Integrating Computer Aided Design and Computer Aided Process Planning: A Computational Techniques Model Approach

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Abstract: - One of the most daunting challenges in Computer Integrated Manufacturing (CIM) is bridging the gap between Computer Aided Design (CAD) and Computer Aided Process Planning (CAPP). Past research into CAPP, considered one of the most important and most complicated computer aided systems, resulted in a wealth of knowledge but unresolved problems still exist. The actual CAPP systems are considered large, complex, and monolithic, with limited extensibility, low-level of integration with other applications, and high development and maintenance costs. Consequently, this paper focuses on a computational technique model for CAD/CAPP integration. Supported by authorities, evidence or logic, it is demonstrated that a limited number of important design and manufacturing features can be used to achieve an integrated product model that provides not only a direct interpretation of CAD data to the CAPP system, but supplies sufficient information for the generation of the correct process plan's operations sequence. The approach simplifies engineering drawing's information complexity, and offers better computability, reusability and improved communication between CAD and CAPP. As a result, the approach is used to develop software applications that apply object-oriented programming as a new way of thinking about solving CAD/CAPP problems and as a promising alternative to other techniques.

Key-Words: - CAD, CAPP, Computational Technique

1 Introduction

In order to ensure a smooth transition from the engineering design to computer aided manufacturing (CAM), the evolution of part representation was regarded as a continuous interplay between what we want to achieve and how we want to achieve it [1].

In spite of this, there are still shortcomings in CAD/CAPP (Computer Aided Design/Computer Aided Process Planning) communication, where process planning was defined as the transformation of the detailed engineering drawing specifications into manufacturing operating instructions [2]. The main reasons for these shortcomings have been considered the methods used in design for product representation and the lack of accepted design and manufacturing features that affected not only CAPP development, but also Computer Integrated Manufacturing (CIM) where CAPP plays a fundamental and increasingly crucial role [3].

Therefore, considering the above circumstances, this paper focuses on a computational technique model for CAD/CAPP integration. Subsequently, section 2 formulates the problem by identifying from the existing body of knowledge, research gaps and advancing hypothesis. Then, in section 3, the paper answers to the hypothesis and problem solution is presented using a software prototype. Finally, section 4 draws conclusions about the hypothesis and highlights its theoretical and practical implications.

2 Problem Formulation

The part representation evolved from wire modelling, to surface modelling, to solid modelling, and to feature modelling. However, the shortcomings in CAD/CAPP communication persisted. For example:

- In wire frame models manufacturing features such as threads and grooves were considered difficult to define [4];
- CAD surface models were too complex to interpret and only suitable for parts produced by one process [5];
- The solid models were non-unique in nature and only useful for subtractive volumes to be cut out [5]; and
- Features were still a bottleneck [3] and a challenging research area [6] because their recognition was a complex, cumbersome and problematic process that led to different descriptions of the product [7] and so, had an insignificant practical impact [3].

Furthermore, although the CAD knowledge was hard to manage and access because its detailed data geometry that made the automated reasoning highly complex to implement [8], and excessive details were considered often inadequate for most circumstances [32], most academic research and developers attempted to recognize very detailed design information that was believed a waste of time, cost, efficiency and could even affect the accuracy of process plans [9] [6]. In addition, the tolerance and surface finish data were not real attributes of CAD models, but simply text representations on the drawing, the same as technical notes [3], that made the actual CAD systems inconvenient for most manufacturing applications [10].

Moreover, the engineering drawings were not only represented by geometry elements but also drafting symbols and text that provided the designer with an added flexibility in design [11] and that yielded enough input to determine many of the characteristics of the manufacturing process [6]. In addition, although an experienced human planner utilizes only important features that would influence the process planning [9], the CAD/CAM systems were not available at this high level of integration [3] considered crucial for mapping traditional CAD data on the process planning systems [12].

Finally, although Artificial Intelligence (AI) has been used in CAPP as a major technique, expert systems have not provided significant results [13] [14], Genetic Algorithms (GA) were far from having an impact in practice [15] and it was unusual to see reports about successfully general CAPP solutions based on AI [5] [16].

Subsequently, all the above led to the:

Hypothesis: **A CAD system that uses common designs and manufacturing objects and preserves most of the actual design representations will enhance CAD/CAPP communication, and lead to the development and implementation of a better CAPP software system.**

3 Problem Solution

Section 3 describes the solution to the problem presented in section 2. Also, it aims to show that the methodologies and the decisions that have been taken to answer the research hypothesis are supported by authorities, evidence or logic.

In this paper, the high-level creative phase of design was viewed as one component of a higher-level conceptual map that links design and manufacturing and that intends to establish meaningful and practical relationships between the item's functional requirements (FRs), design's parameters (DPs), process plan's operations sequence and parameters (PPs), company's facilities (CFs) and company's rules (CRs) parameters (Figure 1).

