Advances in Forestry Control &
Automation Systems in Europe

# INTEGRATION OF OR AND MPC TECHNIQUES TO THE BIOMASS SUPPLY CHAIN FOR ENERGY PRODUCTION


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# Agenda

1. Problem definition
2. Solution method
    1. MIP model
    2. Matheuristic
    3. “Control” level
    4. Feedback loop
3. Preliminary computational results
4. Concluding remarks
5. References

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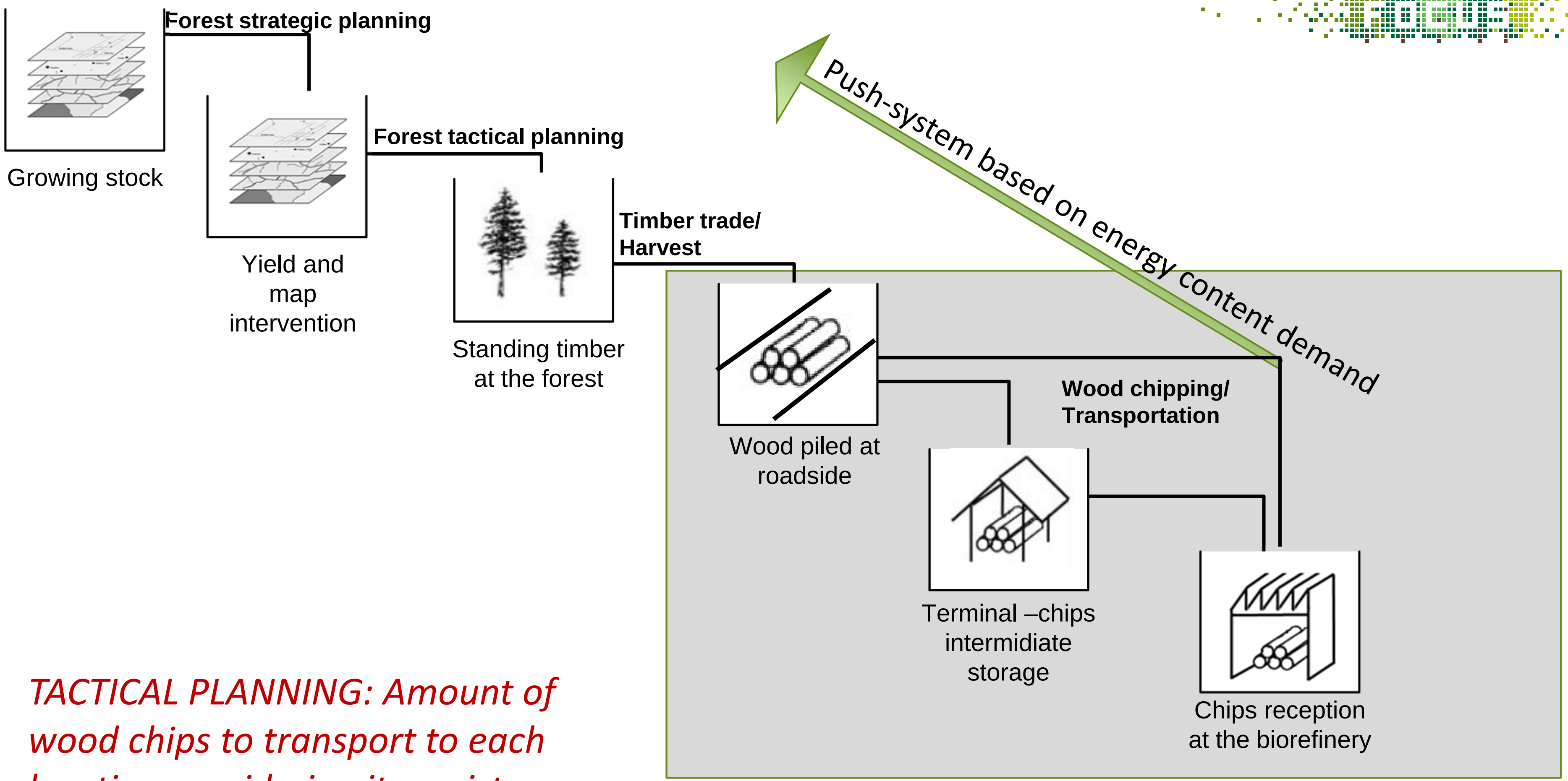
# Wood chips delivery planning problem




*TACTICAL PLANNING: Amount of wood chips to transport to each location considering its moisture content (flow variables)?*

