

SYMBOLIC COMPUTATION

Computer-Aided Design and Manufacturing

Methods and Tools

Second, Revised and Enlarged Edition

Edited by
U Rembold and R Dillmann

With 304 Figures



Springer-Verlag

World Publishing Corporation

Computer-Aided Design and Manufacturing

Methods and Tools

Second, Revised and Enlarged Edition

Edited by
U. Rembold and R. Dillmann

With 304 Figures



Springer-Verlag

World Publishing Corporation

Prof. Dr.-Ing. Ulrich Rembold
Dr.-Ing. Rüdiger Dillmann
Universität Karlsruhe
Institut für Informatik III
Postfach 69 80
D-7500 Karlsruhe 1

This book is a completely revised version of the Lecture Notes
in Computer Science, Vol. 168 "Methods and Tools for Computer
Integrated Manufacturing", Springer-Verlag Berlin Heidelberg
New York Tokyo 1984

Reprinted by World Publishing Corporation, Beijing, 1988
for distribution and sale in The People's Republic of China only

ISBN 3-540-16321-2

Springer-Verlag Berlin Heidelberg New York

ISBN 0-387-16321-2

Springer-Verlag New York Berlin Heidelberg

ISBN 7- 5062-0270-0

Library of Congress Cataloging-in-Publication Data.

Computer-aided design and manufacturing.

(Symbolic computation. Computer graphics)

Completely rev. version of Methods and tools for computer integrated manufacturing.

Bibliography: p.

1. CAD/CAM systems - Congresses. I. Rembold, Ulrich. II. Dillmann, R., 1949-.

III. Advanced CREST Course on Computer Integrated Manufacturing (1983 : Karlsruhe, Germany). Methods and tools for computer integrated manufacturing. IV. Series.

TS155.6.C644 1986 670.427 86-19943 ISBN 0-387-16321-2 (U.S.)

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically those of translation, reprinting, re-use of illustrations, broadcasting, reproduction by photocopying machine or similar means, and storage in data banks. Under §54 of the German Copyright Law where copies are made for other than private use, a fee is payable to „Verwertungsgesellschaft Wort“, Munich.

© Springer-Verlag Berlin Heidelberg 1986
Printed in Germany

The use of registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting, printing and binding: Konrad Tritsch, Graphischer Betrieb, 8700 Würzburg
2145/3140-543210

SYMBOLIC COMPUTATION

Computer Graphics

Managing Editor: J. Encarnação

Editors: K. Bø J. D. Foley R. A. Guedj

P. J. W. ten Hagen F. R. ã. Hopgood M. Hosaka

M. Lucas A. G. Requicha

Springer Series

SYMBOLIC COMPUTATION – *Computer Graphics*

J. Encarnação, E. G. Schlechtendahl:
Computer Aided Design. Fundamentals and System
Architectures. IX, 346 pages, 183 figs., 1983

G. Enderle, K. Kansy, G. Pfaff:
Computer Graphics Programming. GKS – The Graphics
Standard. XVI, 542 pages, 93 figs., 1984

J. Encarnação, R. Schuster, E. Vöge (eds.):
Product Data Interfaces in CAD/CAM Applications.
Design, Implementation and Experiences. XIV, 254 pages,
147 figs., 1986

U. Rembold, R. Dillmann (eds.): Computer-Aided Design
and Manufacturing. Methods and Tools. 2nd, revised and
enlarged edition. XIV, 458 pages, 304 figs., 1986

Introduction

Manufacturing contributes to over 60% of the gross national product of the highly industrialized nations of Europe. The advances in mechanization and automation in manufacturing of international competitors are seriously challenging the market position of the European countries in different areas. Thus it becomes necessary to increase significantly the productivity of European industry. This has prompted many governments to support the development of new automation resources. Good engineers are also needed to develop the required automation tools and to apply these to manufacturing. It is the purpose of this book to discuss new research results in manufacturing with engineers who face the challenge of building tomorrow's factories.

