Prof. Alexandre Dolgui

Deputy Director for Research of the Henri Fayol Institute
and UMR CNRS 6158, LIMOS

École des Mines de Saint-Étienne
(Saint-Étienne School of Mines)
France

dolgui@emse.fr

www.emse.fr/~dolgui

Ecole Nationale Supérieure des Mines SAINT-ETIENNE

I invite you to submit your best results to IJPR which celebrates this year its 50th volume anniversary

Ecole Nationale
Supérieure des Mines
SAINT-ETIENNE

Saint-Etienne School of Mines (EMSE)

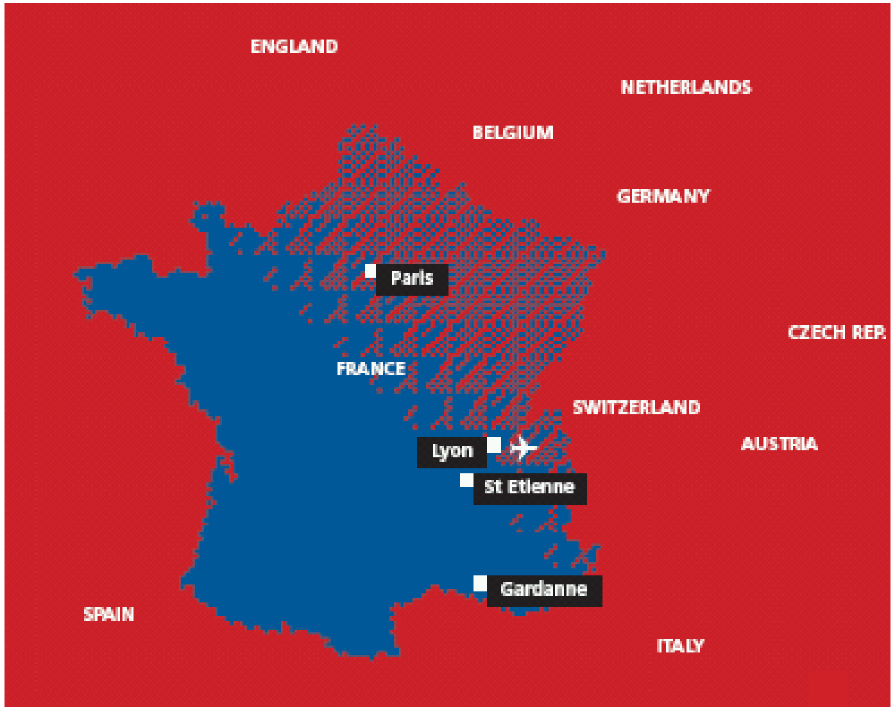
- Created by Royal decree on the 2nd of August 1816

- One of the oldest Schools of the group “Grandes Ecoles” (a sort of Ivy League), with Ecole Polytechnique, Ecole Centrale de Paris, etc.

Our School is often classed among the Top 10 Graduate Engineering Schools in France

The EMSE produces outstanding industrial managers

St-Etienne: pop. 400 000
56 km from Lyon



Saint-Etienne School of Mines (EMSE)

is structured around five divisions:

- **Henri Fayol Institute**
- Materials Science Centre
- Chemical Engineering Centre
- Microelectronics Centre
- Engineering and Health Centre

Just a couple who have made history from our School:

Benoît Fourneyron (1802-1867) - inventor of the hydraulic turbine
Henri Fayol (1841-1925) - known for his theory of management

The laying of the first French rail route (Saint-Etienne to Andrézieux) which opened in **1825** is also credited to the School

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Henri Fayol Institute

The Institute was named after one of the fathers of modern management, **Henri Fayol** who graduated from our School in **1860**

Our institute deals with industrial management, systems engineering and information technology

Composed of four departments:

- **Decision in the Enterprise: Modeling and Optimization**
- Industrial and Environmental Management
- Distributed and Cooperative Multi-agent Systems
- Behavior Management and Social Sciences

Henri Fayol Institute

Key figures:

40 Faculty members, 43 Ph.D. candidates and 7 full time employees

50 articles in refereed scientific journals
95 conference presentations

800 000 euros of industrial contracts
15 000 teaching hours

constitute the "steady state" annual performance of the Institute

Optimization in Design of Automated Machining Systems

Prof. Alexandre Dolgui

Ecole Nationale Supérieure des Mines de Saint-Etienne, France

www.emse.fr/~dolgui

dolgui@emse.fr

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Outline

- Major challenges of machining line design
- Types of automated machining lines
- Lean manufacturing approach
- Architecture of decision-aid software
- Illustrations of applications
- Optimization models
- Conclusions

Machining system design

Typical industrial partner

PCI (Process, Conception, Ingénierie):
Leading French Company for Design and Manufacturing of Industrial Equipments, www.pci.fr

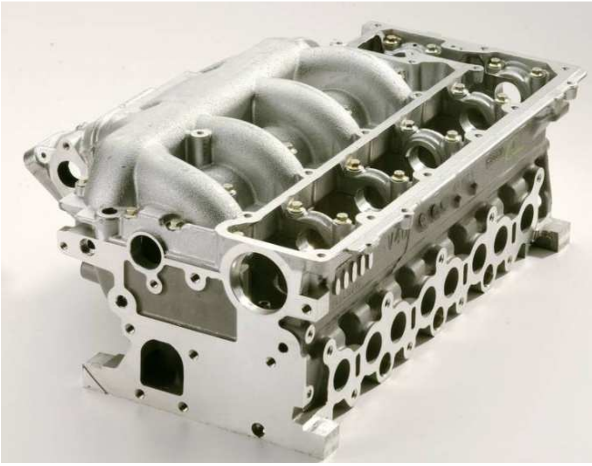
PCI-SCEMM in Saint-Etienne

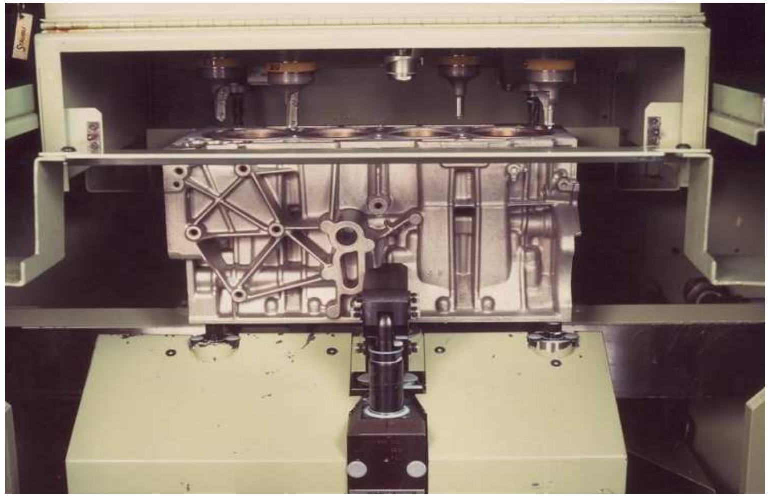
Designing, executing and commissioning machines and machining lines ensuring mass production of cast iron or aluminum parts. These applications relate to engine casings, gearbox casings, cylinder heads, knuckles, etc...

PCI
PROCESS CONCEPTION INGÉNIERIE

Examples of sophisticated parts for which these lines are designed

PCI
PROCESS CONCEPTION INGÉNIERIE





PCI-SCEMM business activity

New product

Product specifications
Production volume

Set of tasks, constraints...

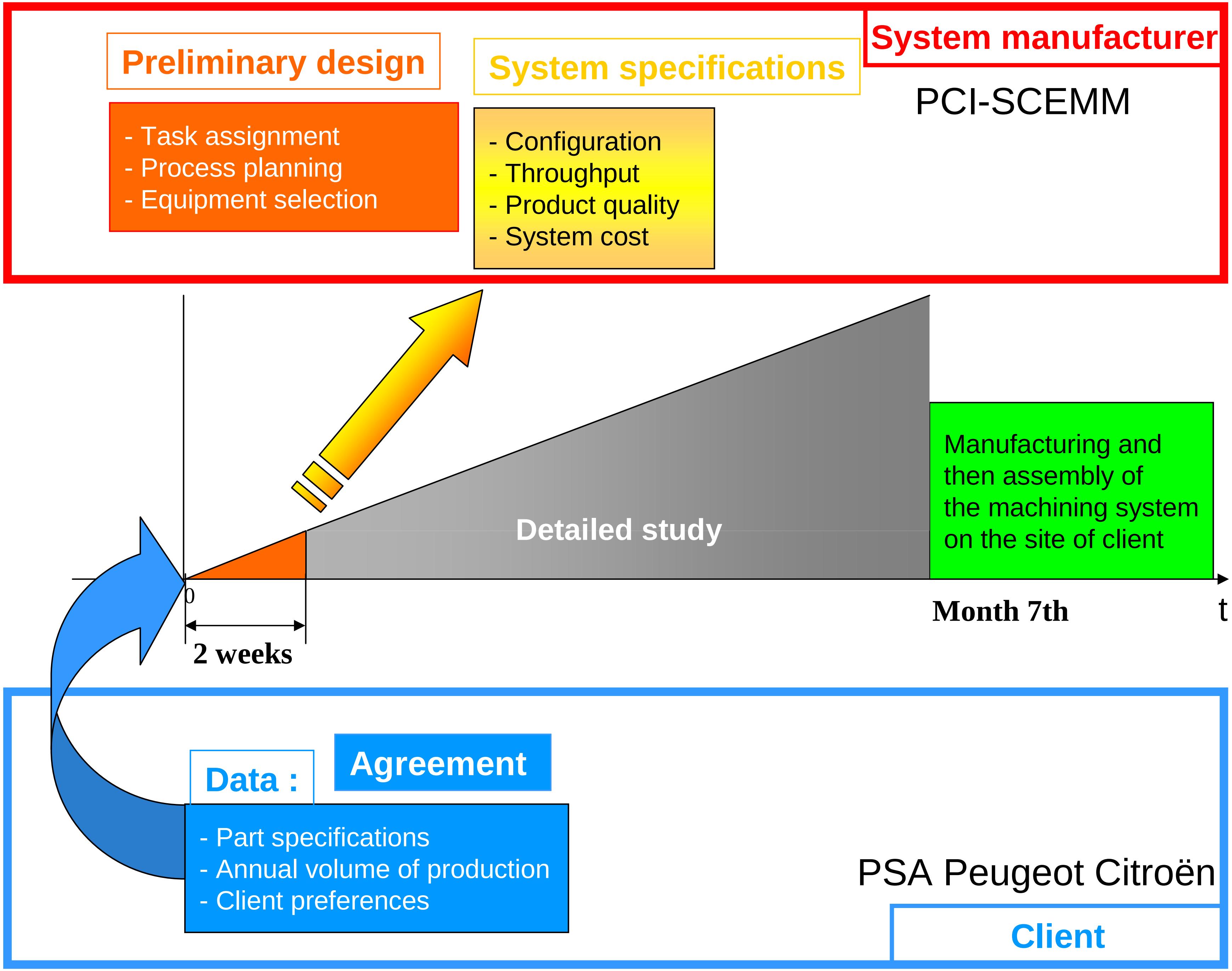
Task (operation) assignement and equipment selection

New machining system

Workstations with spindle heads, system configuration

Client

PCI-SCEMM


System manufacturer
PCI-SCEMM
Preliminary design
- Task assignment
- Process planning
- Equipment selection
System specifications
- Configuration
- Throughput
- Product quality
- System cost
Detailed study
Manufacturing and then assembly of the machining system on the site of client
0
2 weeks
Month 7th
t
Data :
- Part specifications
- Annual volume of production
- Client preferences
Agreement
PSA Peugeot Citroën
Client

Automated machining systems produced by PCI-SCEMM (especially for the automotive industry) are:

- complex

- costly (from 500 thousand to 5-10 million euros)

- excessive time for accurate system design, but limited time for contract negotiation (max 2 weeks)

This market is exceedingly competitive

Thus development of decision-aid tools to optimize machining systems and speed up the design is critical

Preliminary design

- **Number of possible solutions is enormous**
- **Each potential interesting solution should be studied in detail**
- **The time of preliminary design is limited (to 2 weeks maximum)**
- **Modifications of part specifications are frequent during the preliminary design**
- **The offer to client must verify all the constraints and be profitable for both manufacturers and clients**
- **Major challenge: *propose design solutions quicker, of better quality, and at lower cost than the competition***

