Computer Aided Parts Estimation

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Abstract

In 1991 Ford began deployment of the Computer Aided Parts Estimating System (CAPE), a highly advanced knowledge-based system designed to generate, evaluate and cost automotive part manufacturing plans. CAPE is engineered on an innovative, extensible, declarative process planning and estimation knowledge representation language, which underpins the CAPE kernel architecture. Many manufacturing processes have been modelled to date, but eventually every significant process in motor vehicle construction will be included. Significant cost reductions are among the many benefits CAPE brings to Ford.

Introduction

CAPE is a highly significant system for Ford of Europe, in terms of the business needs it satisfies and the corporate acceptance of AI applications:

- CAPE represents a major investment with significant person-years of effort spent on pre-deployment development alone.
- CAPE is the first large-scale production expert system to be deployed within Ford of Europe.
- Cost estimating is a critical business function. With a total annual materials budget of several billion dollars, cost-control is at the heart of Ford's business.
- Reducing the lead time for new model programs is seen as providing a key competitive advantage. CAPE reduces estimating response time by 50%.
- This system is enormously ambitious. The final system will capture the combined knowledge of estimating experts in all areas of automotive manufacture.

The Purchase Cost Estimating Domain

Of all the parts that comprise a Ford motor vehicle, the majority are actually manufactured by external suppliers, then purchased by Ford. In order to effectively manage this substantial vehicle cost component, Ford dedicates a whole division to this task. Purchase Cost Estimation and Analysis (PCE&A) employs a large number of estimators in Europe, typically production engineers, each one expert in some area of vehicle component manufacture.

The estimator is first involved at the design stage for future vehicle model programs. Working from initial engineering drawings, they provide feedback on production feasibility and economic considerations. When a design becomes accepted for a new model, the estimators do an extremely detailed estimation of each component. These estimates form the basis of price negotiations between Ford and its suppliers.

The estimator starts by drawing up a process plan, that is, an ordered set of operations, machines, and materials required to manufacture a part. There may be competing methods of producing the components of the part, dictated by engineering constraints. There will be different levels of automation possible. Typically, higher automation yields a lower piece cost, but requires a higher investment. The estimator explores the major combinations of possibilities, choosing the plan with the best balance of piece and investment cost to economically achieve the daily production volume. Interestingly, the preferred plan may differ from one source country to another throughout Europe, owing to the differing labour, material and facility costs.

To justify a negotiating stance, each operation in the process plan must be specified to a high level of technical detail. The type, size, power rating, and operating cost of the selected machine; the constituents of the floor to floor cycle time; the raw material specification, quantity and cost; the power consumption, current, force, lock pressure, linear feed and rotational speed; and the design and machining cost of investment tools such as broaching, moulding, pressing or casting tools are all examples of the justification the estimator must provide.

In order to know their subject matter in sufficient detail, estimators must specialise in one particular area of production. Thus individual estimators are expert in such areas as: injection moulding of plastics; fabrication by metal pressing; pressure die casting of aluminium and zinc; forging and sand casting; general assembly; fabrication by welding; surface finishing techniques such as painting and plating; and the vast area of machining covering such diverse techniques as turning, milling, broaching, drilling, gear making, grinding, boring, heat-treating, straightening, and shot-blasting.

An estimator responsible for a given part may not be expert in all the manufacturing techniques required to produce that part. To complete the estimate, they may call upon the expertise of their colleagues, or they may compare the design variance of the new part to a known and previously estimated and purchased part. As skills shortages and economic pressures prevent replacement of expertise lost through retirement, fewer estimators with less knowledge must produce more estimates faster. This gives them less time to investigate alternatives to sufficient depth, resulting in sometimes shallow comparisons to previously purchased part prices and possible propagation of previous errors going unrecognized.

The Objectives of CAPE

CAPE is a knowledge based estimators assistant capable of timely generation, investigation and costing of alternate production plans from a component description, justifying its decisions with comprehensive technical detail. The objectives driving the CAPE project are:

- To capture and consistently utilize a huge wealth of localized pockets of corporate manufacturing knowledge;
- To reduce the time taken to produce detailed estimates, and thus contribute to a reduction in "Concept to Customer" lead time;
- To more accurately model manufacturing costs in order to effectively contain them through improved design and price negotiation; and
- To facilitate simultaneous engineering between purchase cost estimators and designers, that is, to design for cost effectiveness.

Why an AI solution?

CAPE must posses and effectively apply vast amounts of experiential knowledge and technically detailed data to achieve its objectives. Representing this knowledge in a declarative rather than procedural way is vital to the clarity and maintainability of a system of this size. Expert system technology lends itself to the management and application of such a base of knowledge.

CAPE must perform a heuristically guided search to find an optimal solution. Combinatorial explosion would make an exhaustive search infeasible. Sophisticated Artificial Intelligence (AI) techniques of declarative constraint description and propagation are required to prune the search space and direct its navigation.

To accurately predict and justify costs to the required level of detail, CAPE must effectively simulate the manufacturing environment with all its interacting agents. Object-oriented modelling is the natural choice for this kind of real world simulation.

