

Information Management in Production Systems

CAPP**Computer-Aided Process Planning****József Váncza**

MTA SZTAKI

BME GIT

vancza@sztaki.hu

Information Management CAPP 2005

József Váncza

1

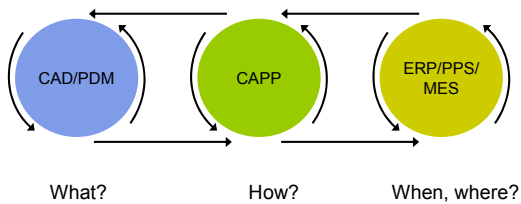
Overview

- **The role of CAPP in Production Informatics**
- **Process Planning (without computers)**
 - Problem statement
 - Example domains
 - Machining of prismatic parts
 - Sheet metal bending
 - Key concepts: features and setups
- **Computer-aided methods**
 - Approaches
 - Variant method
 - Generative CAPP
 - Representation issues
 - CAPP as the weakest link in manufacturing automation
- **A generic CAPP model**
 - Constraint-based planning
 - CAD-CAPP integration
- **Summary**

Information Management CAPP 2005

József Váncza

2

The role of CAPP in Production Informatics

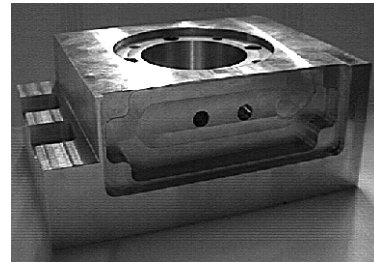
Information Management CAPP 2005

József Váncza

3

Question

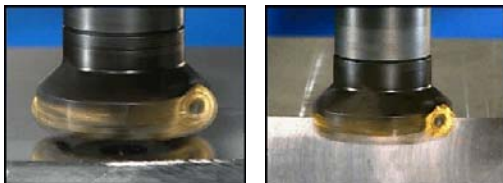
- **How to produce this part?**



Information Management CAPP 2005

József Váncza

4

Answer: by machining operations ...

Information Management CAPP 2005

József Váncza

5

... with specific tools,...

Information Management CAPP 2005

József Váncza

6

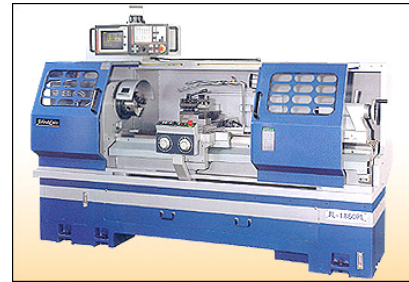
... on (some) machine(s), ...



Information Management CAPP 2005

József Váncza

7

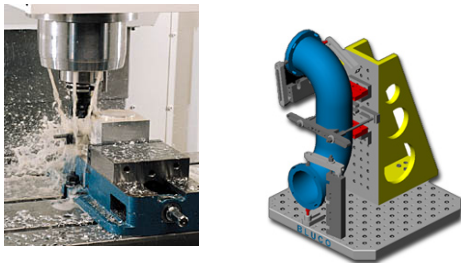


Information Management CAPP 2005

József Váncza

8

... in appropriate fixture(s)



Information Management CAPP 2005

József Váncza

9

Result of process planning: routing

OPERATION SHEET

Part No. CLP034/6-4-9203 Material steel 1040
 Part Name Widset
 Orig. H. Kok Changes
 Checked W.H.E. Manghy Approved D. Corin

No.	Operation	Machine	Setup	Time (hrs.)
0010	Saw off and slug 1.75 dia. hole	Dept 12. Saw 9		3
0015	R Turn 6.00 dia. stock to 5.210/5.190 R Bore 1.75 dia to 2.00 F Bore 2.00 to 2.005/2.015	GE. Turn Lathe	Hold in counter centrifugal Chuck	1.2
0025	Deburr all edges			5 mins.

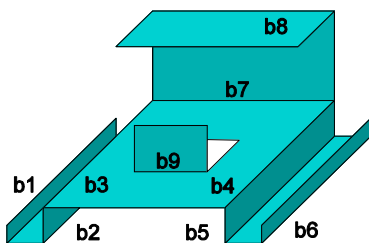
Information Management CAPP 2005

József Váncza

10

Question (2)

- How to fold this part?