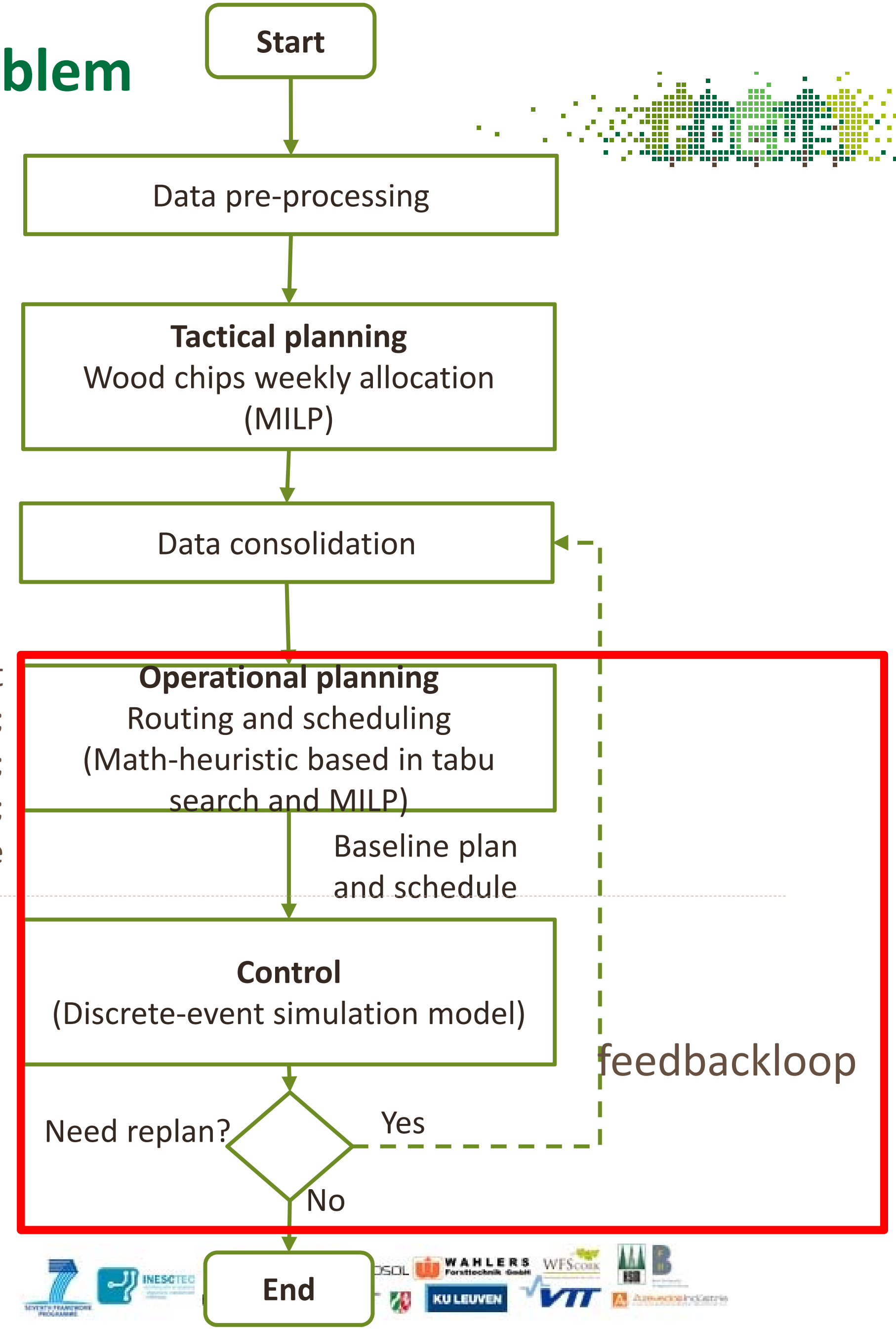
*OPERATIONAL PLANNING: Daily routing and scheduling of trucks and chippers*

# Modelling Approach for the Wood chips delivery planning problem

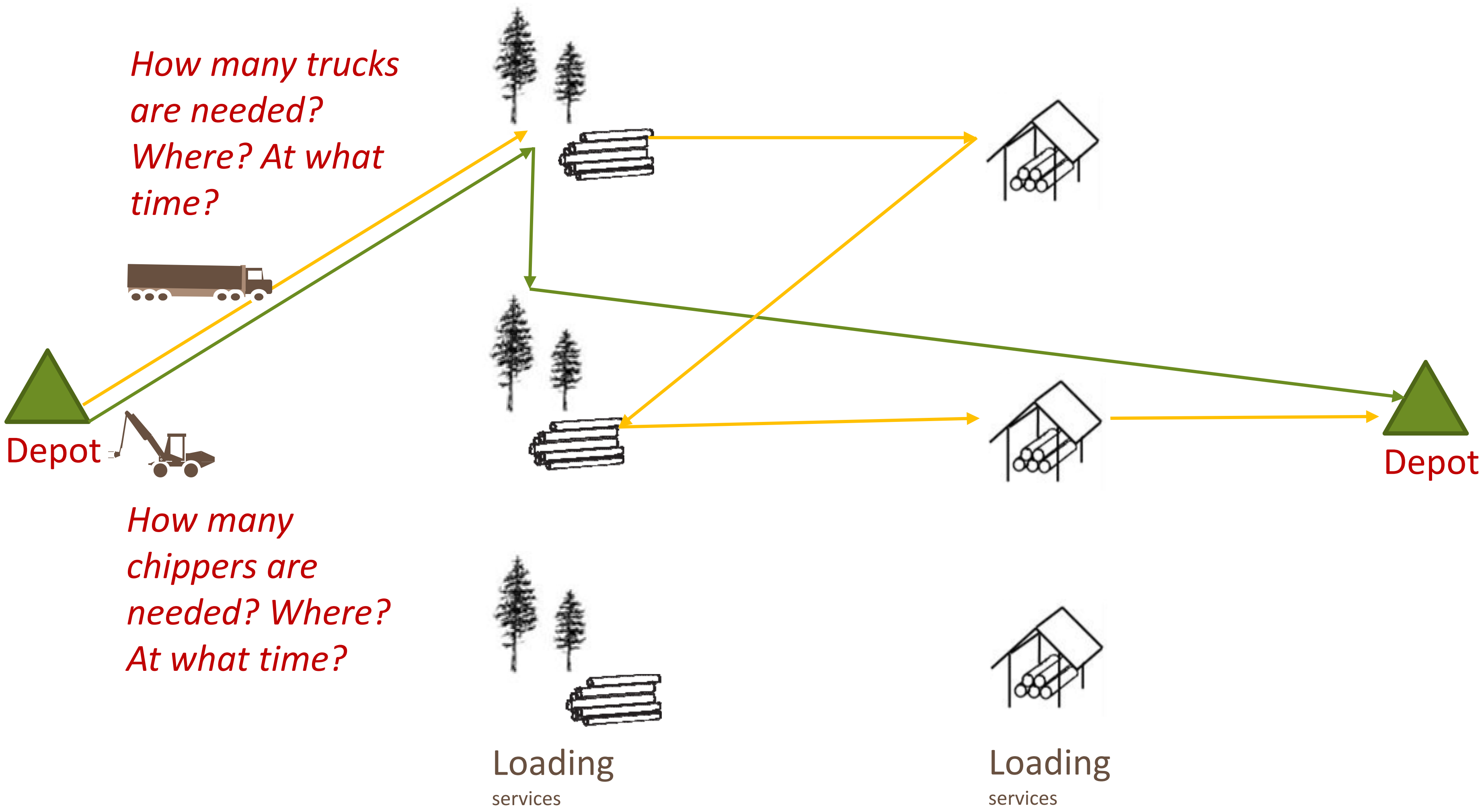
max NPV
✓Allocation of raw materials to the mills;
✓Upper bound for truck fleet and chipper dimensioning