⇓

Development of a decision-aid system is crucial

Part analysis

↓

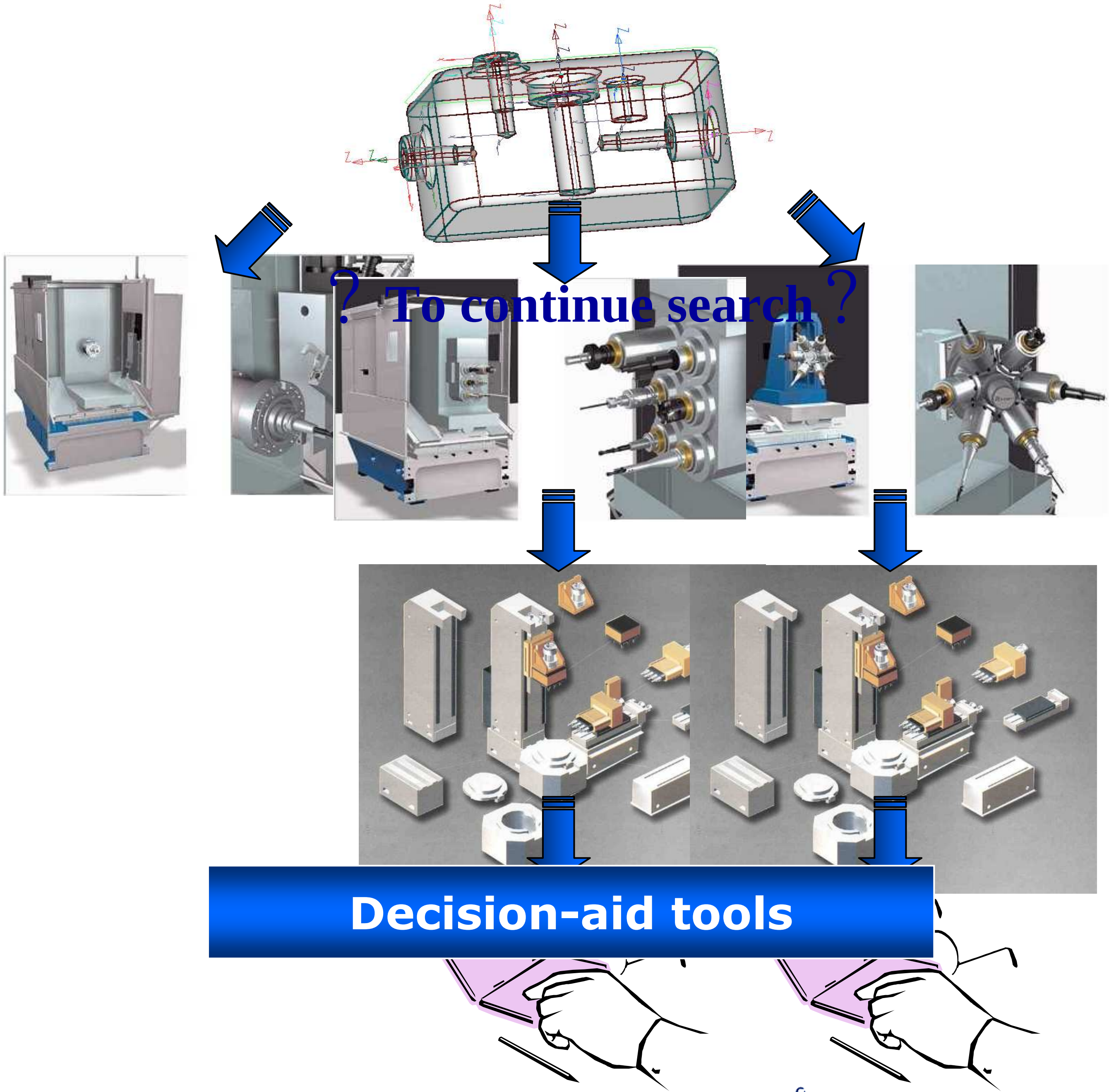
Choice of the type of machining system

↓

Task assignment, equipment design

↓

System's cost estimation



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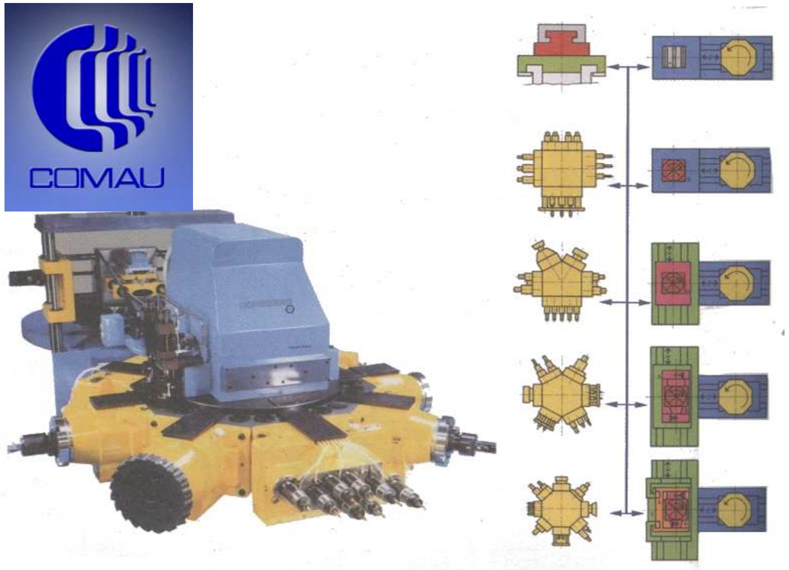
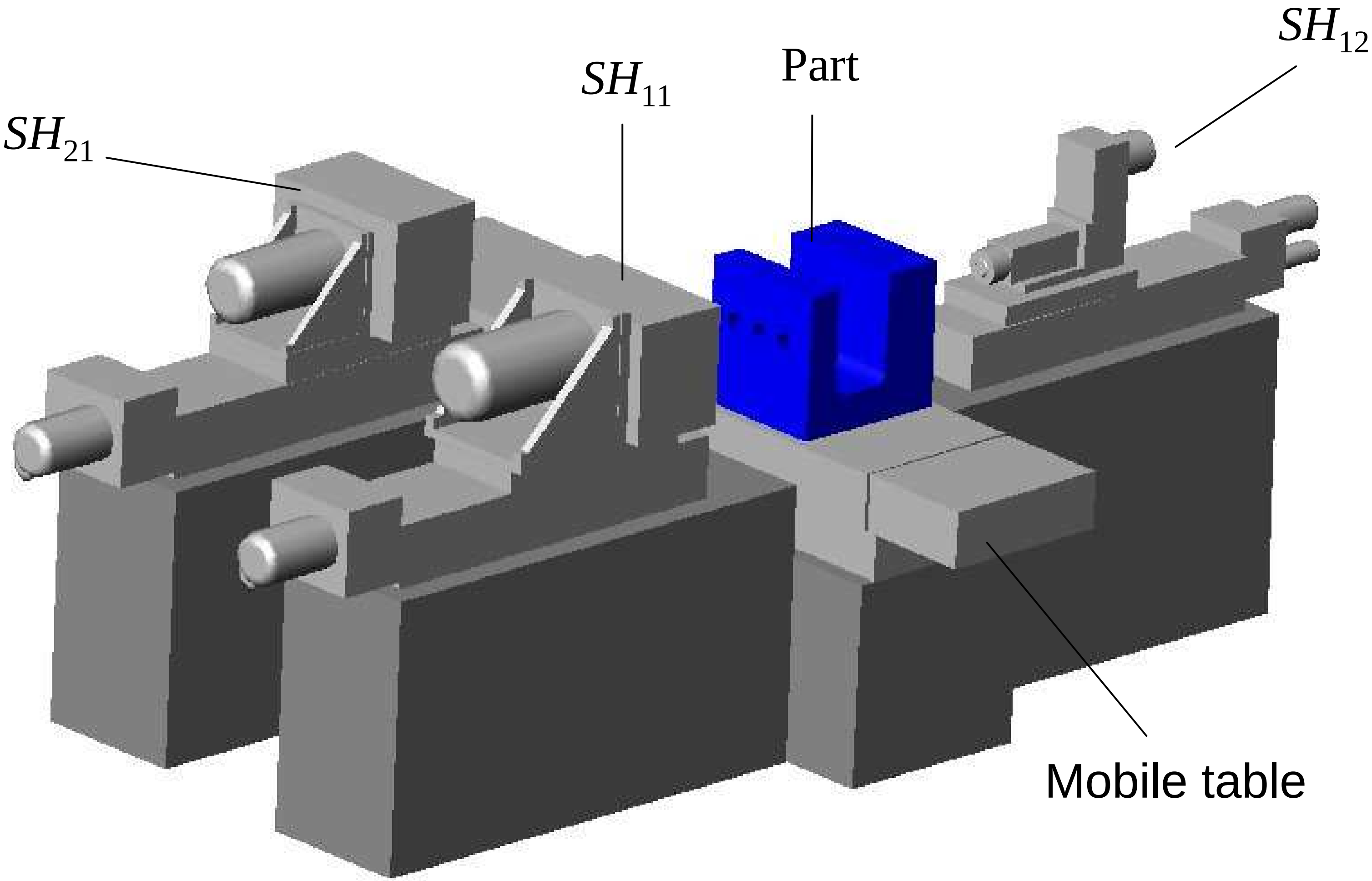
Some machining system manufacturers



LiCON MT
lindenmaier machine tools

Types of machining systems

Machine with a mobile table



All spindle heads at the same station
are activated in parallel

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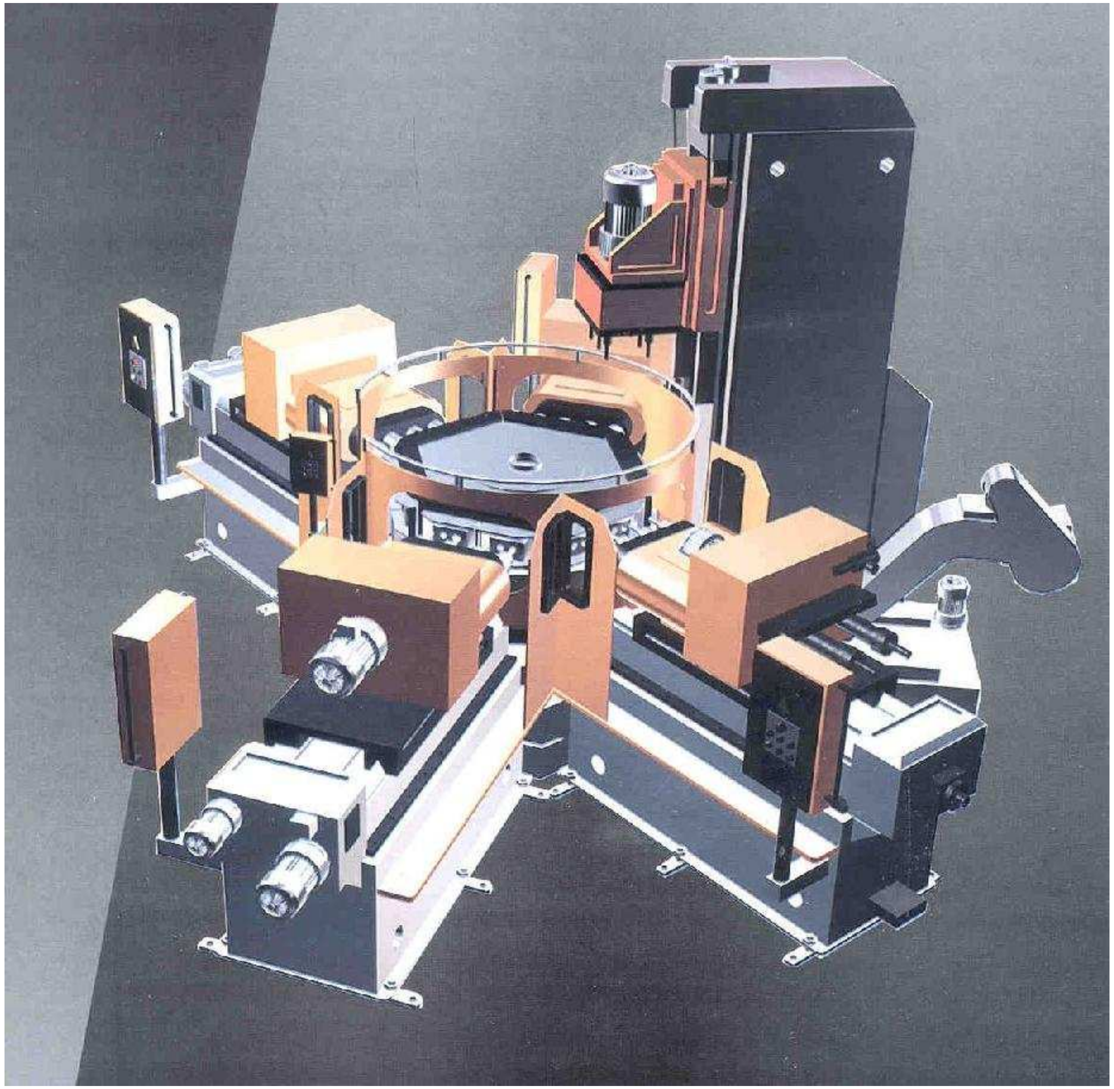
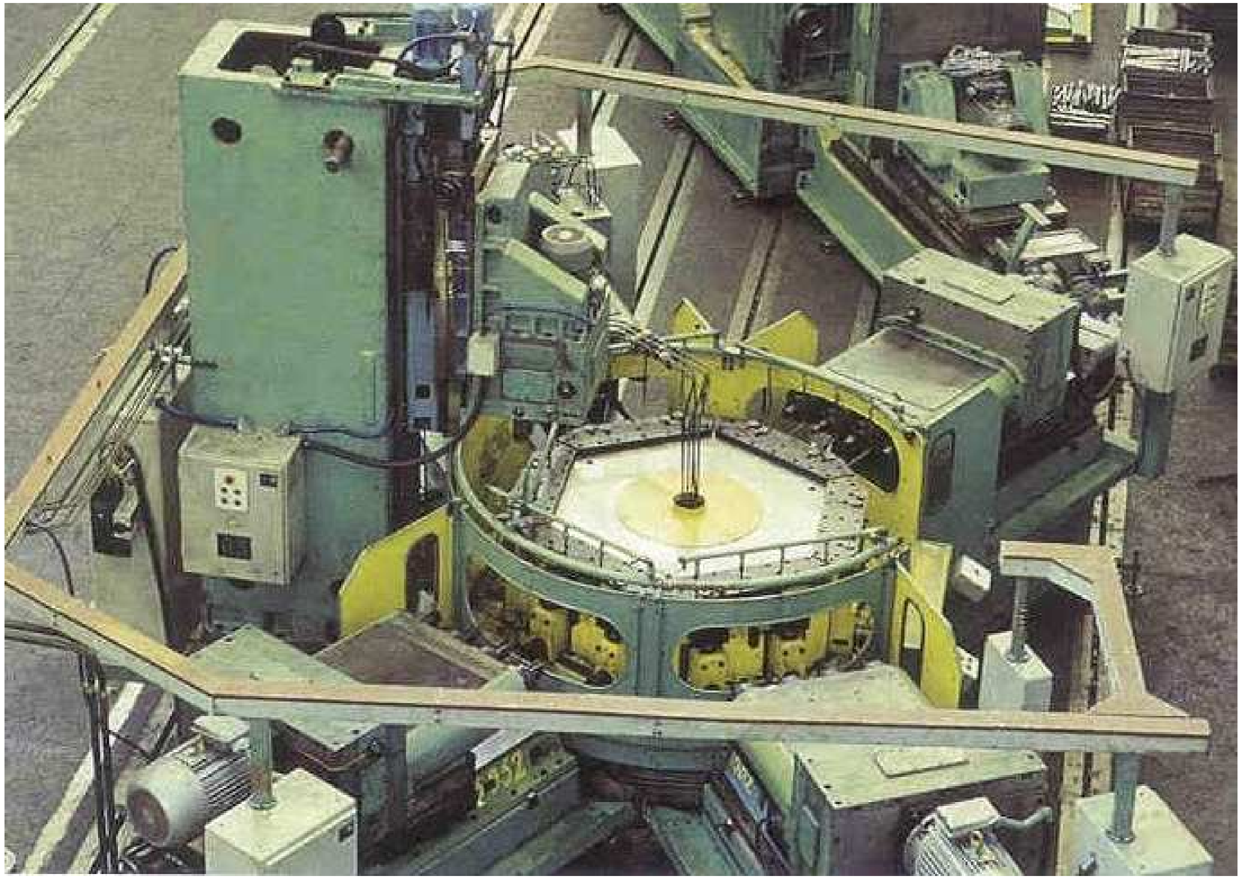
O. Battaïa, A. Dolgui,
N. Guschinsky, G. Levin.
Optimal design of machines processing pipeline parts,
Int. J. of Advanced Manufacturing Technology,
2012 (in Press)

