

A MULTIDISCIPLINARY AND COLLABORATIVE PROBLEM  
SOLVING ARCHITECTURE FOR HIGH-LEVEL COMPUTER  
AIDED PROCESS PLANNING IN DISCRETE  
MANUFACTURING

Ionel Botef

A thesis submitted to the Faculty of Engineering, University of the Witwatersrand,  
Johannesburg, in fulfillment of the requirements for the degree of Doctor of  
Philosophy.

Johannesburg, 2006

## DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

\_\_\_\_\_  
(Signature of candidate)

\_\_\_\_\_ day of \_\_\_\_\_ (year) 2006

## 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 thesis develops a new framework that focuses on a CAPP architecture for problem solving that manages complexity through simplicity, and applies principles and strategies used in manufacturing enterprise management, automation, robotics, and software engineering, that finally leads to a system of systems which is human-centric, architectural-centric, process-centric, and in line with the IT (Information Technology) infrastructure trends. Thereafter, the framework is used to develop a number of software applications that apply object-oriented programming as a new way of thinking about solving CAPP problems and as a promising alternative to other techniques. Then, the capabilities of the new approach are demonstrated through the use of examples. The thesis ends with conclusions about the new CAPP approach, and finally highlights its theoretical and practical implications.

To my family

Ionel Botef

## ACKNOWLEDGEMENTS

I want to thank a few special people who made this thesis possible:

Professor Barry Dwolatzky who inspired my work and shaped my thoughts regarding sound software engineering

My academic colleagues for their support

My wife Carmen and our two daughters Cristina and Irina for years of constant support, encouragement, and understanding

CONTENTS		Page
<b>1</b>	<b>INTRODUCTION</b>	17
<b>1.1</b>	<b>Background of the Research</b>	17
<b>1.2</b>	<b>Justification of the Research</b>	18
<b>1.3</b>	<b>Research Problem</b>	19
<b>1.4</b>	<b>Delimitation of Scope</b>	19
<b>1.5</b>	<b>Research Question and Hypotheses</b>	19
<b>1.6</b>	<b>Source of Data and Methodologies</b>	20
<b>1.7</b>	<b>Contributions</b>	20
<b>1.8</b>	<b>Definitions</b>	21
<b>1.9</b>	<b>Outline of the Thesis</b>	22
<b>1.10</b>	<b>Conclusions</b>	23
<b>2</b>	<b>RESEARCH ISSUES</b>	24
<b>2.1</b>	<b>Introduction</b>	24
<b>2.2</b>	<b>Process Planning and CAPP Systems</b>	25
<b>2.3</b>	<b>Engineering Drawing, CAPP System, and Manufacturing Processes</b>	27
<b>2.4</b>	<b>Manufacturing Systems (MS)</b>	31
<b>2.5</b>	<b>Information Systems</b>	34
<b>2.6</b>	<b>Computer Integrated Manufacturing (CIM)</b>	36
<b>2.7</b>	<b>Automation</b>	37
<b>2.8</b>	<b>People and Automated Systems, Complexity, and Change</b>	38
<b>2.9</b>	<b>Conclusions</b>	41
<b>3</b>	<b>METHODOLOGY</b>	43
<b>3.1</b>	<b>Introduction</b>	43
<b>3.2</b>	<b>Definitions Considered in this Thesis</b>	45