min unproductive time in chiping and transport
✓Chippers routing and scheduling;
✓Trucks routing and cheduling;
✓Synchronization of vehicles;
-> Fleet size

Check impact of events into the plan execution and expected energy content at the end of the day



# Operational planning: Daily routing and scheduling of trucks and chippers



# MIP for the Daily routing and scheduling of trucks and chippers

The problem can be modelled as two interconnected Vehicle Routing Problem, one for chippers and another for trucks, over the same network. They are interconnected through precedence and synchronization constraints:

**Decision variables:**

$$x_{ij}^{v} = \begin{cases} 1, if\ vehicle\ v\ \in R\ transverses\ arc\ (i,j) \in A \\ 0, otherwise \end{cases}$$

$w_i =$ Time spent by a chipper in node $i \in P_i^{1*}$. Note that, this includes the waiting time of a chipper in pile $i \in P$ *(minutes)*

**Objective function: Minimization** of unproductive **waiting** and **deadhead times** (i.e. (empty truck travel times)

# MIP for the Daily routing and scheduling of trucks and chippers

**Constraints:**

- Standard VRP constraints for trucks
- Standard VRP constraints for chippers
- One chippers per wood pile
- Maximum working time for chippers and trucks
- Precedence and synchronization between trucks and chippers

$$\sum_{j \in \delta^+_{O^*}} x^k_{O^*j} = 1 \qquad \forall k \in K$$

$$\sum_{i \in \delta^-_{O^-}} x^k_{iO^-} = 1 \qquad \forall k \in K$$

$$\sum_{j \in \delta^+_i} x^k_{ij} - \sum_{j \in \delta^-_i} x^k_{ji} = 0 \qquad \forall k \in K, i \in P^{1*}$$

$$\sum_{k \in K} D^k_i \leq \sum_{v \in V} D^v_i \qquad \forall i \in P^{1*}$$

Chippers need to arrive first to any pile

$$\sum_{v \in T} D^v_{P^{i*}_s} \leq \sum_{v \in V} D^v_{P^{j*}_s} \qquad \forall s \in P;\ i,j \in P^*_s \wedge i < j$$

Once start chipping, chipp until pile

$$w_s \geq \sum_{v \in V} D^v_{P^{n*}_s} + st \sum_{v \in V} \sum_{j \in \delta^+_{P^{n*}_s}} x^v_{P^{n*}_s j} - \sum_{k \in K} D^k_{P^{1*}_s} \qquad \forall s \in P$$

Hard to solve for real-life instances -> need matheuristic

# Mst

**Precedence/synchronization constraints**

$$\sum_{k \in K} D_i^k \leq \sum_{v \in V} D_i^v \qquad \forall i \in P^{1*} \qquad (17)$$

Vehicle precedence

$$\sum_{v \in T} D_{P_s^{i*}}^v \leq \sum_{v \in V} D_{P_s^{j*}}^v \qquad \forall s \in P;\ i,j \in P_s^* \wedge i < j \qquad (18)$$

Service ordering

$$w_s \geq \sum_{v \in V} D_{P_s^{n*}}^v + st \sum_{v \in V} \sum_{j \in \delta^+_{P_s^{n*}}} x_{P_s^{n*} j}^v - \sum_{k \in K} D_{P_s^{1*}}^k \qquad \forall s \in P \qquad (19)$$

Waiting times

$$x_{ij}^v \in \{0,1\} \qquad \forall (i,j) \in A, v \in R \qquad (20)$$

$$D_s^v, w_l \geq 0 \qquad \forall (i,j) \in A, s \in ND, l \in P \qquad (21)$$

Variables' nature

Given this formulation, **real-size intances are unable to be solved in viable computational time**

# Solution method - MIP model

$$Min\ Z = \sum_{i \in P^{1*}} w_i + \sum_{(i,j) \in A: i \in M^*} \sum_{v \in R} t_{ij}\, x_{ji}^{v}$$

**Minimization** of unproductive **waiting** and **deadhead times**
(empty truck travel times)

s.t.