Early automation efforts were centered around mechanical gear-and-cam technology and hardwired electrical control circuits. Because of the decreasing life cycle of most new products and the enormous model diversification, factories cannot be automated efficiently any more by these conventional technologies. With the digital computer, its fast calculation speed and large memory capacity, a new tool was created which can substantially improve the productivity of manufacturing processes. The computer can directly control production and quality assurance functions and adapt itself quickly to changing customer orders and new products. It allows the automation of long and short range forecasting, product design, process planning, production scheduling and manufacturing control. The flow of information through a plant can be monitored and corrective action can easily be initiated if necessary. Probably the most important asset of the computer is its capacity to integrate the entire manufacturing system from product design to fabrication. Its ability to make decisions will contribute to the conception and design of flexible manufacturing systems. With the progress of artificial intelligence activities and with powerful low cost computing equipment, it will be possible to conceive expert systems for manufacturing. Upon entry of a product order they will be able to plan and supervise automatically the production process. This will be realized with the help of decision rules and a knowledge data base about the production process and the available manufacturing resources.

The object of this book is to discuss advanced and future CAD/CAM technologies. Of course, the vast scope of manufacturing cannot be satisfactorily presented in one volume. Thus only those topics which are of common interest to many manufacturing organisations and which appear to be very important in the future are selected. In addition, an attempt is made to present to the reader the computer activities in manufacturing as an entity. For this reason the contents of the book can be used for courses covering this subject.

The following topics are presented:

- Computer Control for Manufacturing Equipment
- Design of Production Control and Flexible Manufacturing Systems
- CAD Systems and their Interface with CAM
- Technological Planning for Manufacture
- Economic Analysis of Manufacturing Systems
- Quality Assurance and Robot Vision
- The Interface of Process Planning with Production and Facility Planning
- Product Design for Assembly
- Production Control and Information Systems
- Programming of Machine Tools and Industrial Robots

This book is based on the lecture notes of the Advanced Course on Computer Integrated Manufacturing (CIM '83), held at the University of Karlsruhe, September 5-16, 1983, Karlsruhe, Federal Republic of Germany. The course was financed by the Ministry of Research and Technology (BMFT) of the Federal Republic of Germany and by the Commission of the European Communities. The course was a continuation of a course on "Computer Aided Design, Modeling, Systems Engineering, CAD-Systems" held at the Technical University of Darmstadt, September 8-19, 1980. The lecture notes were published in 1980 by Springer-Verlag under the same title, and edited by J. Encarnação.

The principal contributors to this book are:

- R. Dillmann, University of Karlsruhe, Karlsruhe, Germany
- G. Doumeingts, University of Bordeaux, Bordeaux, France
- W. Eppe, University of Karlsruhe, Karlsruhe, Germany
- M. Gini, Politecnico of Milan, Italy
- H. Grabowski, University of Karlsruhe, Karlsruhe, Germany
- F.-L. Krause, IPK-Berlin, Berlin, Germany
- F. Leimkuhler, Purdue University, West Lafayette, Indiana, USA
- P. Levi, University of Karlsruhe, Karlsruhe, Germany
- C. R. Liu, Purdue University, West Lafayette, Indiana, USA
- A. Redford, University of Salford, Salford, Great Britain
- U. Rembold, University of Karlsruhe, Karlsruhe, Germany
- A.-W. Scheer, University of Saarland, Saarbrücken, Germany
- G. Spur, IPK and Technical University of Berlin, Berlin, Germany

All these authors deserve words of sincere thanks for their excellent manuscripts. Mrs. D. Jung and Miss B. Seufert were responsible for typing the final manuscript, and Mr. S. Müller helped with the editing. The authors would like to express their gratitude to all the people who helped to contribute to the success of this book.

Karlsruhe, October 1986

*Ulrich Rembold
Rüdiger Dillmann*

Contents

Introduction	V
1 CAD Systems and Their Interface with CAM	
H. Grabowski and R. Anderl	1
1.1 Introduction	3
1.2 Philosophy of the Application of CAD Systems	3
1.3 Software Structure of CAD Systems	7
1.4 Computer Internal Model	10
1.4.1 Different Geometric Models for CAD	11
1.4.2 Importance of Technology-Oriented Model for CAD/CAM	13
1.5 Interfaces of CAD Systems	15
1.5.1 Database Manipulation Language (DML)	16
1.5.2 Initial Graphics Exchange Specification (IGES)	18
1.5.3 Graphical Kernel System (GKS)	20
1.6 Integration of the Manufacture Planning Process	22
1.6.1 Planning Process Based on CAD Models	24
1.6.2 NC-Machine Tool Programming Based on CAD Models	25
1.7 Economic Aspects	27
1.8 Conclusion	30
1.9 References	30
1.10 Additional Literature	31
2 Design for Assembly	
A. H. Redford	33
2.1 Introduction	35
2.2 Design for Assembly Philosophy	36
2.3 Determination of the Most Appropriate Process	37
2.4 Re-design for Manual Assembly	39
2.4.1 Classification and Coding for Handling and Insertion	39
2.4.2 Sequence of Design Analysis	42
2.4.3 Determination of the Sequence of Assembly	42
2.4.4 Compilation of the Worksheet	42
2.4.5 Determination of Assembly Efficiency	42
2.4.6 Elimination of Potentially Redundant Parts	43
2.4.7 Re-design of High-Cost Handling or Insertion Parts	45