<b>3.3</b>	<b>SACAPP and Design</b>	<b>46</b>
<b>3.4</b>	<b>SACAPP and Manufacturing Systems</b>	<b>58</b>
<b>3.5</b>	<b>SACAPP and Company Information System</b>	<b>62</b>
<b>3.6</b>	<b>SACAPP and CIM</b>	<b>63</b>
<b>3.7</b>	<b>SACAPP and Automation</b>	<b>63</b>
<b>3.8</b>	<b>SACAPP and the Complexity</b>	<b>65</b>
<b>3.9</b>	<b>SACAPP and CAPP Evolution</b>	<b>66</b>
<b>3.10</b>	<b>SACAPP Architecture Baseline</b>	<b>68</b>
<b>3.11</b>	<b>Conclusions</b>	<b>70</b>
<b>4</b>	<b>ANALYSIS OF DATA</b>	<b>71</b>
<b>4.1</b>	<b>Introduction</b>	<b>71</b>
<b>4.2</b>	<b>The YTTJC System</b>	<b>72</b>
<b>4.3</b>	<b>The SAS System</b>	<b>72</b>
<b>4.4</b>	<b>The SAM System</b>	<b>74</b>
<b>4.5</b>	<b>The SADwO System</b>	<b>74</b>
<b>4.6</b>	<b>Object Design Test</b>	<b>75</b>
<b>4.7</b>	<b>The SACAPP System</b>	<b>76</b>
<b>4.8</b>	<b>System Testing</b>	<b>82</b>
<b>4.8.1</b>	<b>Simple Machined Part</b>	<b>82</b>
<b>4.8.2</b>	<b>Another Simple Machined Part</b>	<b>84</b>
<b>4.8.3</b>	<b>A Complex Part</b>	<b>86</b>
<b>4.8.4</b>	<b>Another Complex Machined Part</b>	<b>88</b>
<b>4.8.5</b>	<b>Very Complex Machined Part</b>	<b>90</b>
<b>4.9</b>	<b>Analysis of the Prototype Systems</b>	<b>93</b>
<b>4.10</b>	<b>Conclusions</b>	<b>97</b>
<b>5</b>	<b>CONCLUSIONS AND IMPLICATIONS</b>	<b>98</b>
<b>5.1</b>	<b>Introduction</b>	<b>98</b>
<b>5.2</b>	<b>A Brief Overview of Previous Chapters</b>	<b>99</b>
<b>5.3</b>	<b>Conclusions About The Hypothesis and Research Questions</b>	<b>102</b>

<b>5.3.1</b>	<b>Align both CAD and CAPP architectures</b>	<b>103</b>
<b>5.3.2</b>	<b>Decompose the CAPP complex problems into smaller more manageable sub-problems</b>	<b>103</b>
<b>5.3.3</b>	<b>Keep human in the systems loop</b>	<b>105</b>
<b>5.3.4</b>	<b>Align CAPP architecture with the architecture of the engineering company and manufacturing concepts used in practice</b>	<b>105</b>
<b>5.3.5</b>	<b>Simplify information complexity</b>	<b>106</b>
<b>5.3.6</b>	<b>Include CAD, CAPP, and other categories of data in the communication part of CIM</b>	<b>107</b>
<b>5.3.7</b>	<b>Use of automation principles and strategies</b>	<b>107</b>
<b>5.3.8</b>	<b>Cautious use of the AI</b>	<b>108</b>
<b>5.3.9</b>	<b>SACAPP, object-oriented programming, RUP, UML, and Java</b>	<b>108</b>
<b>5.4</b>	<b>Conclusions About The Research Problem</b>	<b>109</b>
<b>5.5</b>	<b>Research Implications</b>	<b>109</b>
<b>5.5.1</b>	<b>Implications for theory</b>	<b>110</b>
<b>5.5.2</b>	<b>Implications for practice</b>	<b>111</b>
<b>5.6</b>	<b>Research Limitations</b>	<b>111</b>
<b>5.7</b>	<b>Further Research</b>	<b>112</b>
<b>REFERENCES</b>		<b>114</b>
<b>APPENDIX A</b>	<b>GLOSSARY</b>	<b>143</b>
<b>APPENDIX B</b>	<b>CAPP EVOLUTION, DIVERSIFICATION, AND CLASSIFICATION</b>	<b>145</b>
<b>APPENDIX C</b>	<b>CAPP IMPLEMENTATION TECHNIQUES</b>	<b>150</b>
<b>APPENDIX D</b>	<b>CAPP SYSTEMS EXAMPLES</b>	<b>155</b>
<b>APPENDIX E</b>	<b>PART REPRESENTATION</b>	<b>174</b>
<b>APPENDIX F</b>	<b>SACAPP ROADMAP</b>	<b>179</b>
<b>APPENDIX G</b>	<b>SACAPP PROJECT VISION</b>	<b>188</b>
<b>APPENDIX H</b>	<b>BUSINESS MODELING</b>	<b>201</b>



