07	0.2		0.2		0.23	0.2	0.36	0.42	0.09

of the company. To properly trace the expenses to each activity, cost drivers have to be identified for each expense category. For instance, the expense category "rent" associated with the activity "quote preparation" may be driven by square feet, whereas, the expense category "salary" may be driven by the amount of time an employee spends on this activity.

Step 2: List the main activities (administrative, engineering and manufacturing). A flowchart of the process is commonly used as a tool for identifying these main activities.

Step 3: Relate expenses to activities in the Expense-Activity-Dependence (EAD) matrix. Activities that contribute to each expense are identified. In this step checkmarks are placed in the cells where numbers appear in the sample EAD matrix shown in Table 1. These checkmarks simply show which expenses are incurred (if none, no checkmark appears) during each activity that was identified in Step 2.

Step 4: Each cell that contains a check-mark is replaced by a proportion, which is obtained from actual data collection or best estimates by knowledgeable personnel, and represents the percentage of the overall amount spent on that expense during each activity. In Table 1, the administrative costs of engineering are 10% of the entire administration expense while depreciation is made up of 70% engineering activities and 30% quality assurance. Since expenses must be completely attributed to activities, the sum of the proportions in each column is one. These proportions are used later to multiply by the amount spent during a particular time period (a month for example) on an expense to calculate the cost of an activity.

Step 5: Obtain dollar values of activities. In this step the total dollar amount for each expense is multiplied by the proportion in each cell of the EAD matrix to obtain actual dollar values. For example if \$10 K was spent on administration and the proportion for engineering work is 0.1, then \$1 K is placed in that cell and a new EAD matrix is created with actual dollar amounts. The sums of the dollar values for each row represent the overall cost of each activity and will be used in subsequent steps to relate activity expenses to products and finally to customer orders, this is the basis for the ABC methodology.

$$\mathrm{TCA}(i) = \sum_{j=1}^{M} \mathrm{Expense}(j) \times \mathrm{EAD}(i,j), \tag{1}$$

where $\mathrm{TCA}(i)$ is the total cost of activity i, M the number of expense categories, Expense (j) = Dollar value of category j, and EAD (i, j) = Entry i, j.

Step 6: Relate activities to products (Activity-Product-Dependence matrix). In this step checkmarks are placed in the cells where non-zero numbers appear in the sample APD matrix shown in Table 2. At this stage, activities are

Table 2
Activity product dependence matrix proportions

Products Activities	Customer contact	Quote preparation	Engineering work	Material purchasing	Production preparation	Material rec./ handling	Production management	Quality assurance	Product shipment	Customer payment	General management
Product 1	0.00	0.00	0.20	0.14	0.21	0.12	0.34	1.00	0.32	0.21	0.33
Product 2	0.53	0.60	0.10	0.34	0.27	0.41	0.27	0.00	0.26	0.38	0.33
Product 3	0.47	0.40	0.70	0.52	0.52	0.47	0.39	0.00	0.42	0.41	0.34

Table 3
Activity product dependence matrix ($10 K)

Activity Cost Products Activities	$9.19 Customer Contact	$5.02 Quote preparation	$18.88 Engineering work	$8.33 Material purchasing	$3.53 Production preparation	$6.15 Material rec./hand.	$8.01 Production management	$11.83 Quality assurance	$12.51 Product shipment	$4.22 Customer payment	$12.31	Total Cost General management
Product 1	$—	$—	3.78	1.17	0.74	0.74	2.72	11.83	4.00	0.89	4.06	29.92
Product 2	4.87	3.01	1.89	2.83	0.95	2.52	2.16	$—	3.25	1.6	4.06	27.15
Product 3	4.32	2.01	13.21	4.33	1.83	2.89	3.12	$—	5.25	1.73	4.19	42.88

traced to products using second stage cost drivers. For example, material purchasing can be related to each product by the number of purchase orders and engineering work by the number of hours. Activities are represented in the columns of the matrix and products by the rows. If product (i) consumes activity (j) then a checkmark is placed in that cell.