So, by pursuing the goal to establish a meaningful relationship between design and CAPP, the example in Figure 2 is given. It shows four simple similar drawings with no dimensions and no tolerances where it was still possible to develop correct process plans by only considering and combining the drawing's surface finishes and heat-treatment instructions. Furthermore, Table 1 establishes some first useful relationships.

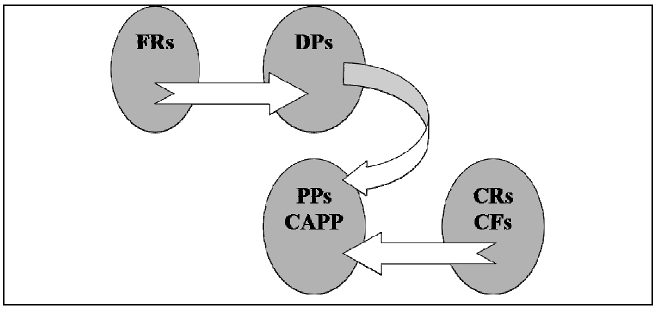

Figure 1. Relationships between conceptual maps

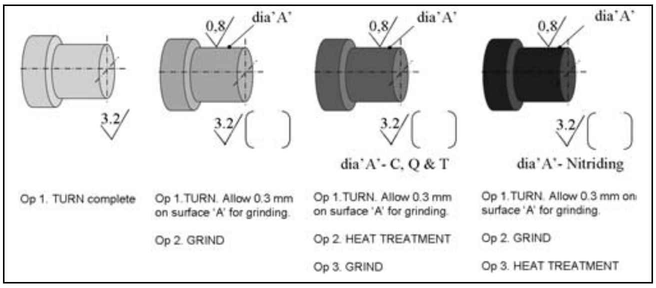

Figure 2. Simple and similar engineering drawings

Table 1. Design/CAPP rules & instructions

Structural fact: - Each item needs a starting material
Action triggering: - Each starting material requires a receiving inspection operation
Inference: - If item is round and general surface finish (GSF) is 3.2 μm - "Turn complete"; - If item is round, GSF is 3.2 μm and at least one surface requires 0.8 μm - "Turn. Allow 0.3

mm for grinding" then "Grind complete";
- If item is round, GSF is 3.2 μm, at least one surface requires 0.8 μm and the heat-treatment of C, Q, & T (Carburise, Quench & Temper) is required - "Turn. Allow 0.3 for grinding", then "Heat-treatment: C, Q, & T", then "Grind".

Following this simple item example, a very complex item for an aerospace engine was considered (Figure 3). It was again observed that, although the drawing has no dimensions and no tolerances, and no specific vertices or surfaces were used, it was still possible to correctly develop the process plan.

Consequently, a high-level conceptual map (see Figure 3) that links design elements with well established manufacturing knowledge was developed without the need to recognise the very detailed design information which was considered unnecessary in process planning and a waste of time, cost, and efficiency [9] [17].

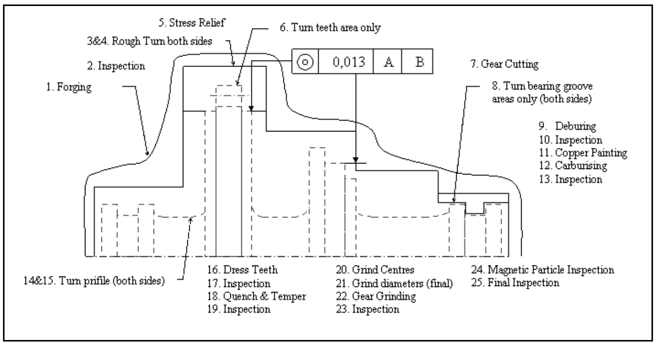

Figure 3. Gear-shaft (dotted-lines) and process planning operations

Also, in order to bring together design and manufacturing data, the SACAPP (South African CAPP) system - currently in development at the University of the Witwatersrand, Johannesburg - coded the relationship between the tolerance and surface finish data and so, used a simple methodology to transfer the tolerance specifications to surface finish specifications and thus avoiding the risks associated with the tolerance representation and interpretation [8].

Furthermore, in the conditions when the vast majority of engineering data was non-geometric in nature [8], SACAPP considered that the drafting symbols and text represented the conscious knowledge explicitly represented, examined, and manipulated [18] [19] that could provide the designer with an added flexibility in design [11], yield enough input to determine manufacturing process [6] [12] and that could be represented inside a computer by character strings or by numbers.

The fact that SACAPP considered the drafting symbols and text for communication was not surprising. Symbols have been used as communication for centuries in arts, mathematics, mechanical engineering designs or electrical circuits' designs. For example, Leonardo da Vinci realised the power of using images and their associations in order to unleash problem solving and see new creative pathways [20]. Furthermore, in modern times, the UML (Unified Modeling Language) - considered the best current software development practices [21] - had applied a similar approach. The UML is a general-purpose visual modelling language used to specify, visualise, construct, and document the artifacts of a software system [22]. Through visual modelling, the UML facilitates the communication between anyone involved with the project, because the complexity of the system to be developed could be understood better when displayed graphically as opposed to written textually.