Previous Ford projects to automate the estimating function with non-AI techniques have resulted in:

- Machine Rate Manual (MRM) - a database of thousands of manufacturing machines with technical descriptions and operating rates in different currencies per minute (based on an economic model of purchase cost, life-time, depreciation, operating expenses, labour skill and level, etc.); and
- Common Estimating System (COESY) - a spreadsheet-like tool for documenting and summarizing estimator generated processing plans, which converts machine cycle times and material usages to cost.

While both projects have been successful, they only perform a limited part of the estimators work, and do not satisfy any of CAPE's objectives. CAPE incorporates the functionality of both the MRM and COESY.

Operational Functionality

The estimator communicates with CAPE through a window based textual and graphical user interface. The estimator first describes a part in an estimate context, CAPE executes the estimate, then the estimator examines the resulting output, modifying the results or further constraining CAPEs choices if necessary. Estimates and parts are then saved to a database for later retrieval and the results communicated to engineering and supply.

Describing the Part to CAPE

Figure 1 below gives an overview of the major windows available for describing a part to CAPE:

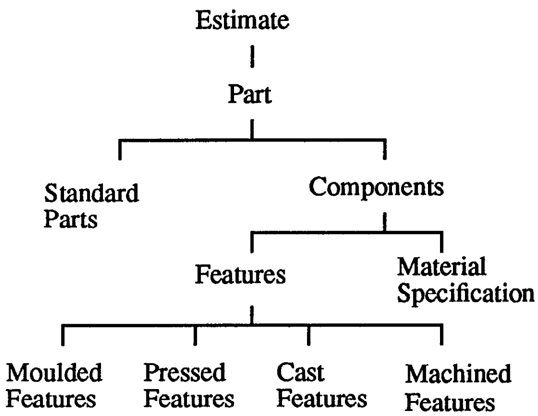

Figure 1. Overview of Part Description Windows

• The estimator starts with the economics of the estimate. The source country (e.g. Germany), the price year (e.g. 1992), and the daily production volume (e.g. 2000 parts per day) are entered. Different volumes may result in completely different manufacturing plans being generated.

• Next the estimator describes the part, which is an assembly of standard parts and components. Standard parts are small items bought in bulk for a set price (e.g. nuts and bolts). Components are atomic manufactured items. The estimator tells CAPE which components and standard parts form subassemblies, and which subassemblies comprise the part. The estimator may tell CAPE how the assembly is performed (e.g. spot welding), or CAPE may infer certain assembly operations from context (e.g. the presence of screws implies a screwing operation).

• The estimator now details each component. This involves describing the features to be manufactured, and any material specification imposed by the component designer. Where materials are only partially specified, or not at all, CAPE will choose the most appropriate material. Standard parts will also have a material specification.

• Moulded, pressed, and cast features, are complex combinations of contours that are created in one shaping operation. The estimator describes these to CAPE using qualitative measures of shape complexity established from critical known cost drivers, rather than geometrically exact measurements (see figure 2 below).

• Machining features, on the other hand, are simpler surfaces typically made by cutting material away. The estimator describes the geometry of these features to CAPE.

