



**IMT Atlantique**  
Bretagne-Pays de la Loire  
École Mines-Télécom

## *Keynote talk*

18th Asia Pacific Industrial Engineering and Management Systems (APIEMS2017), December 3<sup>rd</sup>-6<sup>th</sup>, 2017, Indonesia



**Alexandre Dolgui**

**Professor and Head**

**Dept. DAPI, IMT Atlantique, campus in  
Nantes, France**

**[Alexandre.Dolgui@imt-atlantique.fr](mailto:Alexandre.Dolgui@imt-atlantique.fr)**

**[www.emse.fr/~dolgui](http://www.emse.fr/~dolgui)**





# Combinatorial design of machining lines

**Preliminary design**

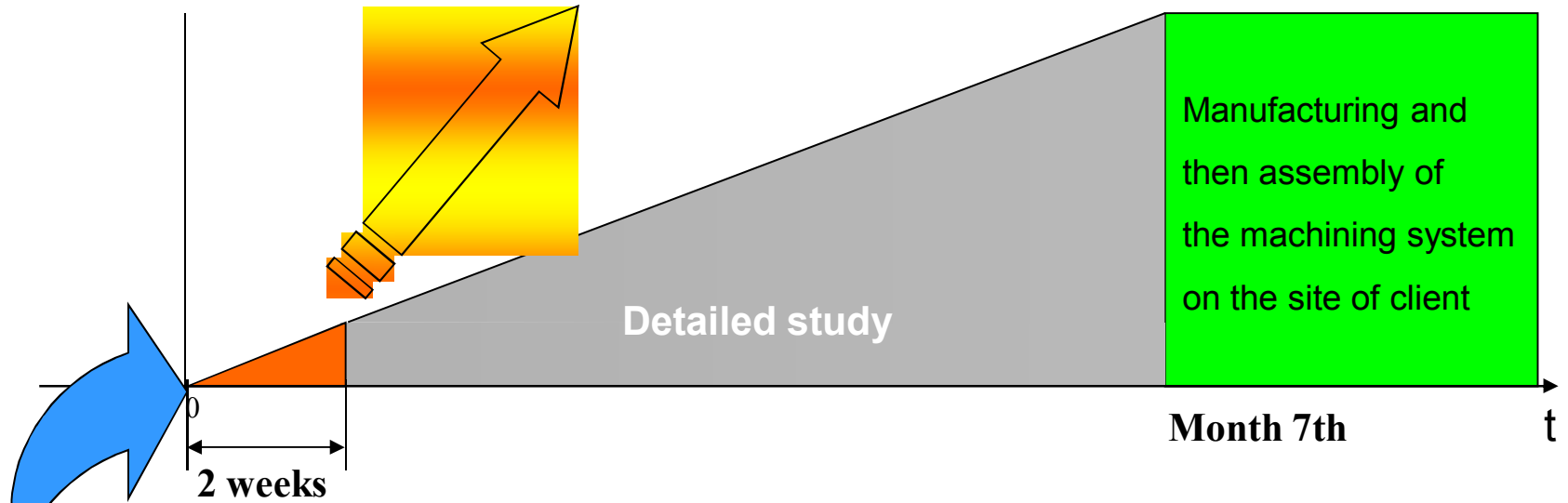
- Task assignment
- Process planning
- Equipment selection

