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A KNOWLEDGE-BASED DECISION SUPPORT SYSTEM FOR FLEXIBLE MANUFACTURING

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ABSTRACT

A decision support system is under development for planning in flexible manufacturing, using a consortium of knowledge-based systems utilizing expert system, database, and simulation techniques. An object-oriented approach is incorporated. There are six basic modules: machine selection optimizer; database; production flow analyzer; rapid modelling techniques system; FMS simulator; supervisor.

The prototype of the machine selection optimizer has been developed, tested, and is under evaluation.

1.0 INTRODUCTION

1.1 Project Background

Beginning in late 1986, a collaborative study was begun by Norrie, Fauvel and Gaines into knowledge-based systems for the design and management of computer-integrated manufacturing. The starting point for this work was the previous research by Gaines into the information structure of manufacturing systems. Specifically, Gaines had shown [1] that the complex information flows within an integrated manufacturing system could be processed using 'knowledge islands' each of which carries out a particular function (such as machine tool grouping, simulation or operation procedures) or stores certain data (such as parts specification, material properties or machining parameters). It was subsequently recognized that the function of the knowledge islands could be carried out by knowledge-based systems. An overall system for design and management of computer-integrated manufacturing could thus be a 'consortium' of knowledge-based systems each carrying out particular functions and interacting with the others according to need.

By 1987, a particular design and management system was under investigation, namely a decision support system for planning flexible manufacturing (FLEXES). The overall structure for this is a consortium of knowledge-based systems utilizing expert system, database and simulation techniques. The present status is that the conceptual design has been almost completed, candidate computer hardware and software has been evaluated and tested, and a prototype for one of the expert systems has been developed in conjunction with the machine tool database. At this point, the investigators believe they have established the feasibility of the overall project.

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2.0 GENERAL DESCRIPTION OF FLEXES PROJECT

2.1 Overview

A decision support system (FLEXES) is being developed for planning in flexible manufacturing using a combination of expert system, database and simulation techniques. The need for such FMS management support systems is well documented [2-4]. Expert systems are suited to the complex procedures and heuristics of these systems [5-7] but require integration not only with databases to handle the volume of information used but also with special purpose packages such as simulators for specialized tasks [8]. FLEXES would interact with the management of an integrated manufacturing system at the equipment procurement stage to specify needed equipment, at the system design stage for machine selection, grouping and layout, and at the system operation stage for process scheduling and operation. There are six basic modules: - a machine selection optimizer; a database of machine parameters and capabilities; a production flow analyzer; a rapid modelling techniques system; a simulator for flexible manufacturing system (FMS) configurations; and an FMS expert system supervisory and coordinator shell. The research studies involved include: design considerations for the overall and component systems; interaction and information flow between the systems; expert system and database architectures; and knowledge engineering of the FMS rule-bases. An object-oriented (OOPS) approach is to be used as far as practical so that each object (such as a machine tool) can not only contain within itself data about its specification and capabilities but also respond to 'messages' by appropriate actions using stored procedures. This is the embodiment at a lower level of the consortium approach described earlier at a higher level. The overall structure is a consortium of knowledge-based and specialized systems.

2.2 Design & Function

The primary objective for the flexible manufacturing 'expert system' (FLEXES) project is the development of a comprehensive planning support system based on the 'knowledge islands' paradigm for integrated manufacturing. This will demonstrate that the design of such support systems can be naturally patterned on the knowledge structures and information flows underlying the integrated manufacturing system. A study of the foundational information systems has indicated [1] a granularity in manufacturing knowledge from macro-level ('rough') to micro-level ('detailed') This, together with consideration of information architectures [9], leads to a guiding design principle: "First structure the system according to the principal factors, then configure the detailed structure by

progressively incorporating the factors of decreasing significance". FLEXES is designed according to this principle and is intended to not only configure the manufacturing system (macro-level) but provide normative plans for process scheduling and operation (intermediary level). To assist day to day scheduling and operation (detailed level), a computer aided process planning (CAPP) module would later be added to FLEXES. Briefly stated, the input to FLEXES would be product data such as number of parts, shape and tolerances of each part and so on and the output would include a listing of machine tools/robots/AGV's required, flexible cell configurations, plant layout, and basic machine schedules. Capital operating cost data would be also generated, as well as production rates. A more detailed description of FLEXES and its operation is given in the following.