• Surface finish specifications, such as painting, pow-

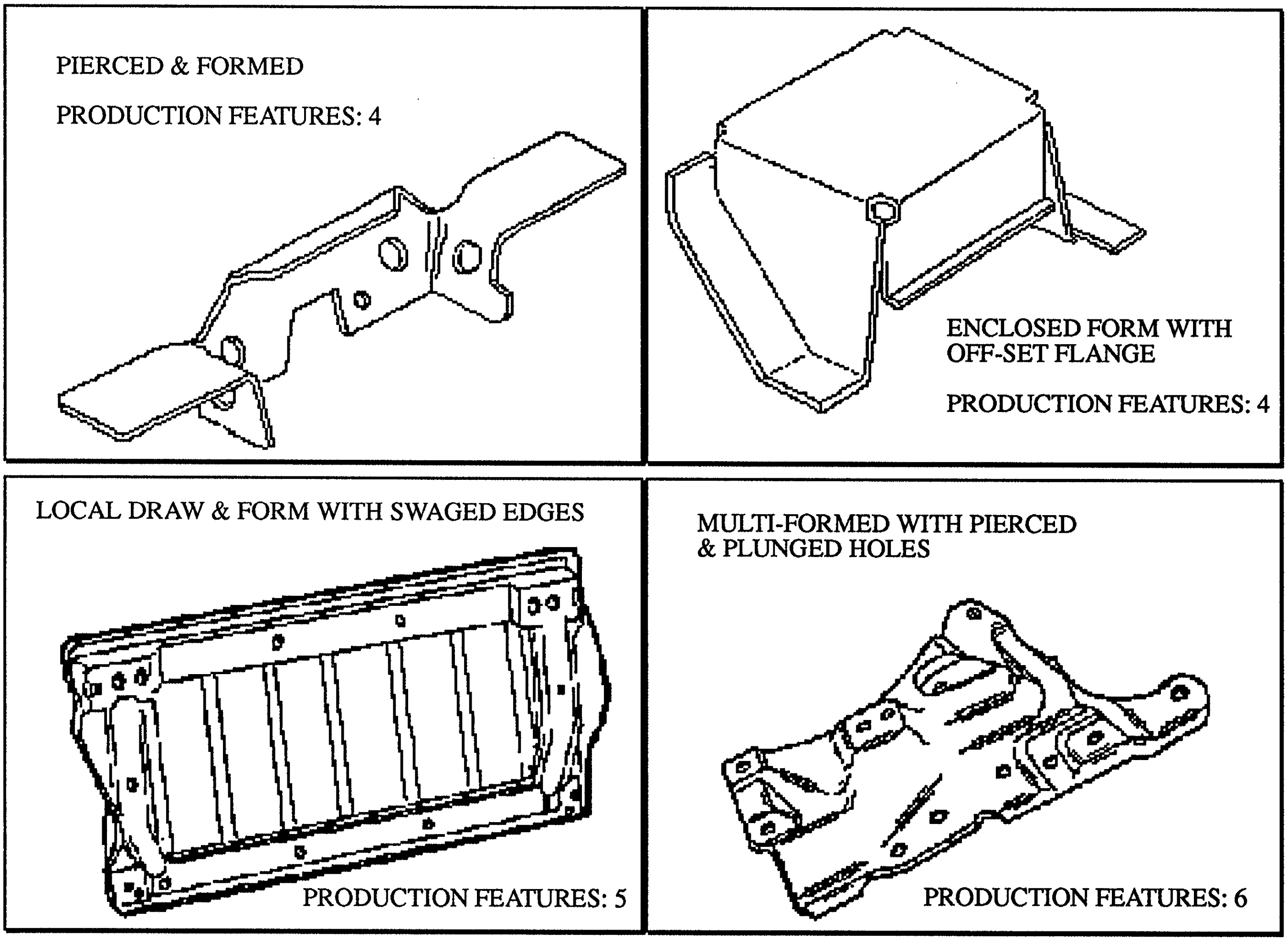

Figure 2. Complex Feature Shape Selection

der coating or zinc plating, are also features. The estimator describes the exact nature of the surface finish requirements to CAPE.

In addition to components, subassemblies and standard parts may have machined features or surface finish specifications. When the estimator has completed describing the part and all its constituents, CAPE is ready to execute the estimate.

Estimate Execution

CAPE now analyses and classifies the features of each component, considering feasible operations for their manufacture. As a result, a number of competing process plans are generated. Each of these plans is costed, and the decisions (degree of parallelism, machine selection, material selection, etc.) that result in the most cost effective plan are retained. Along with the best plan, CAPE also prepares justifications for the decisions it has taken, and looks for potential risks and opportunities to bring to the estimators attention.

Risks indicate proximity to physical constraints, such as maximum machine power rating, while opportunities indicate measures that could be taken to reduce cost, e.g. extending working shifts by fifteen minutes to reduce the number of machines required to satisfy the daily production volume.

Examining the Output

The estimator now uses a number of visual tools to examine the results CAPE has produced:

- the *Estimate Window* shows the overall cost for each component, and for each subassembly;

- the *Expanded Estimate Window* (see figure 3 below) shows what operations are in the plan for each component, what machines have been chosen for each operation, how long each operation takes, and the manning level chosen for each machine, etc.;

Daily Production Volume	1000	User Country Codes	FOB	Part Number	93BB F6129 AKW
Economic Level	01-JAN-93	Estimator Code	M121	Eng. Level	EGB1E10226991000
Source Country Currency	GBP	Vendor Code	BSCST	Description	BRAKE ASSEMBLY

NO	MT	DESCRIPTION	MRM CODE	MACH USAGE	MAN LVL	MAT USAGE	MAT RTE	LAB RTE	OVH RTE	SCP	A+C	MAT COST	MAN COST	TOT. COST	TOOL COST
23	1	WEDGE PLATE													
		CS2: 41X61X5.5				0.108	1.140			3.0	13.0	0.143		0.143	
		Individual Presses													
	1	GRIP FEED MACHINE	50110	0.010	0.00			0.000	0.329	2.0	20.0		0.004	0.004	
	1	(63T) BLANK (S)	51122	0.010	1.00			0.874	0.431	2.0	20.0		0.017	0.017	12475
	1	ZINC PLATE PLANT	213001	0.018	1.00			1.579	3.076	2.0	20.0		0.102	0.102	
		SUB TOTAL										0.143	0.126	0.266	12475
24	1	INERTIA DISC													
		UNE F-ZNALCU4-1				0.013	2.830			2.0	13.0	0.042		0.042	
	1	MELTING ELECTRIC	450201	0.020	1.00			0.027	0.114	3.0	20.0		0.003	0.003	
	1	FRENCH DAW 5	150101	0.047	1.00			0.916	0.212	2.0	20.0		0.065	0.065	
	1	4 CAVITY DIE													31396
	1	TRIM COINING PRESS	430507	0.058					0.161	3.0	20.0		0.012	0.012	
	1	CLIP TOOL													2972
	1	ROTO FINISHER	201203	0.005	1.00			0.874	0.162	2.0	20.0		0.006	0.006	
	1	DIP WASH MACHINE	211102	0.001	1.00			0.874	0.251	2.0	20.0		0.001	0.001	
	1	CHROMATE PLANT	212110	0.001	1.00			1.086	1.440	2.0	20.0		0.003	0.003	
		SUB TOTAL										0.042	0.090	0.132	34368

Figure 3. The Expanded Estimate Window

• the *Plan Network Diagram* shows the overall structure of the plan, which features are being made by which operations, and which operations are performed in parallel, etc.;

• the *Part Network Diagram* (see figure 4 below) shows the configuration of components, standard parts and subassemblies in the part and the linkages between them;

• the *Operation Detail Window* (see figure 5) shows operation specific data, such as, how the cycle time was derived, the breakdown of the investment tooling cost, what manipulative movements the operators are performing, how long these movements take, how many robots are being utilized, power requirements for the machine selected, etc.;

• the *Risks and Opportunities Window* shows the opportunities and risks associated with the plan.