2.5	Re-design for Automatic Assembly	47
2.5.1	Classification and Coding for Automatic Handling	47
2.5.2	Classification and Coding for Automatic Insertion	50
2.6	Robots in Manufacturing	57
2.7	Characteristics of Assembly Robots	57
2.8	Requirements for Robotic Assembly	58
2.8.1	Faster Robots	58
2.8.2	Limited Capability, Cheap Robots	59
2.8.3	Versatile, Inexpensive Grippers	59
2.8.4	Identification of Assembly Families	60
2.8.5	Improved Assembly Efficiency	61
2.8.6	Low Cost Feeding	61
2.9	Classification and Coding for Automatic Parts Handling for Flexible Assembly	62
2.10	Classification and Coding for Automatic Insertion for Flexible Assembly	62
2.11	Conclusions	63
3	Technological Planning for Manufacture – Methodology of Process Planning	
	G. Spur and F.-L. Krause	65
3.1	Methodology of Process Planning	67
3.1.1	Introduction	67
3.1.2	Tasks of Process Planning	67
3.1.3	Generation of the Process Plan	69
3.1.4	Principles of Process Planning	69
3.2	Development of APT and EXAPT	70
3.2.1	APT System	70
3.2.2	EXAPT System	72
3.2.2.1	Programming of N/C Turning Operations	72
3.2.2.2	Programming of Drilling and Milling Operations	73
3.2.2.3	Programming of Punching, Nibbling and Flame-Cutting Operations	74
3.2.2.4	Programming of Wire-Eroding Operations	74
3.2.2.5	Files for Working Data	75
3.3	Techniques of Computer Aided Process Planning	76
3.3.1	Dialog Aided Planning	76
3.3.2	Algorithms	78
3.3.3	Decision Tables	79
3.3.4	Data Files	80
3.4	Graphical Simulation of Manufacturing Processes in Process Planning	82
3.5	Systems for Computer Aided Process Planning Including Quality Control	85
3.5.1	AUTAP System	85

3.5.2	ARPL System	87
3.5.3	CAPEX System	88
3.5.4	CAPP System	89
3.5.5	DISAP System	90
3.5.6	DREKAL System	91
3.5.7	PREPLA System	92
3.5.8	CAPSY System (Inspection Planning)	93
3.6	The CAPSY Process Planning System	94
3.7	Planning of Assembly Sequences	97
3.8	N/C Technology	101
3.9	N/C Programming on the Shop Floor Using Graphical Simulation Techniques	104
3.10	Programming of Robots Using Graphical Techniques	106
3.11	Integrated Aspects of Technological Planning	110
3.12	References	114
4	Evolutionary Trends in Generative Process Planning	
	R. Srihivasan and C. R. Liu	117
4.1	Introduction	119
4.2	The Principal CAPP Methodologies	120
4.3	Generative Process Planning	120
4.3.1	Extended Part Programming Systems	121
4.3.2	GPP Using Decision Tables and Tree Structures	122
4.3.3	Iterative Algorithms	122
4.3.3.1	Recursive Process Planning	124
4.3.4	The Concept of Unit-Machined Surfaces	124
4.3.4.1	COFORM	124
4.3.4.2	APPAS	126
4.3.4.3	AUTAP and AUTAP-NC	127
4.3.4.4	More Sophisticated GPP Systems	128
4.4	Adequacy of the Existing GPP's in the Wake of New Developments	131
4.4.1	Recent Trends in the Design of CMS Control Systems	131
4.5	Dynamic GPP Using Pattern Recognition Techniques: A New Concept	133
4.5.1	Proposed Representation Schemes	134
4.5.1.1	Object Representation	134
4.5.1.2	Machine Tool Representation	134
4.5.2	Process Planning Steps (Briefly)	134
4.5.2.1	Flexible Planning Logic	134
4.5.2.2	Identification of Surface Precedences	134
4.5.2.3	Selection of Machines, Tool Bits and Clamping Positions	135
4.6	References	135