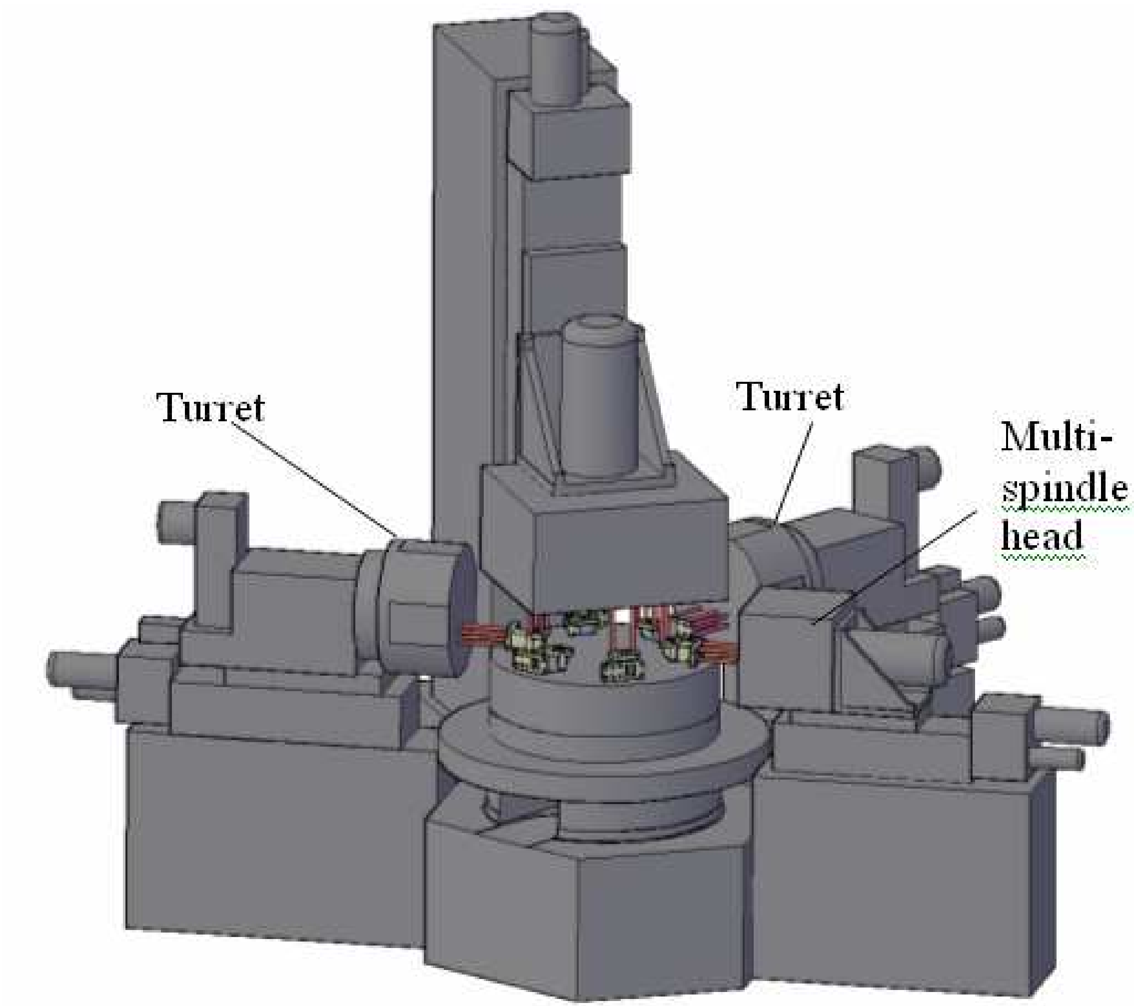
Machine with a rotary table

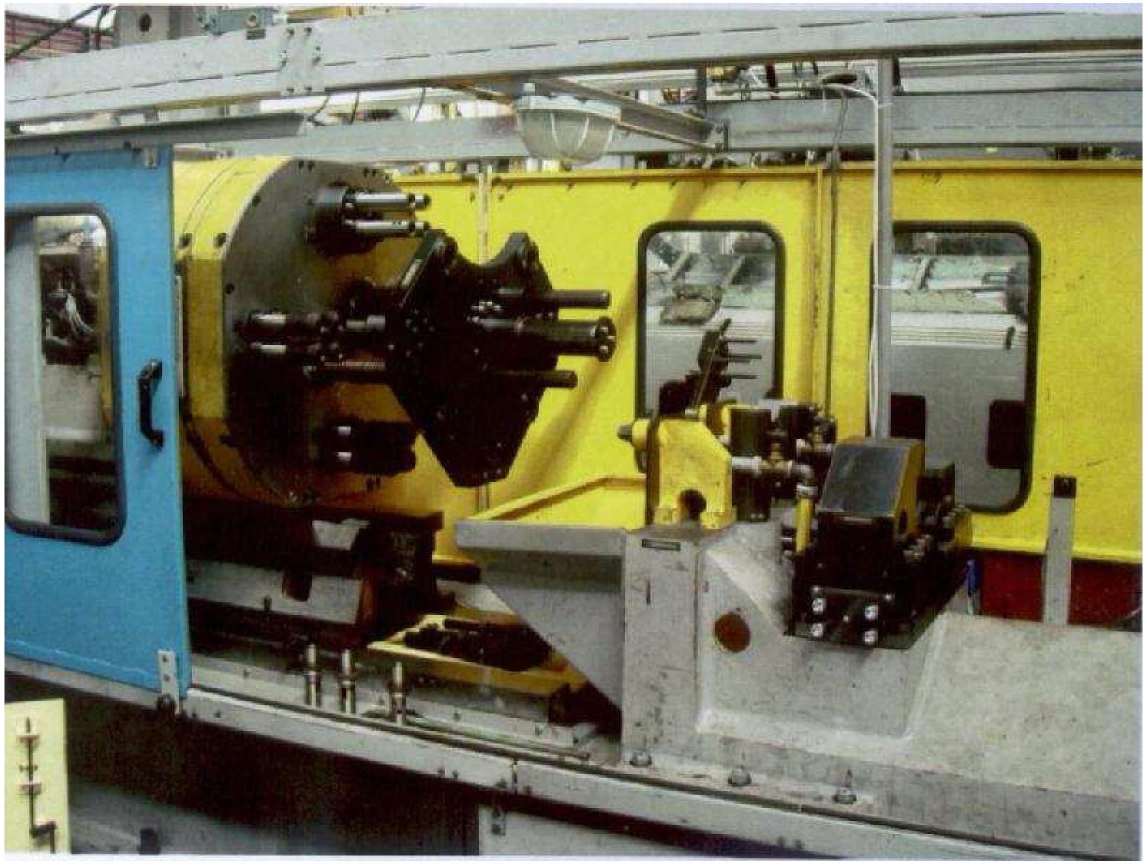




A. Dolgui, N. Guschinsky, G. Levin. **Graph approach for optimal design of transfer machine with rotary table**, *Int. J. of Production Research*, 47 (2), 2009, 321–341.

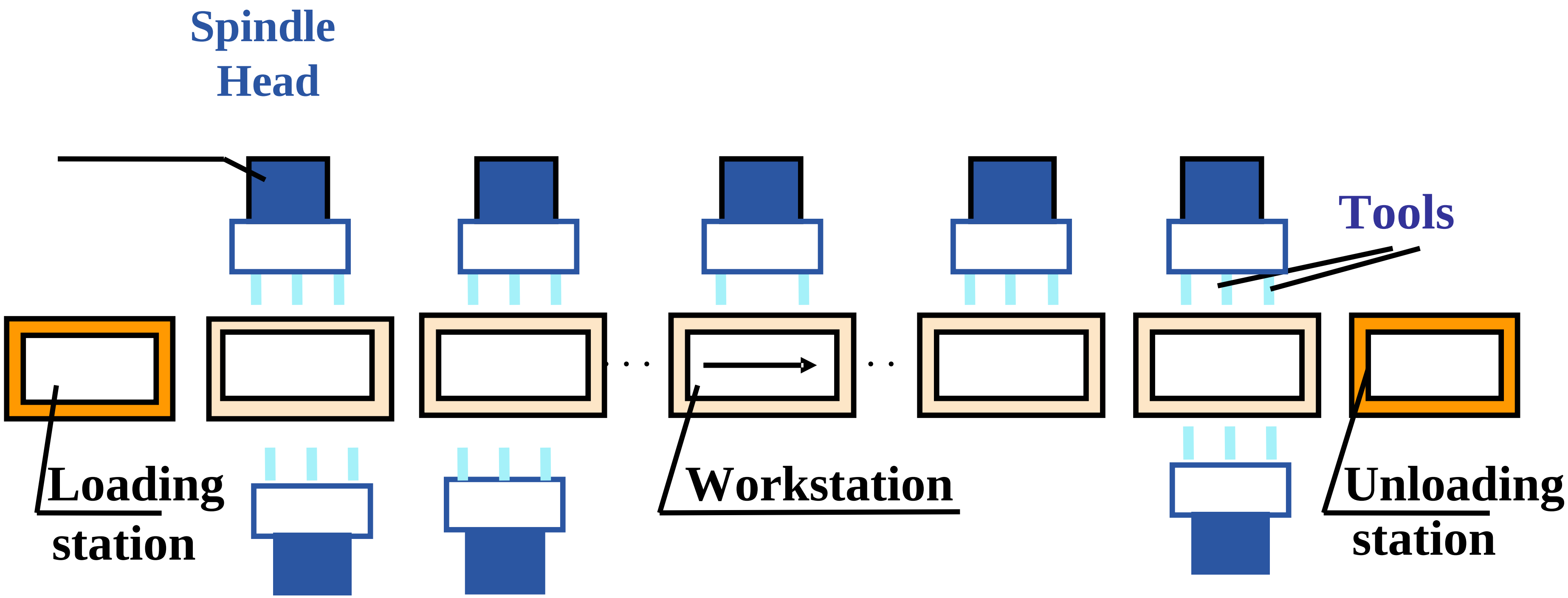
Machines with rotary table and turrets

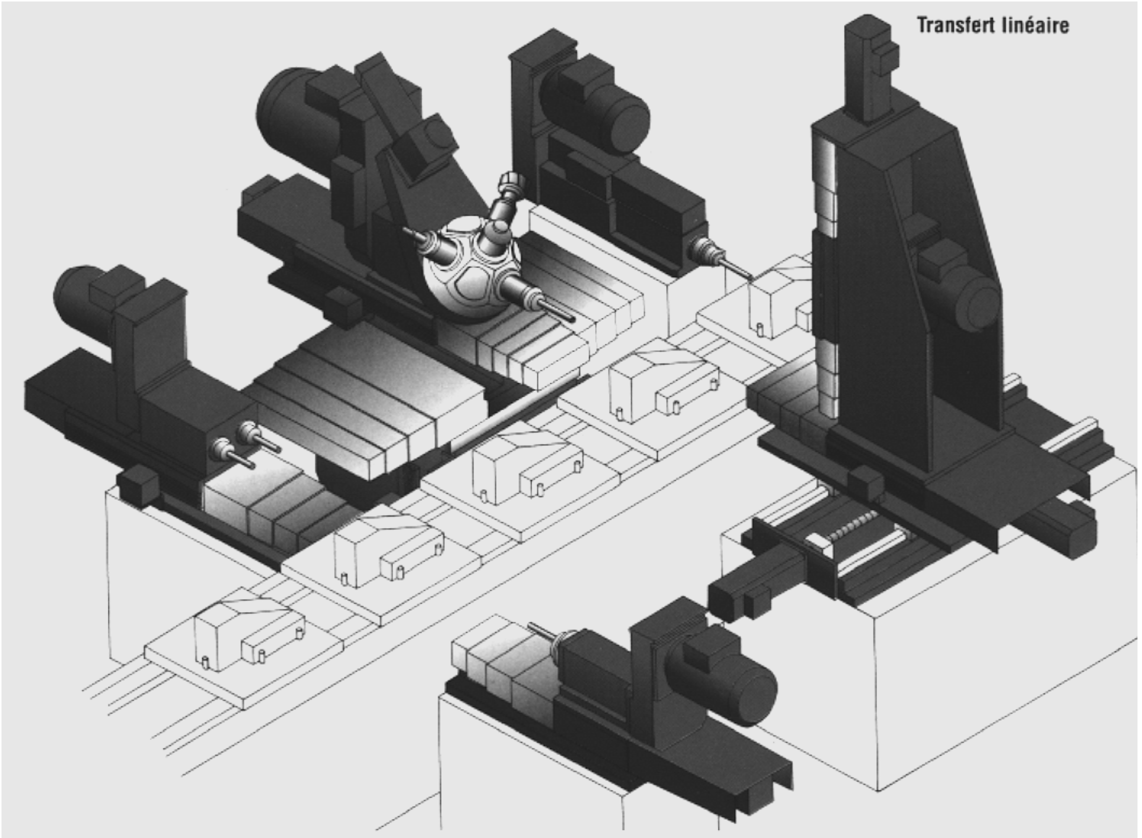




O. Battaïa, A. Dolgui,
N. Guschinsky, G. Levin.
Optimal Design of Rotary Transfer Machines with Turrets, *Proceedings of the IFAC Symposium INCOM'*12, Bucharest, Romania, IFAC-PapersOnline.net.

Machining transfer lines for large series





A. Dolgui, B. Finel, N. Guschinsky, G. Levin, F. Vernadat. **MIP Approach to Balancing Transfer Lines with Blocks of Parallel Operations**, *IIE Transactions*, 2006, 38, 869–882.

IIE Transactions Best Paper Award 2008

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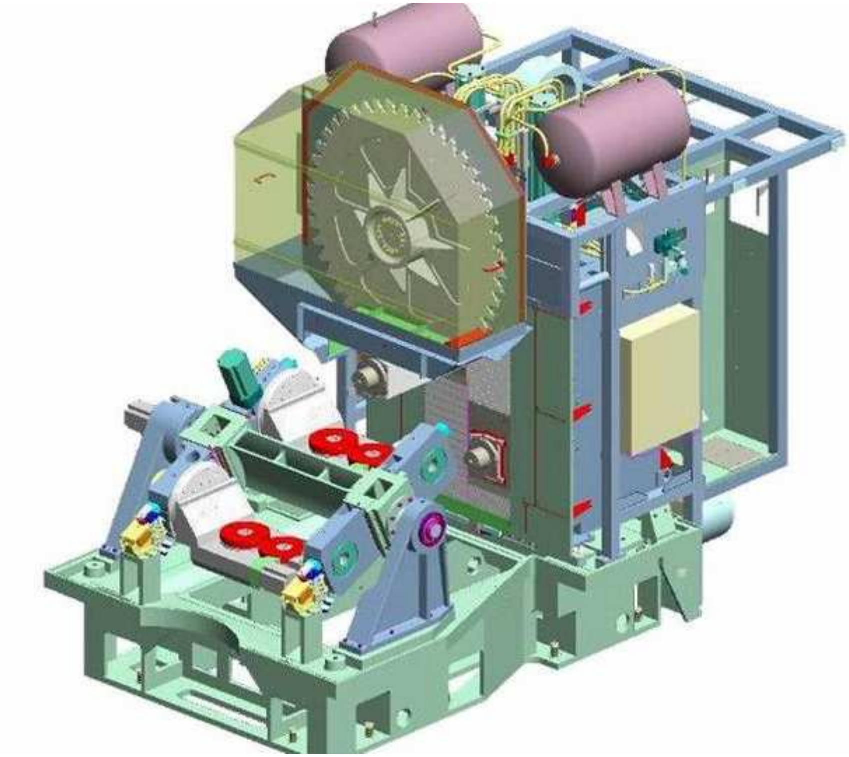
Reconfigurable lines composed of machining centers



M. Essafi, X. Delorme, A. Dolgui.
A Reactive GRASP and Path Relinking for Balancing Reconfigurable Transfer Lines, *Int. J. of Production Research*, 2012 (in Press)

- Mono-spindle CNC machining centers
- Several identical machining centers at each station
- Setup times for tool replacement and/or displacement

Lean manufacturing

(usually associated with manual assembly lines)

Steps of lean process design

- **“Takt time” calculation**

- **Definition of tasks (operations)**

- **Choice of a process plan**

- **Layout type option**

- **Line balancing (assign tasks to workstations)**

- **Equipment selection**

Takt time calculation

$$\text{"Takt Time"} = \frac{\text{Operating time}}{\text{Customer demand}}$$

$$\text{Operating Time} = \text{Shifts} \times \text{Effective Time}$$

"*Takt Time*" imposes the cadence of fabrication needed to meet customer demand

"Effective time" takes into account the shifts worked and makes allowances for stoppages, for predetermined maintenance, and planned team briefings, breaks, etc.

The customer demand includes anticipated average sales rate plus any extras such as spare parts, anticipated rework and defective pieces

Definition of tasks (operations)

The operations that should be kept, are those with added value, i.e. the operation where the product value after the operation is greater than before.