**For the chippers**

Standard VRP const.

$$\sum_{j \in \delta^+_{O^+}} x^k_{O^+ j} = 1 \qquad \forall k \in K \qquad (1)$$

$$\sum_{i \in \delta^-_{O^-}} x^k_{iO^-} = 1 \qquad \forall k \in K \qquad (2)$$

$$\sum_{j \in \delta^+_i} x^k_{ij} - \sum_{j \in \delta^-_i} x^k_{ji} = 0 \qquad \forall k \in K, i \in P^{1*} \qquad (3)$$

$$\sum_{k \in K} \sum_{j \in \delta^+_i} x^k_{ij} = 1 \qquad \forall i \in P^{1*} \qquad (4)$$

Time initialization

$$D^k_{O^+} = 0 \qquad \forall k \in K \qquad (5)$$

Maximum working time

$$D^k_i \leq maxTime \sum_{j \in \delta^+_i} x^k_{ij} \qquad \forall i \in P^{1*} \cup O^-, k \in K \qquad (6)$$

Time elapsed constraints

$$D^k_i + t_{ij} x^k_{ij} \leq D^k_j + maxTime(1 - x^k_{ij}) \qquad \forall i = O^+, j \in \delta^+_i, k \in K \qquad (7a)$$

$$D^k_i + (w_s + t_{ij}) x^k_{ij} \leq D^k_j + maxTime(1 - x^k_{ij}) \qquad \forall s \in P, i \in P^{1*}_s, j \in \delta^+_i, k \in K \qquad (7b)$$

# Solution method - MIP model

For the trucks

$$\sum_{j \in \delta^{+}_{O^+}} x^{v}_{O^+ j} = 1 \qquad \forall v \in V \qquad (8)$$

$$\sum_{i \in \delta^{-}_{O^-}} x^{v}_{iO^-} = 1 \qquad \forall v \in V \qquad (9)$$

$$\sum_{j \in \delta^{+}_{i}} x^{v}_{ij} - \sum_{j \in \delta^{-}_{i}} x^{v}_{ji} = 0 \qquad \forall v \in V, i \in ND \qquad (10)$$

$$\sum_{v \in T} \sum_{j \in \delta^{+}_{i}} x^{v}_{ij} = 1 \qquad \forall i \in M^{*} \qquad (11)$$

$$\sum_{v \in T} \sum_{j \in \delta^{+}_{i}} x^{v}_{ij} = 1 \qquad \forall i \in P^{*} \qquad (12)$$

Standard VRP const.

$$D^{v}_{O^+} = 0 \qquad \forall v \in V \qquad (13)$$

Time initialization

$$D^{v}_{i} \leq maxTime \sum_{j \in \delta^{+}_{i}} x^{v}_{ij} \qquad \forall i \in ND \cup O^{-}, v \in V \qquad (14)$$

Maximum working time

$$D^{v}_{i} + t_{ij} \leq D^{v}_{j} + maxTime(1 - x^{v}_{ij}) \qquad \forall i = O^{+}, j \in \delta^{+}_{i}, v \in V \qquad (15a)$$

$$D^{v}_{i} + st + t_{ij} \leq D^{v}_{j} + maxTime(1 - x^{v}_{ij}) \qquad \forall i \in ND, j \in \delta^{+}_{i}, v \in V \qquad (15b)$$

Time elapsed constraints

$$LTW_{i} \leq D^{v}_{i} \leq UTW_{i} \qquad \forall i \in M^{*}, v \in T \qquad (16)$$

Time windows

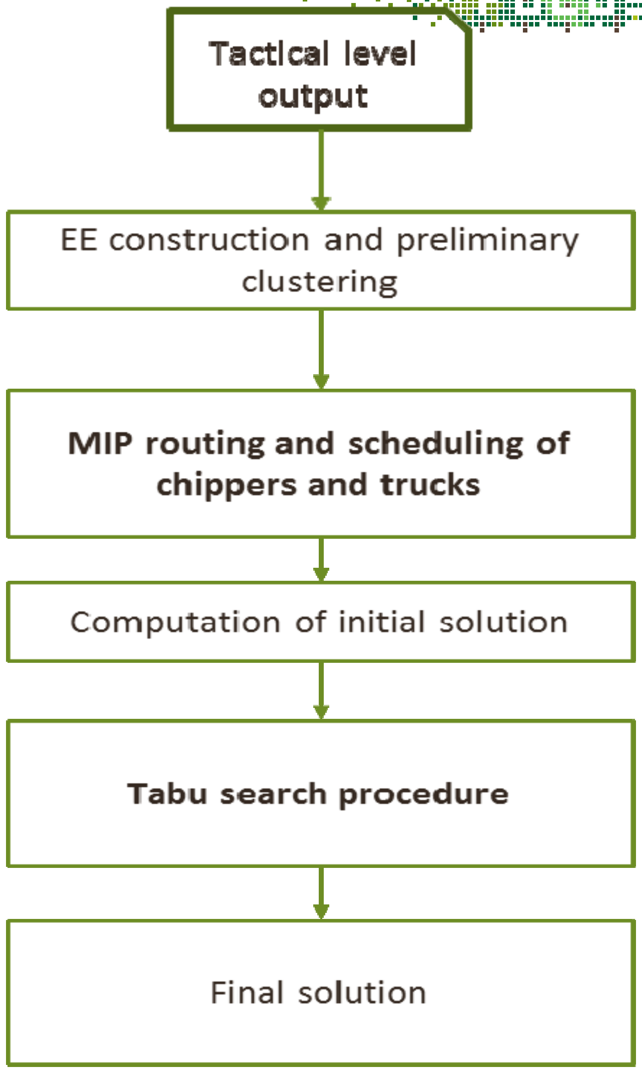
# Matheuristic for operational planning

1. Problem **decomposition methods** (clustering);

2. **MIP models** for clustering and vehicles routing, scheduling and synchronization;