5	Design Methodology of Computer Integrated Manufacturing and Control of Manufacturing Units	137
	G. Doumeings, M. C. Maisonneuve, V. Brand and C. Berard	137
5.1	Introduction	139
5.2	The Need for a Methodology and a Conceptual Model of a CIM System	139
5.2.1	The Use of a Design Methodology	139
5.2.2	The Complexity of Computer Integrated Manufacturing	140
5.3	Conceptual Model of a CIM System	145
5.3.1	The Notion of the System	145
5.3.2	Conceptual Models	146
5.3.3	ICAM Model and Architecture	146
5.3.4	GRAI Conceptual Model	147
5.4	Methods of Designing Production Control Systems	151
5.4.1	The Structured System Analysis and Design Method (SSAD)	151
5.4.2	ICAM Definition Language (IDEF)	152
5.4.3	GRAI Method of Process Analysis	154
5.5	Design of Flexible Manufacturing Systems Using Modelling Techniques and Simulation	158
5.5.1	What is a Flexible Manufacturing System?	158
5.5.2	Design of Flexible Manufacturing Systems	159
5.5.3	GRAI Methodology	160
5.6	The Control of the Manufacturing Unit	170
5.6.1	Scheduling	170
5.6.2	Classification of Scheduling Problems	170
5.6.3	Scheduling Method	171
5.7	GRAI's Approach to Manufacturing Control	175
5.7.1	Introduction	175
5.7.2	GRAI's Approach to Modelling	176
6	Computing Aids to Plan and Control Manufacturing	183
	R. Dillmann	183
6.1	Hierarchical Computer Control Equipment for Manufacturing Systems	185
6.1.1	Introduction	185
6.1.2	Definition of Hierarchical Control Systems	185
6.1.3	Control Tasks at Each Level in the Hierarchy	188
6.1.4	The Communication Network	192
6.1.5	Influence of VLSI Technology on Hierarchical Control Systems	196
6.1.5.1	Minicomputers for Higher Control Levels	197
6.1.5.2	Microcomputers for Operational Control Levels	198
6.1.5.3	VLSI Interface Modules	200
6.1.5.4	Memory	201
6.1.5.5	VLSI Data Peripherals	202

6.1.5.6	Data Peripherals	205
6.1.6	Software and System Development Aids	206
6.2	Hierarchical Control Architecture for Manufacturing Cells	207
6.2.1	Introduction	207
6.2.2	Robot Architecture	208
6.2.3	Internal Robot Data Representation	211
6.2.4	Task Decomposition and Execution	215
6.2.5	Data Flow and Computational Concept	216
6.2.6	Conclusion	218
6.3	Graphical Simulation Techniques for Planning and Programming of Robot Based Manufacturing Cells	218
6.3.1	Introduction	218
6.3.2	System Structure for Interactive Planning with a Graphic Simulator	221
6.3.3	Conclusion	225
6.4	Advanced Computer Architectures (5th Generation)	225
6.4.1	Introduction	225
6.4.2	Components of 5th Generation Computers	226
6.4.3	Applications of 5th Generation Computers	227
6.4.4	The Basic Software System and Programming Languages	228
6.4.5	Computer Architecture of the 5th Generation Computer Systems	229
6.4.6	Conclusion	231
6.5	References	231
7	Programming of Robot Systems	
	G. Gini, M. Gini, M. Cividini and G. Villa	233
7.1	Robot Languages in the Eighties	235
7.1.1	Introduction	235
7.1.2	Robot Programming	236
7.1.3	Languages and Software Environments	238
7.1.4	Functional Language and Logic Programming	240
7.1.5	European Robot Languages	241
7.1.6	Conclusions	244
7.2	Programming Languages for Manipulation and Vision in Industrial Robots	244
7.2.1	Introduction	245
7.2.2	How to Classify Robot Programming Languages	247
7.2.3	Joint-Level Languages: The Example of MAL	249
7.2.4	Manipulator-Level Languages: Mathematical Foundations	253
7.2.5	Object Representation in Robot Programming Languages	255
7.2.6	At the Object Level: AL and Vision	258
7.2.7	Object and Task Levels: Problems	261
7.2.8	Conclusions	262
7.3	Programming a Vision System	262
7.3.1	Introduction	262