3.0 STRUCTURE OF FLEXES

3.1 Feature-Based Approach

The knowledge representation system chosen to symbolically represent the shape of a part is critically important for the design of the machine selection optimizer as well as for the other modules of FLEXES. The traditional representation using points, lines and surfaces has the advantage of a minimal number of primitives but the disadvantage of very large data sets. Higher-level representations of part geometry have been recently explored [10-21] based on 'features'. In these representations, a feature [22] is a geometric form or entity whose presence or dimensions are required to perform at least one CIM function and whose availability as a primitive permits the design process to occur. The features approach is used in FLEXES, where examples of simple features are surface_of_revolution, prismatic_surface, complex_surface and cylindrical hole. Such a feature-based representation is naturally suited to being embodied in an object-oriented representation [23], where each feature is an object in a larger universe of objects. As noted earlier, objects can not only store data but respond to 'messages' from other objects or sources using stored procedures.

3.2 Machine Selection Optimizer

The machine selection optimizer is designed to operate in the following way. For each product part, each of its 'features' (such as prismatic face, cylindrical surface, hole) is specified to the system and this information stored in the database. The selection expert system then uses previously defined rule sets to determine the possible production processes (or sequences thereof) which could be used to produce each feature. It next determines which machine tools could be used for each process, taking into account also the size, shape, materials and tolerances of the part. At this point, heuristics are used to group together the most appropriate set of machines for producing all features of all parts. Among the heuristics being considered are: fewest number of different processes (saves rejigging, setup, transfer); fewest number of different machines (reduces plant training and maintenance costs); capital cost of multiple-use machines versus single-use machines. The optimizer is being developed using the object-oriented expert system NEXPERT together with the DBASE 3+ relational data base.

3.3 Production Flow Analyzer

The output from the selection optimizer includes for each part the set of machines and the process sequence required for that part. This output is stored in the database and becomes a major portion of the input to the production flow analyzer. This module uses group technology (such as the PFA matrix method) to group together those parts that can be produced by a common set of machines. Each resulting set of machines is then used as the basis for a flexible machining cell (FMC). The output from the production flow analyzer comprises the requisite FMC's and the associated parts routing.

3.4 Rapid Modelling Unit

The FMC's derived by the production flow analyzer need to be balanced for machine loading (this may require substitution of one or more machines by a unit with higher or lower production rate or the specification of multiple identical units). These tasks are carried out by the rapid modelling unit, using the recently developed Rapid Modelling Technique (RMT) [24]. RMT relies on mathematical modelling using recent advances in the theories of queuing networks and reliability modelling. For at least a portion of the needed capability in the rapid modelling module, available RMT implementations such as Manuplan II will be investigated.

3.5 Simulation Module

The output from the RMT module comprises essentially balanced FMC's and remaining stand-alone units. The simulation module is now used for the problem of how to integrate these cells and machines into a complete plant, with the inclusion of transfer vehicles or systems. For the simulator, SIMSCRIPT could be used using input from the modeller and the database, with graphic output of the FMS operation and performance being obtained by SIMFACTORY. As alternatives, SIMAN and the use of SMALLTALK will be explored.

3.6 Database

The database is desirably object-oriented but adequate capability is only recently available commercially [23]. A relational data base such as DBASE can be used as the current work demonstrates but an object-based system would be advantageous. Other databases (GEMSTONE, G-BASE) with object structuring are being evaluated.

3.7 Supervisor

The supervisory shell could be based on a relatively simple expert system such as EXSYS or a more sophisticated one such as NEXPERT or GURU. With EXSYS, the frames capability would be an advantage, whereas with NEXPERT its object orientation would be particularly valuable. Programming the shell in SMALLTALK with the Xerox HUMBLE expert system on top of SMALLTALK would give highly desirable flexibility.

3.8 FMS Expert Systems

The design of flexible manufacturing systems using artificial intelligence techniques is in its infancy, although several expert systems for process planning have been developed [25]. A prototypical system for analyzing the output from a FMS simulation and optimizing the configuration has recently been described [26] and demonstrates the advantages of these approaches. FLEXES is much broader in scope, is designed using a foundational theoretic paradigm, and incorporates a number of new approaches, particularly in the machine selection and associated modules.