Expert System Architecture

In the CAPE architecture, there is a clear separation between the Kernel and the Process Models (see figure 6).

The Kernel provides generic support for the object model, search mechanics, and plan costing. Process Models hold specific knowledge for operation definition, possibility generation, plan formulation, and operation costing. The Process Models developed to date are: Feature Assignment, Injection Moulding, Metal Pressing, Pressure Die Casting, Assembly, Welding, Surface Finishing, Turning, Milling, Drilling, Broaching, De-burring, Shot-blasting, Shot-peening, Linishing, Impregnation, Pressure Testing, Inspection, Grinding, De-greasing, and Crack Detection.

Kernel Architecture

Object Model

CAPE employs object-oriented modelling techniques to represents real world and abstract objects. These abstract object classes lie at the heart of the innovation behind CAPE.

• Real world objects are represented by instances of part, component, standard-part, feature, tolerance, machine, material, and price classes. Each of these classes has numerous sub-classes, giving a rich hierarchy of about 500 classifications.

• Planning and estimating objects inherit from classes such as estimate, plan, step, operation and temporal plan step combiners (e.g. serial, parallel, pipe-line).

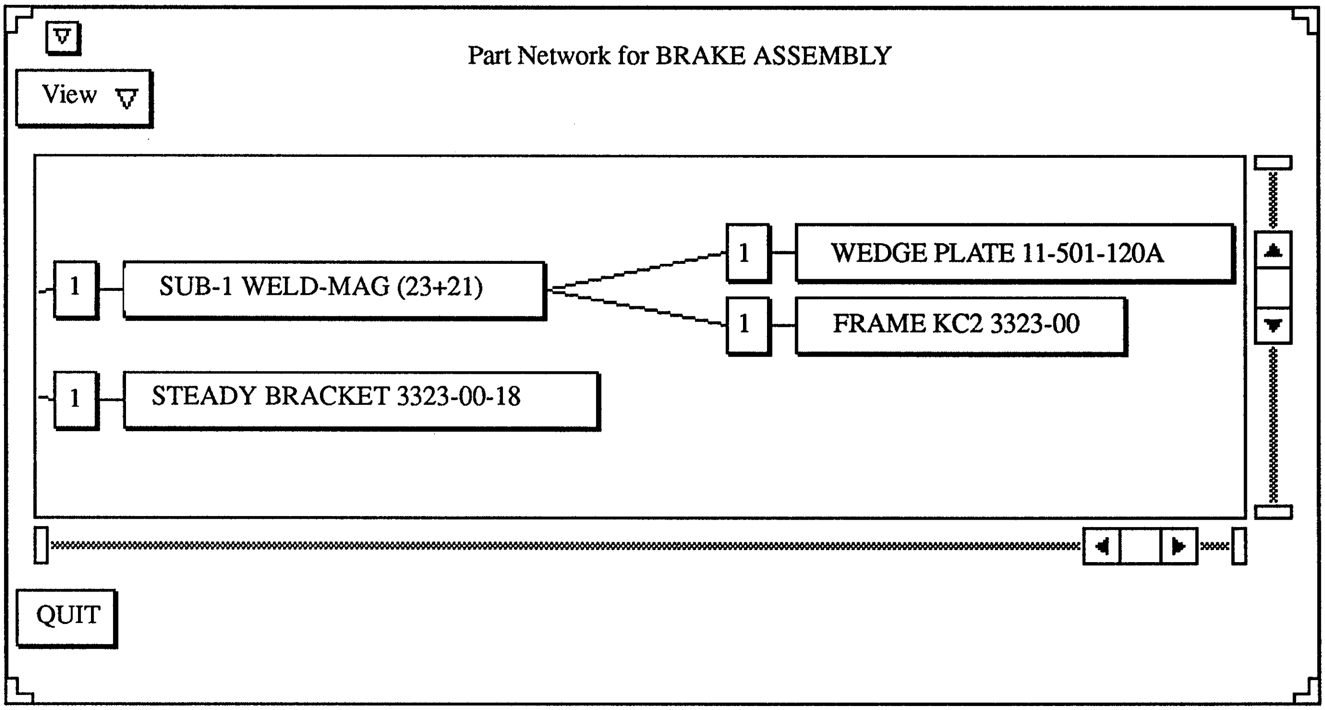

Figure 4. Part Network Diagram

• User interface objects are derived from classes such as window, button, menu, row, field, etc. There are over 300 CAPE specific user interface objects.

• Abstract objects declaratively represent domain knowledge, and search control strategies. These classes include feature classifications, possibilities, possibility generators, search heuristics, cost models and constraints.

• In total there are over 1500 CAPE generic object classes. Many thousands of instances are created dynamically.

Search Mechanics

The CAPE Kernel performs a constrained depth first search over a dynamically changing search space. This search space consists of process specific planning alternatives. To shield itself from process specific knowledge, the Kernel provides a generic searching interface to which all Process Models conform.