**System specifications**

- Configuration
- Throughput
- Product quality
- System cost

**System manufacturer**

PCI-SCEMM



**Data : Agreement**

- Part specifications
- Annual volume of production
- Client preferences

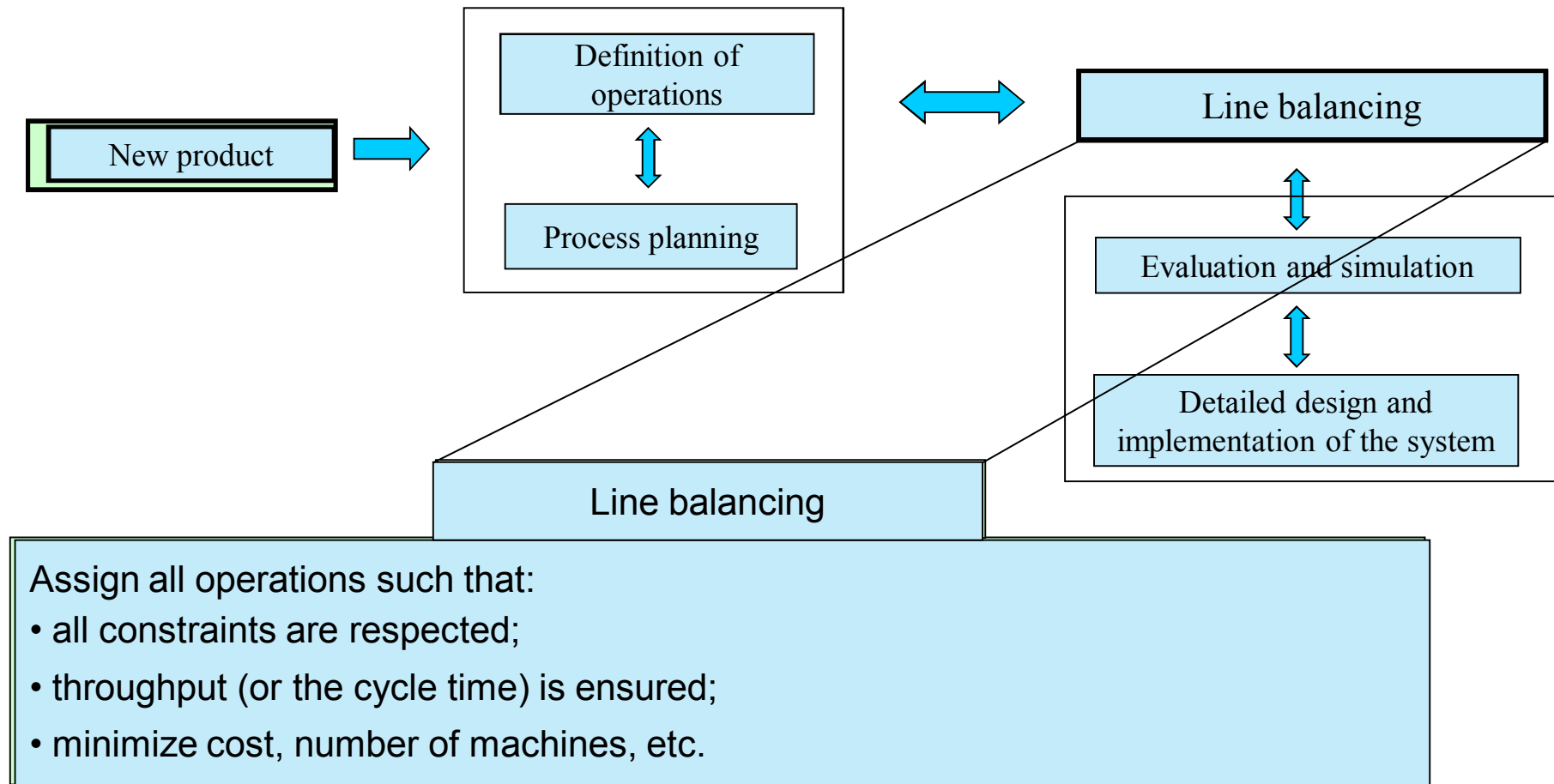
PSA Peugeot Citroën

**Client**



# Decision-aid software for machining line design

## Design of a machining systems





## Steps for decision making

Step 1. “Takt time” calculation and choice of layout type

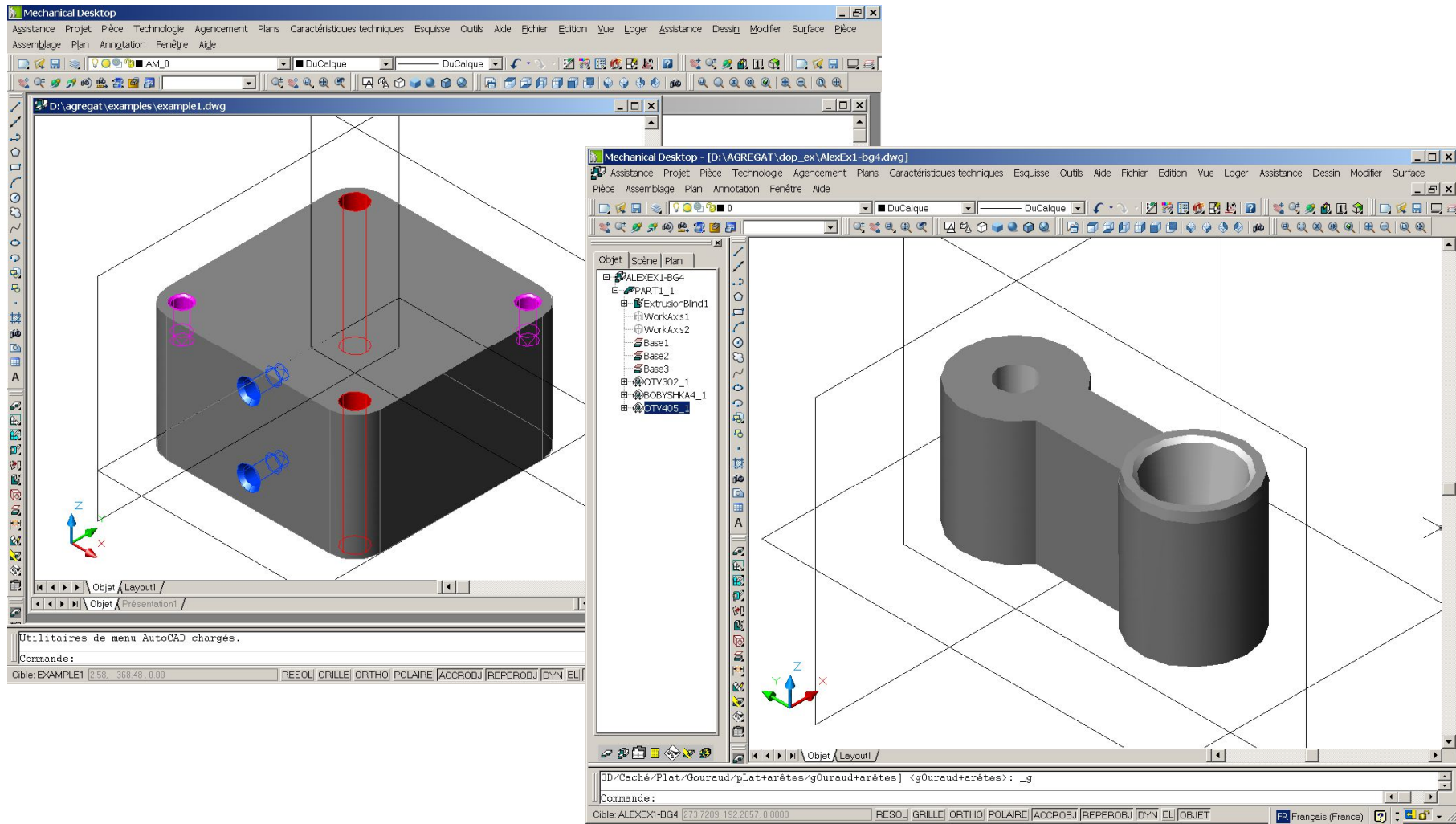
Step 2. Part modeling: using standard features to define tasks