Therefore, just as the UML has been the answer to the two key challenges in software development, namely system's complexity and communication, this paper used the same approach in CAD/CAPP communication. As a result, the engineering design's complexity could, as opposed to individual feature extraction, be better "understood" when displayed as drafting symbols and text with meaning behind them [33]. So, they can be used for visualizing, specifying, constructing, and documenting part of the design artifacts (Figure 4). Consequently, SACAPP used machining features with relevant technological information [3] [12] [23].

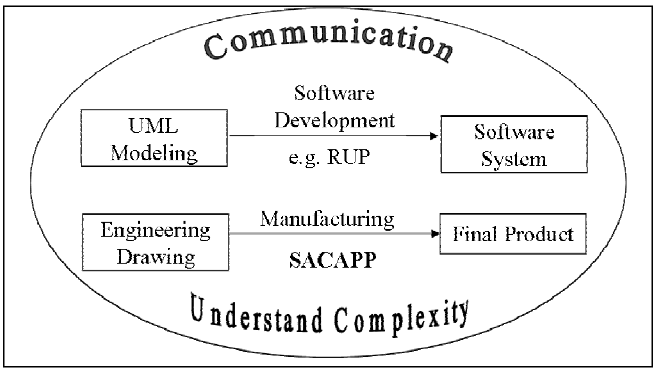

Figure 4. UML/RUP and Design/SACAPP

So, in order to develop the SACPP system, the example from Figure 3 was once again revised and a number of entity, boundary, and control objects were identified (Figures 5 and 6) - entity objects hold information and conduct business' functionality; boundary objects are the Windows of the application and the interfaces to the other applications; and control objects are optional objects that control the flow through the use case.

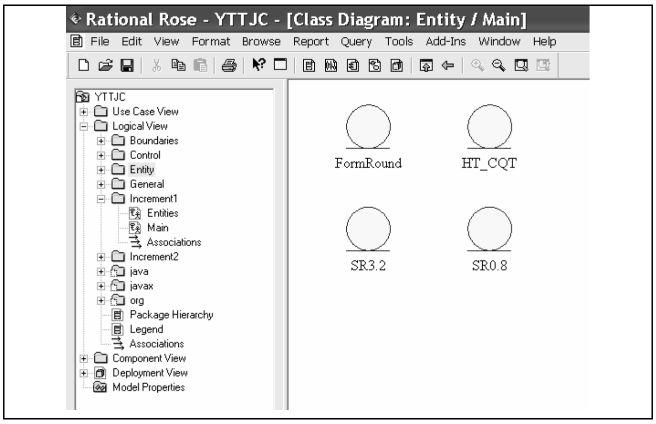

Figure 5. UML Class diagram (first iteration).

For example in Figure 5, the "FormRound" object had:

- Identity, that is, the starting material is round, so not square or hexagonal;
- Attributes such as diameter and length; and
- The only way to access or machine it is through a number of specific manufacturing operations suitable for "this" specific type of round form of material.

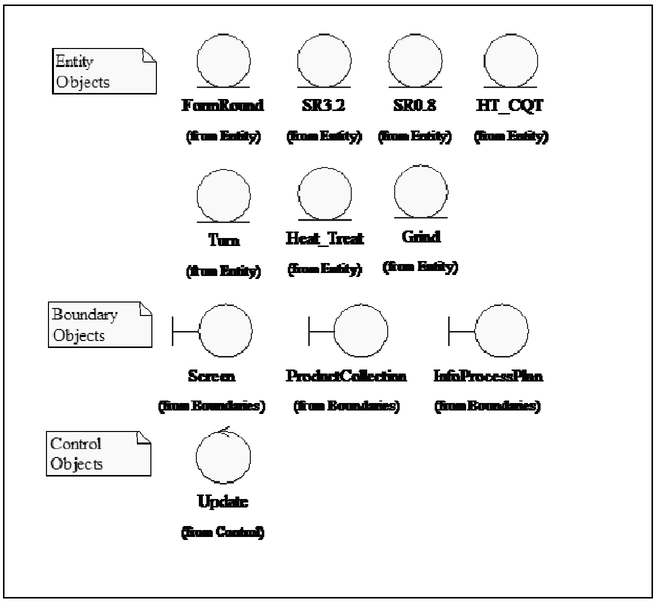

Figure 6. UML Class diagram (second iteration)

After that, it was important to show how these objects work step-by-step together in order to implement one of the flows through the functionality in the use-case example. Thus, Figures 7 shows the UML sequence diagram organised by time and displaying:

- One of the flows through the example;
- The actor which initiated the whole flow;
- The objects that are needed for the flow; and
- The messages the objects sent to each other to assign responsibilities.