Step 7: Replace check-marks by proportions in the APD matrix. Each cell that contains a check-mark is replaced by a proportion. See Table 2. These proportions are determined as before by actual data collection or by best estimates.

Step 8: Obtain dollar values of products. In this step the overhead costs for each product is computed. The resulting APD matrix, shown in Table 3, gives the total overhead costs for each product as well as their origin. The following equation is used for this step:

$$\mathrm{OCP}(i) = \sum_{j=1}^{N} \mathrm{TCA}(j) \times \mathrm{APD}(i,j), \tag{2}$$

where, OCP(i) is the Overhead cost of product, N the Number of activities, TCA (j) the Dollar value of activity j, APD (i, j) the Entry i, j of APD matrix.

In ABC every activity generates costs associated with the resources utilized during that activity. For example, machining time, design, machine depreciation and the use of computers are all components of the cost for each order. In contrast to the traditional costing methods that use direct and indirect costs by department, ABC facilitates the detailed evaluation of costs incurred over a period of time and their subsequent assignment to the activities, services or orders that caused them. Benefits of this method are that both over and undercharging of customers can be minimized and estimates and plans improve continuously over time.

2.3. Application programming interface (API)

An application programming interface (API) is a library of functions in a particular programming language which are available in a particular software program and they play a critical role in CAPP. They provide a direct access to design and manufacturing data residing in CAD/CAM databases and have tools to customize user interactions and automate graphical user interface functionality. As mechanical designers and manufacturing engineers define product specifications and make process planning decisions, the resulting information, including material requirements, setups, machining times and tooling become available for processing in real time. CAD/CAM systems use Visual Basic (VB), C, FORTRAN, LISP or a proprietary language to access API functions. Advances in the tools provided by these languages and better CAD/CAM database structures present opportunities to automate many repetitive tasks and retrieve design and manufacturing data.

The VB API in Autodesk Inventor™ and the C language (PCI/PDI) in EdgeCAM are described later as they relate to the work in this paper. API's continue to be very limited and difficult to use for accessing CAD/CAM databases and lack standardization and documentation. The system proposed in this paper does not pretend to have complete integration between all programs and databases. Inventor and EdgeCAM have been incorporated into the process planning module of the application using VB6 objects which can be used to open and pass control to other applications. Some basic API's have been programmed to study the interaction required to transfer data either directly using VB or with text files. Future work is planned to expand on the current capability and define the data structures needed to achieve closer integration. Sample VB code from Inventor to retrieve mass properties through the API and a sample program to

rajretrieve tool information through EdgeCAM's PCI language follows:

Inventor^{TM}:

```
Public Sub GetPartMassProps()
  Dim oPartDoc As PartDocument
  Set oPartDoc = ThisApplication.ActiveDocument
  Dim oMassProps As MassProperties
  Set oMassProps = oPartDoc.ComponentDefinition.MassProperties
  'Display the mass properties of the part.
  Debug.Print "Area: "& oMassProps.Area
  Debug.Print "Center of Mass: "& _
    oMassProps.CenterOfMass.X & ", "& _
    oMassProps.CenterOfMass.Y & ", "& _
    oMassProps.CenterOfMass.Z
  Debug.Print "Volume: "& oMassProps.Volume
  Dim Ixx, Iyy, Izz, Ixy, Iyz, Ixz As Double;
  Call oMassProps.XYZMomentsOfInertia(Ixx, Iyy, Izz, Ixy, Iyz, Ixz)
End Sub
```

EdgeCAM^{TM}:

In this example bSet is 1 when a value is returned for tool diameter or 0 when no value is returned, and _realtooldiam is used to store the returned diameter value.

```
* Diameter
%AddCmdModToOperation = [OpId],[cmtTool],47,^"Tooling"17
%AddCallBackReference = [OpId],tsFinish,[#IndexDiameter],[cmdTool],[#ModDiameter]
%Label = DoOpMods
%DoOperationMods = nOpRet = [OpId]
%GetModifier = bSet = [cmdtool],47,_realtooldiam
```

3. Industry evaluation and company selection

The ITCR encourages academic researchers to define projects that directly benefit local industry and that any technology or software applications can be implemented. For this project, the team performed a study related to automation being used in a variety of different manufacturing companies. Based on the results of the evaluation, the academic team selected the company to be used as a model for subsequent system development. Questionnaires, interviews and plant visits were used for the final analysis and selection.