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

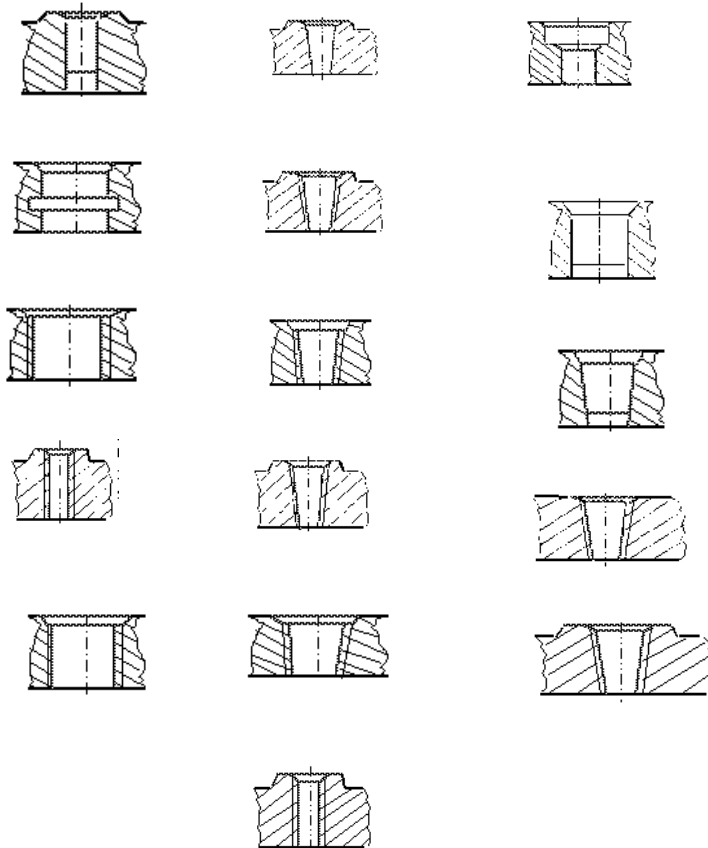
Step 5. Preliminary 3D model

## Step 2: Part modeling to define tasks





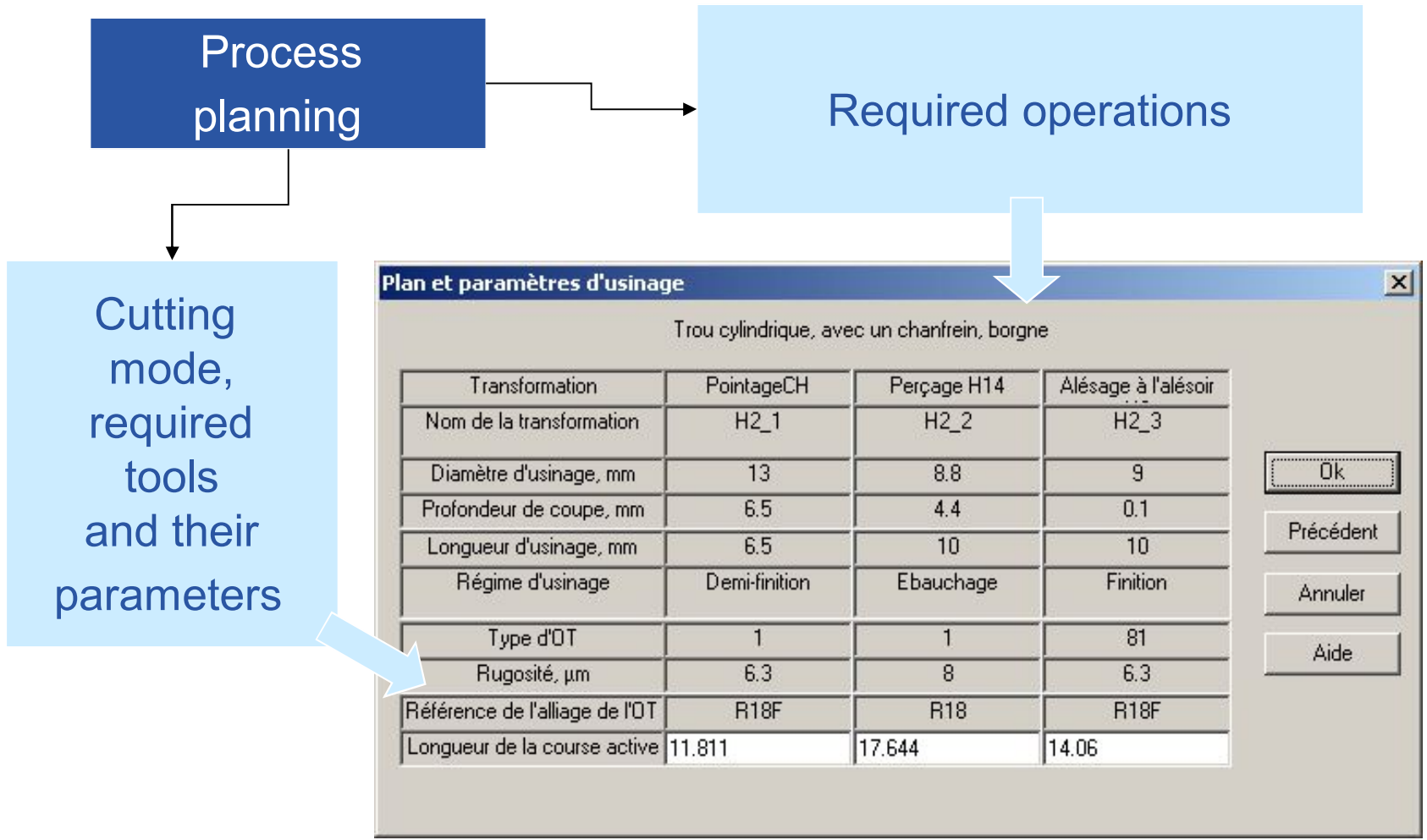
## *Database with features*



Examples of different  
types of holes  
from our database



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



## Generation of constraints

**Contrainte de précédence**

Complément à la règle	Opération i	Opération j
	H5_2	H2_1

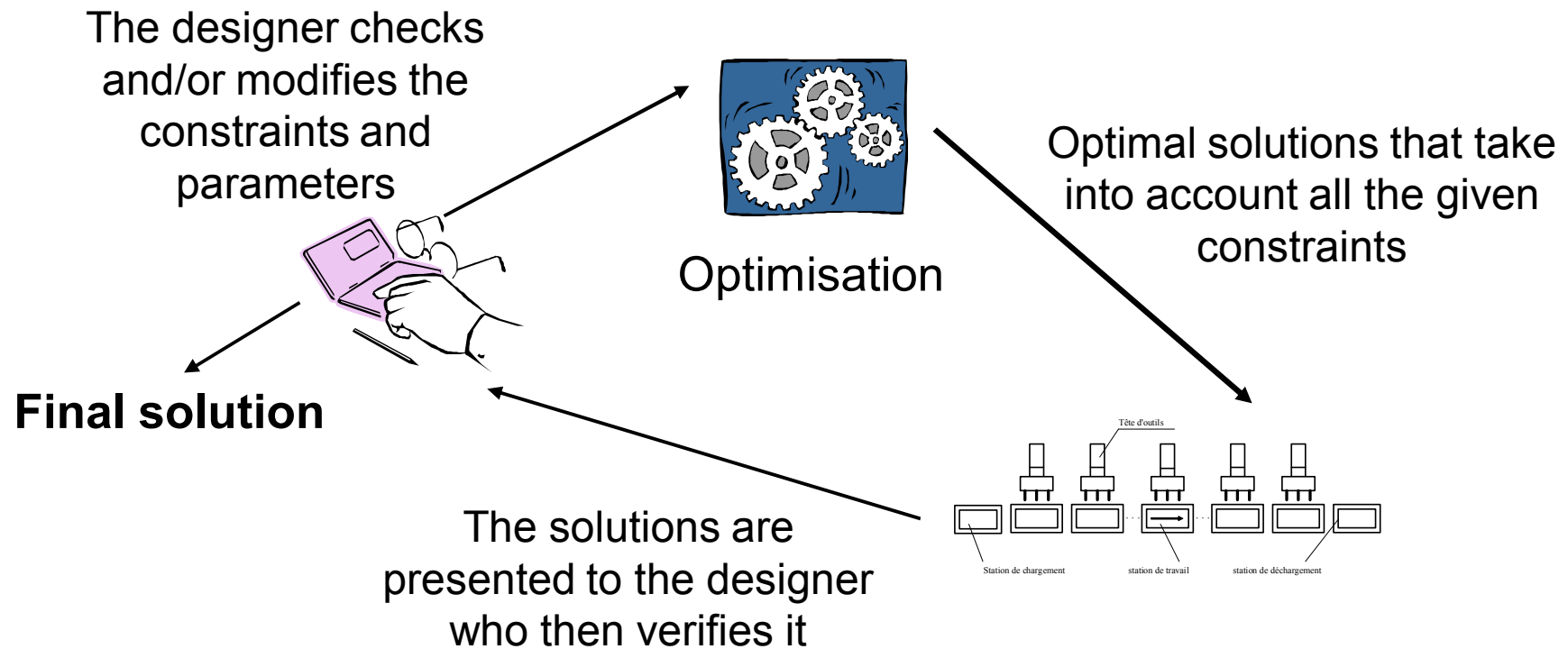
Ok  
Annuler  
Aide

**Contrainte d'exclusion dans un bloc au niveau de la distance minimale entre les centres des EST**

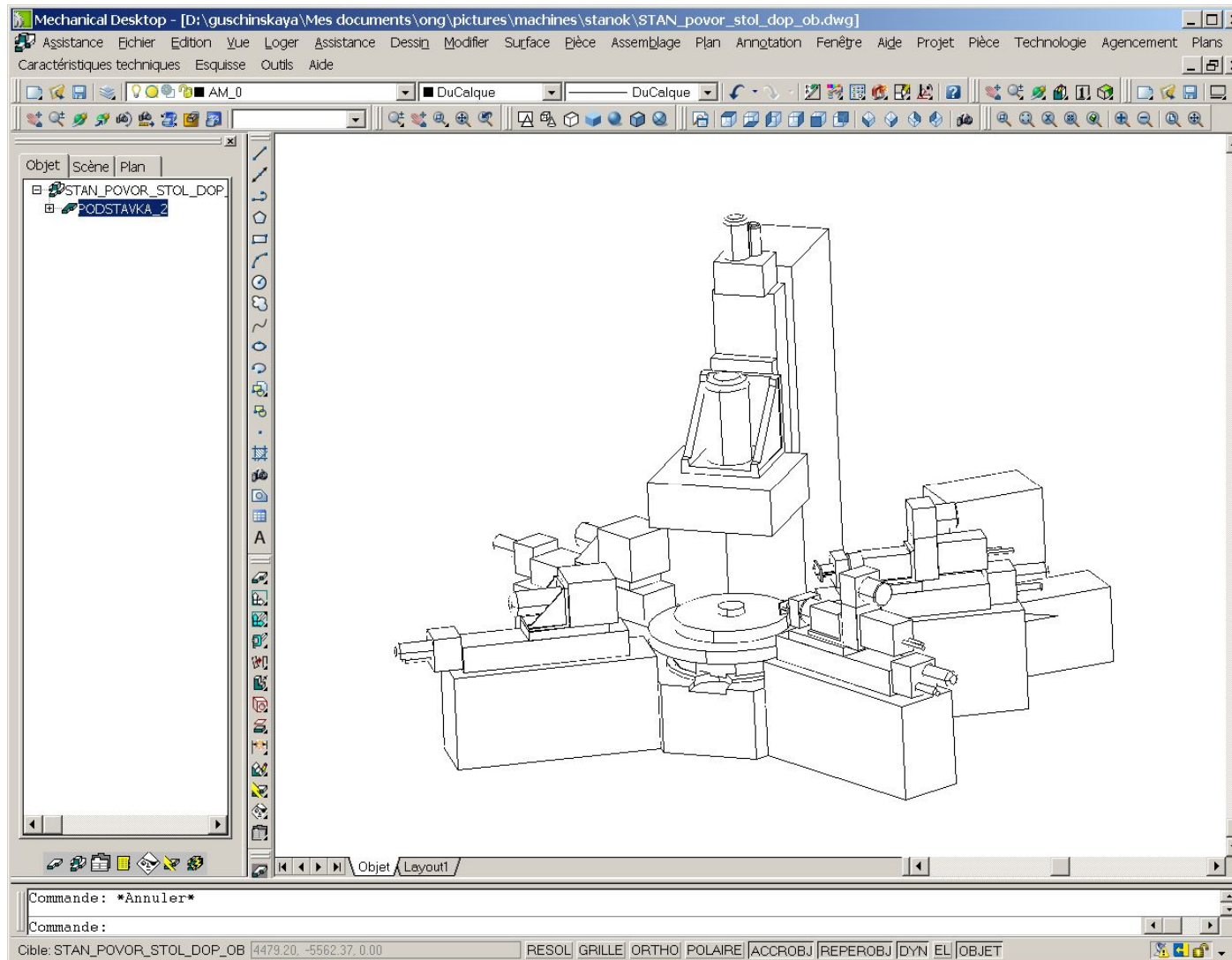
Possibilité d'application	Axes d'usinage	Opération i	Opération j	EST d'opération i	EST d'opération j	Distance entre les centres des EST	
						Réelle	Minimale
<input checked="" type="checkbox"/>	H1	Perçage H14	PointageCH	H3	H4	18	40.5
<input checked="" type="checkbox"/>		Perçage H14	Perçage	H3	H4	18	40.5
<input checked="" type="checkbox"/>		Perçage H14	FiletageF	H3	H4	18	43
<input checked="" type="checkbox"/>	V3	PointageCH	FiletageF	H7	H6	42	91
<input checked="" type="checkbox"/>		Perçage	FiletageF	H7	H6	42	91
<input checked="" type="checkbox"/>		FiletageF	PointageCH	H7	H6	42	91
<input checked="" type="checkbox"/>		FiletageF	Perçage	H7	H6	42	91
<input checked="" type="checkbox"/>		FiletageF	FiletageF	H7	H6	42	91