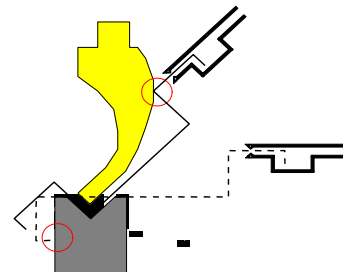


Information Management CAPP 2005

József Váncza

11

Answer: by bending operations ...



Information Management CAPP 2005

József Váncza

12

... with appropriate tools, grippers and machine

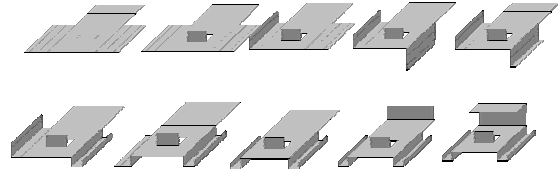


Information Management CAPP 2005

József Váncza

13

Result: bending sequence ...

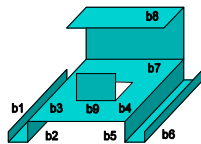
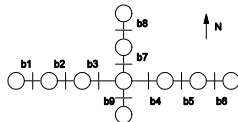


Information Management CAPP 2005

József Váncza

14

... with tool and gripping specifications



op	tprof	tlen	ori
b9	leftgn	10	N
b2	leftgn	50	E
b4	leftgn	50	E
b6	leftgn	50	E
b5	leftgn	50	E
b3	leftgn	50	E
b1	leftgn	50	E
b8	leftgn	50	S
b7	leftgn	50	S

Information Management CAPP 2005

József Váncza

15

Process Planning

• What is planning in general?

- Given
 - Initial state and a goal state of the world,
 - Set of actions that can change the state of the world
 - Preconditions and effects
 - Optimization criteria
- Find
 - The best sequence of actions that transform the world from the initial state to the goal state.

• Worlds (domains) of Process Planning

- Manufacturing
 - Machining of rotational and prismatic parts
 - Sheet metal bending
- Assembly/Disassembly
- Inspection planning

Information Management CAPP 2005

József Váncza

16

Process Planning: problem statement

• Given:

- Specification of the blank and the finished part
 - Geometry -- dimensions and tolerances
 - Materials
 - Surface finishes
- Description of available resources
 - Machines
 - Fixtures
 - Tools
- Relevant technological knowledge
- Criteria for best solutions

• Find:

- Executable,
- If possible, (close-to) optimal plans

Information Management CAPP 2005

József Váncza

17

Phases of Process Planning

• Part and process analysis

- Technological interpretation of design specifications
- Determination of the entities to be produced – so-called *features*
- Production alternatives

→ feature-based part model

• High-level (macro) planning

- Selection resources
- Specifying the actual operators
- Determining the sequence of operations
- Determining *setups*

→ routing

• Low-level (micro) planning

- Determining the paths for moving the tools
- Parameter for operations (cutting speed, etc.)

→ NC program

Information Management CAPP 2005

József Váncza

18

Example: bending (2)

• Problem

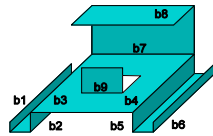
- Avoid collisions
- Conflicting criteria
- Local bends → global changes

• Typical pieces of advice

- *Make outside bends first to avoid "rolling up" the part.*
- *Produce channels (b1-b2-b3) from inside toward outside.*
- *Postpone tall flanges as far as possible.*
- *Make bends determining the shape of the part as late as possible.*
- *Make strictly toleranced bends without changing resources.*
- *After making b3 and b4, b7 can be made with exact length tool only.*

• Properties

- Conditional rules
- Contradictions between rules



Information Management CAPP 2005

József Váncza

25

Manufacturing features

• "Micro" worlds of planning

- Atomic tasks and solution patterns
- Mediating between design and production
- Mapping of local geometry, tolerances to manufacturing processes
- Engineering interpretation of design drawings

• Design vs. manufacturing features

• Ambiguity

- "One man's hole is another's bore."