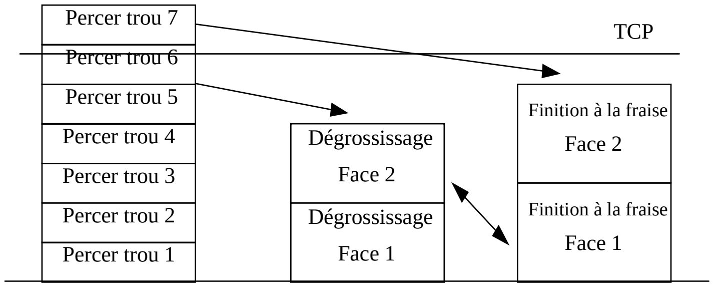
For example holding and transport operations have no added value and should be reduced (or eliminated if possible).

Assembly line balancing (ALB)

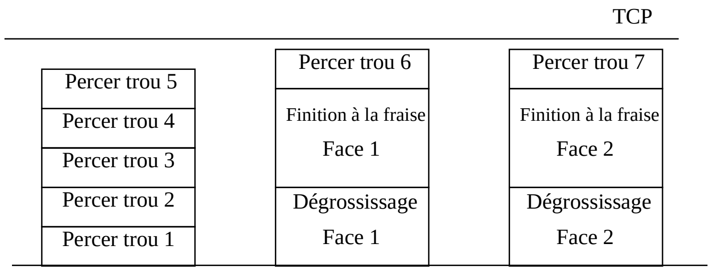
At this step, the assignment of operations to workstations is made under Takt time and precedence constraints.

The load of each station cannot exceed the Takt time (TCP in this figure).

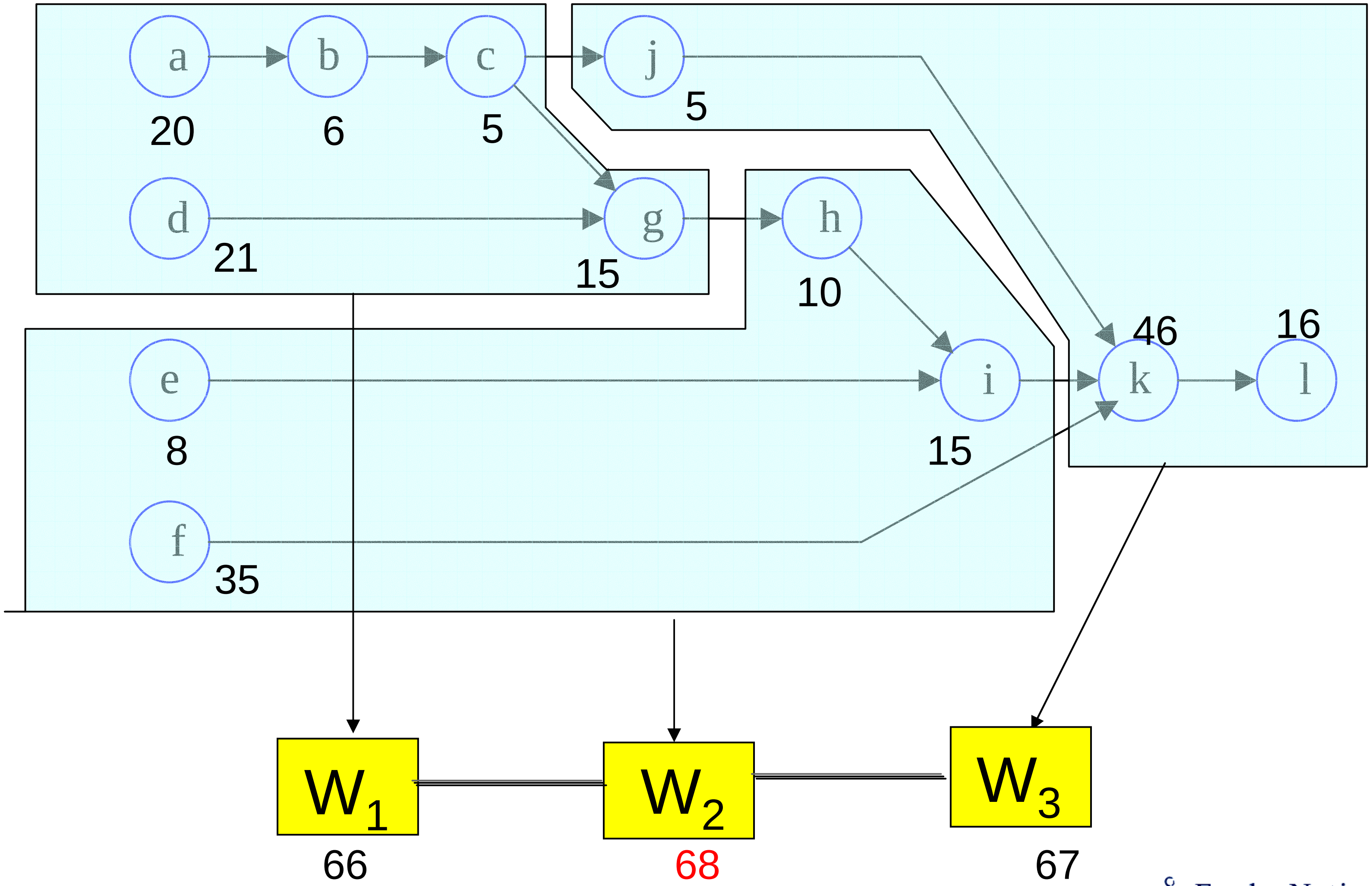
Situation initiale : Déséquilibre Charge Machine



Avec éléments de tâches individuelles transférés



Example of ALB (hard combinatorial problem)



ALB methods

Methods

- **Exact**
  - Branch and Bound
  - Dynamic Programming
- **Meta-Heuristics**
  - Taboo search
  - Genetic Algorithms
- **Heuristics**
  - RPW
  - COMSOAL (random search)

In general, this is a NP-hard combinatorial optimisation problem

Dolgui, A. (Ed.) **Balancing Assembly and Transfer Lines**,
European Journal of Operational Research **168**, 2006 , 663 - 951.

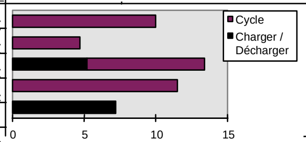
An example of ALB document used in industry

Fiche d'Equilibrage

Projet: *Armature* **Code-pièce n°:** *23456789*

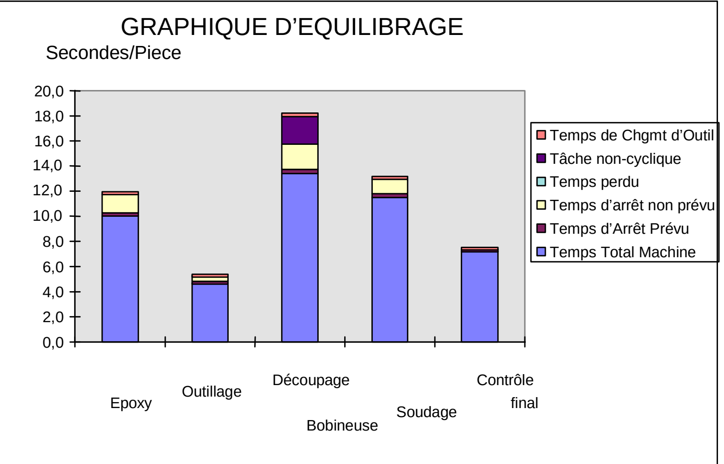
Date: *20/07/97* **Cycle («Takt Time»)** *6,41*

NOM DE LA MACHINE	CHARGER / DECHARGER	TEMPS DE CYCLE MACHINE	GRAPHIQUE DU TEMPS TOTAL MACHINE	TEMPS TOTAL MACHINE	TEMPS SUPPLEMENTAIRE	TEMPS MACHINE EN CHARGE
Epoxy	0	10		10,0	2,0	12,0
Outillage découpe	0	4,7		4,7	0,7	5,4
Bobineuse	5,2	8,2		13,4	4,8	18,2
Soudage	0	11,5		11,5	1,7	13,2
Contrôle final	7,2	0		7,2	0,3	7,5



PERTES DE PRODUCTION : % ET SECONDES / PIECE

NOM DE LA MACHINE	TEMPS D'ARRET PREVU %	TEMPS D'ARRET PREVU sec/pièce	TEMPS D'ARRET NON PREVU %	TEMPS D'ARRET NON PREVU sec/pièce	TEMPS PERDU %	TEMPS PERDU sec/pièce	CONTENU DE TACHE NON-CYCLIQUE %	CONTENU DE TACHE NON-CYCLIQUE sec/pièce	TEMPS DE CHANGEMENT D'OUTILS %	TEMPS DE CHANGEMENT D'OUTILS sec/pièce
Epoxy	0,03	0,3	0,15	1,5					0,02	0,2
Outillage découpe	0,03	0,1	0,10	0,5					0,02	0,1
Bobineuse	0,03	0,3	0,15	2,0				2,2	0,02	0,3
Soudage	0,03	0,3	0,10	1,2					0,02	0,2
Contrôle final	0,03	0,2							0,02	0,1



Equipment assignment

Which type of equipment should be used at each workstation?

ALB considers that
i) all stations can process any task; *ii*) task times are independent of the station any *iii*) task can be processed at any station

So by definition the equipment selection is made after line balancing.

The tools, machines, etc. are selected to minimize the line cost while respecting *Takt time* and equipment compatibility.

It is interesting to combine the *assembly line balancing* with *equipment selection, as for example* in Bukchin, J. and M. Tzur (2000). *Design of flexible assembly line to minimize equipment cost, IIE Transactions, 32, 585-598.*

Because optimizing each separately does not necessarily equal optimal when combined.

Decision-Aid Tool for Machining System Design

Steps for decision making

Step 1. "Takt time" calculation and choice of layout type

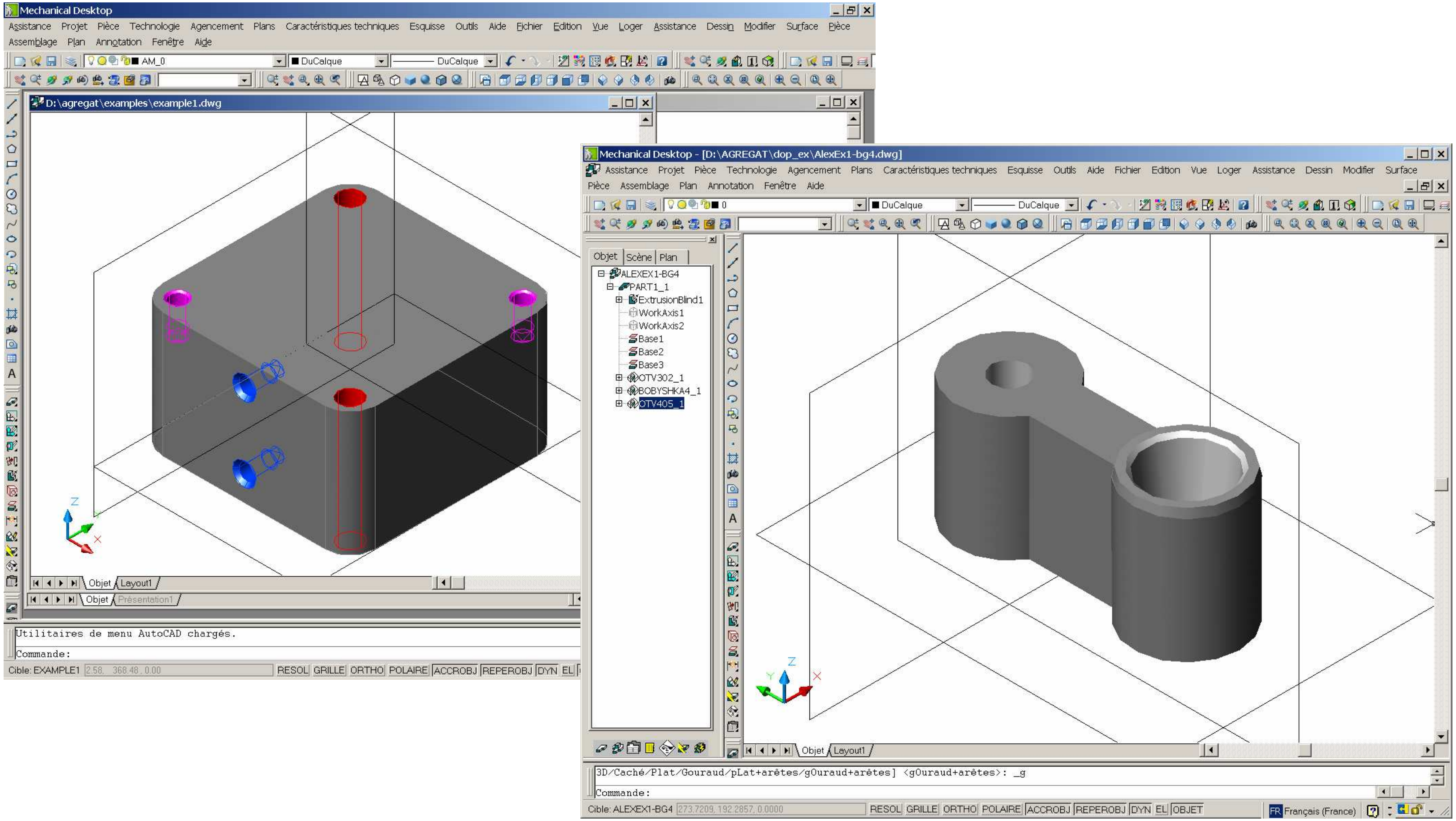
Step 2. Part modeling: using standard features to define tasks

Step 3. Process planning, i.e. choice of a process plan (required operations, tools, technological constraints,…) by using an *expert system*

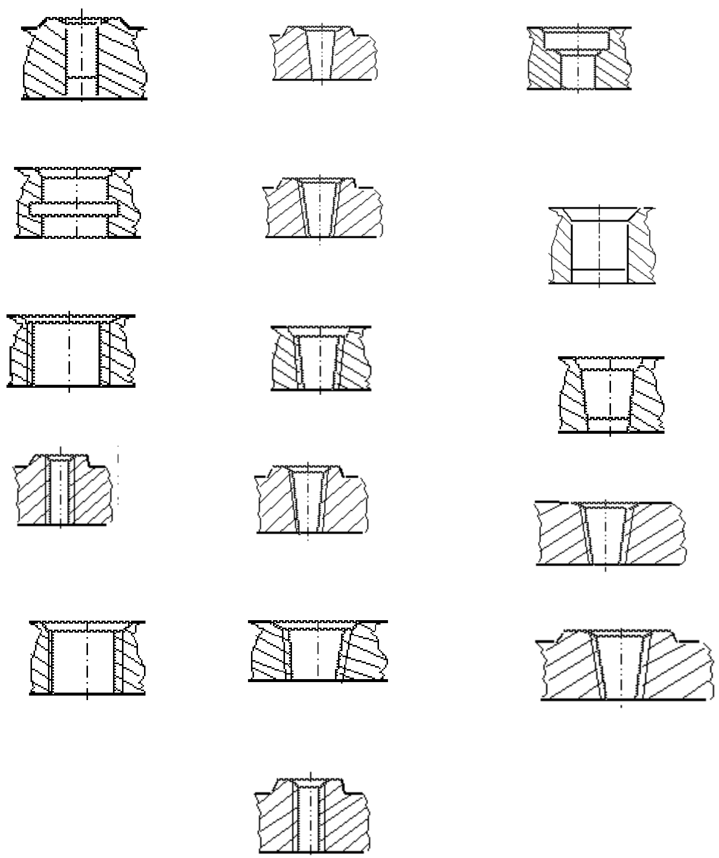
Step 4. **Synthesis of the manufacturing process using optimization models**: line balancing and equipment configuration taking into account cutting modes and parameters