3.1. Industry study details

The following items were used as a guideline when evaluating each company: Type of industry, Product families, Production type, Design, Engineering, Quality control, Software, Cost control and Equipment. The team paid close attention to how interested management was in supporting project objectives since they would have to be open to sharing many private details related to business practices. The discrete part manufacturing sector, where CAPP and CNC machining is most prevalent, was identified as the most appropriate for proposed research due to the computerized nature of these tasks and the ability to closely monitor orders. The results of the evaluation are summarized in Table 4.

3.2. Company selection

FEMA Industrial S.A., (column 4 in the table above) was selected because of the variety of products manufactured, existing computer resources available and the enthusiasm demonstrated by management to collaborate with the academic team. FEMA employs sixty five people in six departments and uses both conventional and CNC machines. In addition to machining processes, secondary operations such as heat treatments, finishes, welding and inspection make FEMA one of the top five shops in the country. An in-house material supply store and separate quality control and engineering departments, made the environment a good match for research objectives. Improvements in design and process planning software also qualified FEMA as the best candidate for computerized information management. FEMA management was open and enthusiastic about working with the university, a key for success in collaborative projects.

The business cycle at FEMA is divided into six departments; Administration, Customer Service, Design, Engineering, Production and Quality Control. The team closely monitored document flow and interviewed key personnel to identify how orders are processed and costs accumulated. The team identified three critical points when the overall cost of a product can be evaluated: (1) the price quoted to the customer, (2) after design and process planning are completed and (3) when the product is

Table 4
Results of industry study

Process Type	Prolex Semi-automated	Conair Semi-automated	Atlas Semi-automated	FEMA Semi-automated
Equipment	CNC Lathes and conventional mills. Manual planning few computers and QC	Assembly lines with material handling, Plastic injection, few mills and lathes	Hydraulic CNC punch press, 1 CNC machining center, 1 lathe	CNC lathes and mills. Manual machines, grinders, welding, instruments
Product	Welding and soldering tips and specialized tools.	Hair dryers and other hair related products, molds.	Refrigerators and stoves. Repair Components	Components, molds, replacement parts, assemblies, tooling.
Personnel	Trained	Trained	Trained	Trained
Infrastructure Management	Not Adequate	Adequate	Adequate	Adequate
Interest in Project (1–10)	7—low product variety, manual planning, non integrated departments	7—outsourcing of components, mostly assembly, lack of CAPP knowledge	5—mostly sheet metal processes, low integration, little machining	9—large variety of parts, vision toward integration and cost control, well defined departments.
Software	AutoCAD, Excel	AutoCAD, Mastercam	AutoCAD, SPC	Inventor, EdgeCAM Excel, Access

completed. A comparison of these costs can be used to evaluate quoting and planning practices for accuracy.