• Feature relations

- Workpiece as a set of interrelated features
- Multiple interpretations

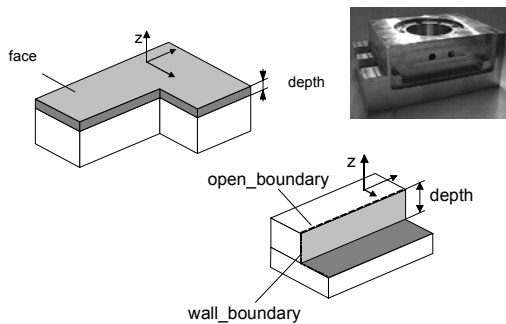
• Feature interactions

Information Management CAPP 2005

József Váncza

26

Features in machining: face and step

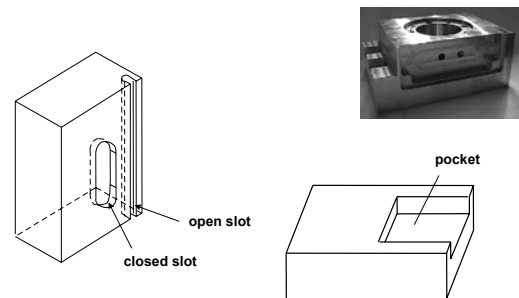


Information Management CAPP 2005

József Váncza

27

Pocket and slot

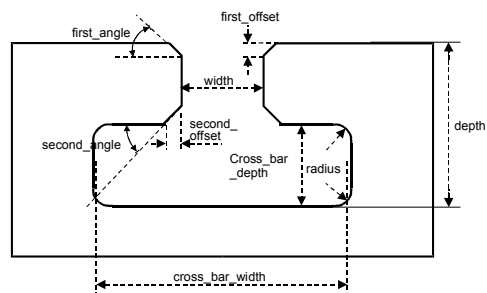


Information Management CAPP 2005

József Váncza

28

T-slot

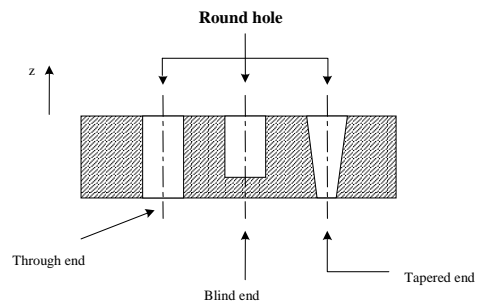


Information Management CAPP 2005

József Váncza

29

Holes

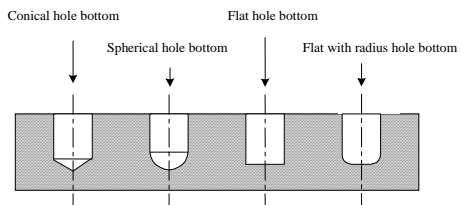


Information Management CAPP 2005

József Váncza

30

Holes: bottom conditions

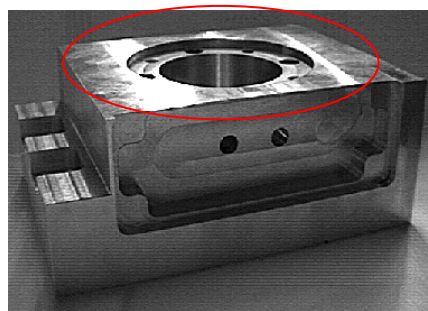


Information Management CAPP 2005

József Váncza

31

Compound features

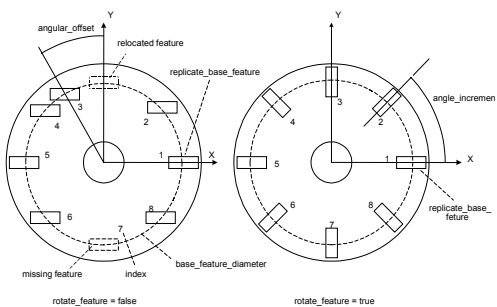


Information Management CAPP 2005

József Váncza

32

Feature patterns

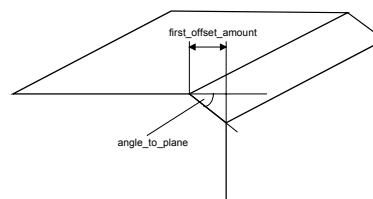


Information Management CAPP 2005

József Váncza

33

Subfeatures: e.g. chamfer



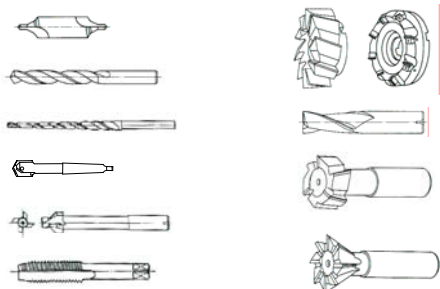
Information Management CAPP 2005

József Váncza

34

Tools

• Features – processes -- tools



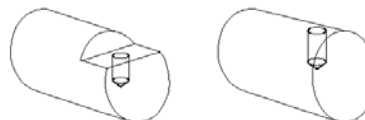
Information Management CAPP 2005

József Váncza

35

Interaction of features

- Crossing holes
- Strict tolerances
- Holes on non-orthogonal surfaces



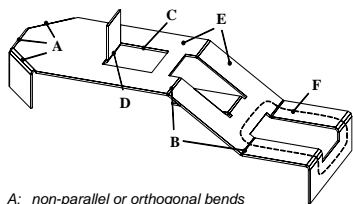
- Much more ...

Information Management CAPP 2005

József Váncza

36

Features in bending



A: non-parallel or orthogonal bends
 B: non 90°-bends
 C: internal contour
 D: internal bend
 E: double connected flanges
 F: closed loops of flanges

Information Management CAPP 2005

József Váncza

37

Setups

- **Set of operations executed without changing a basic resource**

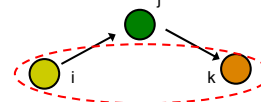
- Machining – same fixturing and part orientation
- Bending – same tool

- **Rationale**

- Tolerance requirements
- Cost

- **Setup planning**

- Grouping operations
- Strong interaction with resource selection and operation sequencing