Step 5. Preliminary 3D model

Step 2: *Part modeling to define tasks*



Database with features



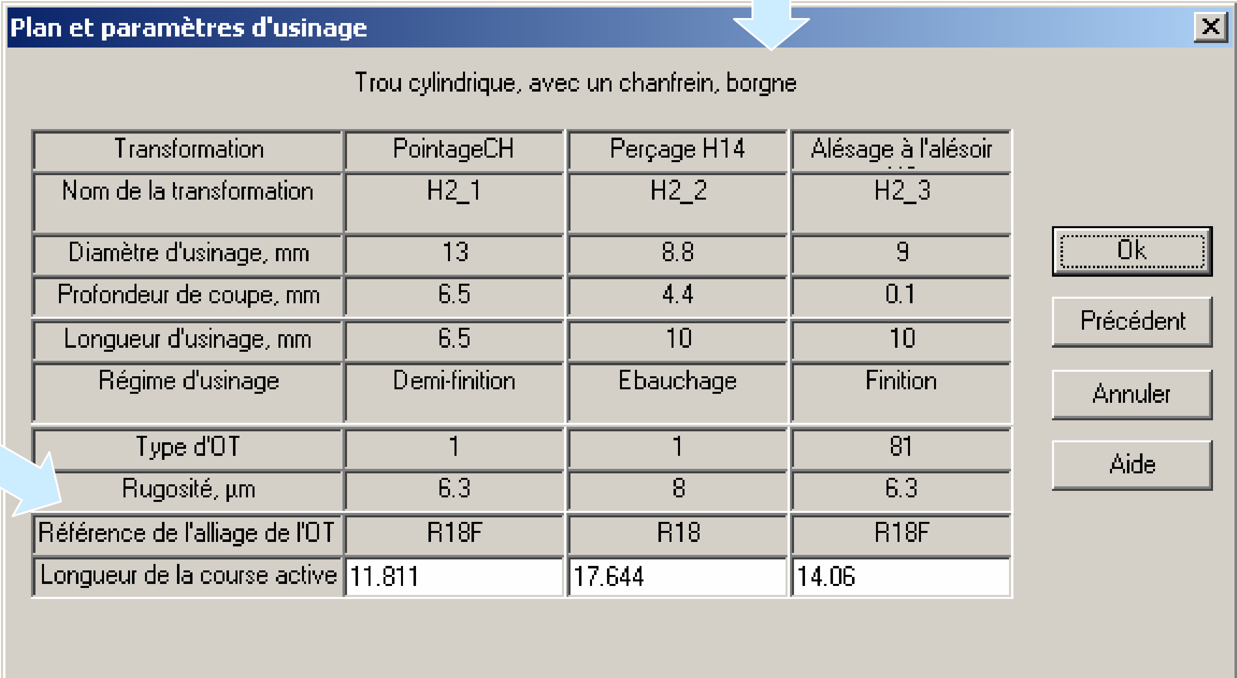
Examples of different
types of holes
from our database

Step 3: Choice of a process plan (expert system)

Process planning

Required operations

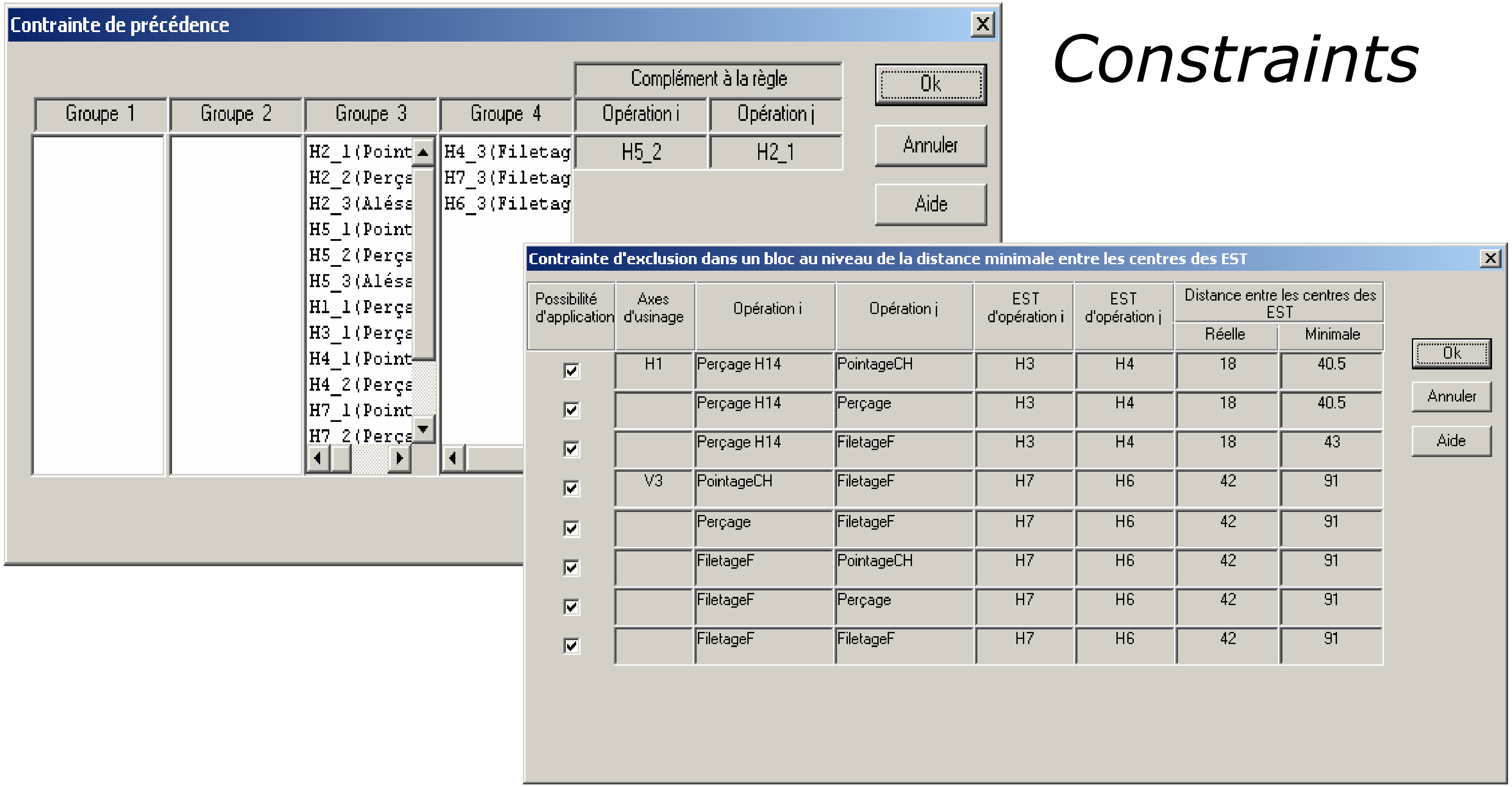
Cutting mode, required tools and their parameters


Plan et paramètres d'usinage

Trou cylindrique, avec un chanfrein, borgne

Transformation	PointageCH	Perçage H14	Alésage à l'alésoir
Nom de la transformation	H2_1	H2_2	H2_3
Diamètre d'usinage, mm	13	8.8	9
Profondeur de coupe, mm	6.5	4.4	0.1
Longueur d'usinage, mm	6.5	10	10
Régime d'usinage	Demi-finition	Ebauchage	Finition
Type d'OT	1	1	81
Rugosité, µm	6.3	8	6.3
Référence de l'alliage de l'OT	R18F	R18	R18F
Longueur de la course active	11.811	17.644	14.06

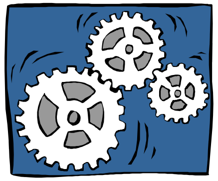
Constraints



Possibilité d'application	Axes d'usinage	Opération i	Opération j	EST d'opération i	EST d'opération j	Distance entre les centres des EST	
						Réelle	Minimale
☑	H1	Perçage H14	PointageCH	H3	H4	18	40.5
☑		Perçage H14	Perçage	H3	H4	18	40.5
☑		Perçage H14	FiletageF	H3	H4	18	43
☑	V3	PointageCH	FiletageF	H7	H6	42	91
☑		Perçage	FiletageF	H7	H6	42	91
☑		FiletageF	PointageCH	H7	H6	42	91
☑		FiletageF	Perçage	H7	H6	42	91
☑		FiletageF	FiletageF	H7	H6	42	91

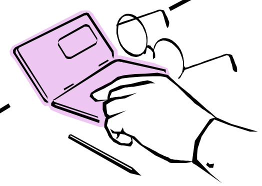
Step 4: Line balancing and equipment selection

The designer checks and/or modifies the constraints and parameters

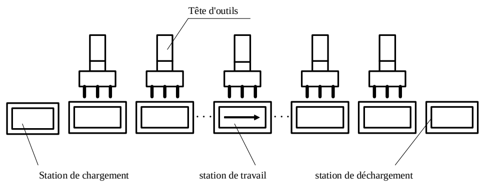


Optimisation

Optimal solutions that take into account all the given constraints

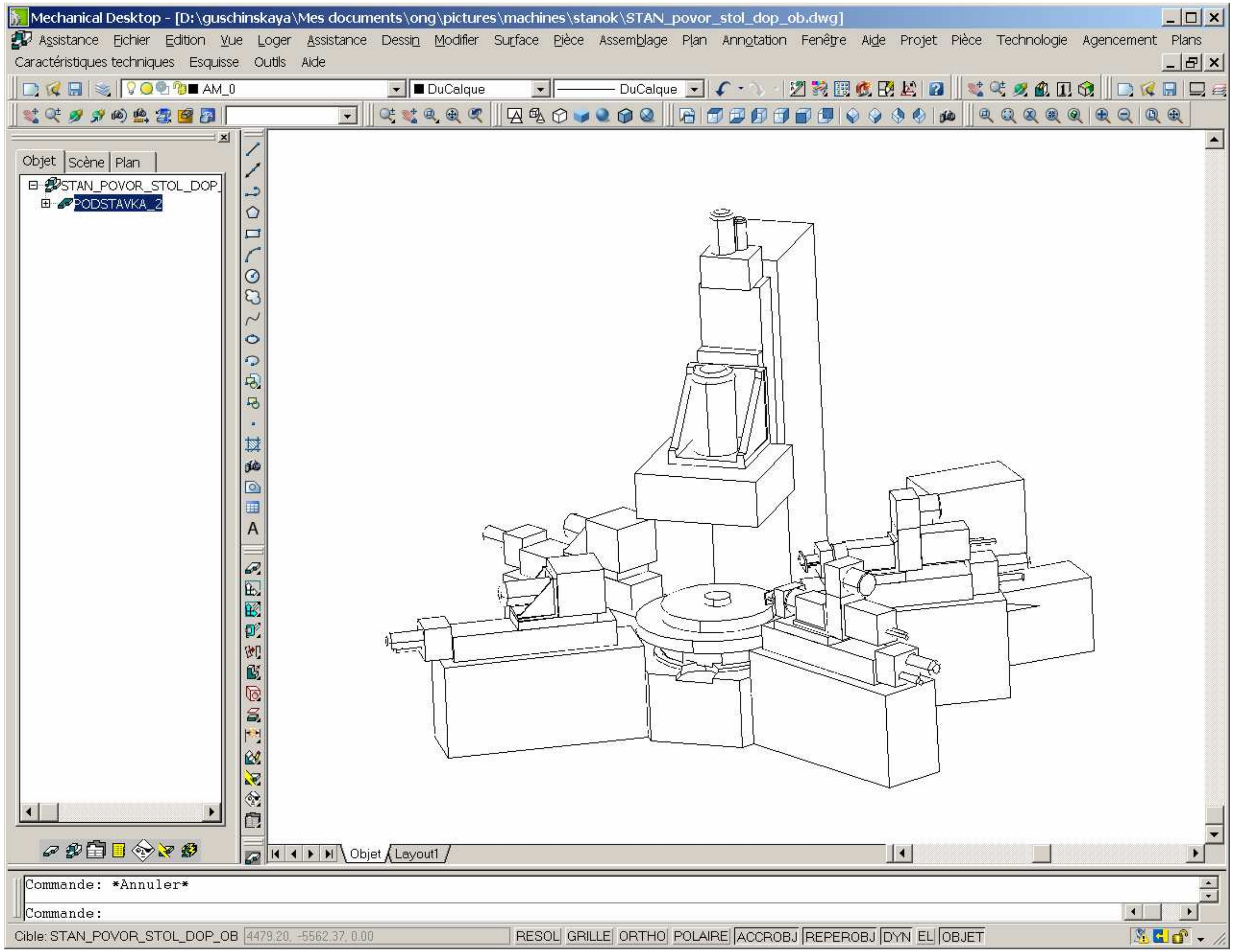


Final solution



The solutions are presented to the designer who then verifies it

Step 5: 3D layout



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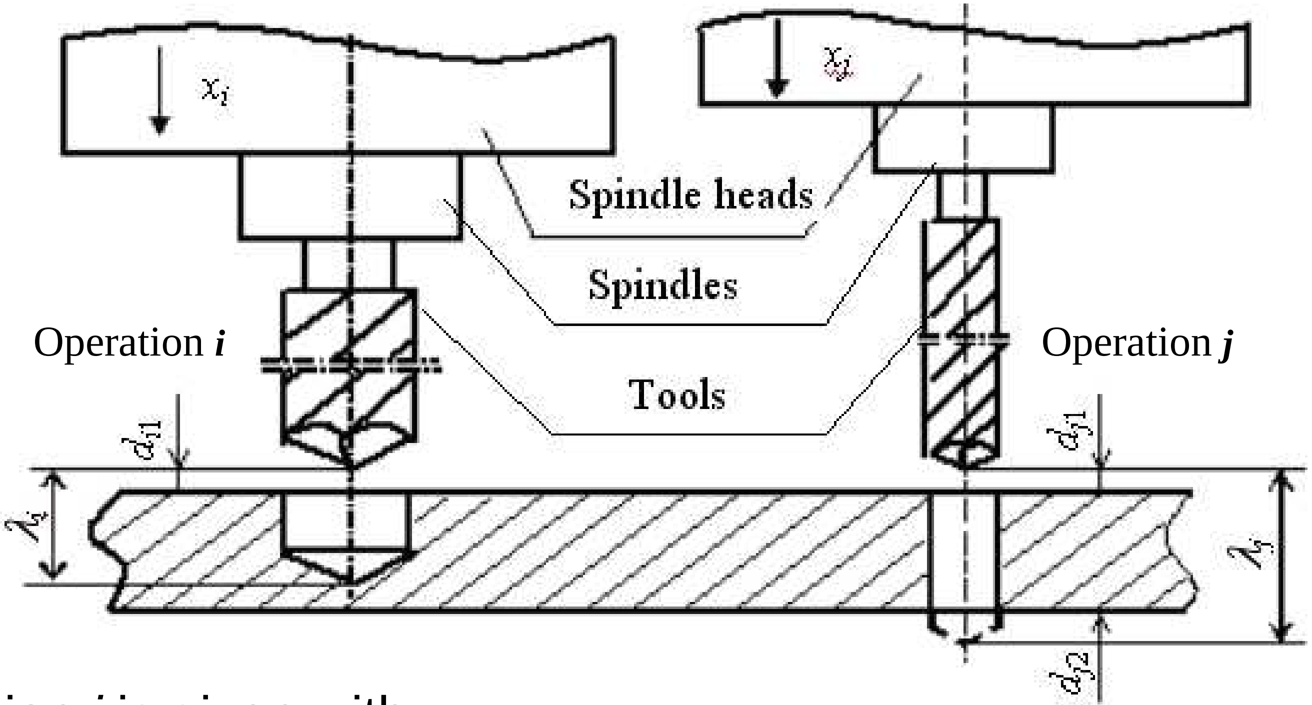
Mass production machines with multi-spindle heads