4.0 PROGRESS ON THE FLEXES PROJECT

By early 1988, the conceptual development had progressed to the stage where detailed development could begin. The machine selection optimizer was envisaged as being the most difficult and so was chosen for the initial development. This module considers each part in turn and from its features determines successively the set of possible manufacturing process sequences and the minimal set of specific machines needed. The feature 'cylindrical_hole' was selected as being representative and a sub-system developed which implemented

the machine selection optimizer function for this feature. The sub-system was programmed using the NEXPERT object-oriented expert system interfaced with the DBASE 3+ relational database. There were 37 rules required, totalling 500 lines of code. The DBASE programs, which were used for both processing and data storage/retrieval, numbered 110 comprising 5,000 lines of code in total. The sub-system has been developed, tested and evaluated.

5.0 THE CYLINDRICAL HOLE SUB-SYSTEM

5.1 Sub-System Structure

From manufacturing handbooks (Refs 27, 28) and operational experience, the relationships between the characteristics of the hole (such as depth-to-diameter-ratio, tolerance, surface finish) and the manufacturing processes required were reviewed in detail and it was found that these could be represented by the decision tree partly shown in Fig. 1. Note particularly, that the tree involves not just 'EITHER' branches but also 'OR' branches (where these are alternate processes) and these latter require special treatment. For a given hole the possible process-sequences for its creation can be obtained by traversing the tree. Alternatively, since a decision tree can be represented as a set of rules, the possible process-sequences can be derived by chaining through the rule-set (using an appropriate inference engine).

The rule-set approach was chosen and the rules implemented in NEXPERT in such a way that all the holes for a particular part are processed at the same time. At the output from this stage, the holes for a part are 'sieved' through, so that for each machining process a file is created listing the holes which could potentially use this process and for each hole there is a file which identifies the possible process-sequences, as well as other data on the hole.

The next step is to consider, for a particular process, each specific machine and to determine whether it is suitable for the holes now listed as potential users of that process. Suitability is decided by checking critical parameters of the part and the hole against the machine specification e.g. Is the part in which the hole is to be created too large for the machine (too wide or high?). This stage of the processing is carried out by a group of DBASE 3+ programs.

The final step is to minimize the total set of machines needed to make all holes by selecting for the holes those processes which would make maximum common use of particular machines. The output from this stage specifies for each hole the possible process-sequences, with for each process a single machine being listed (chosen from the minimal total set). These programs have also written in DBASE 3+ code.

The successive actions within the machine selection optimizer are summarized in Fig. 2. If 'feature_1' were to be a 'cylindrical_hole', then the sub-system for this would deal with all the feature_1's (i.e. holes) for all parts, in the manner outlined above. The sub-systems for other features would operate in a generally similar fashion.

5.2 Sub-System Rule Structure

For the cylindrical hole sub-system, the rules which implement the decision tree structure of Fig. 1 are written in NEXPERT format. These rules basically follow the standard production-rules expert system pattern:

[IF (A AND B ----) THEN (M AND N and----)]

In the NEXPERT version used, OR's could not be used directly and had to be implemented by multiple rules. Fig. 3 shows typical rules. The lines containing @ refer to data to be written to specified DBASE 3 files.

Rule 33

If there is evidence of holes_no_ax_sym_with_dp_to_dia_le_8
Then write_shallow_holes_no_axial_symm
is confirmed.
And Writing in hl_drill.dbf
@DBF3;@ADD;@NAME="hole"!hl_id_num!;
@PROPS=axial_symmetry.depth_to_dia_ratio.surface_finish;
@FIELDS=axial_symm.dep_to_dia,surfacefin
@ATOMS=<drilling>.axial_symmetry,<drilling>.depth_to_dia_ratio,
<drilling>.surface_finish;
And Writing in hl_drill.dbf
@DBF3;@ADD;@NAME="hole"!hl_id_num!;
@PROPS=tolerance;@FIELDS=tolerance;@ATOMS=
<drilling>.tolerance;
And Writing in hl_torch.dbf
@DBF3;@ADD;@NAME="hole"!hl_id_num!;
@PROPS=axial_symmetry,depth_to_dia_ratio,surface_finish;
@FIELDS=axial_symm,dep_to_dia,surfacefin;
@ATOMS=<torches>.axial_symmetry,<torches>,depth_to_dia_ratio,
<torches>.surface_finish;
And Writing in hl_torch.dbf
@DBF3;@ADD;@NAME="hole"!hl_id_num!;
@PROPS=tolerance;@FIELDS=tolerance:@ATOMS=
<torches>.tolerance;

Rule 37

If there is evidence of write_lathe_boring_or_reaming
And <lathe_reaming>.surface_finish is less than or equal to
30.00
Then internal_cyl_grinders
is confirmed.
And Create Object <lathe_reaming> internal_cyl_grinders
is confirmed.
And Create Object <lathe_reaming> internal_cyl_grinders
And <lathe_reaming>.process_3 is set to
internal_cyl_grinders

Fig. 3. Sample Selection Rules

5.3 Critical Parameter Checking

At this stage, for each process there is:

(a) a list of holes for which the process is suited, and

(b) a list of machines which can perform that process.