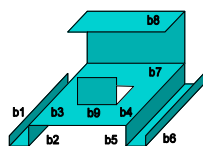
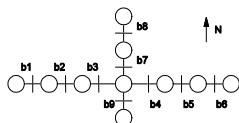


Information Management CAPP 2005

József Váncza

38

Setup example: bending



op	tprof	tlen	ori
b9	leftgn	10	N
b2	leftgn	50	E
b4	leftgn	50	E
b6	leftgn	50	E
b5	leftgn	50	E
b3	leftgn	50	E
b1	leftgn	50	E
b8	leftgn	50	S
b7	leftgn	50	S

Information Management CAPP 2005

József Váncza

39

Computer-Aided Process Planning

- **Aim: supporting engineering problem solving**

- Efficient use of deficient knowledge
- Finding a match between
 - available domain knowledge, its
 - appropriate representation, and
 - efficient utilization

- **Representation issues**

- **Solution: reasoning and search**

- Even in face of *inconsistency*, *incompleteness* and
- In the presence of *complexity*

- **Optimization**

- Finding the best solutions

- **Integrating different sources of knowledge**

- Interactive modeling and solution generation

Information Management CAPP 2005

József Váncza

40

Variant approach to CAPP

- **Similarity-based problem solving**

- **From the pre-computer era**

- **Method**

- Previously prepared process plans are stored in a database
 - Group technology
 - Complex parts
 - Complicated coding and classification system
 - Indexing
- Retrieve and adapt – manually

- **Problems**

- Considers only workpiece similarity
- Optimization cannot be performed
- Conservative

Information Management CAPP 2005

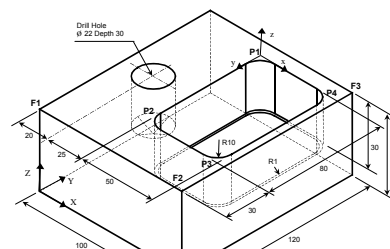
József Váncza

41

Generative CAPP

- **How to represent what we know?**

- **How to exploit the represented knowledge efficiently?**



Information Management CAPP 2005

József Váncza

42

Representation issues

- **Part model**
 - General attributes + features + feature relations
- **Features**
 - Geometric attributes + technological parameters
 - Primary/sub; compound; pattern
 - Sequence of feature states (raw, fine, superfine, ...)
- **Resources**
 - Machines
 - Setups
 - Tools
- **Machining operations**
 - Produce feature states
 - With resources specified
- **Process plans**
 - Sequence/network of operations