Ok  
Annuler  
Aide

## Step 4: Line balancing and equipment selection



## Step 5: 3D layout



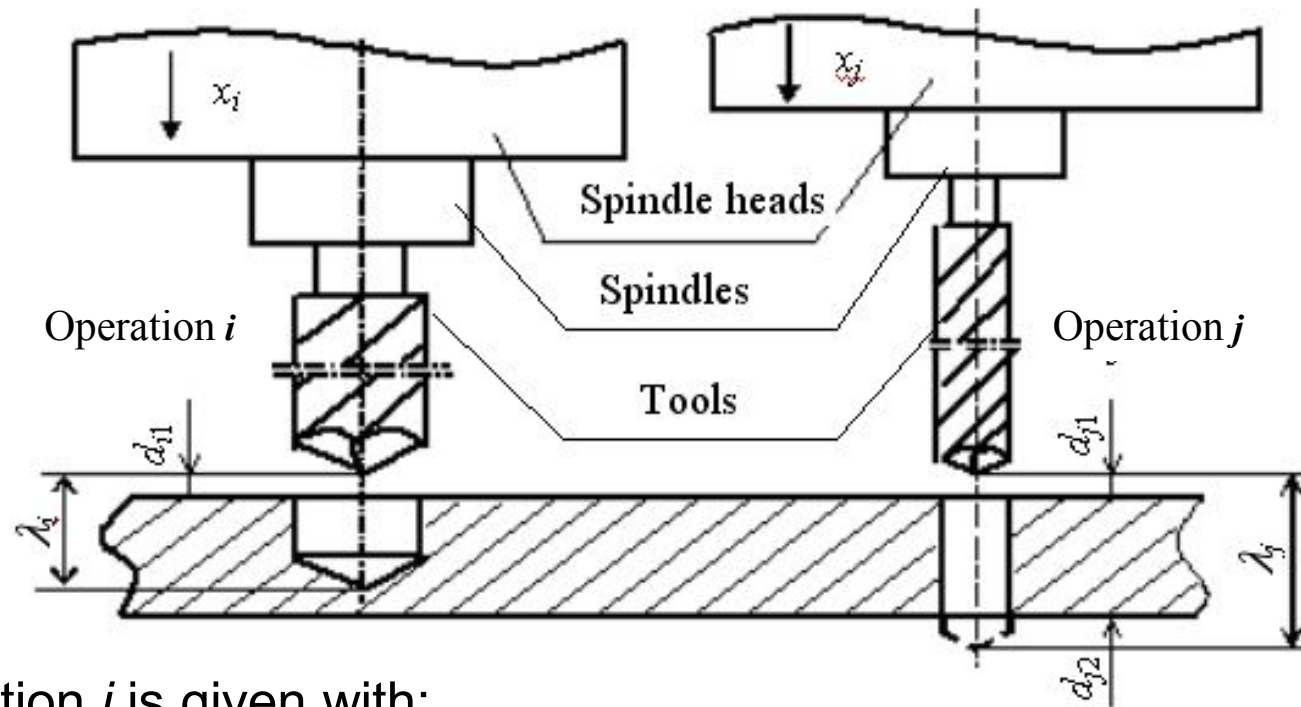


# Optimisation models for mass production lines with multi- spindle heads

## Multi-spindle heads



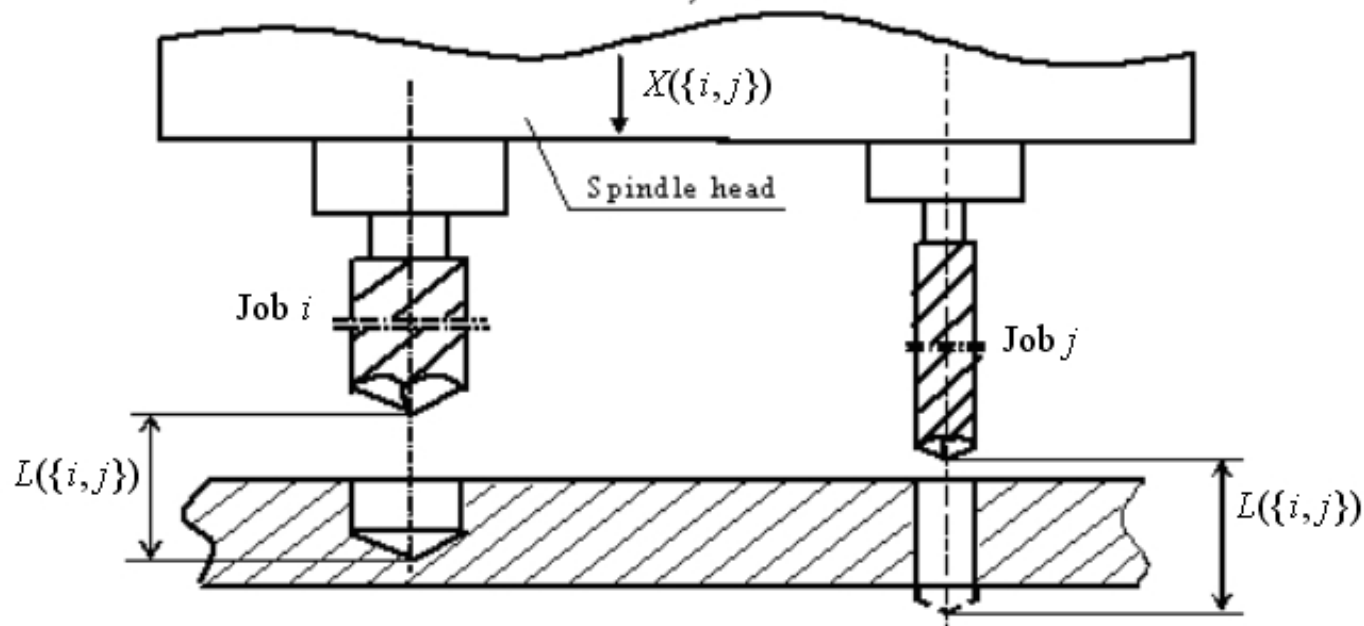
## Operation's parameters



Operation *j* is given with:

Machining length  $\lambda_j$

Feed per minute  $x_j$



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*

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

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

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

## 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:

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



- Exclusion constraints:

$$e \notin N_{kl}, e \in \overline{EB}, k=1, \dots, m, l=1, \dots, n_k$$

$$e \notin N_k, e \in \overline{ES}, k=1, \dots, m;$$

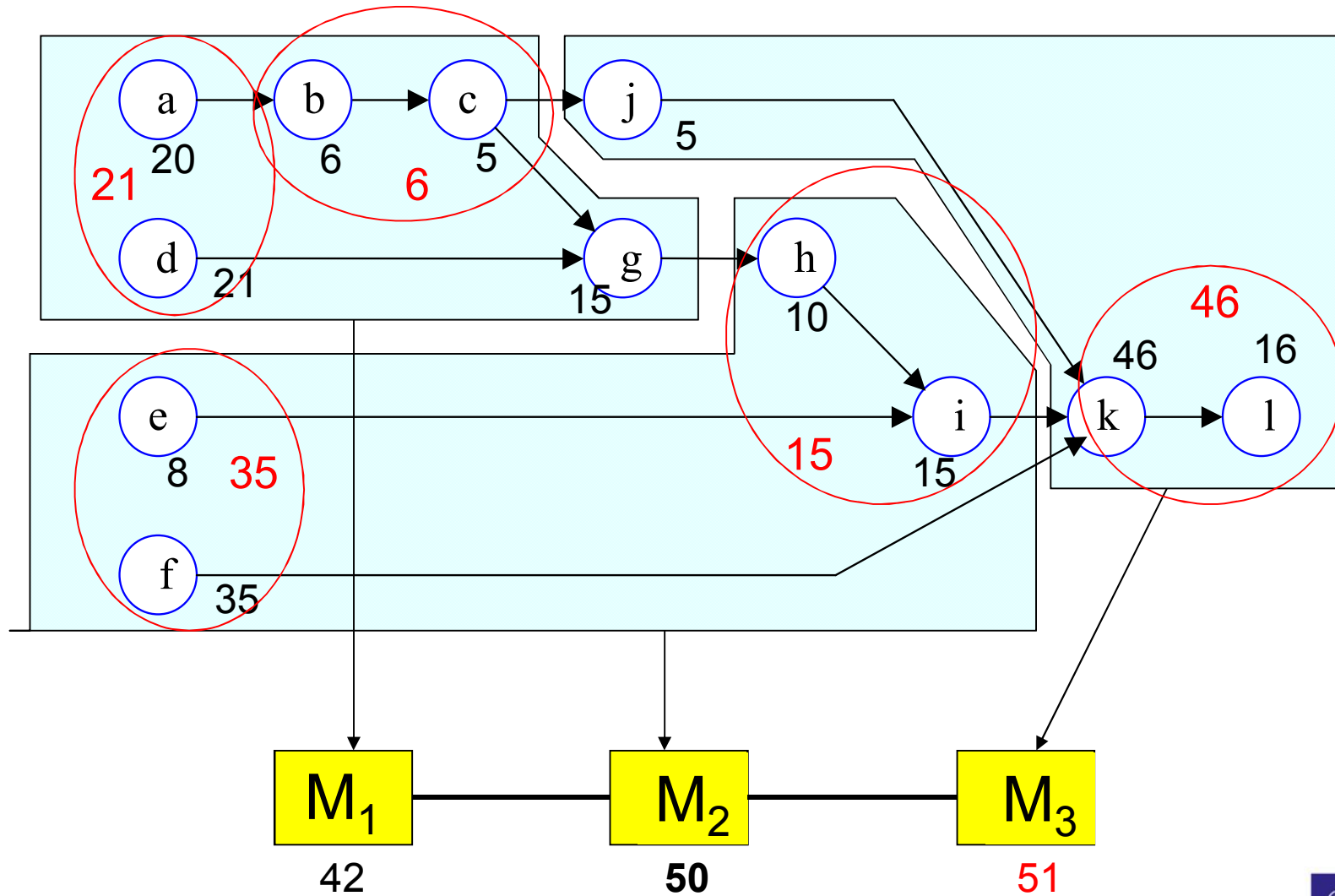
- Number of working stations:

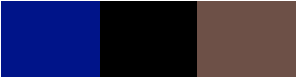
$$m = m(P) \leq m_0$$

- 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



## MIP model (Cplex)

**Analysis of constraints** to reduce  
the number of binary decision  
variables



**Cplex solver** for MIP model

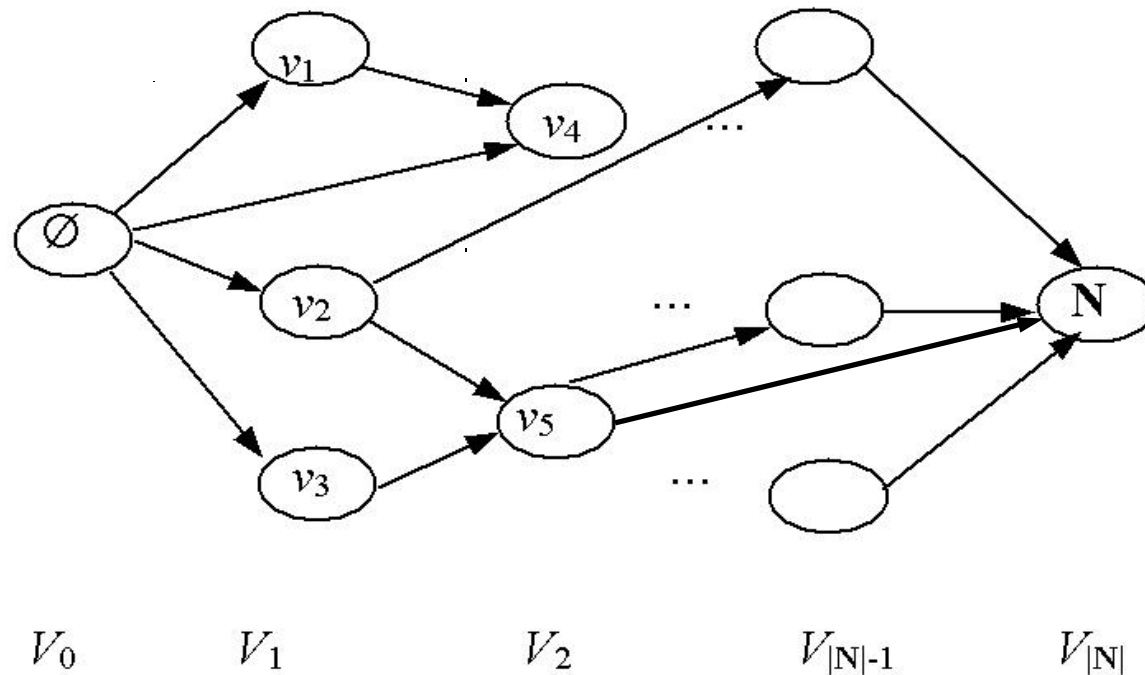
Note that without this constraint analysis:  
Only problems with maximum 40 tasks  
were optimally solved in 10 hours