Furthermore, Figure 8 shows the objects that directly communicate with each other – this is indicated with a line drawn between them so, the absence of a line means that no communication occurs directly between objects.

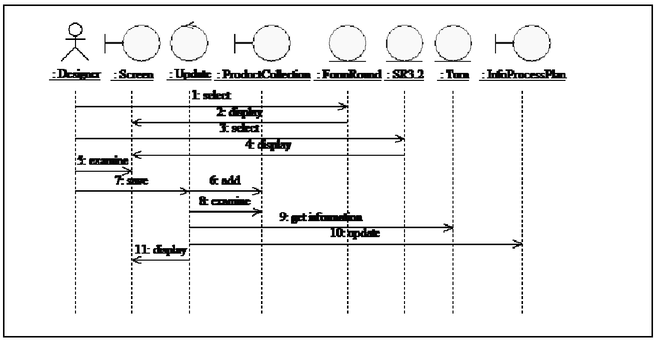

Figure 7. SACAPP at machine level

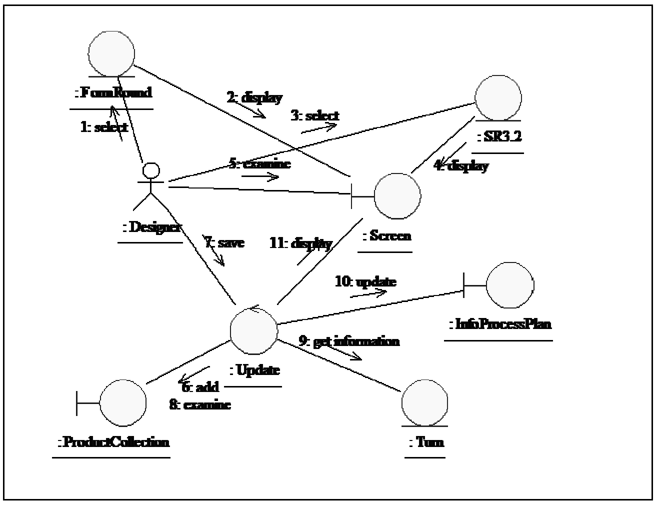

Figure 8. UML Collaboration diagram with no reference to the time

In addition, when dealing with a greater number of objects such as in Figure 3, SACAPP used:

- Centres of process gravity which use the same principles similar to: the group technology and modularity manufacturing concepts [24];

- The modular software principles to make its architecture work in the real world [25]; and
- The automation and robotics recommendations which require the determination on all sites a central focus or series of central focuses about which all other activities revolved [25] [26].

Consequently, in order to develop a technique to be used for constructing process planning sequence of operations, the operations indicated in Figure 3 were broken down into smaller, independent, self-contained and co-operative groups of operations (see Table 2), and doing so, transformed the process plan of a complex item into a sequence of modules classified in "common sense" (CS) e.g. the start and the end of a process plan; "critical" e.g. a central focus about which all other activities revolve; and "technological" (Tech) that represent the process planner's specific knowledge.

Table 2. Groups of operations and their centers of gravity (CG)

No	Content of the module	Classification
0	1. Forging, 2. Inspection	CS
1	3&4. Rough Turn, 5. Stress Relief	Tech
2	6. Turn	CS
3	7. Gear Cut	Critical
4	8. Turn	Tech
5	9. Debarring, 10. Inspection, 11. Copper Painting, 12. Carburising, 13. Inspection, 14. Quench & Temper, 15. Inspection	Critical
6	16. & 17. Turn profile both sides	CS
7	18. Grind Centres, 19. Grind diameters, 20. Gear Grinding, 21. Inspection, 22. Magnetic Particle Inspection	CS
8	23. Final Inspection	CS

Furthermore, because features were considered central to design, process planning and manufacturing tasks integration [28] [29] [30], the different schools of thoughts about features in design and manufacturing were analysed in the first iteration (Table 3).

Then, during the second iteration, these features were re-analysed by considering that each object had to be built out according to the object-orientated programming of (Identity, Variables and Methods), or (Identity, State and Operations) [31].

As a result of this analysis, only those objects that represented a natural association between both design and process plan have been retained (Table 4).