Information Management CAPP 2005

József Váncza

43

Representing engineering knowledge

- **Interpretation of the design**
 - Part analysis
 - Feature recognition
- **Use of resources**
 - Mapping feature states and operations
 - Determining admissible resource combinations
- **Elaboration of alternatives**
- **Partial ordering of operations**
 - Generating precedence relations between operations
 - Prohibiting change of resource

Information Management CAPP 2005

József Váncza

44

Representation techniques (AI)

- **Conceptual hierarchies**
 - Class structure
 - Classes and instances
 - Inheritance
 - So-called frame systems
 - Appropriate for describing objects
 - Features, tools, setups, machines
- **Rule-based representation methods**
 - Condition-action pairs
 - Condition patterns
 - Several applications of the same rule
 - Intuitive for engineers
 - For capturing (fragments) of
- **Both methods rooted in logic**

Information Management CAPP 2005

József Váncza

45

Representation of features (ISO)

```

ENTITY workplace;
  its_id:          identifier;
  its_material:    OPTIONAL material;
  global_tolerance: OPTIONAL shape_tolerance;
  its_rawpiece:    OPTIONAL workplace;
  its_geometry:    OPTIONAL advanced_brep_shape_representation;
  its_bounding_geometry: OPTIONAL bounding_geometry_select;
  clamping_positions: SET [0:?] OF cartesian_point;
END_ENTITY;

ENTITY machining_feature
  ABSTRACT SUPERTYPE OF (ONEOF(planar_face, pocket, slot, step,
    round_hole, generic_feature, general_outside_profile, compound_feature))
  SUBTYPE OF (two5D_manufacturing_feature);
  depth:          toleranced_length_measure;
  planar_radius:   OPTIONAL toleranced_length_measure;
  orthogonal_radius: OPTIONAL toleranced_length_measure;
  surface_roughness_bottom: OPTIONAL property_parameter;
  surface_roughness_sides:  OPTIONAL property_parameter;
END_ENTITY;

```

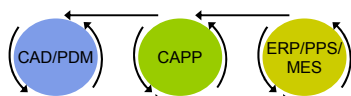
Information Management CAPP 2005

József Váncza

46

Why is CAPP so hard?

- **Contradictions**
 - Conflicts of local pieces of advice in the global context of a particular planning problem
 - Logic cannot help
- **Complexity**
 - Of large constrained optimization problems
 - Search cannot help
- **Failure of pure logical approaches**
- **Features divide but not conquer the problem**
- **CAPP as the weakest link in automation**



Information Management CAPP 2005

József Váncza

47

A generic CAPP model

- **Main requirements**
 - For all kinds of relevant domain knowledge
 - Applicable on several fields
 - With engineer-friendly representation
 - Coming from either human or machine source
- **Efficient plan generation and optimization**
 - Consolidation of conflicting pieces of knowledge
 - Multi-criteria optimization
 - Handling incomplete models → CAD integration
- **Decision support**
 - Interaction
 - Mixed-initiative problem solving
 - Supporting both variant and generative strategies

Information Management CAPP 2005

József Váncza

48

Constraint programming

- **Variables**
 $X = \{x_1, \dots, x_n\}$
- **Finite domains**
 - For all x_i the set of possible values D_i
- **Constraints**
 - Logical relations on variables that restrict the possible values.
 - Properties
 - Express partial information
 - Not directed
 - Declarative
 - Additive
 - Common variables \rightarrow bind together constraints
- **Solution**
 - A value for all x_i such that all the constraints are satisfied
 - Several solutions \rightarrow optimization