Multi-spindle heads

Operation's parameters

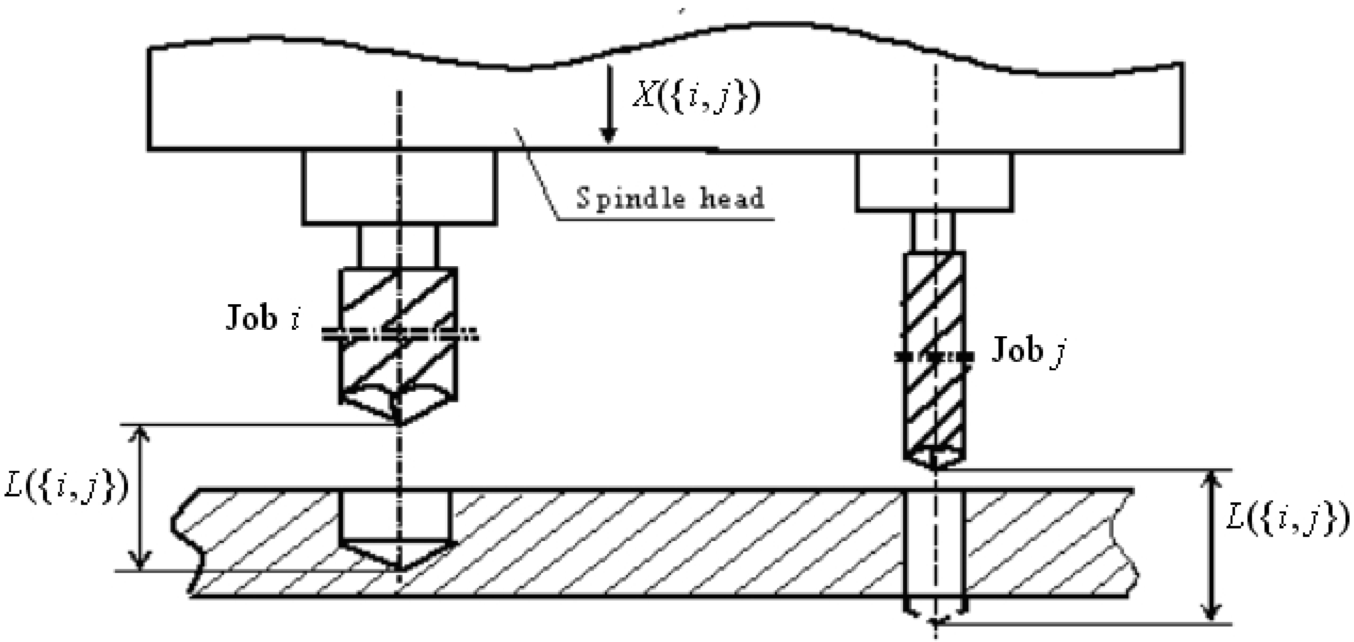


Operation *j* is given with:

Machining length λ_j

Feed per minute x_j

Spindle head's parameters



Working length $L(N_{kl}) = max\{\lambda_j \mid j \in N_{kl}\}$

Spindle head's feed $X(N_{kl}) = min\{x_j \mid j \in N_{kl}\}$

Goal function

$$\text{Min} \quad m\,C_1 + Q\,C_2$$

where

m	number of working positions (stations)
Q	total number of spindle heads
C_1	cost of 1 working position (station)
C_2	cost of 1 spindle head

Design decision

$P = \{N_1 = \{N_{11}, \ldots, N_{1n_1}\}, \ldots, N_m = \{N_{m1}, \ldots, N_{mn_m}\}\}$

Subject to

Takt time constraint:

$$T(P) = \max\{ t^s(N_k) \mid 1 \leq k \leq m \} \leq T_0$$

- Precedence constraints

  if $(i, j) \in D$ then $a)\ k(i) < k(j)$ or $b)\ k(i) = k(j)$ and $l(i) \leq l(j)$

- Inclusion constraints:

  $N_k \cap e \in \{\emptyset, e\}$, $e \in ES$, $k=1, \ldots, m$

- Exclusion constraints:

$$e \not\subset N_{kl},\ e \in \overline{EB}\ ,\ k=1, \dots, m,\ l=1, ..., n_k$$

$$e \not\subset N_k,\ e \in \overline{ES}\ ,\ k=1,\dots,m;$$

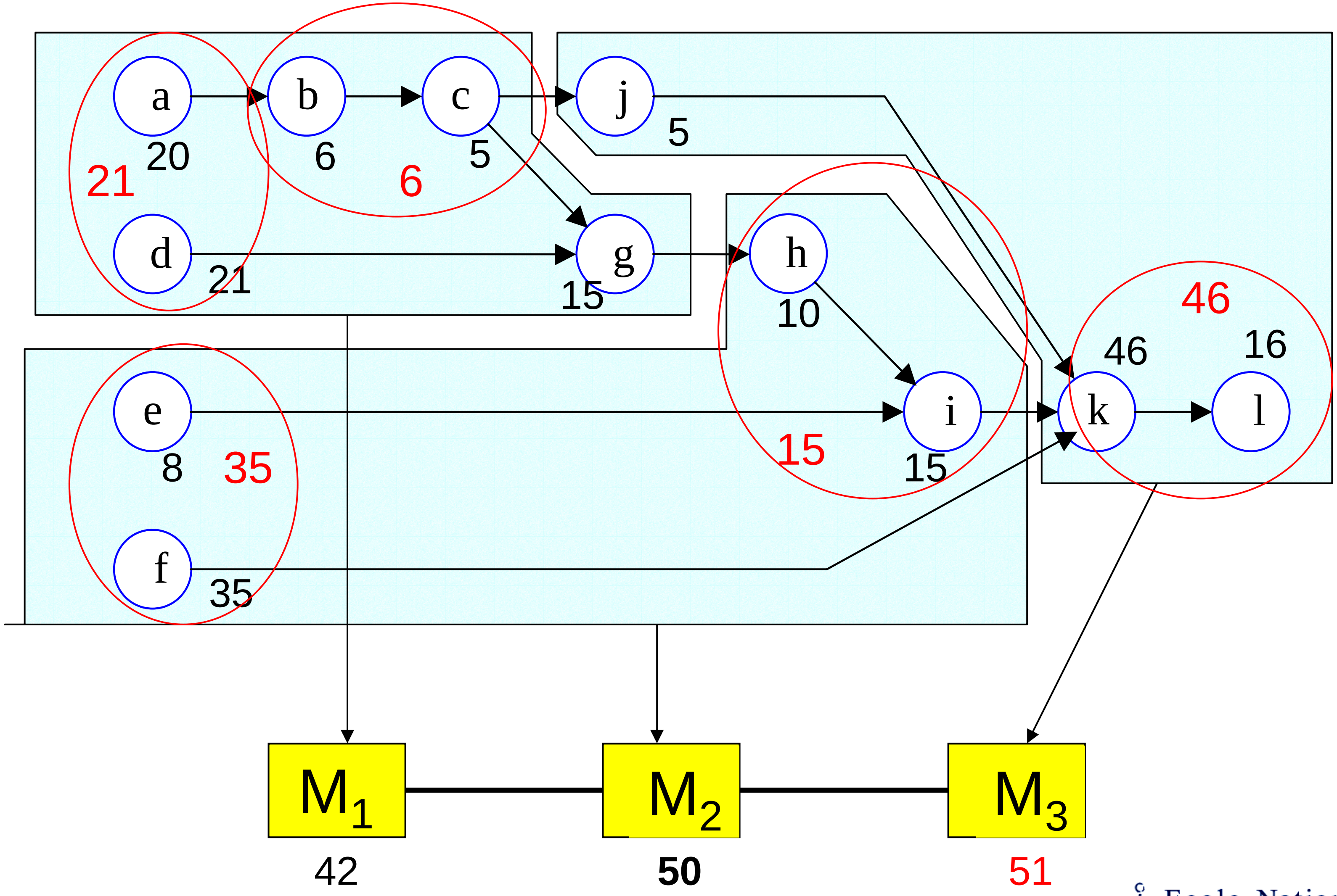
- Number of working stations:

$$m=m(P) \leq m_0$$

- Number of spindle heads per station:

$$n_k = n_k(P) \leq n_0,\ k=1,\dots,m.$$

New problem: multi-spindle machining line balancing



Comparison with assembly line balancing (ALB) and their generalizations:

- Operation times are not known before optimization
- Assignment restrictions (constraints) are more complex
- Operations of the same spindle head are executed in parallel
- Line balancing simultaneously with equipment selection/design

Dimensions of industrial problems

~ 30 – 350 operations

~ 5 – 50 stations

~ 2 – 4 spindle heads by station

⇨ **Hard decision problem**

MIP model (Cplex)

Analysis of constraints to reduce the number of binary decision variables

↓

Cplex solver for MIP model

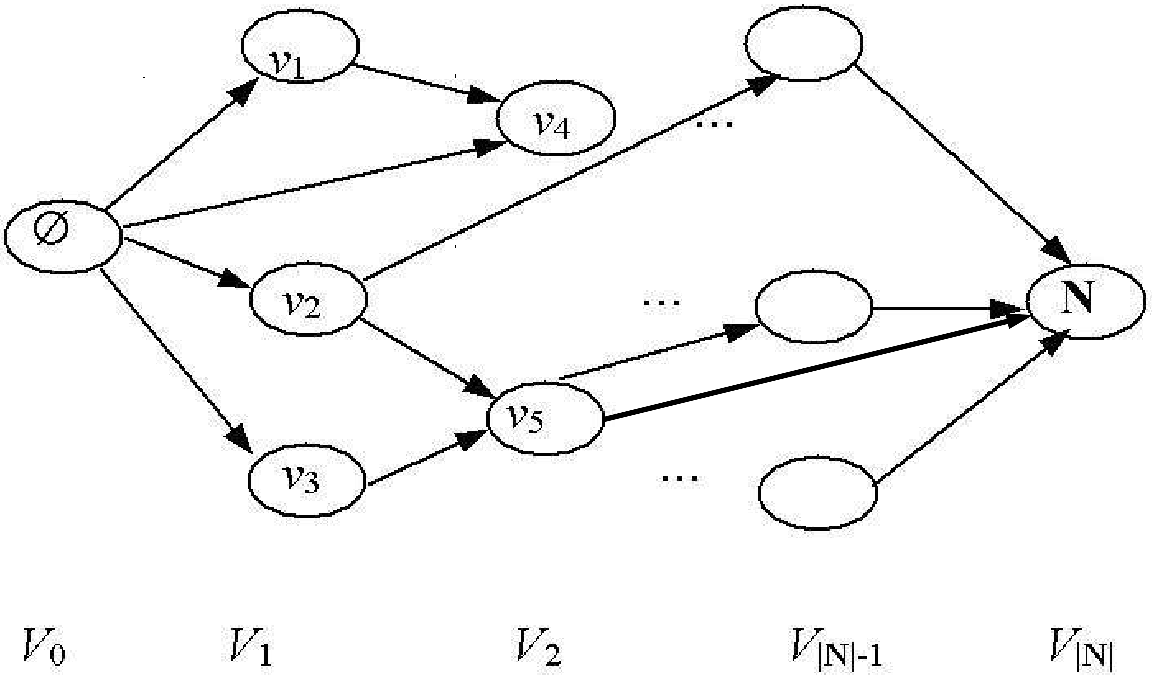
Note that without this constraint analysis:
Only problems with maximum 40 tasks were optimally solved in 10 hours

Dolgui et al., MIP Approach to Balancing Transfer Lines with Blocks of Parallel Operations, *IIE Transactions* 38, 2006, 869–882

Battaïa and Dolgui. *Reduction approaches for a generalized line balancing problem*, *Computers & Operations Research* 39, 2012, 2337–2345

Dolgui et al. Enhanced mixed integer programming model for a transfer line design problem, *Computers & Industrial Engineering* 62, 2012, 570–578

Graph approach



A. Dolgui, N. Guschinsky, G. Levin, J.-M. Proth. Optimisation of multi-position machines and transfer lines, Eur. J. of Operational Research 185, 2008, 1375–1389.

A. Dolgui, N. Guschinsky, G. Levin. A Special Case of Transfer Lines Balancing by Graph Approach, Eur. J. of Operational Research 168, 2006, 732–746.

Dominance properties to reduce the size of graph

Constraint shortest path

$$Min\ Q(z) = \sum_{k=1}^{m(z)} C(u_k \backslash u_{k-1});$$

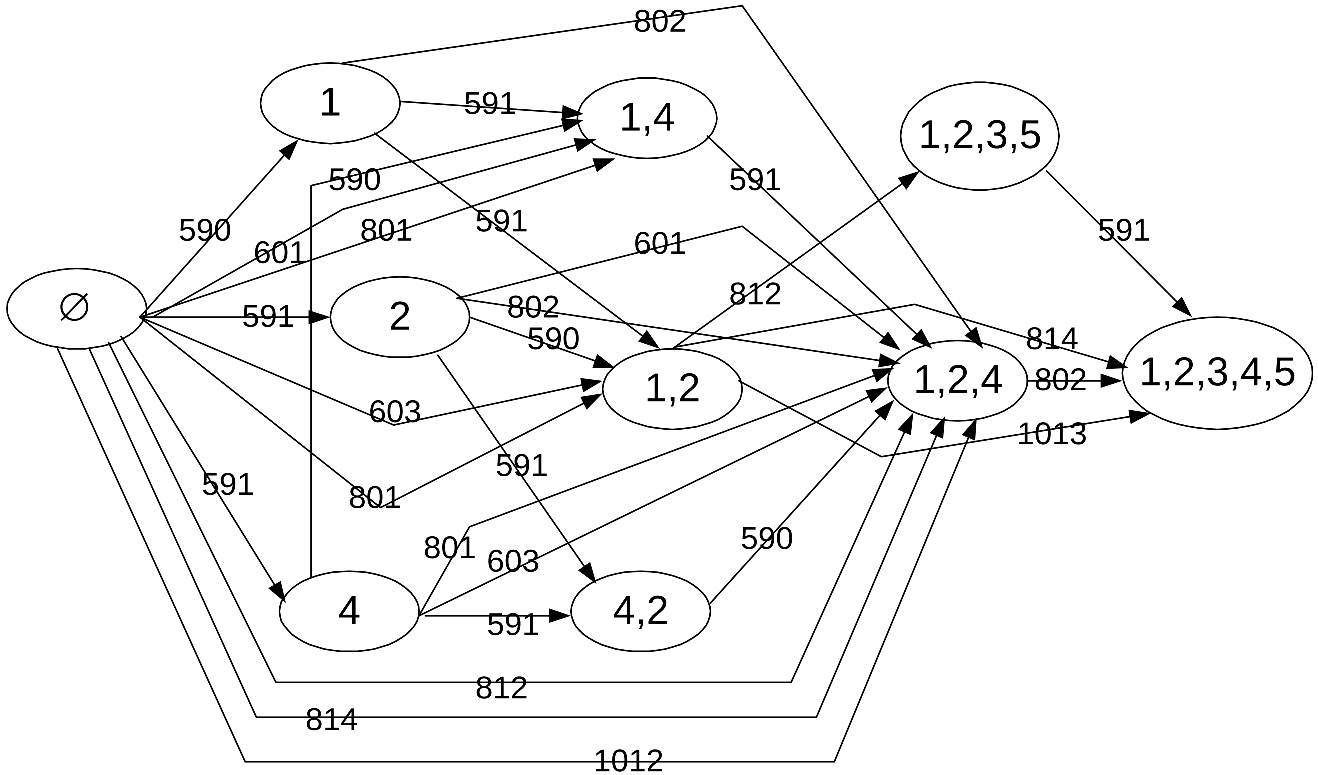
$$\sum_{k=1}^{m(z)} \underline{t}(u_k \backslash u_{k-1}) \leq T_0 - \tau'';$$