4. System design and functionality

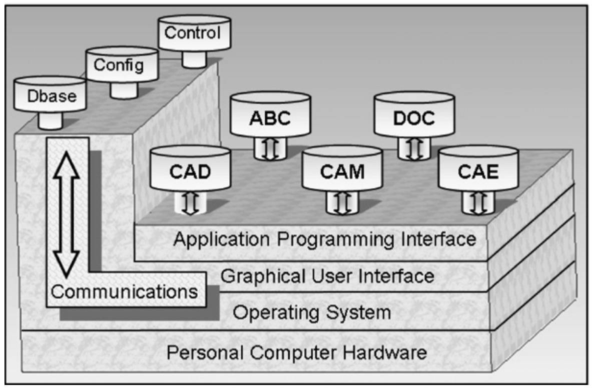
A high priority was placed on the design of a generic interface and to allow for easy expansion and reconfiguration of other program modules and applications. Fig. 3 represents the system architecture and the relationship between the GUI, operating system, databases and the APIs. The list on the right side of the figure shows the specific software selected by the research team to build a prototype but, the model is generic and the possibility of interchanging one or more programs is an option, providing it has the same capabilities and is compatible with the base system. The hardware platform is a PC with Pentium 3 or compatible processor with 512M RAM and 60GB hard disk and high end graphics card for operating CAD/CAM programs. The Windows XP professional operating system was used but, the home version of XP, NT (home or professional) or Millennium could also be used. The user interface and API's were developed in VB6 with the exception of EdgeCAM which uses an API programmed in C. The selection of CAD/CAM systems was based on availability, functionality and API accessibility. Both Autodesk Inventor™ and EdgeCAM™ provide API tools, are integrated for feature based design, CAPP, CNC code generation, and operate under Windows XP. If a software or database does not use VB for applications as its API, it can be interfaced using file based communications (i.e. Text files or sequential data files). The database was implemented in Microsoft (MS) Access, the Cost module (ABC) and documentation (DOC) in MS Excel. The control and configuration represent tools available in VB6. In general, other programs such as SQL for databases, Word or VB for reports, and SolidWorks for CAD could be used as they operate in Windows and provide a library of API functions. No CAE application is currently implemented.

4.1. Graphical user interface (GUI)

Based on software availability, team experience and widespread use of Windows programs, and VB6 was selected for constructing the user interface. There were different considerations that led to making that decision. Through VBA (visual basic for applications) databases in Access or SQL can be presented to the user and modified, other applications can be opened and closed using VBA and data can easily be processed and distributed. The modules described in the following section represent the actual flow of orders as documented and studied during the evaluation of practices at FEMA S.A.

An important objective of this work was to replicate the exact steps and information flow utilized by personnel within the different departments of the company and tie business functions to engineering and process planning. Since quotes, invoices and orders are all documents generated automatically by the system, data such as the name of the company, contact person, method of payment, etc. are all collected through the software user interface. The design and flow of the system represent the exact steps taken by personnel from the time the customer comes into the reception area, through the preliminary evaluation, on to engineering and so on. Since all the information is included with the order, generating forms and monitoring the time spent and costs associated with each activity is facilitated by the software.

The startup VB6 screen is presented in Fig. 4. The *Database Administration* buttons are for viewing and editing the Access database information such as clients, suppliers, machines, tools, etc. On the lower left of the screen are the *Order Management* functions. Each of the areas; *Customer Service*, *Process Planning*, *Data Collection*,



GUI –	Visual Basic 6™
OS –	Windows XP™
CAD –	AD Inventor 6™
CAM –	PT EdgeCam™
CAE –	**Not Implemented**
ABC –	Excel Application
DOC –	Excel Form Set
Dbase -	MS Access™
Config. –	Visual Basic 6™
Control –	MS Outlook™

Fig. 3. Model for the development of computer aided process planning system.

Fig. 4. Main operating screen of CAPP system.

Cost Analysis and Documentation are described in the following sections. The interface was created with easy to change logos and editable data for quick reconfiguration and adaptability. Currently these changes cannot be made at runtime and require the services of an experienced VB programmer.

4.2. Description of modules

Customer service: The first step in processing an order relates to gathering customer information such as the name of the company, contact person, date, general description of product, etc. Next, a planner must study the product for the purpose of creating a quote. The material, specifications, processes, inspection methods, time estimates and the number of parts needed are necessary components of the initial evaluation. The final step of this phase is the generation of the quote.