Information Management CAPP 2005

József Váncza

49

Constraint-based CAPP model

- **Variables, domains and constraints**
- **Operations**
 - $op_i, i \in 1, \dots, N$
 - Position of operations $pos[op_i] : [1, \dots, N]$
 - Each executed only once **all** $pos[op_i]$ **different**
- **Resources**
 - Alternatives for each operation
 - Part orientation $orient[op_i] : ORIENT_i \subseteq O$
 - Tool $tool[op_i] : T_i \subseteq T$
 - Tool length $tlen[op_i] : TLEN_i \subseteq TL$
 - Tool profile $tprof[op_i] : TPROF_i \subseteq TP$
 - Allowed combinations
- **Process plan**
 - Completely specified sequence of operations
 - Each operation with specific position and resources

Information Management CAPP 2005

József Váncza

50

Constraint-based model (2)

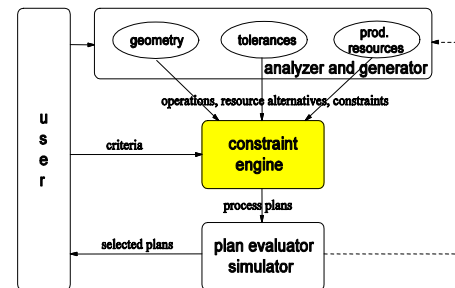
- **Constraints**
 - Express properties of executable plans
 - Represent *results* of engineering reasoning
 - Natural to understand, generate and modify
- **Model is generated from part and tool geometry**
 - By hand (machining)
 - Automatically (bending)
- **Optimization criteria**
 - Minimal changeover of resources
 - Setups in machining
 - Tool in bending

Information Management CAPP 2005

József Váncza

51

Constraint-based CAPP



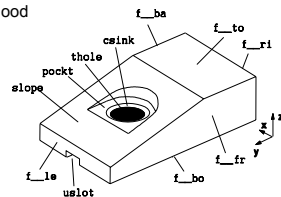
Information Management CAPP 2005

József Váncza

52

Constraint types

- **Ordering**
 - operation precedence
 - Centering a hole must be done before drilling it.
 - Make large faces first.
 - If through-hole is made from the bottom face, make it before u-slot.
- operation neighborhood



Information Management CAPP 2005

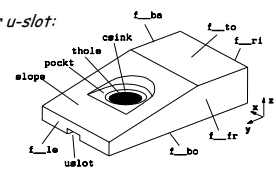
József Váncza

53

Constraint types (2)

- **Resource assignment**
 - In this orientation the top face can be made by a face-milling tool.
 - Resource combinations for u-slot:

Operation	Tool	Holding
u-slot	e_mill	+x-y-z
	s_mill	-y-x-z
		-x-y-z
		+y-x-z
		-z-y-x
		+y-z-x
		-z-y-x
		-y-z+x



- **Resource sharing (setup formation)**

- Common resource
- Common resource sequence
 - Make final states of strictly tolerances features in one setup.

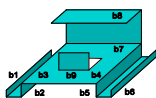
Information Management CAPP 2005

József Váncza

54

Constraint types (3)

- **Ordering**
 - operation precedence
 - Make small tabs first.
 - Make outside bends before inside bends.
 - Make internal tabs first.
 - Produce channels from inside toward outside.
- **Resource assignment**
 - After bending 6 and 7, bends 2 and 3 need exact size tool.
- **Resource sharing (setup formation)**
 - Common resource sequence
 - If possible, perform two collinear bends in one operation.
 - Make parallel bends without changing the tool.
 - Try to execute parallel bends of the same lengths immediately after each other, using the same resources.



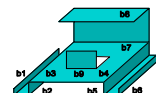
Information Management CAPP 2005

József Váncza

55

Hard and soft constraints

- **Hard constraints**
 - Always to be observed
- **Soft constraints**
 - Weight for each constraint
 - Total weight e_G and limit l_G limit for each G constraint type
 - $e_G \geq l_G$
 - Express properties of good plans
- **Conditional constraints**
 - Hard only
 - Bound to logical condition



If b3 and b4 is made before b7, b7 needs exact length tool.

```
(pos[b3] < pos[b7]) & (pos[b4] < pos[b7])
=> (tlen[b7] = t150);
```

Information Management CAPP 2005

József Váncza

56

Solution: reasoning + search



- **Reasoning: constraint propagation**
 - Reducing the domains of variables
 - Proving infeasibility (empty domain)
 - Incomplete
- **Search**
 - When reasoning does not help more
 - Making a try with adding a new constraints C or its negation $\neg C$