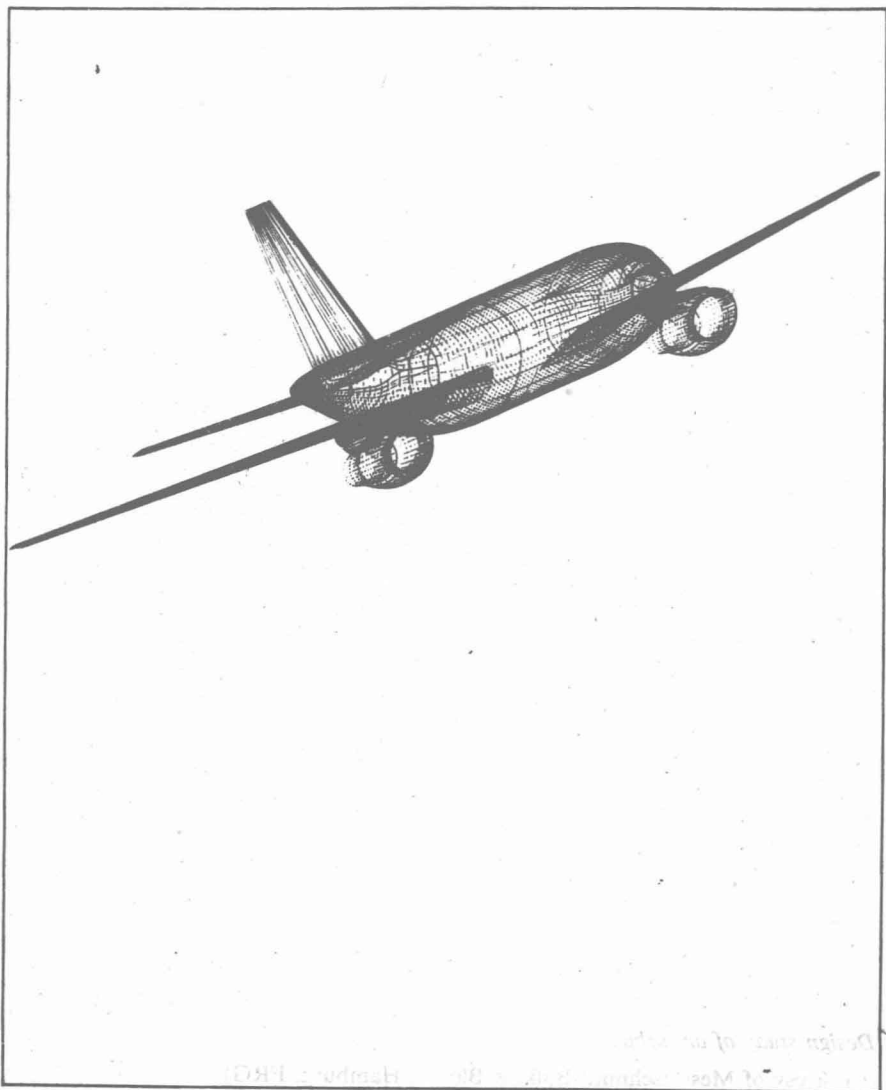
7.3.2	A Vision System for Industrial Applications	263
7.3.3	Logical Organization of GYPSY	264
7.3.4	LIVIA: The User Programming Language	265
7.3.5	Examples of LIVIA Programs	268
7.3.6	Additional Position-Independent Features for Blobs and Models	270
7.4	Towards Automatic Error Recovery in Robot Programs	271
7.4.1	Introduction	271
7.4.2	A Method for Automatic Error Recovery	272
7.4.2.1	Dynamic Model	272
7.4.2.2	Semantics	273
7.4.2.3	Knowledge Base	274
7.4.2.4	Recovery Procedure	275
7.4.3	Concluding Remarks	275
7.5	References	276
8	Present State and Future Trends in the Development of Programming Languages for Manufacturing	
	U. Rembold and W. Eppl	279
8.1	Introduction	282
8.2	Programming of Machine Tools	283
8.2.1	The APT Language	283
8.2.2	The EXAPT Programming System	284
8.2.3	Interactive Symbolic Programming	288
8.2.4	Special Purpose Languages	290
8.2.5	Generative Programming by the Machine Tool Control	292
8.3	Programming Languages for Robots	293
8.3.1	General Requirements for Programming Languages for Robots	293
8.3.2	Programming Methods for Robots	295
8.3.2.1	Manual Programming	295
8.3.2.2	Programming with the Help of the Robot's Brake System	295
8.3.2.3	Sequential Optical or Tactile Programming	295
8.3.2.4	Master-Slave Programming	296
8.3.2.5	Teach-In-Method	296
8.3.2.6	Textual Programming	296
8.3.2.7	Acoustic Programming	296
8.3.2.8	Design Considerations for a High Order Language	296
8.3.3	A Survey of Existing Programming Languages	298
8.3.4	Concepts for New Programming Languages	299
8.3.5	Programming with a Natural Language	304
8.3.6	Implicit Programming Languages	304
8.3.7	Programming Aids	304
8.4	Process Control	309
8.4.1	Extensions of Existing Programming Languages	309
8.4.2	PEARL - A Process and Experiment Automatic Realtime Language	310