Table 3. Analysis of feature definitions in design (D), manufacturing (M), and their influence (I) in design (I_D) or manufacturing (I_M) (1st Iteration)

Characteristics in (reference, code) format
Part geometry ([35], M)
Form, shape ([1], D), ([36], I_M), ([17], M)
Shapes serving certain functions ([28], I_D)
Functional meaning ([1], I_D), ([7], I_D), ([30], I_D)
Physical properties ([1], I_D)
Material quality ([36], I_M), ([17], M)
Raw material ([35], I_M)
Heat treatment process ([36], I_M), ([17], M)
Accuracy, surface finish (Timings, 1998, I_M), (McMahon et al., 1997, M)
Quantity ([36], I_M)
Equipment process capability ([36], I_M)
Cost ([36], I_M), ([17], M)
Physical element with eng. meaning ([5], M)
Surfaces formed by machining processes ([28], M)
Individual characteristic e.g. cylindrical surface, screw thread, slot ([37], D & M)
A unit of form with semantic meaning ([10], D)
A set of information ([28], D)
Functional, geometric, as well non-geometric job characteristics that can facilitate any form of computer decision making ([38], I_M)
A simple feature frequently machined ([39], M)
Natural association of knowledge between domains ([40], D & M)
Important or critical feature ([9], I_D & I_M)
A natural way to describe a work piece ([41], M)
Schematic descriptions of parts that can be task-based at all levels ([30], D)
A visual image of the part with a high-level information and never the computerized raw data ([42], I_D)
Feature has three perspectives: shape (e.g. hole), structure (e.g. stepped hole), and information support (e.g. size, tolerance, surface finish, heat treatment) ([43], I_D)
The drawing features' interpretation should help identify the critical processing factors ([44], I_M)
Geometrical features that have a major influence on the selection of manufacturing processes ([44], I_M)
Available production facilities, ([17], M)

After that, the third and final iteration established the list of design and manufacturing objects decided to be used not only in SACAPP's design system, but also for CAD/CAPP communication (Table 5).

Table 4. Feature analysis (Iteration 2)

Group	Name	A few Examples
1	Form, Shape	Round, Square
2	Material quality	655M13, 826M40
3	Raw material	Bar, Forging
4	Surface finish	3.2 or 0.8
5	A unit of form with semantic meaning	Keyway, Hole, Gear Teeth
6	A visual image with high-level information	Surface roughness symbol

Table 5. CAD/CAPP partial object list (Iteration 3 - final)

Group	Name	Example	Notation Example
1	Item's general shape	Round, Prismatic	Round, Prismatic
2	Material quality	655M13, 826M40	655M13, 826M40
3	Starting material	Bar, Forging	Bar, Forging
4	Heat treatment	C, Q, & T	HT_CQT
5	Surface roughness	3.2 or 0.8	SR3.2 or SR0.8
6	Keyway, Slot	Keyway	Keyway
7	Gear teeth	Gear teeth	GearTeeth
8	Hole other that e.g. the central hole of a hollow item	Holes	DrillHole
9	Other textual notes	Balancing	Balancing

Then, the modules have been placed into a graphical format, and observed that they resembled an array of objects (Figure 9).

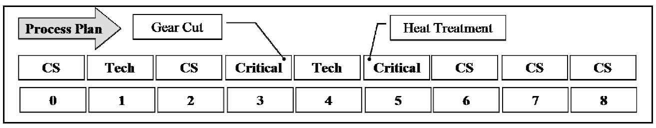

Figure 9. List of centres of gravity

Consequently, the CAD/CAPP object feature definition was established (see below) and then verified for its consistency with object-orientated programming definition (Figures 10 and 11).

CAD/CAPP object feature definition: A CAD/CAPP object feature is a unitary, consistent, homogeneous, and conscious conceptual entity model of some part of the real world of both designer and process planner which has identity, information and representation independence, syntax behind it, and meaning, that is semantics, and used for visualizing, specifying, constructing, and documenting part of their artifacts.

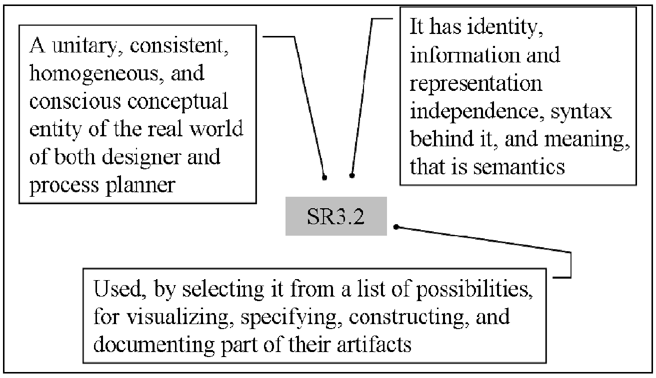

Figure 10. SACAPP feature example 1

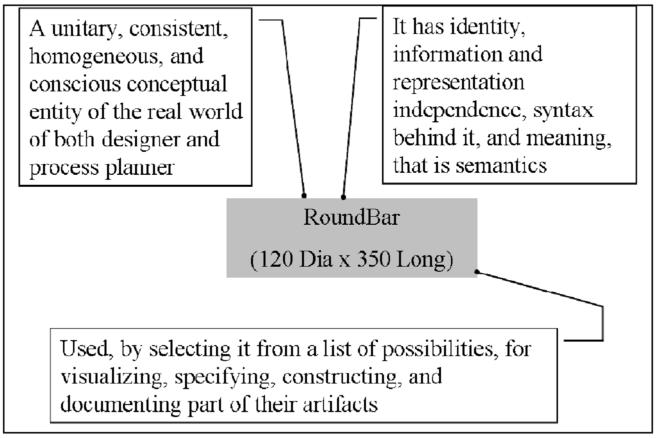

Figure 11. SACAPP feature example 2

Finally, by going through each of the array's elements and defining their contents, the process plan's sequence of operations was possible to be constructed, and so achieving the most critical activities of the process planner's activity because it involved knowledge about facts, procedures, "if-then" rules [27], machine-tools' availability, manufacturing time and human-resident experience or established local practice.