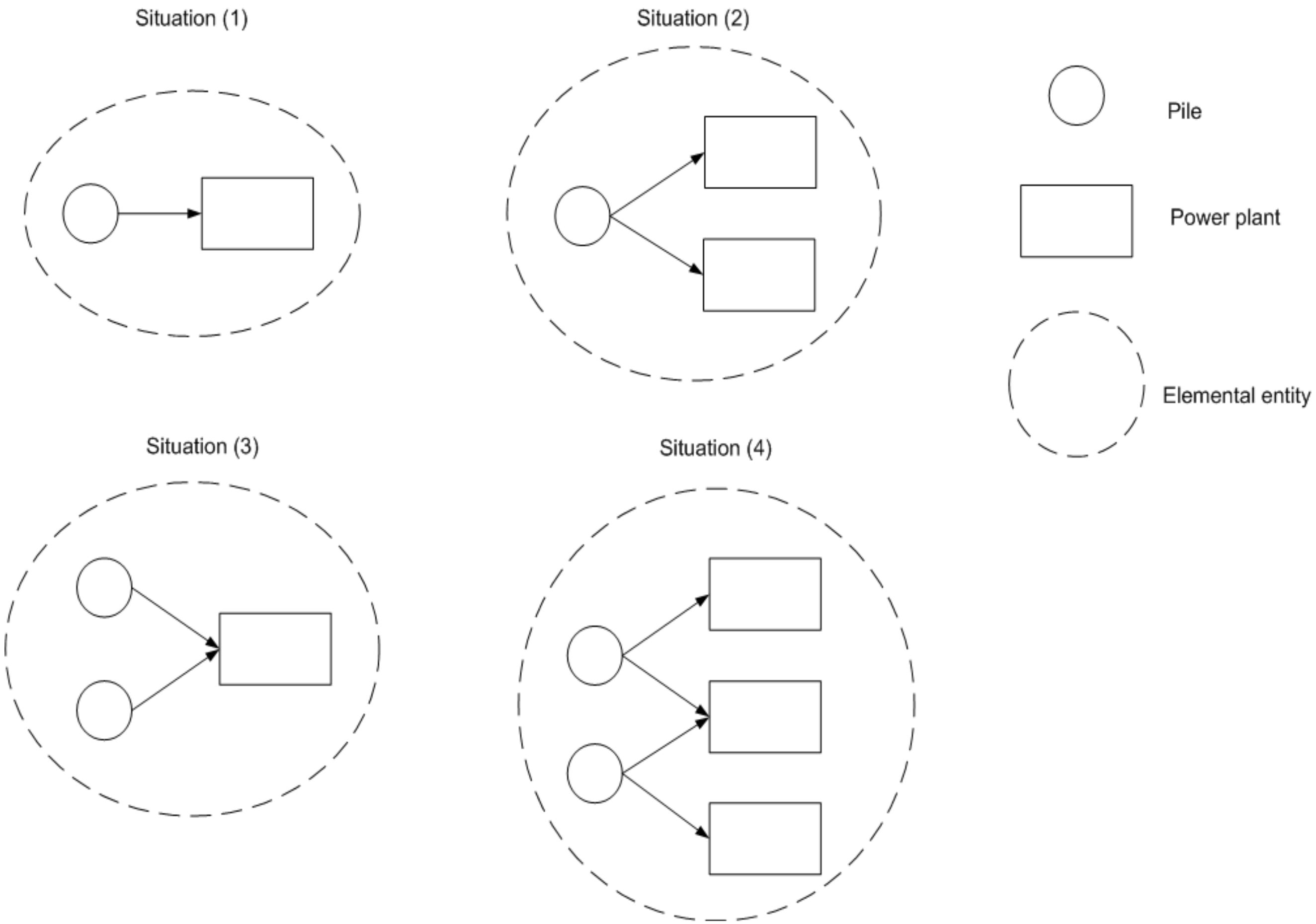
3. Meta-heuristic inspired **in Tabu Search**:

Doerner, K.F., Schmid, V., 2010.; Maniezzo, V., et al. 2010.



# Matheuristic > Defining Elemental Entities based on output from tactical planning

An EE is composed of all piles and power plants so that the material flows are contained in that EE.



# Matheuristic > MILP model for Clustering EE's

Decision variables

$$x_{ik} = \begin{cases} 1, if\ the\ Elemental\ Entity\ i\ \in E\ is\ assigned\ to\ cluster\ k\ \in K \\ 0, otherwise \end{cases}$$

$$y_k = \begin{cases} 1, if\ \ cluster\ k\ \in K\ is\ used \\ 0, otherwise \end{cases}$$

$NC$ Number of clusters

e.g. Barreto, S., et al. 2007.