8.4.3	ADA	311
8.4.4	Tools for the Development of Process Control Systems	313
8.5	Commercial Data Processing	317
8.6	Future Trends	318
8.7	References	321
9	Quality Assurance and Machine Vision for Inspection	
	P. Levi	323
9.1	Introduction	325
9.2	Quality Assurance: Functions, Problems and Realizations	326
9.2.1	Quality Assurance Functions	326
9.2.2	Design of a Computer Integrated QA System	329
9.2.3	Hierarchical Computer Systems for Quality Assurance	333
9.2.4	Architecture of a Data Acquisition System	334
9.2.5	Quality Assurance Methods	340
9.2.6	Measuring Methods for Quality Assurance	341
9.2.6.1	Contact Measurement	341
9.2.6.2	Non-Contact Measurements	346
9.2.6.3	Manual Input	347
9.2.7	Computer Languages for Test Applications	348
9.2.8	Implementation of a QA Computer System	349
9.3	Machine Vision: Inspection Techniques, Mensuration and Robotics	351
9.3.1	Visual Inspection Tasks	351
9.3.2	Machine Vision Techniques for Inspection	353
9.3.2.1	Template Matching	353
9.3.2.2	Decision-Theoretic Approach	353
9.3.2.3	Syntactical Approach	354
9.3.3	Automated Microscopic Material Testing	355
9.3.4	Laser Based Measurements and Inspection	356
9.3.4.1	Quantitative Mensuration	356
9.3.4.2	Semi-Quantitative Mensuration (Scanner)	359
9.3.5	Synthetic Images for Defect Classification	362
9.3.6	Robot Vision for Recognition and Sorting	364
9.3.6.1	Interfacing of a Vision System with an Assembly Robot	364
9.3.6.2	Sorting of Castings	369
9.4	References	372
10	Production Control and Information Systems	
	A.-W. Scheer	375
10.1	Strategies for the Selection of Software Packages in Production	377
10.2	Data Management Requirements for Production Control	381
10.2.1	Development of a Data Base Scheme for Primary Data	381
10.2.1.1	Bill of Materials	381

10.2.1.2	Work Descriptions	383
10.2.1.3	Manufacturing Equipment	383
10.2.2	Special Cases of Variant Production	384
10.2.3	Data Management with Software Packages	385
10.2.3.1	Conventional File Management	385
10.2.3.2	Specialized Data Base Systems	385
10.2.3.3	General Data Base Systems	385
10.2.3.4	System-Independent Data Bases	388
10.2.4	Future Developments in Data Management	388
10.3	Planning Strategies for the Implementation of Production Control Systems	389
10.3.1	Planning Stages	389
10.3.1.1	Master Production Scheduling	389
10.3.1.2	Material Requirement Planning	390
10.3.1.3	Capacity Planning	391
10.3.1.4	Job Shop Control	393
10.3.1.5	Data Collection	393
10.3.2	Implementation Strategies	393
10.4	The Interface Between CAD and Production Control	396
10.5	The Interface Between Production Control and Marketing	396
10.5.1	Master Production Scheduling	397
10.5.2	Order Handling	399
10.6	Factors Influencing the Acceptance of Production Control Software	399
11	Economic Analysis of Computer Integrated Manufacturing Systems	
	F. Leimkuhler	401
11.1	Introduction	403
11.2	Process Planning	404
11.3	Capacity Analysis Using CAN-Q	406
11.4	Capital and Labour Requirements	408
11.5	Payback, Capital Cost, and Taxes	410
11.6	Cost Comparisons	413
11.7	System Efficiency	416
11.8	Justification and Automation Equipment	418
11.9	Summary	423
11.10	References	426
11.11	Appendix	427
	Subject Index	445
	Contributors	455

1 CAD-Systems and Their Interface with CAM

H. Grabowski and R. Anderl



Design study of an airbus

(Courtesy of Messerschmidt-Bölkow-Blohm, Hamburg, FRG)