Subsequently, the array of objects was implemented using Java programming language – example follows:

```
// Import Java Collection classes
import java.util.collections.*;
…
```

```
//Create two Java Collections ArrayList (one for the
//process plan and one for the route sheet) that
//represent in this example /the centre of gravity for
//the end of the plan
ArrayList end_gPS = new ArrayList();
ArrayList end_gRS = new ArrayList();
…
// EndPlanGravityList() method
public void writeEndPlanGravityList() {
   G_EndPlan g_end = new G_EndPlan();
   // adds operations to the ArrayList
   end_gPS.add(g_end.getInspStampPS());
   end_gRS.add(g_end.getInspStampRS());
   if (comboDataBook.getSelectedIndex() == 1)   {
      end_gPS.add(g_end.getInspDataBookPS());
      end_gRS.add(g_end.getInspDataBookRS());   }
   if (comboRecordSize.getSelectedIndex() == 1)  {
      end_gPS.add(g_end.getInspRecordSizePS());
      end_gRS.add(g_end.getInspRecordSizeRS()); }
   if (comboInspReport.getSelectedIndex() == 1)  {
      end_gPS.add(g_end.getInspReportPS());
      end_gRS.add(g_end.getInspStampRS());        }
   end_gPS.add(g_end.getInspStoresPS());
   end_gRS.add(g_end.getInspStoresRS());
}//end centre of gravity end plan
```

The process plans and route sheet were built in the same way. For example:

```
// Create two Java Collection ArrayList that collects
// all centres of gravity
ArrayList mergePS = new ArrayList();
ArrayList mergeRS = new ArrayList(); …
// The inference method
   public void newInference() { …
   writeEndPlanGravityList();  …
// the "addAll" method is used to add centres of
gravity to the ArrayList
   mergePS.addAll(0,start_gPS);
   mergePS.addAll(end_gPS);
```

During testing, the SACAPP system automatically generated the process plans based on the input data extracted from the:

- SACAPP system's own pre-set operation description and constraints (Figure 12), supplemented by
- Data from a number of key workflow software modules [34] such as sales module that provides e.g. customer's name (Figure 13) and
- Management module that specifies e.g. machine availability in the company (Figure 14), not discussed in this paper.