Computer aided process planning: Once the quote has been approved by the customer, design and process planning activities can be performed using CAD/CAM. Decisions made here have critical consequences on the final cost of the component or assembly. The results of this phase include the design specifications, a complete process plan, NC programs and information related to machining times, material, tooling, etc. The CAD phase of CAPP is completed with Inventor and includes the 3D solid model design of the part, feature definitions, tolerance and finish specifications and final drawings. Because of the compatibility between Inventor and EdgeCAM, the solid model is imported without creating a file in a neutral format (i.e. IGES, STEP, DXF) and features are automatically recognized using EdgeCAM's feature finder. This integration is made more powerful in that if the design is changed at some point in Inventor, EdgeCAM notifies the user and tool paths and machining conditions can be updated to reflect those changes. The EdgeCAM strategy manager offers solutions to a problem experienced by many CAM programmers—how to capture information about a machining job and apply some or all of it to subsequent jobs. Strategy Manager includes an interactive, graphical method to define and capture the way in which parts are to be cut. The strategies created can then be re-applied to other EdgeCAM parts to automate the programming process. EdgeCAM Strategy Manager combines logic and flow chart methodology to capture working practices and define strategies. Once planning is completed, information that can be retrieved through the CAD API includes a bill of materials and mass properties while machining statistics and tooling data comes from the CAM API. As mentioned earlier, only examples of API programs were constructed for this project, the rest of the data was collected from the user and processed in cost calculations and document creation. A key part of extending CAPP to include business functions is the use of API's to retrieve data related to design and manufacturing in real time. There are many limitations with API programming languages because commercial CAD/CAM systems vary considerably with respect to database structures and user interaction. Descriptions of Inventor and EdgeCAM functionality which directly relate to this project are shown below and the process planning screen from the VB6 interface is displayed in Fig. 5.

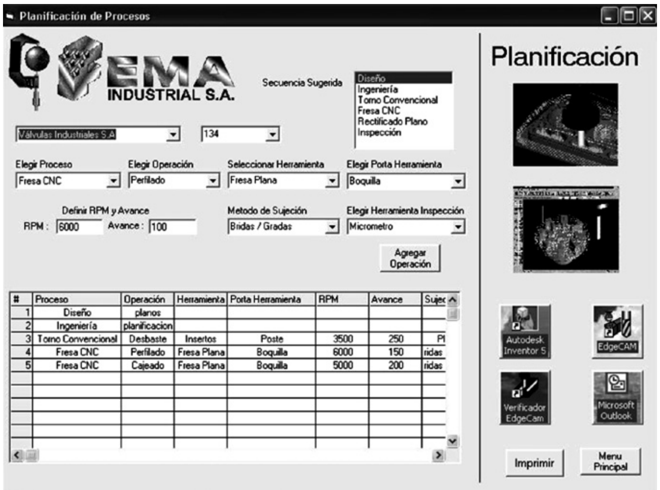


Fig. 5. Process planning screen of system.

Autodesk Inventor 6^{TM}: 3D Parametric Solid Modeling and Visual Basic Programming Interface
Inventor is a fully functional 3D solid modeling. The software simplifies the transition from 2D to 3D, provides tools for managing large projects and facilitates the output of detailed mechanical drawings and documentation. Inventor produces files that can be imported directly into many commercial CAM and CAE systems. The Autodesk Inventor API enables users and 3rd party developers to extend and customize Inventor. Microsoft Visual Basic for Applications (VBA) provides a programming environment within Inventor. For example, you can write a program that interfaces with your company's database to obtain the current price for components. You can also write a program that extracts data from assemblies to provide MRP systems with their information [19].

PathTrace EdgeCAM 8.75^{TM}: Solid Machinist and Programming Interface
"EdgeCAM Solid Machinist provides the ability to directly load and machine solid files without the need for translation. The Feature Finder command will automatically find prismatic features on the solid model. Identification tools allow you to manually identify machinable features. Associativity with the design model is retained. Strategies provide a means of automatically generating the optimum set of machining instructions. By building conditions into your strategies you can make them adapt; for example to feature attributes and materials. EdgeCAM offers various programming tools to automate and customize system operation. PCI is a parametric macro language. PDI is the C language API for EdgeCAM that can be used to access internal databases and export/import data [20].

Data collection: Once the process plan is complete and sent to the shop floor, knowing where the order is would allow for a more accurate estimate of time to completion and supply valuable information for customers and planners. The data collection module currently collects feedback from operators related to final processing times and changes made to process plans. This tool is useful for improving estimating and planning procedures. The screen contains a layout of the shop floor with VB interaction textboxes that prompt the user to type in information related to processes being carried out at each station.