<b>APPENDIX I</b>	<b>SACAPP ROADMAP CONTINUED</b>	231
<b>APPENDIX J</b>	<b>THE PROTOTYPE SYSTEMS APPROACH</b>	238
<b>APPENDIX K</b>	<b>SAS CLASSES AND UML DIAGRAMS</b>	240
<b>APPENDIX L</b>	<b>SADwO UML DIAGRAMS</b>	249
<b>APPENDIX M</b>	<b>INTRODUCTION TO THE UML</b>	253

## LIST OF FIGURES

<b>Figure</b>		<b>Page</b>
1.1	The thesis contributions to knowledge	21
1.2	Thesis organization on chapters	23
2.1	Main research problem and directly related disciplines	24
2.2	CAPP domains and techniques evolution and diversification	26
2.3	Tolerance and surface finish relationship	30
2.4	Hierarchical structure of the FrMS	32
2.5	Manufacturing concepts	32
2.6	IT infrastructure trends	35
2.7	Computerised tool classification	35
2.8	Major paradigms in manufacturing	39
2.9	Main research problem, relationships, and directions for action	42
3.1	Chapter's map	43
3.2	High-level conceptual maps	47
3.3	Four simple and similar drawings and process plan examples	47
3.4	Typical gear-shaft for an aerospace engine	48
3.5	The final item (red lines) and the process planning operations	49
3.6	UML, design, RUP, manufacturing relationships	51
3.7	UML Class diagram example (first iteration)	51
3.8	UML Class diagram example (second iteration)	52
3.9	The UML sequence diagram	52
3.10	The UML collaboration diagram	53
3.11	List of the centres of gravities	54
3.12	SADwO/SACAPP feature example 1	57
3.13	SADwO/SACAPP feature example 2	58
3.14	CAPP and manufacturing systems	58
3.15	Manufacturing enterprise relationships	59
3.16	Manufacturing enterprise, people skills and level of automation	59

<b>3.17</b>	Closed loop principle applied at machine-tool level	60
<b>3.18</b>	SACAPP and manufacturing concepts	61
<b>3.19</b>	Categories of business rules	62
<b>3.20</b>	Process planning and the CNC operation	64
<b>3.21</b>	Automation principles and strategies	64
<b>3.22</b>	Web and the extended enterprise	65
<b>3.23</b>	SACAPP environment	67
<b>3.24</b>	SACAPP new dimensional analysis	67
<b>3.25</b>	Steps in deciding the preliminary baseline architecture	68
<b>3.26</b>	A layered and collaborative system of systems	69
<b>3.27</b>	UML SACAPP class diagram interface	69
<b>3.28</b>	SACAPP Deployment diagram	70
<b>4.1</b>	The Chapter's map	71
<b>4.2</b>	The YTTJC system interface	72
<b>4.3</b>	IWO during its development using JBuilder	73
<b>4.4</b>	SAS and IWO view	73
<b>4.5</b>	The SAM system frames	74
<b>4.6</b>	SADwO with a number of opened frames	75
<b>4.7</b>	Object design test 1	75
<b>4.8</b>	Object design test 2	76
<b>4.9</b>	Object design test 3	76
<b>4.10</b>	SACAPP interface	77
<b>4.11</b>	SACAPP – sales input window	77
<b>4.12</b>	SACAPP – engineering drawing input window	78
<b>4.13</b>	SACAPP manufacturing operation description setting	78
<b>4.14</b>	SACAPP constraints setting for the carburising process	79
<b>4.15</b>	SACAPP output window Process Plan Sheet	79
<b>4.16</b>	SACAPP output window Route Sheet	80
<b>4.17</b>	SACAPP Centre of Gravity for the heat-treatment	81
<b>4.18</b>	SACAPP Centre of Gravity for the End of the process plan	82
<b>4.19</b>	Simple item created with the SADwO system	82
<b>4.20</b>	IWO created with the SAS system	83