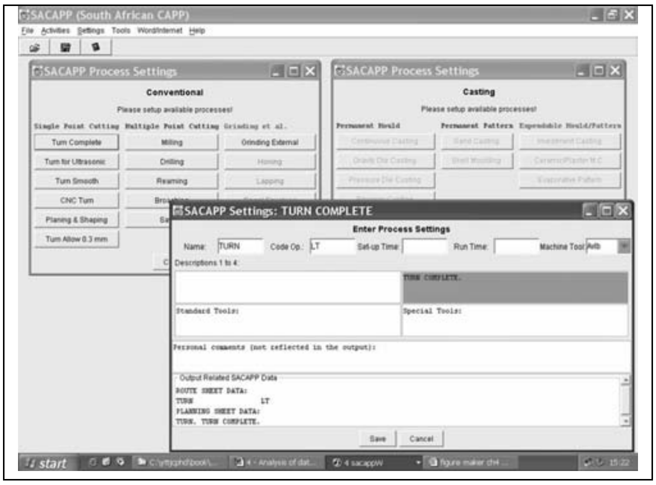

Figure 12. SACAPP operation description and constraints

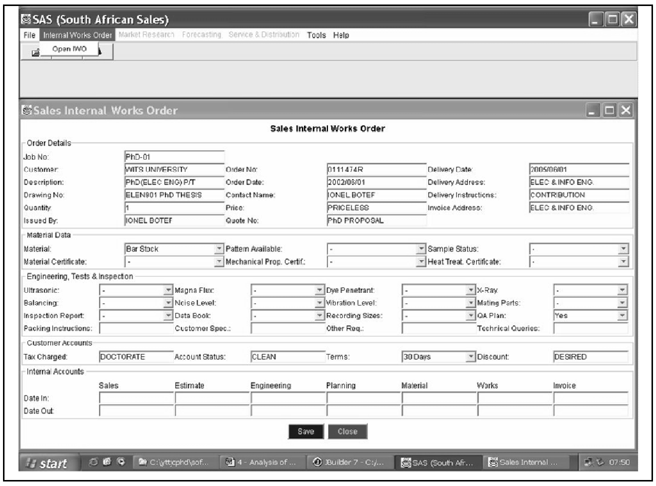

Figure 13. Sales module example

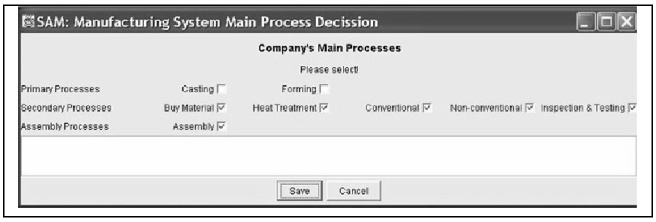

Figure 14. Managerial module screen shot

Finally, during testing, the SACAPP system automatically generated the process plans (Figure 15 and 16) and the Route Sheet (Figure 17).

Therefore, it was concluded that a CAD system that uses common designs and manufacturing objects and preserves most of the actual design representations will enhance CAD/CAPP communication, and lead to the development and implementation of a better CAPP software system.

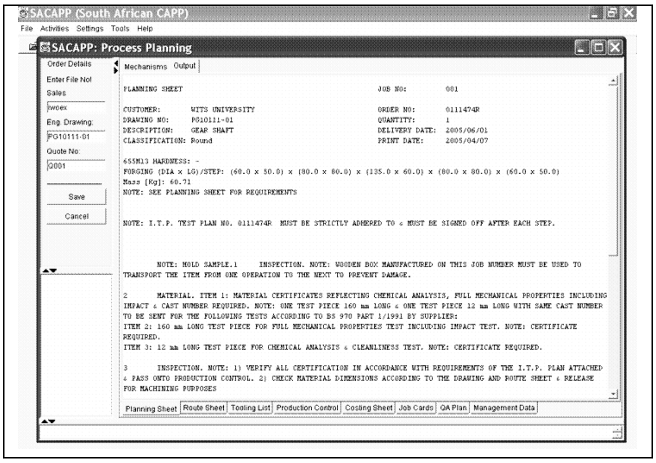

Figure 15. SACAPP screen shot

PLANNING SHEET JOB NO: xxx

CUSTOMER: WITS UNIVERSITY ORDER NO: xxx
DRAWING NO: Complex3 QUANTITY: 1
DESCRIPTION: GEAR SHAFT DELIVERY DATE: xxx
CLASSIFICATION: Round PRINT DATE: xxx

MATERIAL: 655M13, FORGING: (Dia60 x 50 LG) x (Dia 90 x 80 LG) x (Dia 140 x 60 LG) x (Dia 90 x 80 LG) x (Dia 60 x 50 LG)

NOTE: I.T.P. TEST PLAN NO. 0111474R MUST BE STRICTLY ADHERED TO & MUST BE SIGNED OFF AFTER EACH STEP.