Cost analysis: This module is a cost calculator that sums the costs of all the individual activities utilizing the ABC methodology described earlier. When the user selects a specific order number, all the activities that contributed to designing, manufacturing and inspecting the product are listed on the screen for review and analysis. At this point there is a comparison made between the quoted cost, the cost after process planning and the real cost once real data has been collected.

Documentation and job history: The final module of the system is used to create the documents with the information related to each order. By storing the data input in the previous steps, a complete job history is available in digital format. The data is output to standardized forms which are very easy to personalize for different companies. One obvious advantage to having this job history is the ability to retrieve existing plans when similar orders are processed in the future. The types of documents available include the quote, part drawing, work order, material, order, process plan, and CNC program among others. The templates representing all the documents mentioned above have been completed and the automatic data insertion using VB has been done for the quote, work order and material requirements.

5. Case study

A final evaluation of the system was performed using various test parts so that real data could be studied and presented. A standard spacer for a pipe flange connection was selected because of the combination of turning and milling required and the simplicity and size of the part design (see Fig. 6).

A meeting with FEMA engineers allowed the team to follow the same steps as any other customer approaching the shop with a job, completing both an evaluation of the processes and material required as well as the preparation of an official quote. A 3D model and drawings were created with Inventor and used as input to the CAPP system where features were automatically identified and programmed using the EdgeCAM Solid Machinist application. The decisions made by the CAPP system included the tooling to be used for rough and finish cuts, the number of cuts to be made, how much material to leave for finish passes and the cutting conditions based on the material that was selected (i.e. speeds and federates). The results from this phase were

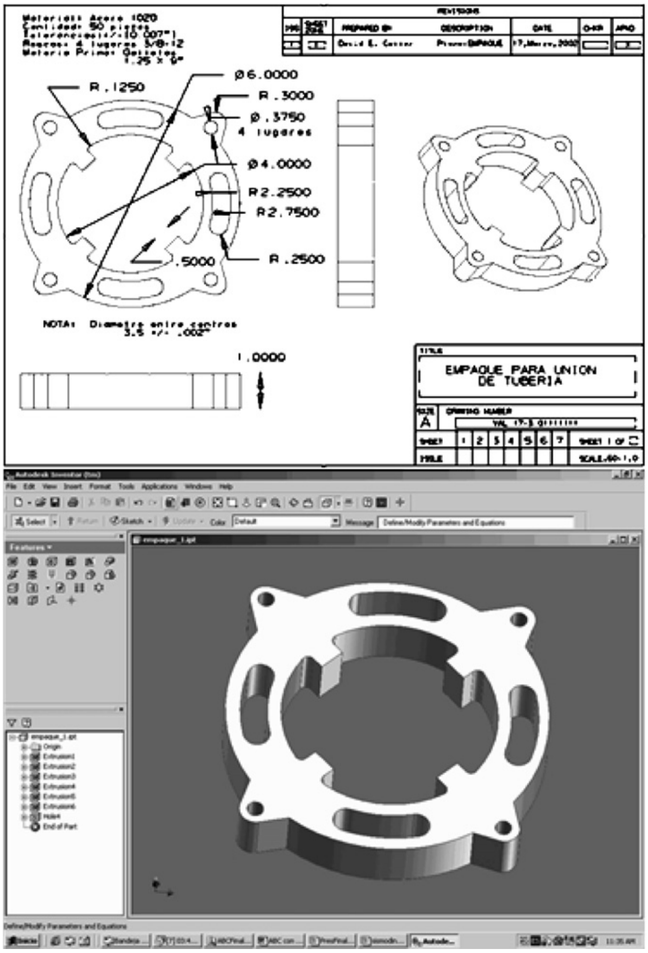


Fig. 6. Drawing and 3D model of sample part.

the NC programs for cutting each feature of the part on the selected machine tool, NC verification images, tooling data and cutting statistics such as the time for the operations, volume of material removed and tool changes made based on the sequence of operations selected by the user. The information was placed on a report generated by EdgeCAM in web page format (html) and the variables used by the EdgeCAM API were identified for subsequent processing. The results of the CAPP and CAM phases of the process were similar to the strategies selected manually by experienced machinists and were not optimized based on time or cost criteria, the strategies stored in the EdgeCAM graphical flowchart format were used to create the part programs.