Model

$Min\ Z = NC$

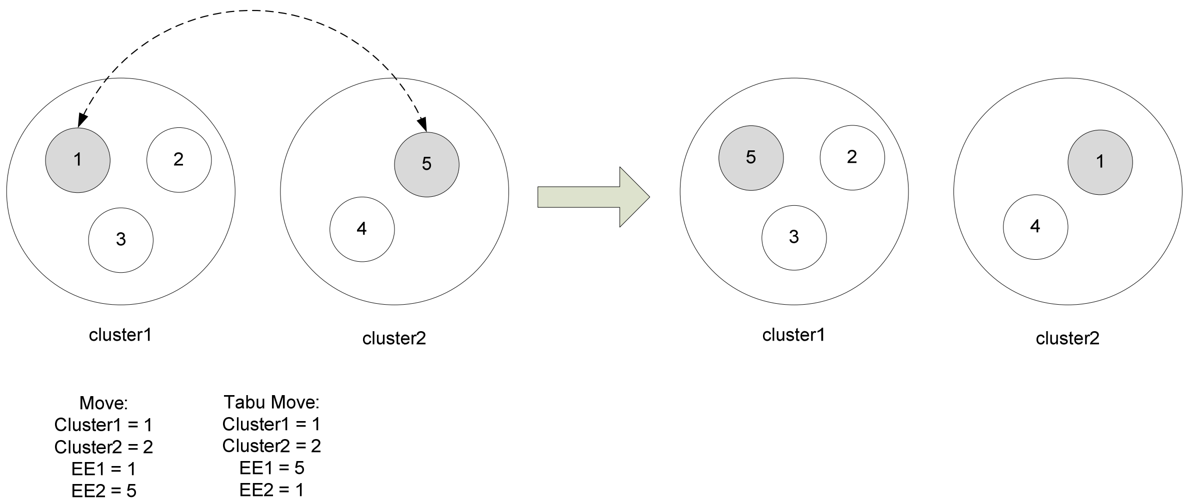
$s.t.$

| | | | |
|---|---|---|---|
| $\sum_{k \in K} y_k \le NC$ | | (1) | Number of clusters |
| $x_{ik} \le y_k$ | $\forall i \in E, k \in K$ | (2) | Linking constraints |
| $\sum_{k \in K} x_{ik} = 1$ | $\forall i \in E$ | (3) | An EE will only belong to one cluster |
| $\sum_{i \in E} n_i x_{ik} \le Max_{\#}$ | $\forall k \in K$ | (4) | Maximum number of dummy nodes |
| $x_{il} \in \{0,1\}$ | $\forall i \in EE, l \in K$ | (5) | |