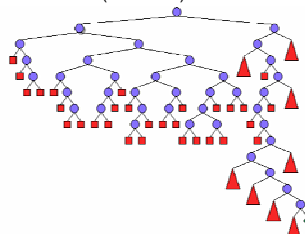
Information Management CAPP 2005

József Váncza

57

Solution: example

- **Tree search**
- **At the nodes**
 - First propagate (do reasoning)
 - Then cut or decide (do search)



Information Management CAPP 2005

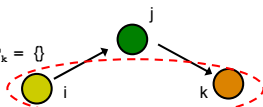
József Váncza

58

Solution of the CAPP model

- **Key issues**
 - Complexity
 - Sequencing and resource assignment decisions are *not* separated
 - Even relaxed problem is NP-complete
 - Inconsistencies: handling soft constraints
 - Interaction of sequencing and
 - Resource assignment decisions
- **Example**

```
pos[i] < pos[j] < pos[k]
commonOriSeq[i, k]
ORIENTi ∩ ORIENTj ∩ ORIENTk = {}
→ no solution exists
```



Information Management CAPP 2005

József Váncza

59

Solution of the CAPP model (2)

- **Requirements towards the solver**
 - Satisfy soft constraints above a threshold
 - Or: maximize accepted domain knowledge
 - Find the best solution
 - Work with short response time
- **Looking for the Pareto set of solutions**
 - P is a subset of all solutions S
 - All solutions in $S \setminus \{P\}$ are dominated by P
 - No solution in P is dominated by another solution in P
- **Several solution strategies**
 - First consolidate soft constraints, then optimize plan
 - Efficient, but not complete
 - Extensions of *branch-and-bound*
 - Recent solutions bound search
 - Complete but expensive
 - Soft constraints make it much better (*best practice*)

Information Management CAPP 2005

József Váncza

60

Geometry

- **At the bottom of plan correctness**
- **Constraints**
 - Capture only the results of geometric considerations
- **Issues**
 - Automatic generation of constraint-based models
 - Checking of (partial) solutions
 - Augmenting incomplete models during problem solving
- **Answers**
 - Narrowed scope -- bending (2,5D)
 - Geometric modell, preprocessor and evaluator
 - Solver working on "open" model

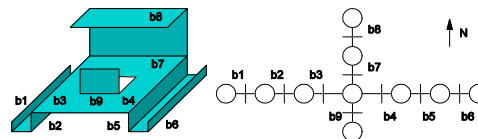
Information Management CAPP 2005

József Váncza

61

Geometric model in bending

- **Part geometry**
 - Connectivity graph with pane and bend nodes
 - Rectangular solids on panes



- **Tool geometry**
 - Tool length
 - Front and back profile of punch
- **Holding: part orientation**
- **Machine: forbidden areas**

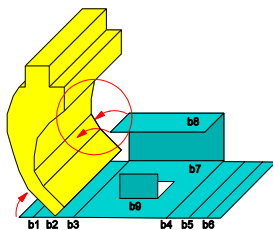
Information Management CAPP 2005

József Váncza

62

Collision test and constraint feedback

- **Collision test by simulating the bending process**
 - Each time one more operation has been specified
 - Sweep volume collision test
- **Reasons of failure**



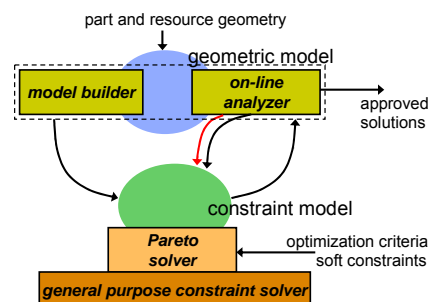
$$\begin{aligned}
 &(\text{pos}[b7] < \text{pos}[b2]) \ \& \\
 &(\text{pos}[b8] < \text{pos}[b2]) \ \& \\
 &(\text{pos}[b2] < \text{pos}[b3]) \\
 \Rightarrow & \\
 &(\text{tprof}[b2] \neq \text{leftgn})
 \end{aligned}$$