Next, the ABC application was tested using the formulas and methods presented in Section 2.2. An order of 50 parts (Fig. 6) made out of stainless steel. Fig. 7 shows the breakdown of costs in the following order: customer service, design, planning, engineering, manufacturing, quality control, setup, material handling, shipping, marketing and sales and administration. The three columns represent the estimated cost used for the quote, the actual cost based on ABC and the difference. This comparison

Cliente	Pedido	Producto	Fecha
Valvulas Industriales	Pedido	Valvulas	4/30/2002

Costos de deducción directa:	Monto Estimado	Real	Diferencia (R-E)
Materia Prima	¢267,200.00	¢293,920.00	¢26,720.00
Componentes	¢11,000.00	¢11,000.00	¢0.00
Costos de deducción indirecta:			
Entrevista	¢82,214.79	¢107,573.24	¢25,358.45
Diseño	¢92,442.07	¢113,478.33	¢21,036.26
Planificación y programación	¢8,902.30	¢7,117.19	-¢1,785.12
Ingenieria	¢23,936.75	¢31,357.91	¢7,421.16
Manufactura	¢2,146,511.68	¢2,089,500.00	-¢57,011.68
Control de Calidad	¢55,696.11	¢59,932.56	¢4,236.45
Preparación de maquinas	¢18,597.81	¢16,956.25	-¢1,641.56
Transporte de materiales	¢7,233.33	¢10,500.00	¢3,266.67
Finalización y envio	¢26,448.97	¢31,417.15	¢4,968.18
Mercadeo y Ventas	¢5,818.06	¢7,757.41	¢1,939.35
Administracion	¢6,774.73	¢9,032.97	¢2,258.24
Costo Total	**¢2,752,776.61**	**¢2,789,543.01**	**¢36,766.40**

Fig. 7. Activity based costing breakdown for sample part.

Fema Industrial
300 m norte de la plaza de deportes, La Lima, Cartago
TelFax:552-73 73 / 552-00 00

INDUSTRIAL S.A.

HOJA DE SET UP

Clien

Empresa Válvulas Industriales S.A
Departam Taller
Solicitant Arnoldo Brenes
Tel 279 00 10 Fax 279 00 11

Fecha 14/03/02
Pieza empaque
N' Pedido 1/1/1900
Operación Torno/Fresa

Materia Prima Galletas de Acero 10/20 (1 1/4 " 9" 50 PZ)

rramientas y portaherramient

# Herr	Descripción	Porta Herr	Operación
1	Cuchillas (Carburo)	Poste	Desbaste Diámetro
2	Cuchillas (Carburo)	Poste	Refrentado 2 caras
1	Fresa (1/2) (HSS)	Boquilla	Perfilado / Cajeado
2	Broca de Centros	Boquilla	Centrado
3	Broca 5/8	Boquilla	Taladrado
4	Macho 3/4 " 12 "2	Boquilla	Roscado

Dispositivos de sujeción

NO	Descripción de Dispositivos	Operación
	Mandril - 3 mordazas EXT	Refrentado / Interno
	Mandril - 3 mordazas INT	Desbaste Diámetro
	Bridas / Gradas 4 (Med)	Perfilado / Cajeado
	Bridas / Gradas 4 (Med)	Ranurado / Taladrado

Figuras

Ced. Jur. 3-101-111861, TelFax: 552-7373 / 552-0000

Fig. 8. Set-up sheet for sample part.

could be a valuable tool for engineers responsible for quote preparation and job estimates because the actual differences can be traced directly to the activity responsible for the variation.