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

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

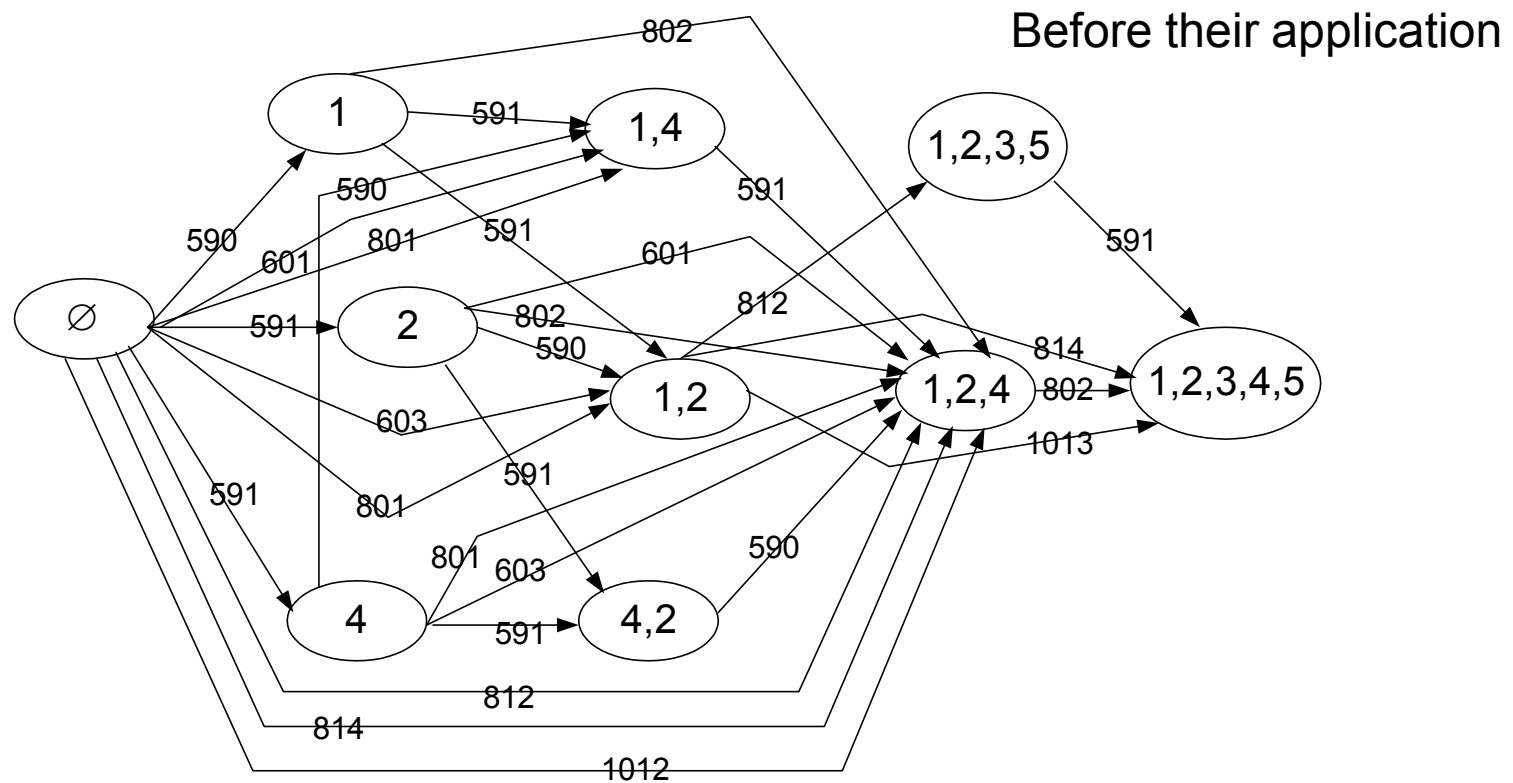
$$\sum_{k=1}^{m(z)} \underline{t}(u_k \setminus u_{k-1}) \leq T_0 - \tau'';$$

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

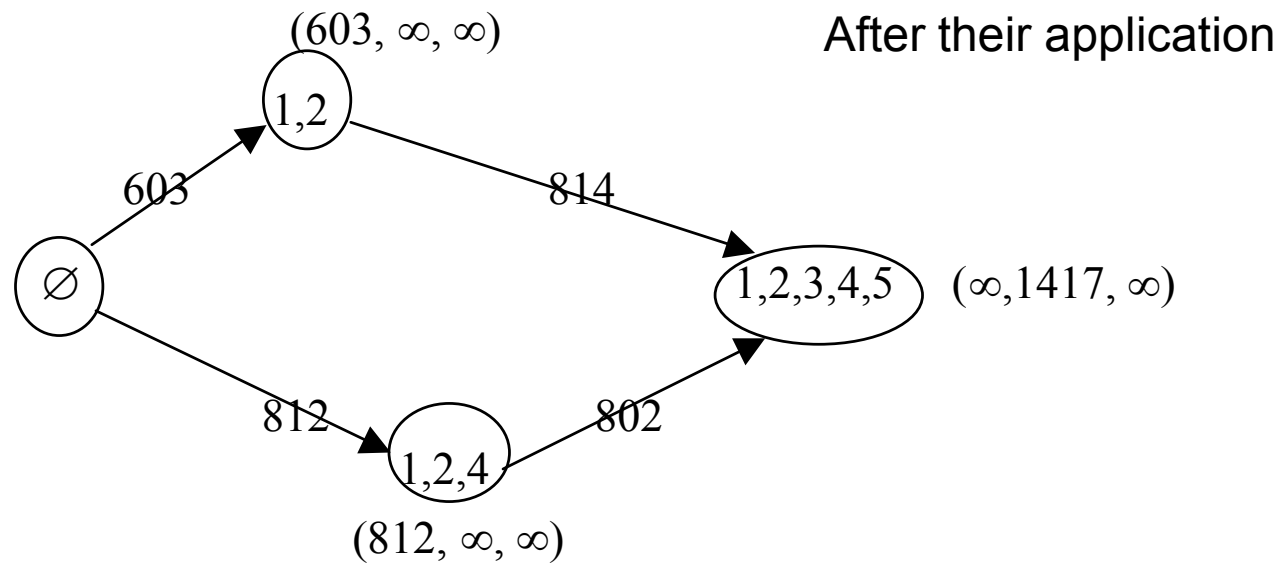
$$m(z) \leq 3.$$



## Powerful dominance properties: An example

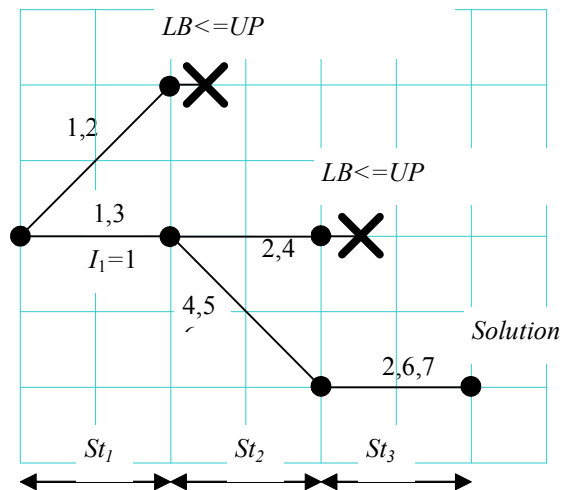


## Powerful dominance properties: An example



## Branch and Bound

- Enumerate solutions
- Evaluate Lower (LB) and Upper (UP) Bounds  
(a novel approach using set partitioning)
- Prune branches where  $LB \leq UP$
- 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**
- **6 mathematical models (one per type of system)**
- **3 exact approaches (B&B, Graph and MIP with Cplex)**
- **8 heuristic procedures (list, GRASP, decomposition, ...)**