$$z \in \mathbf{Z};$$

$$m(z) \leq 3.$$

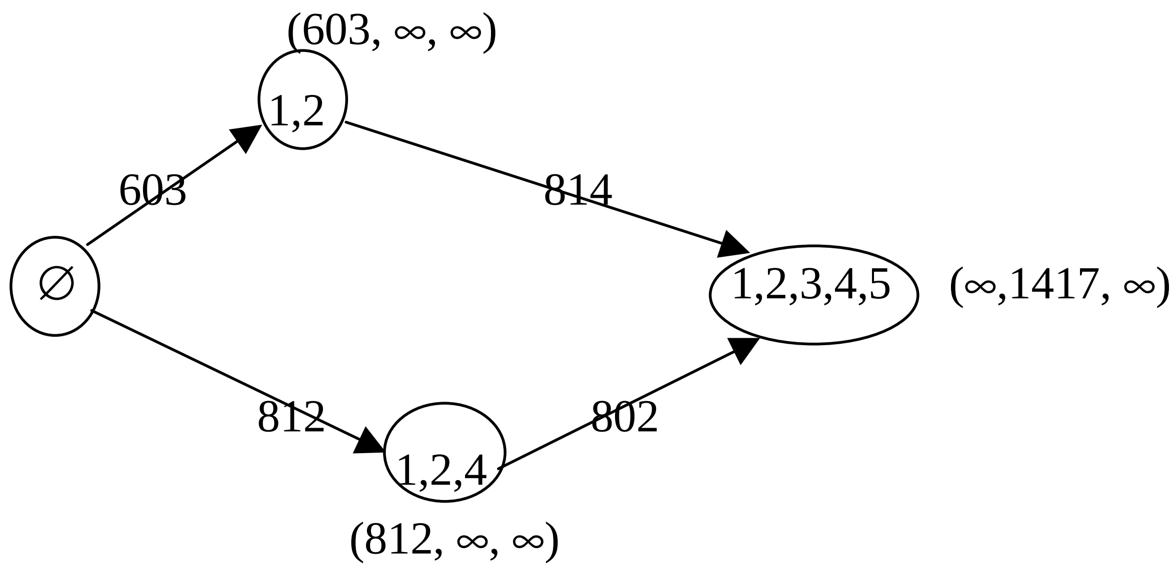
Powerful dominance properties: An example

Before their application



Powerful dominance properties: An example

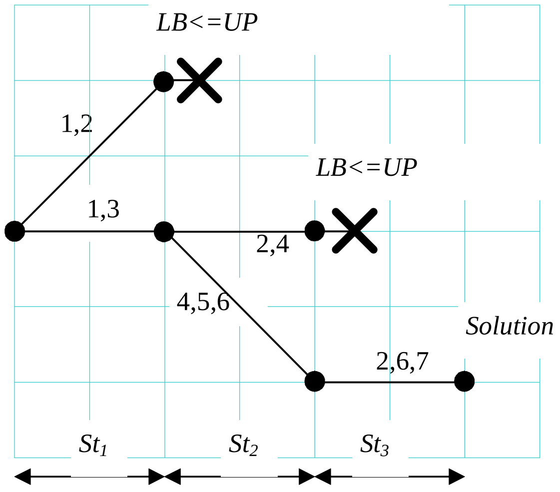
After their application



Branch and Bound

- Enumerate solutions
- Evaluate Lower (LB) and Upper (UP) Bounds

  (a novel approach using set partitioning)
- Prune branches where LB<=UP
- Verify dominance properties: remove dominated nodes



A. Dolgui and I. Ihnatsenka.
Branch and Bound Algorithm for a Transfer Line Design Problem: Stations with Sequentially Activated Multi-spindle Heads, *Eur. J. of Operational Research* 197, 2009, 1119–1132

Heuristics

- **Random search** (COMSOAL like heuristics, Backtracking with learning, GRASP,…)

- **Decomposition**

a) Breakdown the initial problem into several sub-problems

1. Based on precedence graph
2. Based on a feasible solution

b) Solving sub-problems by an exact method

1. Independent solving
2. Aggregate solving

O. Guschinskaya, A. Dolgui, N. Guschinsky, G. Levin. A Heuristic Multi-Start Decomposition Approach for Optimal Design of Serial Machining Lines, *Eur. J. of Oper. Research* 189, 2008, 902–913.

A. Dolgui, B. Finel, N. Guschinsky, G. Levin, F. Vernadat. A heuristic approach for transfer lines balancing. *J. of Intell. Manufact.* 16, 2005, 159–171.

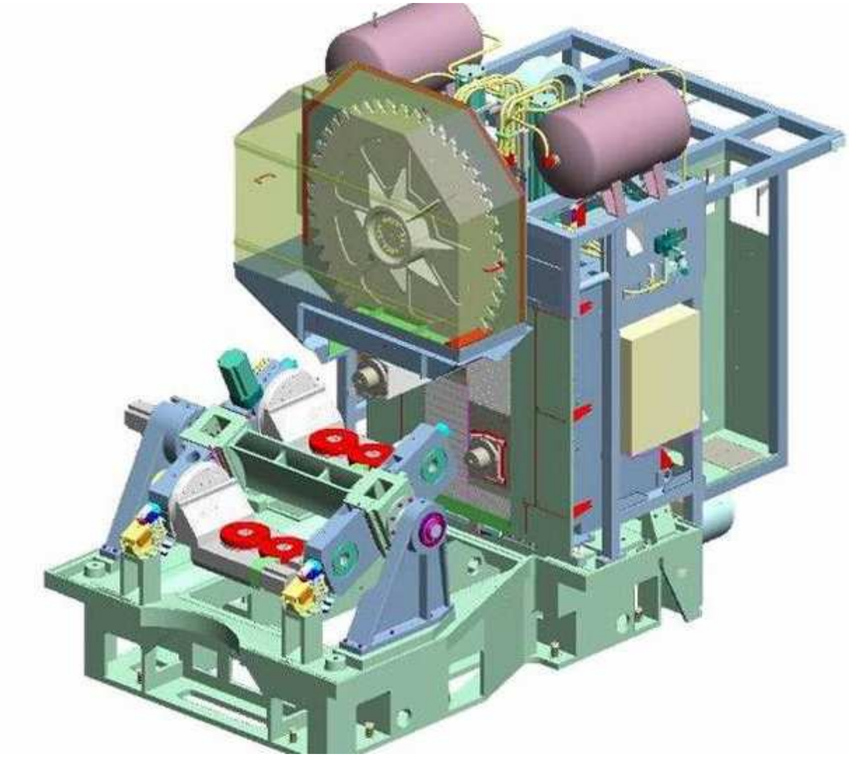
Optimization modules in our software:

- Problem size reduction procedures
- Lower bounds and dominance properties
- 4 mathematical models (one per type of system)
- 3 exact methods (B&B, Graph and MIP with Cplex)
- 8 heuristic procedures (list, GRASP, decomposition, …)

Comparison of the methods:

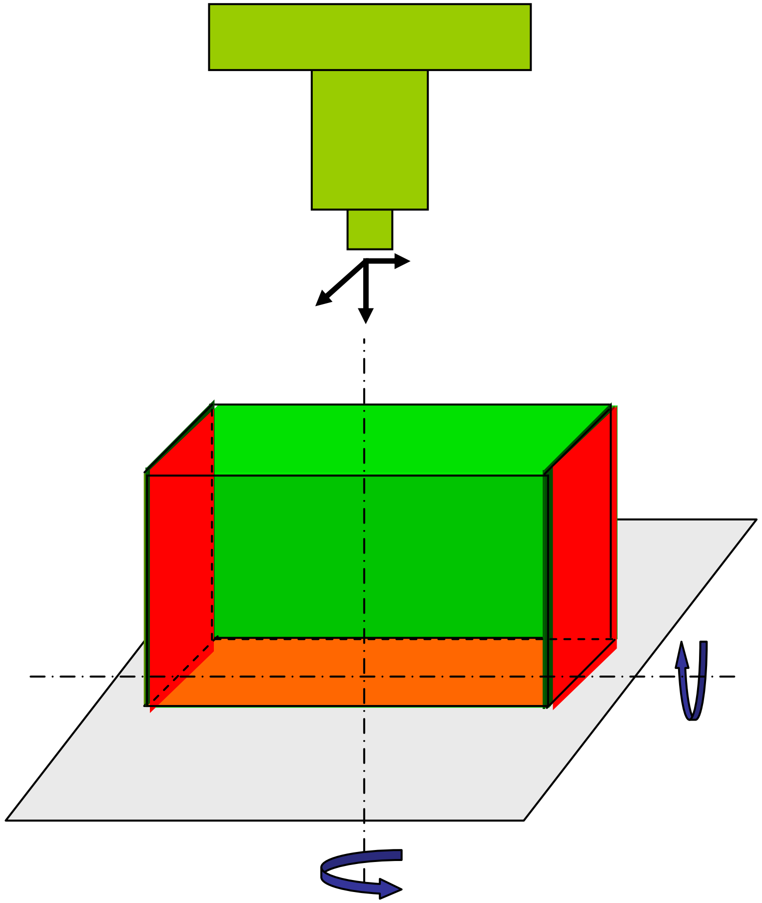
Problem size	Level of constraints	Best method
Small	low	MIP
	high	Graph approach or Branch and Bound
Medium	high	
	low	GRASP
Large	high	
	low	