Not every machine in list (b) could be used for making each hole in list (a), however. For example, Machine_27 when checked against Hole_18 may be found unsuitable because the part to which Hole_18 belongs is too large (wide, high) to be handled by Machine_27. Therefore, a set of critical parameter checks are carried out and machines which are found unsuitable are removed from list (b).

A problem that was foreseen with the machine selection optimizer was a kind of combinatorial expansion of data through the sequence of actions shown in Fig. 2. Because of this, it was considered important to 'prune' the data in ways such as the above, at appropriate stages through the sequence.

5.4 Minimization of Total Set of Machines

Table 1 illustrates how the minimization of the total set of machines is carried out. For each of the holes, successive processes are indicated by checkmarks, with one process per line for clarity. For each such process, the machines which are suitable are indicated by checkmarks in the same line. The totals show the maximum number of times a machine could possibly be selected. The minimization begins by selection of the machine

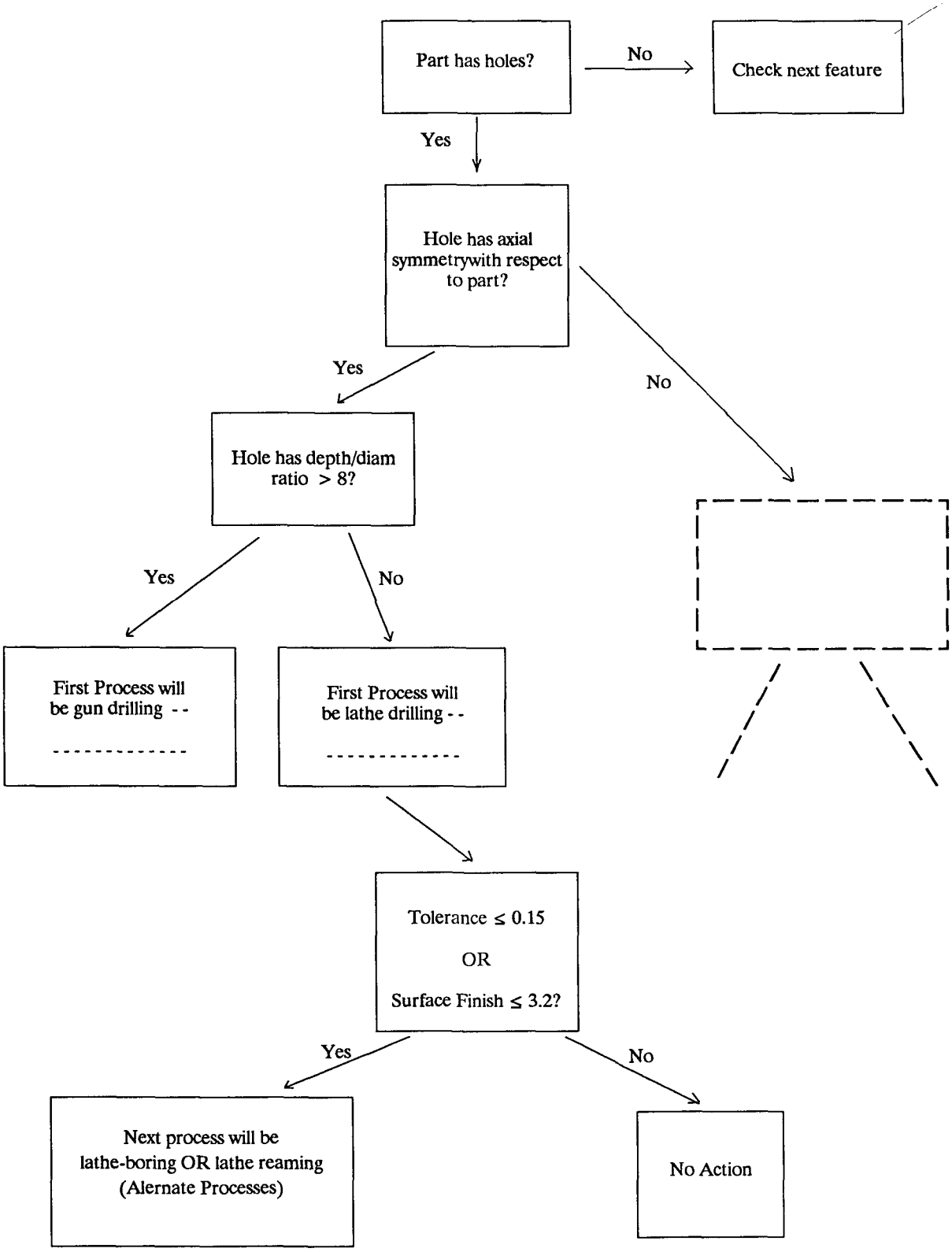

Fig. 1 Partial Decision Tree for Production of Cylindrical Holes

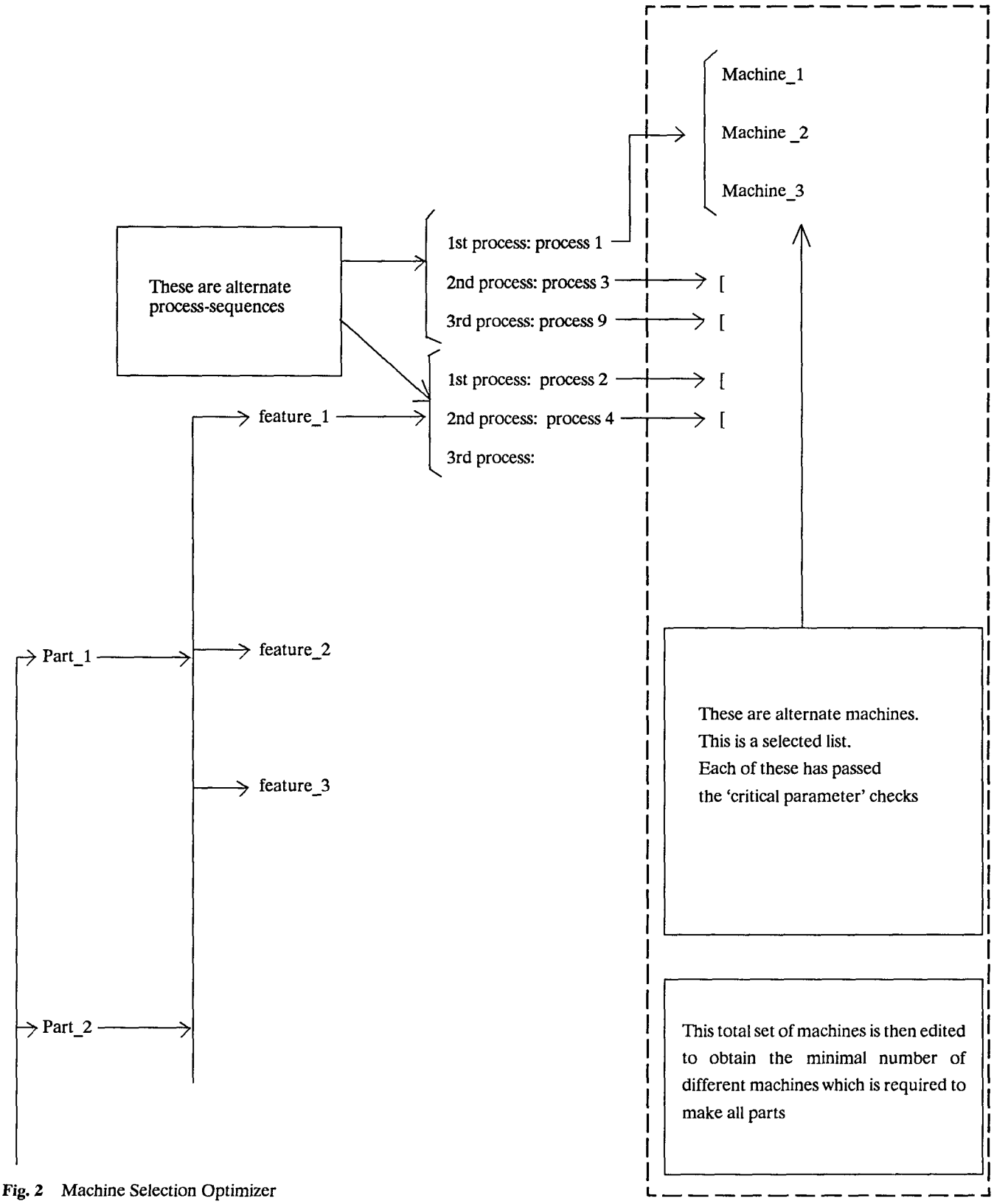

Fig. 2 Machine Selection Optimizer

	PROCESSES								MACHINES				
Hole Number	A	B	C	D	E	F	G	H	M1	M2	M3	M4	M5
1	√								√		√●		
			√							√	√●		√
				√							√●		√
2		√									√●		
					√					√			√●
3	√								√		√●	√	
				√							√●		√
							√			√			√●
TOTALS									2	3	6	1	5

Table 1. Illustration of the Minimization Process

with the highest total ('popularity') of checkmarks followed by the insertion of a filled circle in the column wherever there is a checkmark. This process is repeated for the second most popular machine but now circles are only entered for rows which do not contain a circle already. The procedure is continued for as many machines as needed, until there is a circle in every row. A machine which has