Table 5
Results and benefits of system implementation

Item	Before changes	After changes
Customer service	Customers were directly routed through engineers and job evaluators without screening and introduction into the order chain. Critical personnel were used for screening and basic customer data and needs were not collected.	A reception desk was created to collect basic order information and engineers were trained to evaluate incoming jobs and produce quotes. Efficiency in job entry and quoting increased up to 15% over the first 3 months.
Engineering evaluation	A very informal interview was conducted to gather job information, including part and material specifications, quantities, tolerances and finishes.	Formal job evaluations drastically improved the transition from design to manufacturing and eliminated the duplication of planning decisions once job quote has been approved.
3D CAD drawings	2D models and drawing layouts were produced using AutoCAD and Mechanical Desktop. Other parts were produced directly from the sketches and informal paperwork often turned in by customers.	All parts are produced in Inventor 3D solid modeling and drawings created from 3D model. Time savings are estimated at 20% once personnel are completely trained. The volume of work and the increased complexity of designs have created new opportunities.
Paper based communications	All communication between departments was done using a series of 12 different forms that were filled out and distributed by hand, often by critical personnel. The lost forms and misinterpretations regularly caused delays.	Quotes, invoices, drawings and supply orders were computerized, eliminating expenses including paper, time, errors and saving job histories.
Activity based costing methods	An incomplete understanding of costs incurred during order processing caused overcharging and undercharging of customers. Forecasting and analysis of data was very difficult due to the incompleteness of job histories and actual costs incurred during engineering and manufacturing.	Forecasting and monthly/yearly evaluations became common practice and company losses have led to a more thorough understanding of how costs are managed and jobs processed. Although difficult to completely quantify, it is estimated that up to 15% savings have been attributed to changes from ABC.

The above mentioned categories are all related to indirect costs which is the basis for ABC as explained in Section 2.2. In the top section of Fig. 7 are the direct costs of raw materials and components (i.e. Gaskets, bolts and nuts). A set of documents was completed using the data collected during the trial run. An example of the process setup sheet is shown in Fig. 8. The information includes the list of operations, tooling requirements, fixture orientations and images of setups.

The values obtained were very comparable to the corresponding information produced from manually processing the order but, due to the limitations of the companies' CAD/CAM capabilities and the estimation of costs not available during the trial, exact comparisons and a more detailed evaluation of the system were not possible.

6. Results of implementation phase

Once work was completed, the customer service and the preliminary process planning modules were implemented at FEMA Industrial S.A. This included the databases in MS Access, VB graphical user interface and programs for generating the quote and work order. Installing the complete system was not possible because CAD and CAM integration were in their early stages and computing resources were not available in every department to facilitate digital data distribution. The customer service and quote generation portions of the program were installed and utilized by the company for evaluating new jobs and documenting the processes and corresponding times which were estimated for the quote. One of the biggest benefits of the project to the company was the motivation to migrate to a 3D solid modeling environment and purchase EdgeCAM to take advantage of an expanding mold and die market in the country. The most important results and benefits are summarized in Table 5.

7. Conclusions

Continued advances in CAPP and CAD/CAM technology are constantly creating opportunities to reach more advanced levels of integration between administration, engineering and shop floor production. This paper lays the foundation for further work in API programming to retrieve data critical for accurate handling of customer orders and more efficient distribution of information between departments. The important contributions of this research on are: (1) it presents an architecture for a CAPP system with an integrated costing tool for evaluating company performance and providing valuable feedback to planners and management personnel, (2) it combines developed and commercial software, including independent CAD and CAM systems, in an framework that can be expanded and modified to meet company requirements and (3) it utilizes a single user interface to combine both administrative and engineering tasks.

The results from this project received praise from local manufacturers and were published in both university and local newspapers [21]. Other companies that viewed the software also expressed the need that exists for soft automation tools that bring administration and engineering together. An important key to the success of this project, aside from the team effort and the motivation exhibited by the students, was the pre-existing relationship which existed between the author and the owners of the machine shop. Other projects to implement CNC and resolve machine code format and communications problems had already been completed. This resulted in a confidence to share real information and openness between the university participants and the shop management, allowing the system to reflect day to day operations.

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