<b>4.21</b>	Another simple item created with the SADwO system	84
<b>4.22</b>	Complex item created with the SADwO system	86
<b>4.23</b>	Another complex item created with the SADwO system	88
<b>4.24</b>	A very complex item	90
<b>5.1</b>	Chapter's map	98
<b>5.2</b>	Decompose the CAPP complex problems into smaller more manageable sub-problems	104
<b>5.3</b>	Developed systems and how the human was kept in the loop	105
<b>5.4</b>	Simplify information complexity	106
<b>5.5</b>	Thesis contributions to knowledge	110
<b>5.6</b>	Future research	113

## LIST OF TABLES

<b>Table</b>		<b>Page</b>
<b>3.1</b>	Hypothesis and research question analysis	44
<b>3.2</b>	Relationships - design/process planning rules and instructions	48
<b>3.3</b>	Process-surface roughness link	49
<b>3.4</b>	Groups of operations and their centres of gravity classification	54
<b>3.5</b>	Feature analysis (Iteration 1)	55
<b>3.6</b>	Feature analysis (Iteration 2)	56
<b>3.7</b>	SADwO objects' list (Iteration3, Final)	57
<b>4.1</b>	Hypothesis and research questions	94
<b>4.2</b>	Hypothesis, research problem, and systems analysis	95

## LIST OF SYMBOLS

	conditional OR
	unconditional OR
/	division
==	equal to
!	not
!=	not equal to
&	unconditional AND
&&	conditional AND
^	exclusive OR
\n	linefeed
\r	tab

## NOMENCLATURE

AI	Artificial Intelligence
AM	Agile Manufacturing
AMT	Advanced Manufacturing Technology
BFU	Basic Fractal Unit
BOM	Bill of Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CAR	Corrective Action Request
CASE	Computer Aided Software Engineering
CBR	Case-Based Reasoning
CIM	Computer Integrated Manufacturing
CE	Concurrent Engineering
CNC	Computer Numerical Control
CSG	Constructive Solid Geometry
DIC	Drawing Issue Controls
ERP	Enterprise Resource Planning
FMS	Flexible Manufacturing System
FrMS	Fractal Manufacturing System
GRN	Good Received Note
GA	Genetic Algorithms
GT	Group Technology
GUI	Graphical User Interface
IMS	Intelligent Manufacturing Systems
IWO	Internal Works Order
JIT	Just In Time
KBS	Knowledge-Based Systems
LM	Lean Manufacturing

M	Machining
MS	Manufacturing Systems
NC	Numerical Control
NNs	Neural Networks
QA	Quality Assurance
RR	Rectification and Replacement Request
RUP	Rational Unified Process
SABS	South African Buro of Standards
SADwO	South African Design with Objects
SACAPP	South African CAPP
SAE	South African Estimation
SAEM	South African Engineering Management
SAM	South African Management
SAS	South African Sales
SASM	South African Sales and Marketing
SMEs	Small and Medium Enterprises
STEP	STandard for the Exchange of Product model data
TQM	Total Quality Management
TPM	Total Productive Maintenance
UML	Unified Modeling Language
UoD	Universe of Discourse
VM	Virtual Manufacturing
YTTJC	It indicates the name for a hypothetical industrial company (see page 188 – Project Vision) for which the system "YTTJC" was developed.