# Matheuristic >Tabu search procedure

## Move from one solution to the next within its Neighborhood…

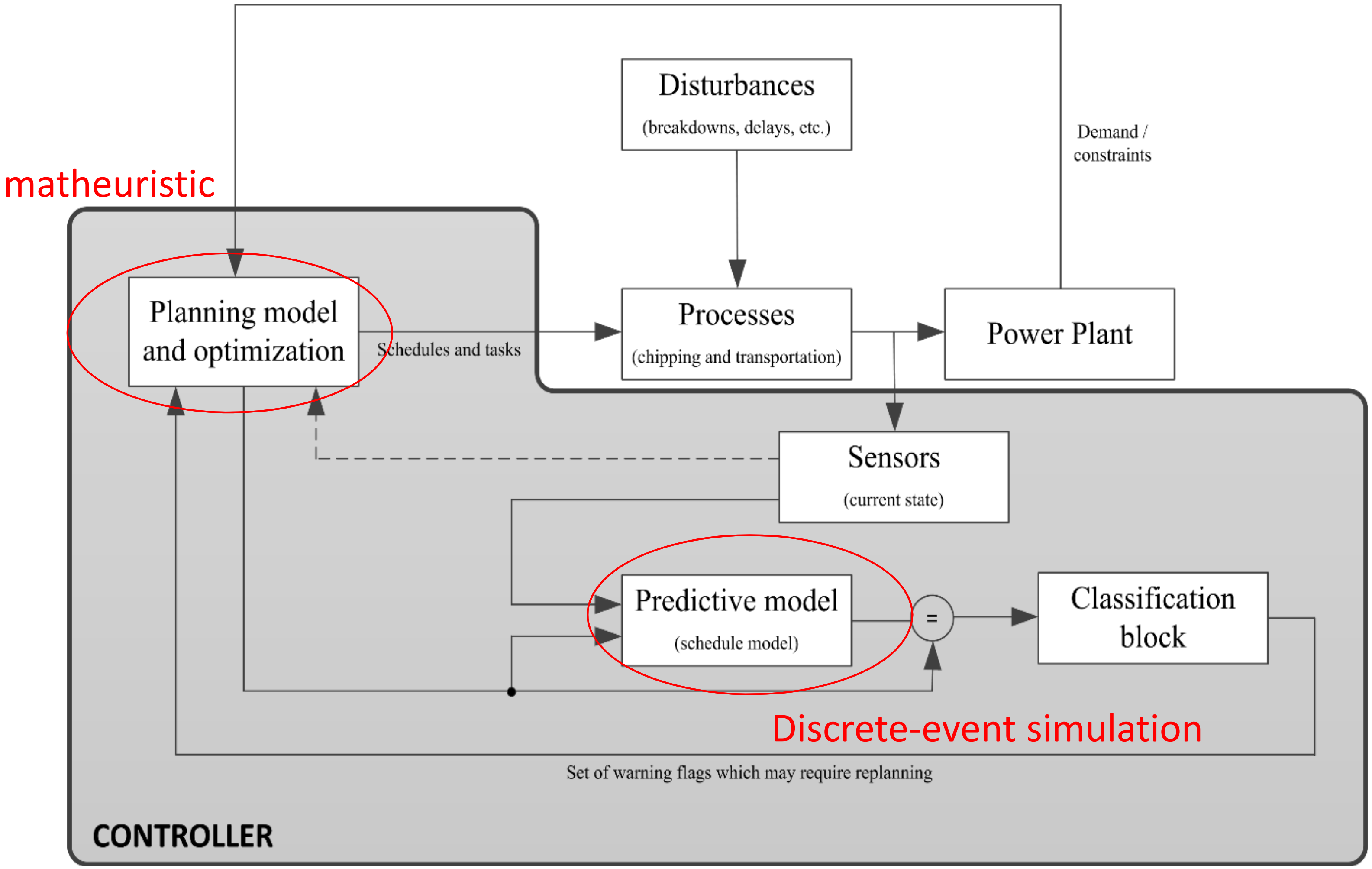
## … by swapping EE’s



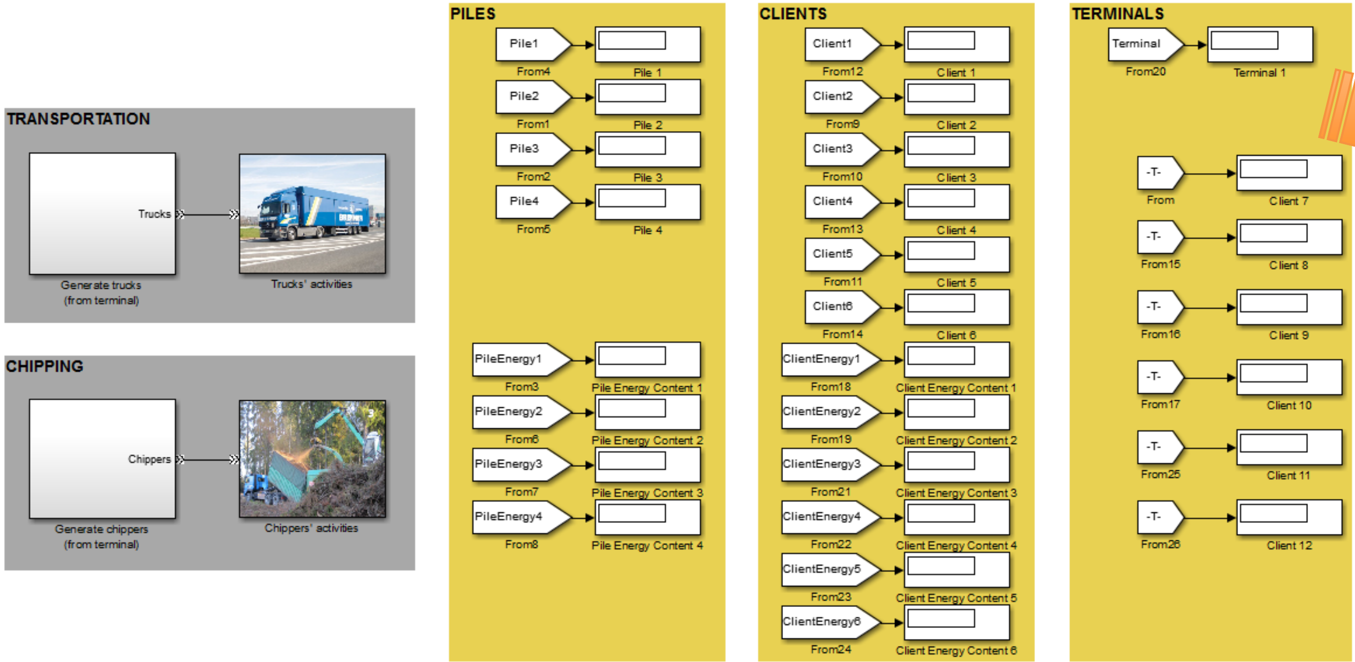

## … evaluate new solution -> solve MILP within each cluster

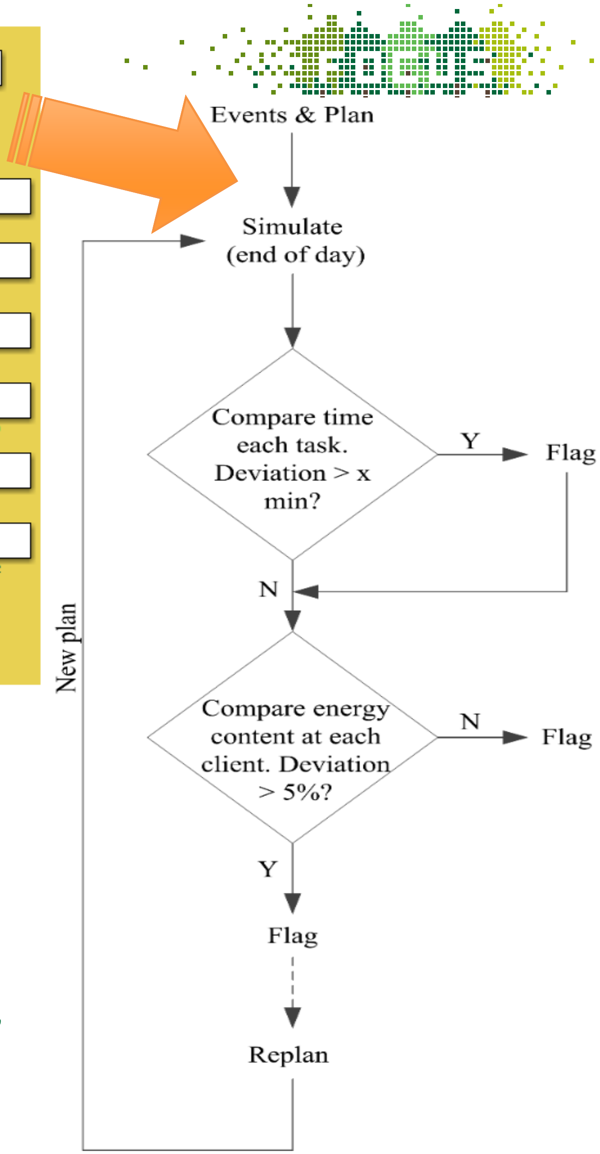
## Update tabu list

# The Model Predictive Control approach



# The discrete-event simulation model




- Simulate the execution of the plan defined by the planning
- Integrate the real data acquired by sensors and simulate the remaining period of time until the end of the day
- Analyse the impact of disturbances (such as breakdowns and delays) in the initial plan
- Connected with a classification block that send warning “flags” to the FOCUS Core regarding the result of that analyses

# “Control” phase

| Vehicle \ Time | 195 | 202 | 225 | … | 463 | 473 | 493 | 498 | … | 588 | 596 | 606 | 636 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chipper 1 | | p4d1 | p4d1 | … | p1d1 | | | t | | | | | |
| Chipper 2 | p2d1 | p2d1 | p2d1 | … | p3d1 | p3d1 | p3d1 | p3d1 | … | t | | | |
| Truck 1 | | p4d1 | | … | p1d4 | | | | … | | | | |
| Truck 2 | | | p2d2 | … | | c1d3 | | | … | | c6d4 | | t |
| Truck 3 | p2d1 | | | … | | c6d1 | | | … | | | t | |
| Truck 4 | | | | … | | | p3d2 | | … | | | | |