one or more circles in its column belongs to the minimal set. For the example shown in Table 2, machines M3 and M5 constitute the minimal set and hence every process can be accomplished by selecting from this set of two machines. The advantages of minimizing the number of different machines to be used in a factory are self-evident.

The minimization is carried out using programs written in DBASE 3+ code which operate on process and machine lists in essentially the manner described above.

5.5 Input and Output of the Machine Selection Optimizer

The 'cylindrical_holes' sub-system of the machine selection optimizer was programmed in NEXPERT rule code and DBASE 3+ as described. This sub-system was developed for testing and evaluation as a stand-alone package on a Zenith 386 computer under DOS 3.2 and Windows 386. Input comprises both the rule-set and those machines files which list the available machine tools and their characteristics. A screen menu allows output to be selected for the total machine set, as derived either before or after the minimization stage. The sub-set for either an individual feature (hole) or a desired group of these can also be obtained by menu selection.

Figure 4 shows a sample of output (from the post-minimization stage). It will be seen that for Hole #9 there are five sequential process stages. One of these (#2) has alternate choices, namely, lathe_boring and lathe_reaming. The minimization process has shown that whichever choice is taken, however, the same machine (#34 Model J82 Lathe) can be used.

Hole Number: 9 Optimum Selection of Machines

Process 1:	lathe_drilling	
Machine Number	Machine Type	
34	Model J32 Lathe	
Process 2:	lathe_boring	
Machine Number	Machine Type	
34	Model J32 Lathe	
Alternate Process 2:	lathe_reaming	
Machine Number	Machine Type	
34	Model J32 Lathe	
Process 3:	internal_cyl_grinders	
Machine Number	Machine Type	
40	Model X4 Internal Cylindrical Grinder	
Process 4:	hones_rotate_wp	
Machine Number	Machine Type	
42	Model 91BF Hone rotates w/p	
Process 5:	internal_cylindrical_laps	