• DEFOPERATION is a macro for declaratively defining an operation's choice sets (e.g. machine, number of spindles, level of automation), choice set generators, and operation specific attributes. It also provides a linking to constraints, possibility generators, and cost models.

• DEFCONSTRAINT is a macro for declaratively defining constraints on operations and their choice sets. Choice set constraints are used in database retrieval for choice set population.

• DEFPOSSGEN is a macro for declaratively defining choice set selection behaviour (possibility generation). It also provides a link to process specific planning modules.

The Kernel searches by calling the possibility generators at each operation node in the evolving plan, applying constraints as it goes. The possibility generators will cause further plan branches to be built, with new operations, which in turn have their possibility generators invoked.

Plan Costing

The searching mechanisms result in competing plan

Press Details								
51122 Double Sided Power Press		63.0 Tonnes		140.0 Strokes per minute				
OPERATION		TIME						
Handling (from strip)		0.000						
Press Cycle (for blanking)		0.009						
Total Cycle Time		0.009						
Labour Efficiency Factor		17.6%						
Costed Machine Usage		0.010						
TOOL/OPERATION	MRM CODE	MAT USE	MAT RATE	LAB USE	LAB RATE	MAT COST	LAB COST	TOTAL
BLANK (SIMPLE)								
MATERIAL		39.91	5.40			216		216
DESIGN	600108			14.18	136.88		1941	1941
ROUGH MACHINING	600614			28.36	86.95		2466	2466
PRECISION MACHINING	600414			23.64	98.12		2319	2319
FITTING	600101			23.64	80.78		1909	1909
TRYOUT	600501			4.73	110.97		525	525
SUB TOTAL						216	9160	9376
GUAGING								2000
DIESET								1099
TOTAL								12475

Figure 5. Operation Detail Window

fragments being generated. These must be comparatively costed taking both manufacturing and tooling investment costs into account to further direct the search. To again shield the process specific knowledge from the generic mechanism, the Kernel provides a costing interface.

• DEFCOSTMODEL is a macro for declaratively defining which factors are significant cost contributors, and how they are combined to produce piece and investment costs.

Each operation in any plan fragment will have a cost model, which the Kernel invokes with the method COST applied at any level of the plan.

Process Model Architecture

Operation Specification

Process Models' knowledge is represented in operation and constraint definitions. These are defined using DEFOPERATION and DEFCONSTRAINT respectively. There are two distinct levels of operation:

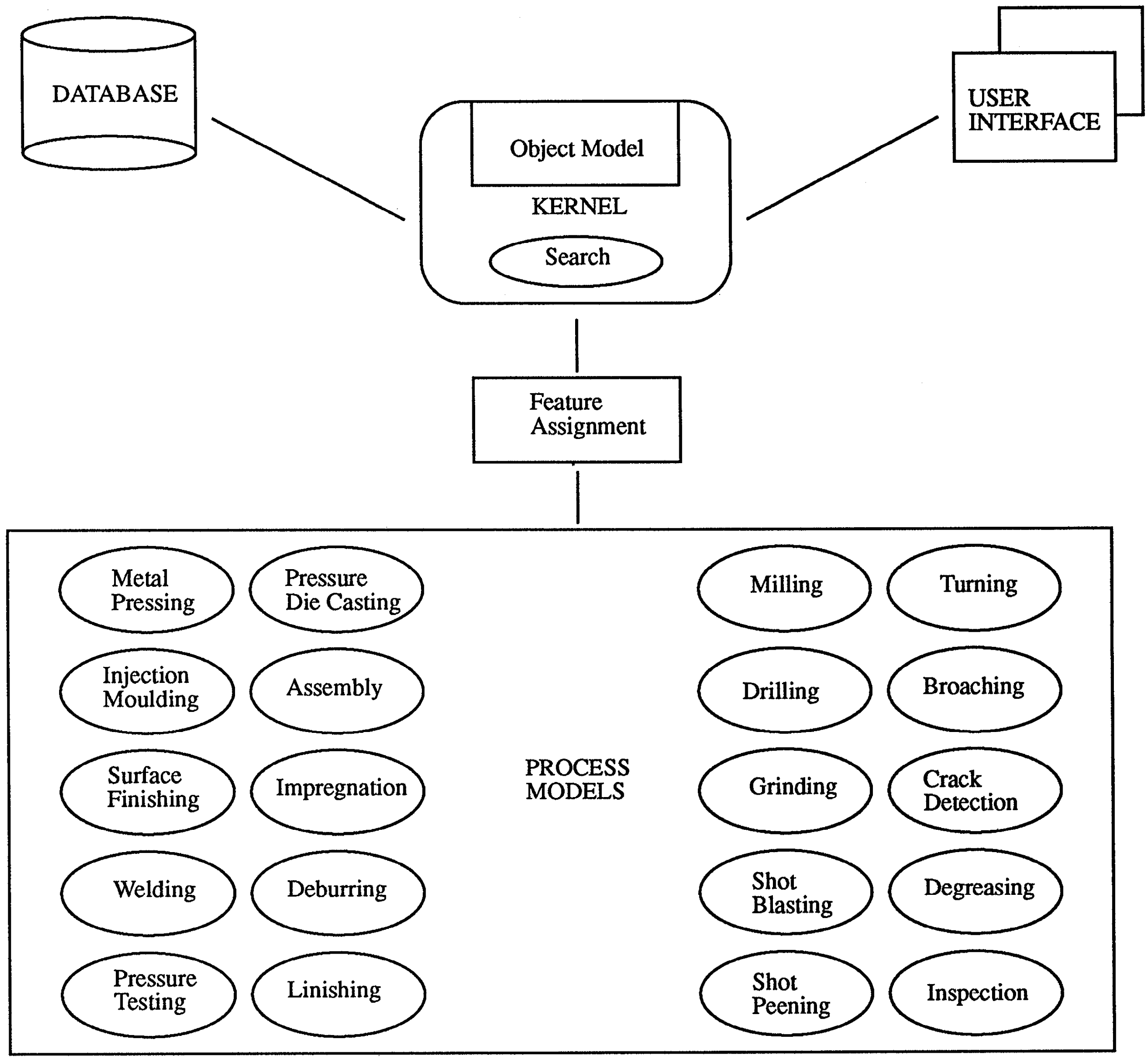

Figure 6. CAPE Architecture

• *Pseudo-operations* represent a particular machine performing this operation on possibly many features of a component. The principle choice set is machine selection. Pseudo-operations are linked to a specific possibility generator and a cost model.

• *Leaf-operations* represent one of the possibly many features being made under the pseudo-operation (e.g. milling cut, hole tapping). There is usually no choice set nor any possibility generator. Leaf-operations are linked to a specific cost model (which is different from the pseudo-operation cost model).

Possibility Generation

Each Process Model must define how the choice sets are used. A possibility generator may return each combination in the choice sets cross-product as a separate possibility (where this is a manageable number), or it may optimise the choices returning only a few key possibilities. The Kernel tests each possibility for feasibility using declared and propagated constraints.

Plan Formulation

For each valid possibility (a set of instantiated choice set selections), the Process Model generates a plan containing pseudo-operations and leaf-operations. This plan represents the manufacture of the component given the choices made in this possibility. Plan generation is often optimised, by reusing generic plan templates rather than recreating plans for each possibility.

Operation Costing

The process specific cost models, defined using DEFCOSTMODEL, compute the piece and investment cost of this operation, in the context of the current possibility. For example, on a particular machine, a specific operation will take a particular number of seconds which at this machine's operating rate will cost a certain amount.

Feature Assignment

In between the generic searching mechanisms and the knowledge of specific processes, there is feature knowledge. This feature knowledge dictates which processes are appropriate for the manufacture of which features. Indeed, some features can be made by any one of several processes. These are known as competing processes, as CAPE must decide which to include in the plan.

Feature Assignment involves classifying features, eliminating some operations from each class, generating competing plan branches with alternate assignments, and adding conditional operations where appropriate.

Feature Classes hold knowledge of different classifications of feature. Membership criteria, competing operations, and operation elimination tests are held declaratively.

Primary and Secondary Feature Classes dictate feature assignment priority. Some features can be assigned to processes independently, while others require related assignments to have been done first.

Conditional Operation Classes hold knowledge of other processes that may be inferred in addition to those that make the feature. These may improve the surface finish, or remove burrs for example.

Constraints, propagated throughout the plan, remove plan branches in conflict.

Implementation

CAPE's object system is built on top of the Common Lisp Object System (CLOS). A number of desirable features have been added, such as support for automatic inverse relationship maintenance and class instance registries. The entire expert system has been written in Lisp, making much use of object centered knowledge representation through methods.

Inference's Automated Reasoning Tool (ART) has been used in a number of areas. ART-Windows is the basis of the user interface (UI). The ART notification system is used to ensure consistency between the kernel objects and the UI objects. The ART iteration package and the ART garbage free programming package are used throughout the system for garbage reduced code performance. An extended ART SQL interface is used for data transfer between the expert system and the local database.

Integration Issues

The successful deployment of CAPE to a wide user base required that the system be integrated into the Ford business environment using existing platforms and linked to corporate IBM databases. In terms of development effort, this has been as great a task as the development of the expert system itself.

• A local Oracle database was developed in parallel to expert system development. This local database stores all extensional data used by the expert system. This database also serves as a buffer between the corporate databases and CAPE itself. A mapping layer developed in Lisp translates data from the expert system to database format and vice-versa.

• In addition to the detailed estimating function, estimators are required to report analyses of each estimate to two corporate databases. One of these is to support design variance and the other shows commodity splits - a high level economic breakdown of the estimate into "commodity" groupings. Both these functions were previously performed manually by the estimator but are now performed automatically by CAPE and the results dispatched from within the CAPE environment.

CASE tools were used extensively for this development. SQL-Plus, CASE-Dictionary and CASE-designer were used to design and document the Oracle database. Systems analysts working on links to the IBM databases use Information Engineering Facility, a COBOL based code generator, as their standard analysis and design tool. This is supplemented by a limited amount of C code used in the Oracle to IBM links for reasons of speed and efficiency.

Innovative Features of CAPE

In terms of AI techniques, CAPE employs a constraint language, constraint propagation, limited depth first search, heuristics, object oriented modelling, object centered knowledge representation, fuzzy logic, generate and test, and simulation.

CAPE could be considered innovative for the mix of technologies, for the sheer size of the task it tackles, and for the combination of process planning and estimating, but what makes CAPE unique is its use of abstract object classes to construct a declarative planning and estimating knowledge representation language.