**Daily plan:**

- Number of chippers / trucks
- Tasks and schedules of chippers and trucks for a day
- Expected amount of material in the power plants

# Preliminary results

| EE_id | #piles | #powerplants | # chippers | # trucks | Computational time |
|---|---|---|---|---|---|
| 0 | 2 | 3 | 5 | 15 | 10 min |
| 0 | 2 | 3 | 2 | 7 | 8.46 sec |
| | | | | | |
| 1 | 1 | 2 | 5 | 15 | 4.95 sec. |
| 1 | 1 | 2 | 1 | 4 | 0.39 sec. |
| | | | | | |
| 2 | 1 | 1 | 5 | 15 | 0.67 sec. |
| 2 | 1 | 1 | 1 | 2 | 0.22 sec. |
| | | | | | |
| 3 | 1 | 1 | 5 | 15 | 0.58 sec. |
| 3 | 1 | 1 | 1 | 4 | 0.22 sec. |
| | | | | | |
| 4 | 1 | 1 | 5 | 15 | 0.55 sec. |
| 4 | 1 | 1 | 1 | 2 | 0.14 sec. |
| | | | | | |
| 5 | 1 | 1 | 5 | 15 | 0.66 sec. |
| 5 | 1 | 1 | 1 | 4 | 0.09 sec. |
| | | | | | |
| 6 | 2 | 1 | 5 | 15 | 0.65 sec. |
| 6 | 2 | 1 | 1 | 2 | 0.34 sec. |
| | | | | | |
| 7 | 1 | 1 | 5 | 15 | 0.75 |
| 7 | 1 | 1 | 1 | 4 | 0.11 sec. |
| | | | | | |
| 8 | 1 | 1 | 5 | 15 | 0.86 |
| 8 | 1 | 1 | 1 | 2 | 0.26 |

**For a given day:**
**9 Elemental entities**

**Grouped into 5 clusters**

# Preliminary results

New daily schedule for one of the clusters:

| Vehicle\Time | 142 | 202 | 225 | 232 | 240 | 270 | 285 | 295 | 315 | 325 | 330 | 333 | 360 | 363 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chipper 1 | p4d1 | p4d1 | | | | Pile 4 - p4 | | | | | | | | |
| Chipper 2 | p2d1 | | | | Pile 2 . P2 | | | | | | | | | |
| Truck 1 | | p4d1 | | | c4d1 | | | p4d3 | | | | c4d3 | | |
| Truck 2 | | | p2d2 | | | c2d2 | | | | p4d4 | | | | c4d4 |
| Truck 3 | p2d1 | | | | c2d1 | | p2d3 | | | | c2d3 | | | |
| Truck 4 | | | | p4d2 | | c4d2 | | | p2d4 | | | | c2d4 | |

| Vehicle\Time | 373 | 403 | 413 | 430 | 433 | 443 | 463 | 473 | 493 | 498 | 503 | 523 | 536 | 543 | 553 | 566 | 576 | 588 | 596 | 606 | 636 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chipper 1 | p1d1 | | | Pile 1 - p1 | | | | | | depot | | | | | | | | | | | |
| Chipper 2 | | | | p3d1 | | | | | | Pile 3 - p3 | | | | | | | | depot | | | |
| Truck 1 | p1d1 | | c1d1 | | | | p1d4 | | | | c1d4 | | | depot | | | | | | | |
| Truck 2 | | | | | p1d3 | | | c1d3 | | | | | | | p3d4 | | | | c6d4 | | depot |
| Truck 3 | | | | p3d1 | | | | c6d1 | | | | p3d3 | | | | c6d3 | | | | depot | |
| Truck 4 | | p1d2 | | | | c1d2 | | | p3d2 | | | | c6d2 | | | | depot | | | | |

# Concluding remarks

1. The proposed solution method efficiency is highly dependent on cluster creation and graph simplification techniques. Some are still to be implemented.

2. Problem decomposition (cluster creation) allows for events management to be addressed in a faster computational time as it only takes into account the part of the system in which it occurs.

3. Further testing will be conducted to properly parameterize the tabu search method governing the local search

4. Results of the matheuristic are promising. Some efficiency procedures are still to be implemented which we expect to improve computational results.

5. The bottleneck, as expected, is the efficiency of the exact method. MIP model resolution methods may be explored further on (Drexl, M. (2012)).

6. Additional testing is required for control and re-optimization

# FOCUS in a nutshell

What?

7 FP SME-target collaborative RTD project
01-01-2014 to 30-06-2016 (30 months)

Why?

Need for integrated processing and control systems for sustainable production in farms and forests.

How?

New FOCUS technological platform that combines sensors and sophisticated software solutions for integrated control and planning of the whole forest-based value chain.
7 Work Packages encompassing specification, development of data collection tools as well as control and planning tools, integration; assessement of prototypes into 4 pilot cases.
Covering the value chains in Europe  of lumber, pulpwood, biomass and cork transformation; from forest planning to industrial processing.
Total budget of ~4M€ (~3M€ EC funding)

By whom?

Consortium of 6 SMEs and 6 RTDs from Portugal, Finland, Belgium, Switzerland, Austria and Germany, combining expertise in forestry, sensors, automation and software development.

**The goal of FOCUS is to improve sustainability, productivity, and product marketability of forest-based value chains through an innovative technological platform**
**for integrated planning and control of the whole tree-to-product operations,**
**used by forest-producers to industry players.**

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# Thank you!