1 INSPECTION. NOTE: WOODEN BOX MANUFACTURED ON THIS JOB NUMBER MUST BE USED TO TRANSPORT THE ITEM FROM ONE OPERATION TO THE NEXT TO PREVENT DAMAGE.
2 MATERIAL. ITEM 1: MATERIAL CERTIFICATES REFLECTING CHEMICAL ANALYSIS, FULL MECHANICAL PROPERTIES INCLUDING IMPACT & CAST NUMBER REQUIRED. NOTE: ONE TEST PIECE 160 mm LONG & ONE TEST PIECE 12 mm LONG WITH SAME CAST NUMBER TO BE SENT FOR THE FOLLOWING TESTS ACCORDING TO BS 970 PART 1/1991 BY SUPPLIER:
ITEM 2: 160 mm LONG TEST PIECE FOR FULL MECHANICAL PROPERTIES TEST INCLUDING IMPACT TEST. NOTE: CERTIFICATE REQUIRED.
ITEM 3: 12 mm LONG TEST PIECE FOR CHEMICAL ANALYSIS & CLEANLINESS TEST. NOTE: CERTIFICATE REQUIRED.
3 INSPECTION. NOTE: 1) VERIFY ALL CERTIFICATION IN ACCORDANCE WITH REQUIREMENTS OF THE I.T.P. PLAN ATTACHED & PASS ONTO PRODUCTION CONTROL. 2) CHECK MATERIAL DIMENSIONS ACCORDING TO THE DRAWING AND ROUTE SHEET & RELEASE FOR MACHINING PURPOSES
4 CAST NO. RECORD ON ROUTE SHEET.
5 INSPECTION. CHECK HARDNESS ON MATERIAL AND RECORD IT ON ROUTE SHEET.
6 TEST. OUTSIDE OPERATION: SEND TEST PIECE 160 mm LONG FOR FULL MECHANICAL PROPERTIES TESTS INCLUDING IMPACT. 2) SEND TEST PIECE 12 mm LONG FOR CHEMICAL ANALYSIS.
7 TURN. CLEAN UP O.DIA'S ON FULL LENGTH FOR ULTRASONIC TEST PURPOSES.
8 TEST. ULTRASONIC TEST TO AAC 999/6. NOTE: CERTIFICATE REQUIRED.
9 TURN. ALLOW 0.3 mm ON THE DIAMETER(S) WITH Ra 0.8 FOR GRINDING.
10 GEAR-CUT. CUT TEETH. ALLOW 0.3 mm ALLOWANCE FOR GEAR GRINDING.
11 DEBARRING. REMOVE SHARP EDGES.
12 INSPECT. CHECK AND RECORD GEOMETRICAL TOLERANCE BEFORE HEAT-TREATMENT.
13 COPPER PAINT. SURFACES REQUIRED TO REMAIN SOFT MUST BE COPPER-PAINTED.
14 HEAT-TREATMENT. CARBURIZING, QUENCH, AND TEMPER (60-63 HRC, 1-1.3 mm DEPTH.)
15 INSPECTION. CHECK AND RECORD GEOMETRICAL TOLERANCES AFTER HEAT-TREATMENT.
16 GRIND. GRIND EXTERNAL DIAMETER(S)
17 GEAR-GRIND. GRIND TEETH (30 TEETH, 4 MODULE)
18 TEST. INVOLUTE, HELIX ANGLE, RUNOUT & PITCH TO PITCH ERROR TO BE CHECKED ON HOFLER TESTER. NOTE: GRAPH REQUIRED.
19 TEST. CARRY OUT MAGNETIC PARTICLE TEST TO AAC 999/6 SPECIFICATION. NOTE: CERTIFICATE REQUIRED.
20 INSPECTION. STAMP ITEM(S) WITH OUR JOB AND SERIAL NUMBER.
21 INSPECTION. DATA PACK OF ALL CERTIFICATION, COMPLETED PROCESS PLANNING SHEET AND FULL INSPECTION CERTIFICATE TO BE DELIVERED WITH THE ITEM(S).
22 STORES. THE ITEM(S) MUST BE PROTECTED AGAINST RUST & SUITABLY CRATED TO PREVENT ANY DAMAGE.
NOTE: RETURN SAMPLE TO CUSTOMER.

Figure 16. Planning Sheet generated by SACAPP

ROUTE SHEET JOB NO: xxx

CUSTOMER: WITS UNIVERSITY ORDER NO: xxx
DRAWING NO: xxx QUANTITY: 1
DESCRIPTION: GEAR SHAFT DELIVERY DATE: xxx
CLASSIFICATION: Round PRINT DATE: xxx

MATERIAL: 655M13, FORGING: (Dia60 x 50 LG) x (Dia 90 x 80 LG) x (Dia 140 x 60 LG) x (Dia 90 x 80 LG) x (Dia 60 x 50 LG)

OP.NO	DESCRIPTION	CODE	SET-UP	RUN TIME
1	INSPECTION	IN		
2	MATERIAL	MA		
3	INSPECTION	IN		
4	CAST NO	CAN		
5	INSPECTION	IN		
6	TEST	TE	OUTSIDE COOPERATION	
7	TURN	LT		
8	TEST	TE		
9	TURN	LT		
10	GEAR-CUT	GC	30	
11	DEBARRING	DEB		
12	INSPECT	IN		
13	COPPER PAINT	CP		
14	HEAT-TREATMENT	CQT		
15	INSPECTION	IN		
16	GRIND	EG	15	
17	GEAR-GRIND	GG	45	
18	TEST	TE		
19	TEST	TE		
20	INSPECTION	IN		
21	INSPECTION	IN		
22	STORES	STO		

Figure 17. Route Sheet generated by SACAPP

4 Conclusion

This paper presented a computational technique model for CAD-CAPP integration. Supported by authorities, evidence or logic, it was shown that a limited number of important design and manufacturing features can be used to achieve an integrated product model in which geometry data and manufacturing information are stored together. As a result, it was possible to employ features inter-relationships rather than just feature-by-feature planning.

In addition, the SACAPP followed the actual trend to unify and simplify size tolerances and surface finishes because the most CAD/CAM packages couldn't "understand", interpret, analyse, or make decisions about the tolerance/surface finish information stored in them, and because tolerances on the work-piece were almost always dependent on the detailed knowledge of the machine-tool operator.

Furthermore, the approach provided not only a direct interpretation of CAD data to the CAPP system, but also supplied sufficient information for the generation of the correct process plan's operations sequence, considered to be the process planner's most critical activity because it involved knowledge about facts, procedures, and "if-then" rules.

Finally, the approach simplified engineering drawing's information complexity, and offered better computability, reusability, and improved communication between CAD and CAPP.

All these in turn are expected to create the environment that will facilitate further research in fields such as process control, semi-automated man-machine interfaces capable of better supporting the human operator, and promote technology transfer, education and training.

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