CAPE is an expert system without any rules! Much use is made of Lisp macros which expand to imaginative combinations of object and method definitions, providing a high level descriptive, application specific language of DEFCOSTMODEL, DEFCONSTRAINT, DEFPOSSGEN, and DEFOPERATION.

This descriptive language separates the expertise from the way in which it is applied. It is this separation of knowledge from processing (normally attributed to rule based systems) that allows new process models to be defined and plugged into CAPE easily. The essence of CAPE is an extensible process planning and estimating language.

Application Development

Few expert systems of the size and complexity of CAPE have been successfully deployed in industry. To minimize the risk involved in development, two separate pilots were carried out. Each pilot was successfully completed before further development was authorized.

Phase I (January - December 1989) was confined to the part family of air cleaners. This entailed developing a process model for injection moulding plus some simpler supporting models for metal pressing and assembly. Phase I was developed as a stand-alone system on SUN workstations.

The following table shows the results of a Phase I test comparing the piece costs produced by a group using CAPE against those produced by a group of estimators using COESY. The same set of 13 air cleaners was used for both groups. The estimates produced by the best Ford estimator were used as a baseline.

	Estimates within 5% of expert	Estimates between 5 and 10% of expert	Estimates over 10% from expert
COESY	54%	38%	8%
CAPE	92%	8%	NIL

The results of this test proved beyond doubt the feasibility of using expert systems techniques for this family of parts.

Phase II (January 1990 - March 1991) had the goal of proving the feasibility of applying these techniques to any manufacturing process. Building on the experience of Phase I, a general representation for manufacturing was developed and applied to the most complex processes that CAPE needs to support. These were:

- *Turning*. Although the component representation is reasonably simple due to its rotational symmetry, the process itself uses a highly complex set of parallel or serial steps as multiple tools work on a single component to machine combinations of features.

- *Milling, broaching, drilling* and *metal pressing*. This involved developing a component representation to qualitatively describe complex, three-dimensional manufactured features. Graphical support for these processes allowed features to be described through icon selection.

- *Assembly*. Constructing an assembly set-up involves deciding between using a flow-line or stand-alone assembly benches, and line-balancing operations between benches to achieve optimum throughput.

Phase III (April 1991 - March 1992) covered the immediate pre- and post-deployment stages. The focus of the project team shifted from proving expert system feasibility to improving the robustness and efficiency of the Phase II system. To this end, formal bug-reporting and release methods were set up, and a rigorous program of testing by the system and user team was performed. Additional process models for welding, pressure die casting, surface-finishing and a number of ancillary operations were developed in preparation for deployment.

Systems development has been carried out by a joint Ford-Inference team. The structure of this team has been relatively unusual in that it has involved both knowledge engineers and systems analysts from different groups within Ford under a common management structure. Four Inference and four Ford personnel have worked full time on expert systems development throughout Phases II and III, in conjunction with a Oracle database administrator and five business systems analysts working on integration to the corporate IBM databases and electronic links to material suppliers. User interface development has required two full-time personnel throughout the project. As would be expected for a team of this size, large development costs have been incurred.

A major factor contributing to development success has been the presence of a team of estimating experts dedicated to CAPE development. This has comprised four estimators and an estimating manager working full-time on functional specification, knowledge acquisition, system validation and testing.

Knowledge Acquisition

The initial knowledge acquisition for each manufacturing process typically involved a member of the user team documenting their knowledge of a process, its areas of applicability and the constraints on its usage. This documentation played an important role in triggering the extraction of knowledge during subsequent interviews with experts. Following these interviews process modelers (i.e. CAPE developers) gained an understanding of the process in a number of ways:

- Visiting the suppliers who use the process and those who provide the machines, materials and tools involved. This enabled developers to gain direct experience of the manufacturing environment.
- Visiting industrial research institutions and consultancies which specialise in the process. Access to pools of expertise beyond Ford itself has helped ensure that the most up-to-date and complete knowledge is incorporated into the system.
- Attending engineering training courses on the theory and practice of the process concerned.

These were generally attended with the expert. The physical proximity of the user team, located on the floor above the development team, helped ensure that user feedback and knowledge refinement were continuous processes.

CAPE Validation

Validating the results produced by CAPE posed some difficult problems in terms of methodology. This is due in part to Ford's relationship with component suppliers - the actual cost to the supplier of manufacturing a part is never known - and in part to differences of opinion between estimators. These factors mean that there is no true objective measure of CAPE's performance.

The methodology chosen consists of comparing the results and justification produced by CAPE to that of the best Ford estimator for each process over a wide range of actual parts. If the estimator using CAPE is prepared to justify an estimate during negotiations with suppliers, and that estimate is not higher than one that would have been produced by the estimator alone, then CAPE's estimate is considered accurate.

Validation of results is performed entirely by the user team, who decide the test suite of parts covering each process and who make the final decision when a process model should become part of the deployed system. Testing each new version for robustness before it is released to the user team is performed by the systems team on a battery of existing estimates. The initial testing of each new version can be performed automatically. Each estimate in the test suite is automatically retrieved, costed and deleted and a report created detailing any errors produced and time spent on estimate execution.