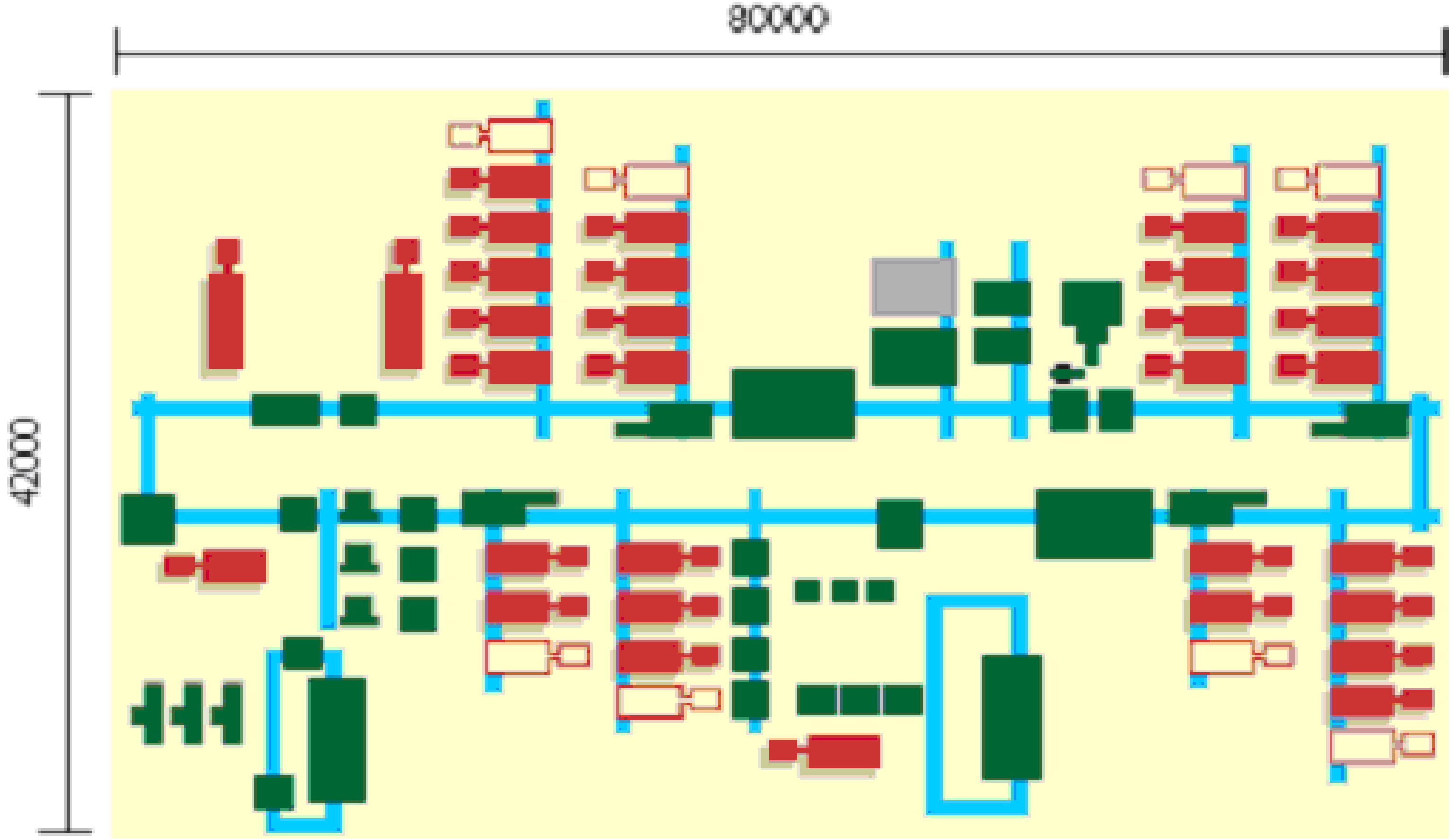
Lines composed of machining centers



4- and 5- axis centers

Accessibility constraints



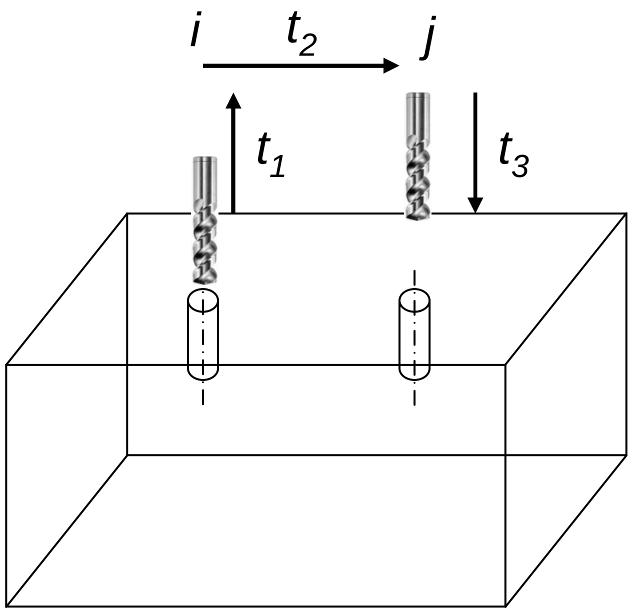


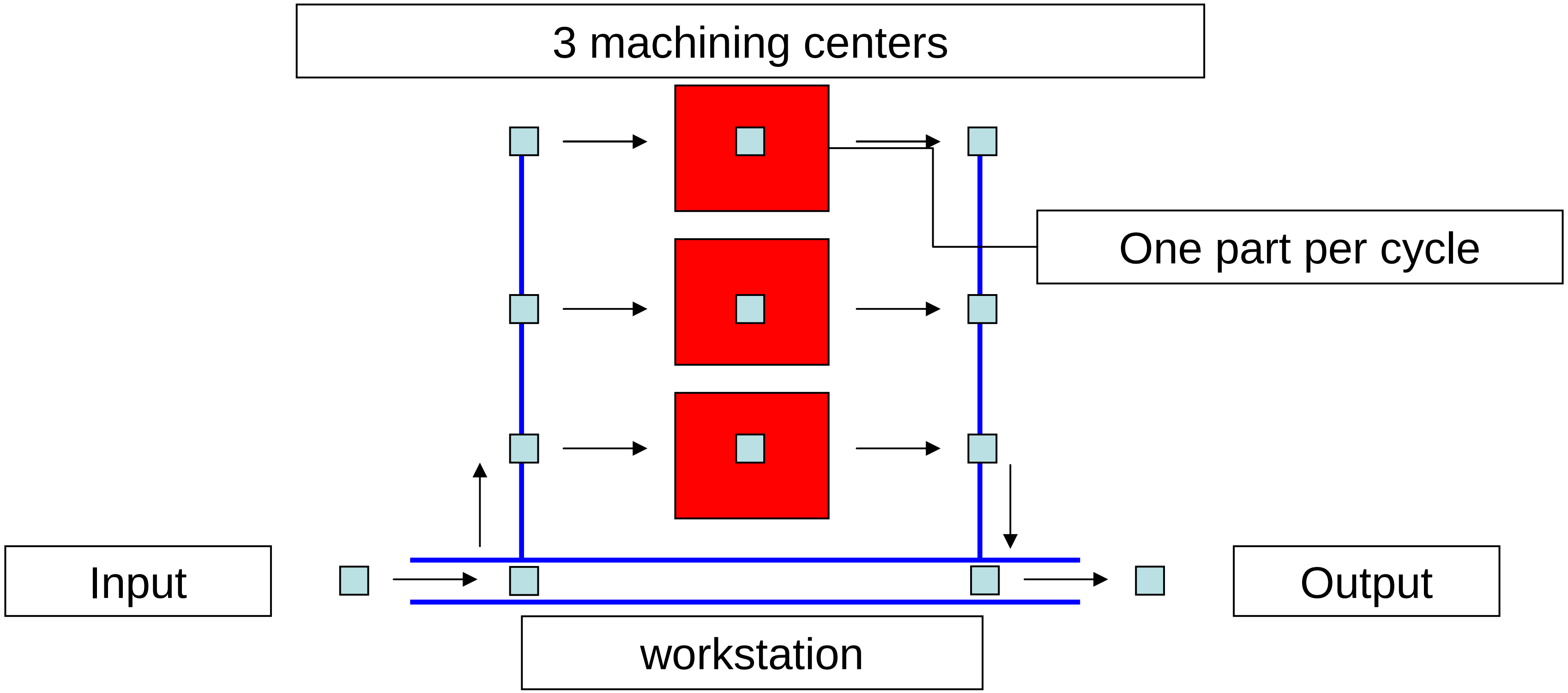
- 1250 parts/day
- 32 machines

Tool change time

Additional setup times

$$t_{ij} = t_1 + t_2 + t_3$$





Parallel machines

- Minimize

$$C_m * \sum_{k=1}^{m_0} \sum_{n=1}^{n_0} n \cdot y_{nk} + C_{WS} * \sum_{k=1}^{m_0} \sum_{n=1}^{n_0} y_{nk}$$

Cost of machines   Cost of stations

Subject to

$$\sum_{n=1}^{n_0} y_{nk} \leq 1, \forall k = 1,2,\ldots, N_s$$

$$\sum_{a \in A} z_{ka} \leq 1, \forall k = 1,2,\ldots, N_s$$

$$\sum_{q \in S(k)} x_{iq} \leq \sum_{a \in A(i)} z_{ka}, \forall k \in K(i), \forall i \in N$$

- Setups

$$\tau_q \geq \sum_{j \in M(q+1) \setminus \{i\}} t_{ij} \cdot (x_{iq} + x_{j(q+1)} - 1),$$

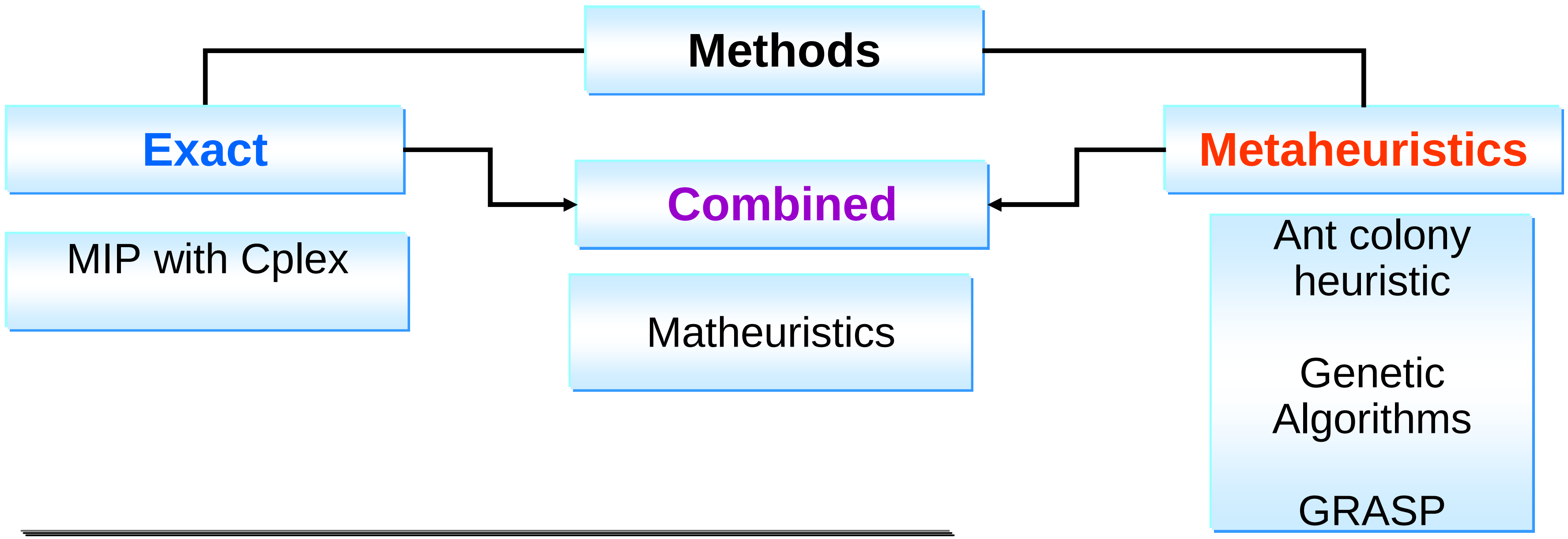
$$\forall i \in M(q), \forall q \in S(k) \setminus \max\{S(k)\}, \forall k = 1,2,\ldots,N_s$$

- Takt time $\sum_{q \in S(k) \setminus \max\{S(k)\}} \tau_q + \sum_{i \in N(k)} \sum_{q \in S(k)} t_i \cdot x_{iq} \leq T_0 \cdot \sum_{n=1}^{n_0} n \cdot y_{nk}, \forall k = 1,2,\ldots,N_s$

- Precedence $1 + \sum_{q \in Q(j)} q \cdot x_{jq} \leq \sum_{q \in Q(i)} q \cdot x_{iq}, \forall i \in N, \forall j \in P_i$

- Inclusion $\sum_{q \in S(k) \cap Q(i)} x_{iq} = \sum_{q \in S(k) \cap Q(j)} x_{jq}, \forall i, j \in e, \forall e \in ES, \forall k \in K(i) \cap K(j)$

- Exclusion $\sum_{q \in S(k)} (x_{iq} + x_{jq}) \leq 1, \forall (i, j) \in \overline{ES}, \forall k \in K(i) \cap K(j)$



M. Essafi, X. Delorme, A. Dolgui, and O. Guschinskaya. A MIP Approach for Balancing Transfer Lines with Complex Industrial Constraints, *Computers & Industrial Engineering* 58, 2010, 393–400

P. Borisovsky, X. Delorme, A. Dolgui. Genetic algorithm for balancing reconfigurable machining lines, *Computers & Industrial Engineering* (under review)

Conclusions

• This is an overview on our research on decision-aid for design of machining systems

• The optimization procedure was structured as follows:
- Takt time calculation, - Definition of tasks, - Choice of process plan, - Choice of system type, - Load balancing, - Equipment selection

• A set of models were developed and tested on real life examples

• Software was developed

Our approach can be used for design other types of production systems

This shows how advanced optimization techniques can be efficiently used for automated manufacturing system design

Some our recent publications

O. Battaïa, A. Dolgui, N. Guschinsky, G. Levin. A decision support system for design of large series machining lines composed of stations with rotary or mobile table, *Robotics and Computer Integrated Manufacturing*, 28 (6), 2012, 672–680.

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A. Dolgui, N. Guschinsky, G. Levin. Enhanced mixed integer programming model for a transfer line design problem, *Computers and Industrial Engineering*, 62(2), 2012, 570–578.

X. Delorme, A. Dolgui, M.Y. Kovalyov. Combinatorial design of a minimum cost transfer line, *Omega*, 40(1), 2012, 31–41.

M. Essafi, X. Delorme, A. Dolgui. Balancing lines with CNC machines: a multi-start Ant based heuristic, *CIRP Journal of Manufacturing Science and Technology*, 2, 2010, 176–182.

M. Essafi, X. Delorme, A. Dolgui, and O. Guschinskaya. A MIP Approach for Balancing Transfer Lines with Complex Industrial Constraints, *Computers and Industrial Engineering*, 58 (3), 2010, 393–400.

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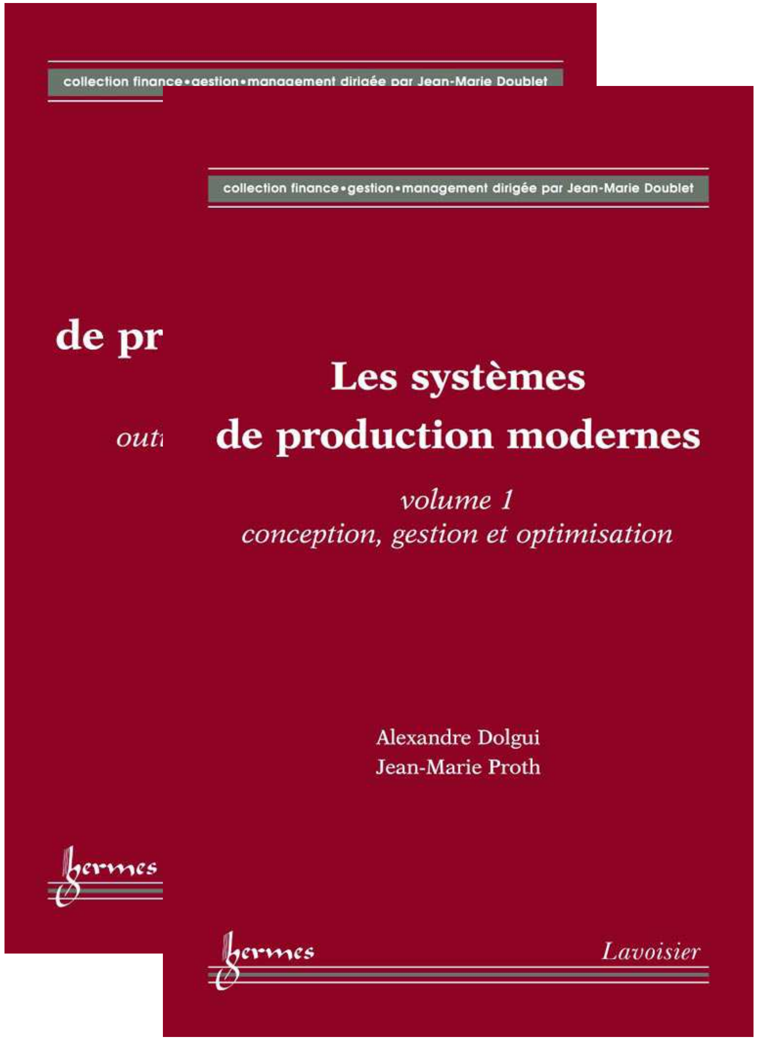
X. Delorme, A. Dolgui, M. Essafi, L. Linxe and D. Poyard. Machining Lines Automation. in: *Springer Handbook of Automation*, S.Y. Nof (Ed.), Springer, 2009, 599–618.



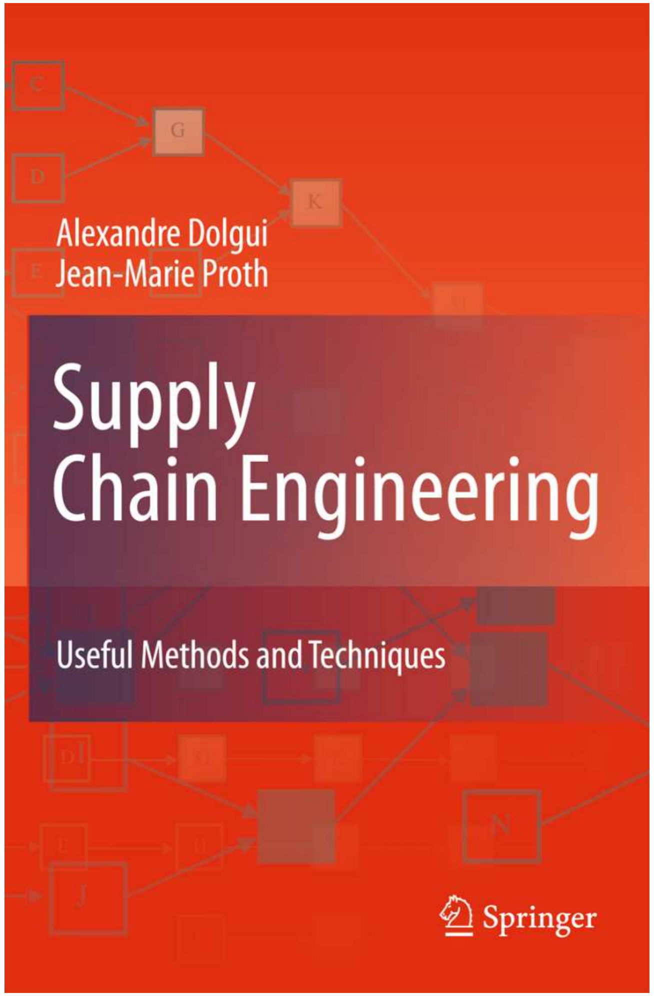
A. Dolgui, J.M. Proth.
Les systèmes de production modernes,
Hermès Science/Lavoisier, 2006,
2 volumes (In French), 806 pages

Other research topics of our team

- Combinatorial Design of Production and Assembly Lines
  - Assembly line balancing
  - Equipment selection
  - Buffer allocation

- Supply Chain Optimization under Uncertainties
  - Sales forecasting
  - Outsourcing
  - Inventory control under lead time uncertainty
  - Lot sizing

- Scheduling
  - Due dates assignment
  - Dynamic scheduling
  - Railway scheduling



A. Dolgui, J.M. Proth.
Supply chain engineering: useful methods and techniques, Springer, 2010, 542 pages

IFAC Conference on **Manufacturing Modelling for Management and Control**

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IPC vice-chair: Agostino Villa, Italy

Deadline for submission of papers (6 pages): **October 1st, 2012**

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Thank you very much for your attention

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