Information Management CAPP 2005

József Váncza

63

System structure



Information Management CAPP 2005

József Váncza

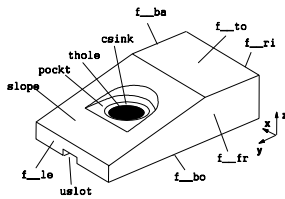
64

Implementation experiments (1)

- **General purpose CAPP system**
 - Domain language and compiler
 - Hard and soft constraint solver
- **Experiments**
 - Prismatic parts

Problem
 operations 13
 setups 20
 tools 7
 hard const. 126
 soft const. 10

Model and solver
 variables 10^5
 propagators 10^6
 size of the tree 10^4
 all soft constraints satisfied
 3 solutions in 80 sec



Information Management CAPP 2005

József Váncza

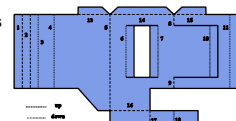
65

Implementation experiments (2)

- **CAPP system with design feedback**
 - Dedicated model builder and analyzer in 2.5D
 - Interactive Pareto solver
 - on top of ILOG Solver

Experiments

- Bending problems up to 18 bends
 - Response time: ~ 0.1 – 10 min
 - Best practice is useful to solve complex problems
- Incomplete models
 - Different sets of initial hard constraints
 - No soft constraints
 - Let the geometric analyzer to detect necessary constraints
 - Learning from failure

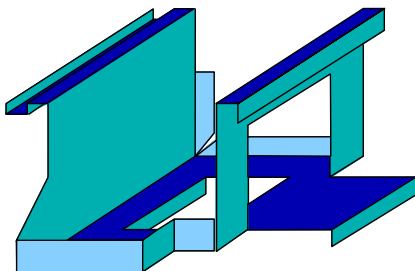


Information Management CAPP 2005

József Váncza

66

Solution of the bending example (1)



Information Management CAPP 2005

József Váncza

67

Solution of the bending example (2)

Experiments with incomplete models

	Full	Slightly incom.	Highly incom.	Empty
Constraints				
Evident	28	28	28	28
Further initial	23	17	10	0
Feedback recognized	2	9	19	27
Solutions				
Found totally	7	14	24	32
Correct	5	5	5	5
Pareto optimal	2	2	2	2
Solution time (s)	16	46	337	1030

op	tprof	tlen	ori
b9	leftgn	10	N
b2	leftgn	50	E
b4	leftgn	50	E
b6	leftgn	50	E
b5	leftgn	50	E
b3	leftgn	50	E
b1	leftgn	50	E
b8	leftgn	50	S
b7	leftgn	50	S

Information Management CAPP 2005

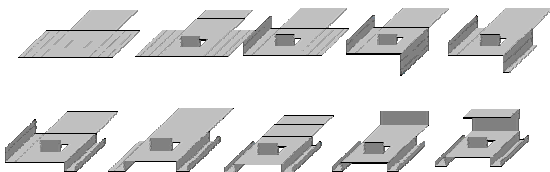
József Váncza

68

Solution of the bending example (2)

One Pareto-optimal plan

- 1 tool change
- 2 holding changes

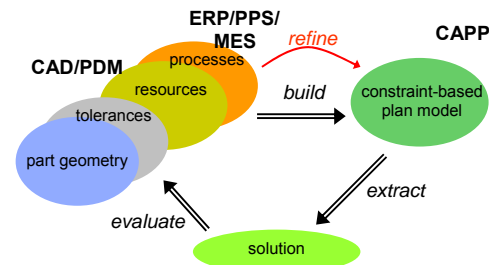


Information Management CAPP 2005

József Váncza

69

Role of CAPP revisited



Information Management CAPP 2005

József Váncza

70

Conclusions

- Constraint programming provides an efficient framework for CAPP**
 - Declarative domain description language
 - Model and algorithm separation
 - Open to mixed-initiative problem solving
- No crisp borderline between hard and soft domain knowledge**
- Complementary CAPP and CAD models**
 - Relieve modeling efforts in CAPP
 - Interaction via constraint feedback
- Current issues**
 - How to make the solution process more efficient?
 - How to generalize?

Information Management CAPP 2005

József Váncza

71