Deployment Process

A step-by-step approach to the deployment of CAPE has been adopted to achieve the maximum return on investment. As the process models needed to support new part families are deployed, the estimators covering those part families migrate from using COESY to using CAPE. The transfer of the estimates in the control of those estimators to CAPE is performed partly automatically from existing systems (for financial information only) and partly by the user team who define the components needed in the expert system format. Training new estimators in the use of the system is provided entirely by the dedicated user team.

Deployment has involved taking a number of actions to increase the efficiency of the system and decrease hardware costs. The main software change for deployment involved porting the underlying object system from ART schemas to CLOS. Whilst ART had been used for development, the deployed system did not make use of much of its expressive power, namely the rule, pattern matching and viewpoint systems. Using the ART configuration script enabled us to build a tailored version of ART without this functionality and hence to reduce the size of the deployed system. The consistent use of an interface layer to the object system implementation allowed this to be done transparently to CAPE developers.

Application Use

The majority of estimator time is spent on detailed estimating, analysis and reporting. Each of these functions is now performed entirely using CAPE as the standard day to day estimating platform and interface to other financial systems.

CAPE has been successfully deployed to estimators in both Britain and Germany while discussions are currently underway with North American estimators to develop the manufacturing process models needed to support a US deployment. This would make CAPE the first worldwide expert system to be deployed by Ford. Initial discussions with Manufacturing Engineering and Product Development areas in Europe also indicate a high potential for CAPE use directly by engineers as a cost-control tool during the design process. Eventually CAPE may be used widely beyond the estimating community.

Benefits to Ford

A detailed cost-benefit analysis of CAPE produced a high time adjusted rate of return on investment (TARR) achieved through:

- The increased speed of estimating and analysis using CAPE which reduces estimating time by 50%. It also gives PCE&A the ability to increase support for new business practices.

- Improved control over tooling costs. CAPE automatically provides detailed tooling costs, which currently require extra work and are only produced at CAPEs accuracy and depth to support one-off studies.

- Potential vehicle cost savings. More detailed and consistent piece cost estimates, faster on-line response to queries, quick evaluation of alternatives and identification of opportunities and risks all improve Product Development decision making by providing timely cost information.

The improved quality and consistency of CAPE estimates has been demonstrated in a number of ways. In the hands of less experienced estimators piece costs savings of up to 30% have been recorded compared to the cost the estimator would have chosen. As CAPE was able to justify the cost given to the level of detail needed to support a negotiation with a supplier, and this justification was supported by the estimator who was the expert in the field, the user was confident in accepting the results.

CAPE has also picked up design inconsistencies that had not previously been noticed. One of these involved an infeasible welding design that had been repeated over a number of years. This had been corrected by the supplier who manufactured the parts but the information had never been fed back to the design engineers responsible.

CAPE has also provided a number of less easily quantifiable benefits to Ford:

- This is the first deployed expert system produced by Ford of Europe and the experience has been invaluable in terms of skills gained. Primary amongst these has been the building of a mature in-house expert systems team with experience of building and successfully deploying a large and complex system.

- CAPE serves as an excellent training tool for new estimators, allowing them to be productive earlier than was previously the case.

Lessons Learned

The process of developing CAPE has been a long and at times painful one. We feel that the following lessons have been learned from this experience:

- Although new technologies are involved in developing AI projects, standard project management and software engineering techniques are vital to their success. This has been the case with CAPE from day one.

- The continuous involvement of a permanent user team was a necessary condition for success. The users have been the driving force behind knowledge acquisition and development throughout the project.

- Communication between members of the project team is paramount to successful implementation. Weekly conference sessions during early development kept the team focused and helped ensure that team members shared a common conceptual model of the problem domain. This was particularly important in a project of this complexity.

- Plan for change. As our understanding of the problem domain has evolved, design modifications have emerged which allow for greater generality while reducing overall complexity. Time needs to be allowed to incorporate such enhancements throughout the project life-cycle.

Maintenance

CAPE is expected to hold the most recent financial and manufacturing knowledge. Maintenance is therefore an on-going process as new manufacturing processes, machines and materials are developed and as prices change with time.

The maintenance of CAPE splits broadly into two key areas:

- *Knowledge-base maintenance*. This is conducted by a team of knowledge engineers. The experience of Ford estimators and experts in the industry has been that each process changes very little over time. We therefore expect that little maintenance of existing processes will be needed. The main work of this team is to add new processes to the system as manufacturing practice changes. An example of this in the past has been the increasing use of plastics in automotive manufacture for part families such as bumpers. Future developments in this area include the increasing use of composite materials in vehicle bodies which will entail new process models being developed.

CAPE has been explicitly designed to support such extensions. The generality of the kernel architecture and the modular, plug-in nature of process models allows new manufacturing knowledge to be easily integrated into the system.

• *Database maintenance*. This is mainly concerned with extensional data used by process models. Price information for machines and materials was maintained on the MRM database prior to the deployment of CAPE and this function has continued unchanged. This price information is updated either yearly or quarterly depending on volatility. Technical material data is maintained through direct electronic links to the main material suppliers.

Conclusion

CAPE has a significant impact on the speed and accuracy with which estimates can be produced. In the long term CAPE will not just supplement existing business practices but will enable new ones to be developed in the critical areas of cost control and new model development. It is a major technical achievement which proves the viability of using AI technology to solve real-world problems in an increasingly competitive environment.

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