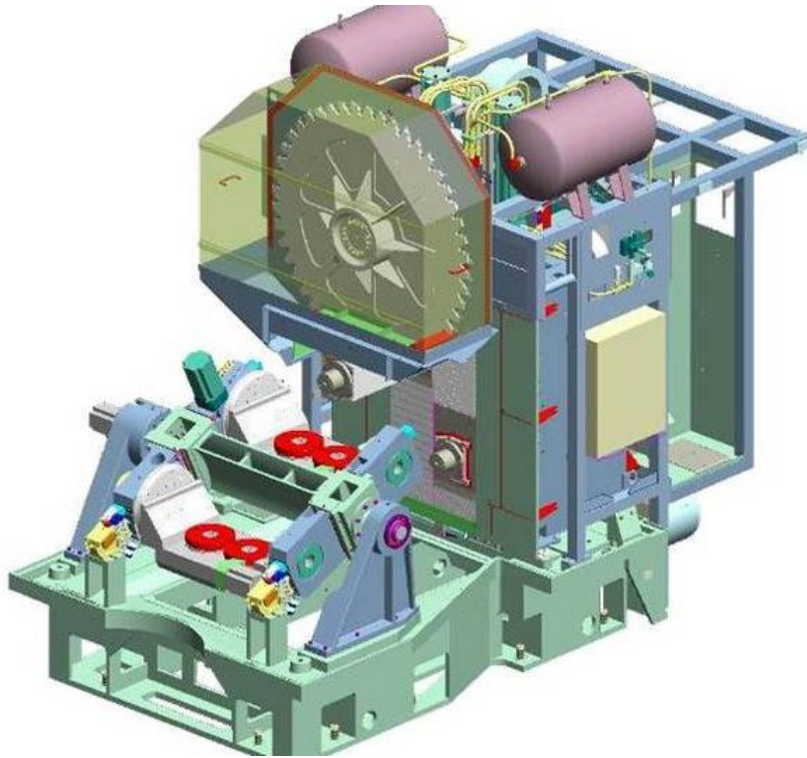


*Comparison of the methods*

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

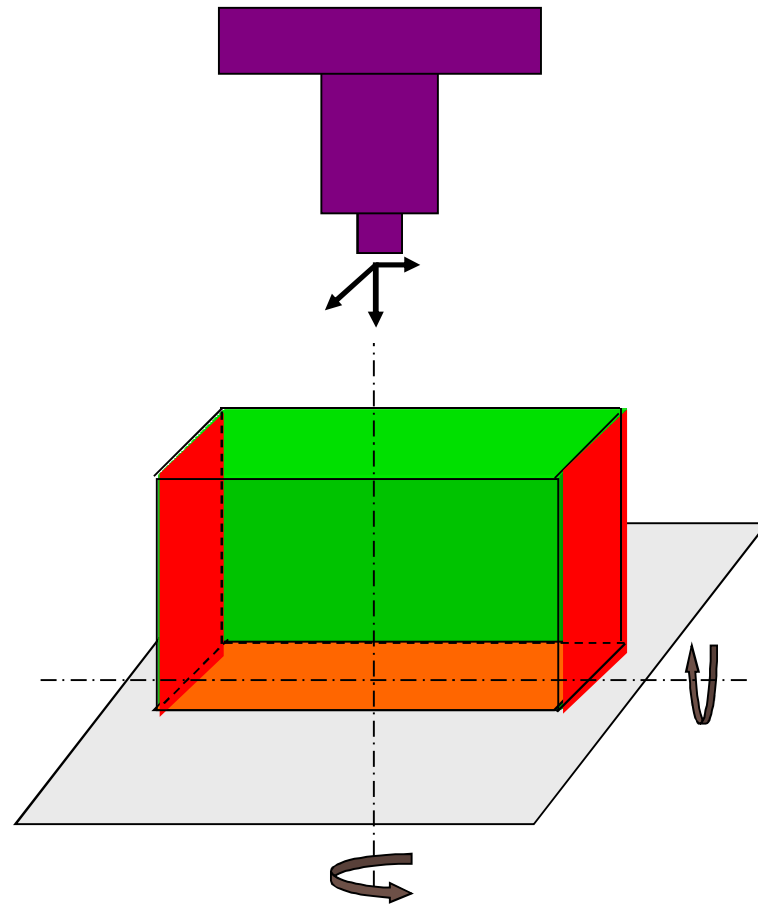


# Optimisation models for lines composed of machining centers

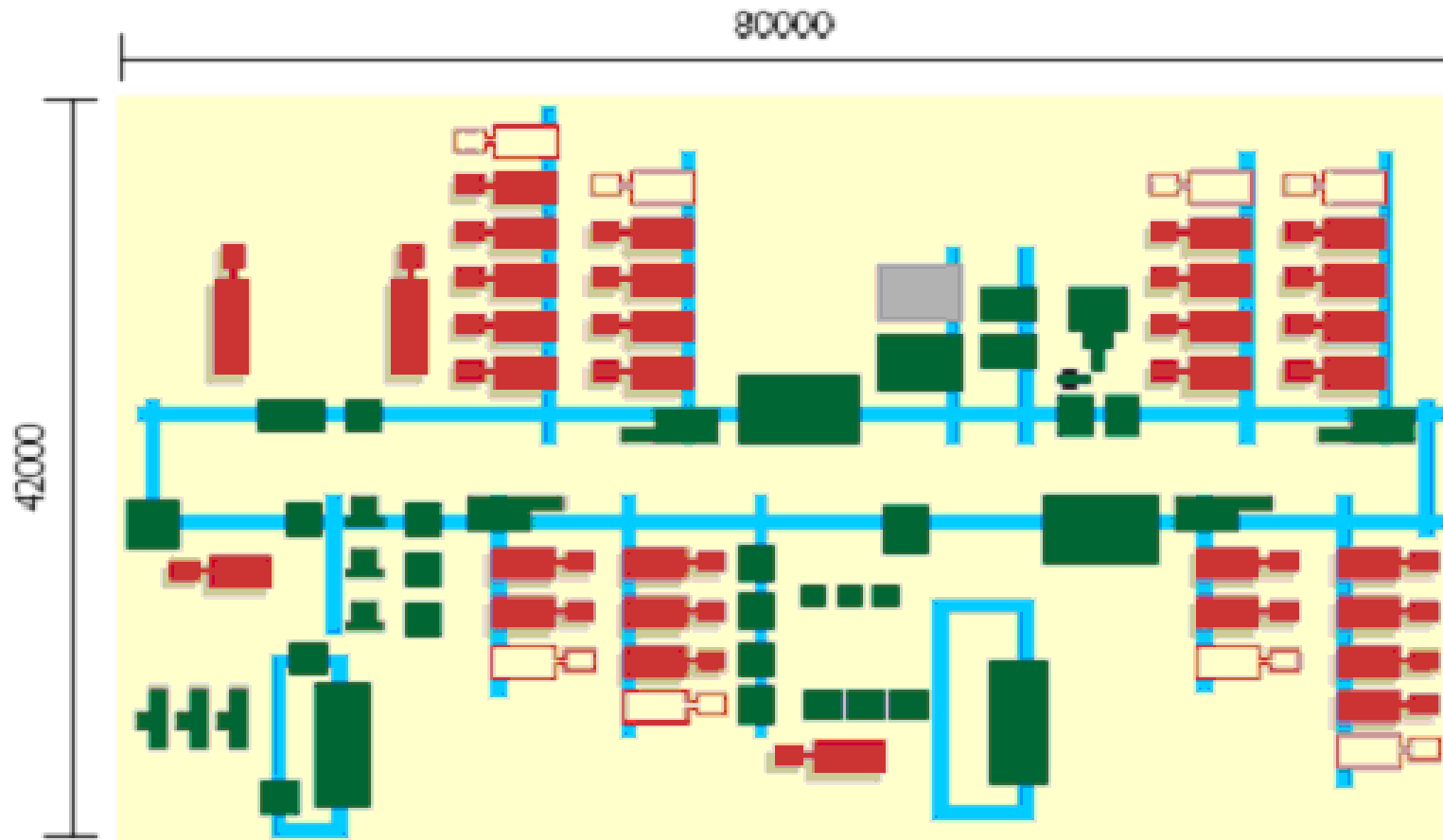


4- and 5- axis centers

### Accessibility constraints







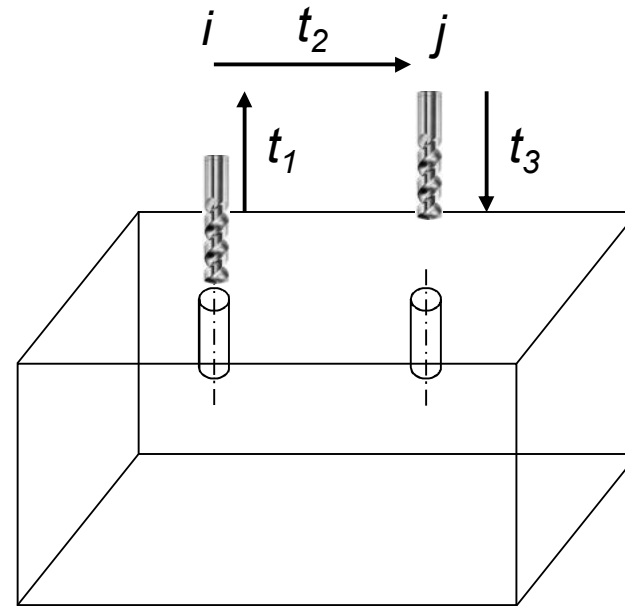
- 1250 parts/day
- 32 machines

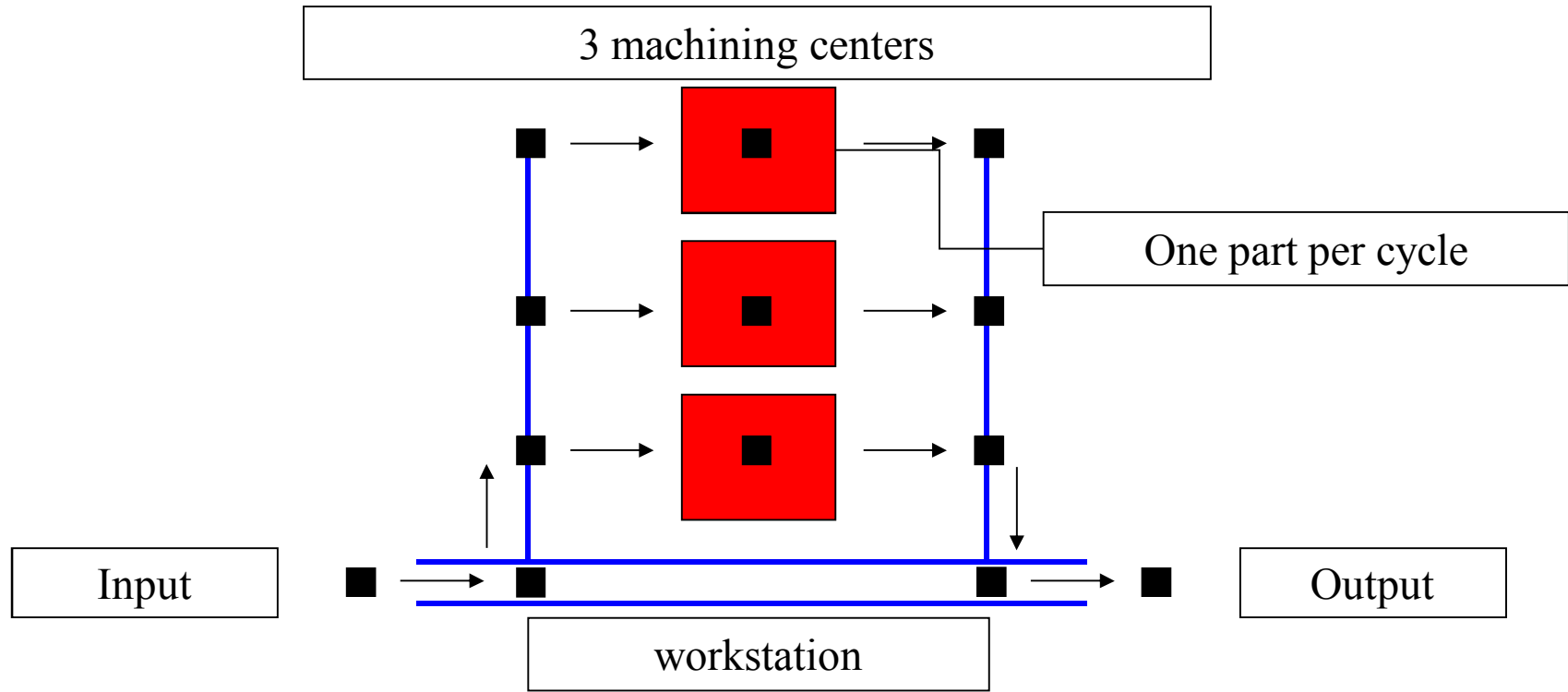


Tool change time

## 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

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

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

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

- Setups

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

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

- Takt time

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

- Precedence

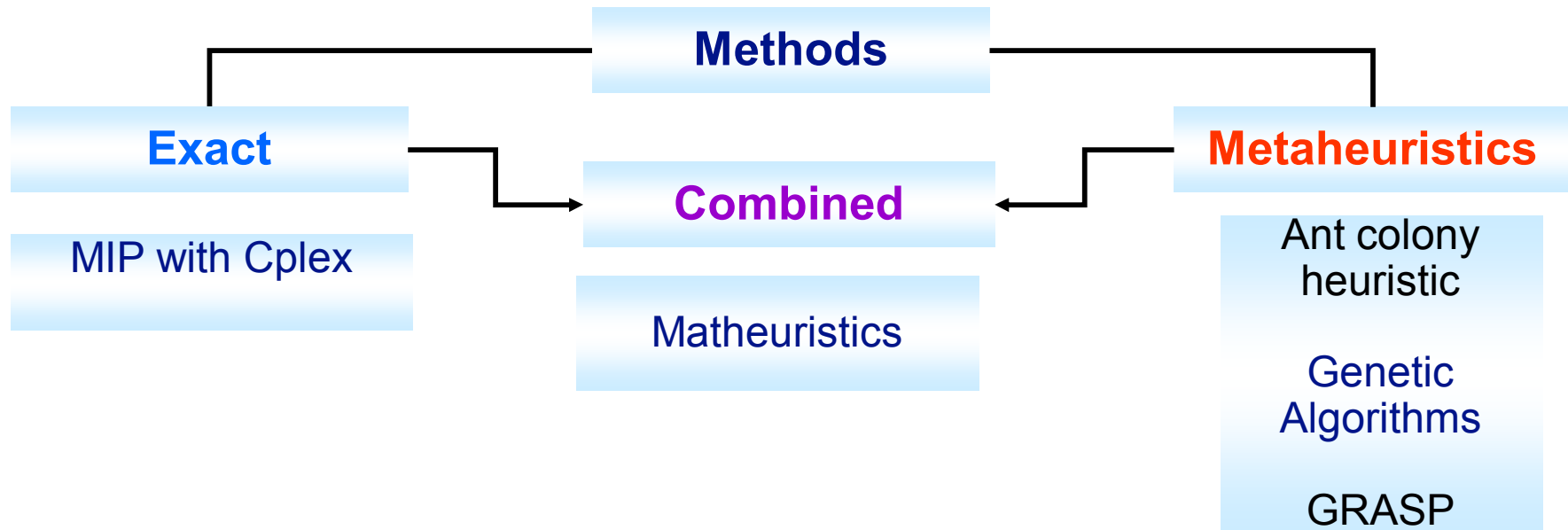
$$1 + \sum_{q \in Q(j)} q \cdot x_{jq} \leq \sum_{q \in Q(i)} q \cdot x_{iq}, \forall i \in N, \forall j \in P_i$$

- 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*, 2013





## 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 other relevant publications of our team

- O. Battaïa, A. Dolgui, N. Guschinsky. [Decision support for design of reconfigurable rotary machining systems for family part production](#), *International Journal of Production Research*, vol. 55, n° 5, 2017, p. 1368–1385
- O. Battaïa, D. Brissaud, A. Dolgui, N. Guschinsky. [Variety-oriented design of rotary production systems](#), *CIRP Annals Manufacturing Technology*, vol. 64, n° 1, 2015, p. 411–414.
- P. Borisovsky, X. Delorme, A. Dolgui. [Balancing recongrurable machining lines via a set partitioning model](#), *International Journal of Production Research*, vol. 52, n° 13, 2014, p. 4026–4036.
- 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.
- O. Battaïa, A. Dolgui. [Reduction approaches for a generalized line balancing problem](#), *Computers and Operations Research*, 39(10), 2012, 2337–2345.
- 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.
- A. Dolgui and I. Ihnatsenka. [Branch and Bound Algorithm for a Transfer Line Design Problem: Stations with Sequentially Activated Multi-spindle Heads](#), *European Journal of Operational Research*, 197( 3), 2009, 1119–1132.
- 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.