Machine Number	Machine Type	
42	Model 91BF Hone rotates w/p	

Fig. 4. Sample Output from Machine Selection Optimizer Sub-system

5.6 Evaluation of Machine Selection Optimizer

Both the structure and the performance of the machine selection optimizer has been critically reviewed by the project group, following testing and debugging. While it has been demonstrated that the approach taken can result in an operational product, the design choices were considered to be restricted by the structure of the expert system shell and the relational data base. Although there are considerable development advantages to using an existing shell and database, there is clearly a significant reduction in design flexibility. An alternative approach to the whole system was therefore considered, using a fully object-oriented language for all modules. All entities within the system would be objects and communication between objects would be through messages. Work on a system of this kind was begun in mid-1988 and is continuing. This system has been denoted the Object-oriented Integrated Manufacturing Planning System (OBJIMPS). For further details on OBJIMPS see [29].

5.7 Subsequent Stages After Machine Selection Optimizer

For all the parts to be processed through the factory in an envisaged period, the machine selection optimizer finds the minimum number of different machines which could be used. This minimum set contains one of each of these machines.

In reality, more than one of each machine will actually be needed in the factory, depending on how many of each part is to be produced. The next major stage in FLEXES is to form clusters or cells of machines, grouping machines according to the principle 'parts with a similar feature should be processed by a cell optimized for this feature' or 'a chosen set of features on a part should be processed by a cell structured for this set'. Following this, the cells should be balanced for load and so on, as outlined previously.

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