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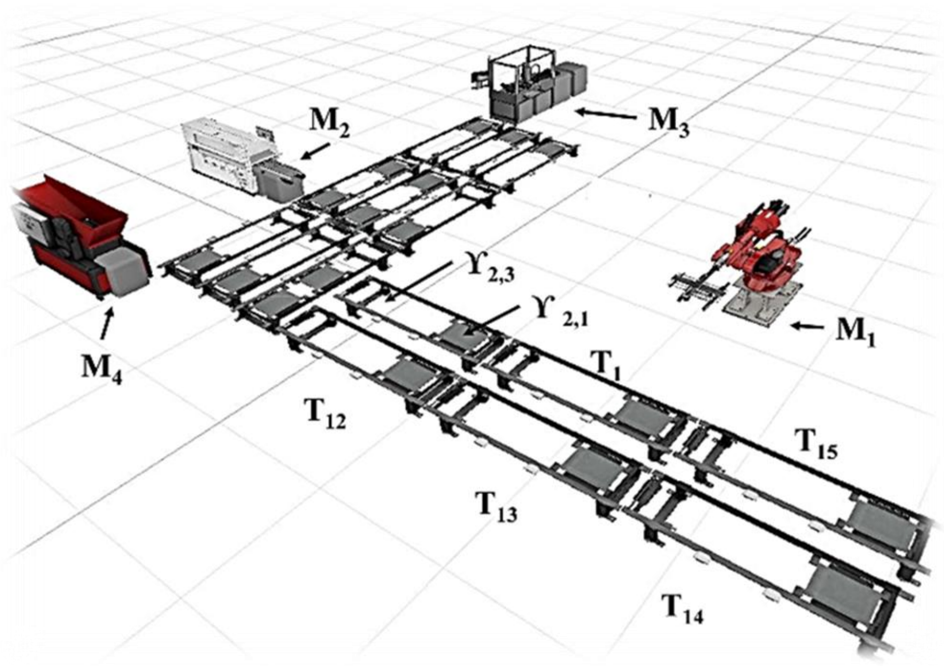
Hierarchical Routing Control in Discrete Manufacturing Plants Via Model Predictive Path Allocation and Greedy Path Following

Lorenzo Fagiano[1], Marko Tanaskovic[2], Lenin Cucas Mallitasig[1], Andrea Cataldo[3], and Riccardo Scattolini[1]

[1] Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano, Italy
[2] Singidunum University, Belgrade, Serbia
[3] STIIMA, National Research Council, Milano, Italy



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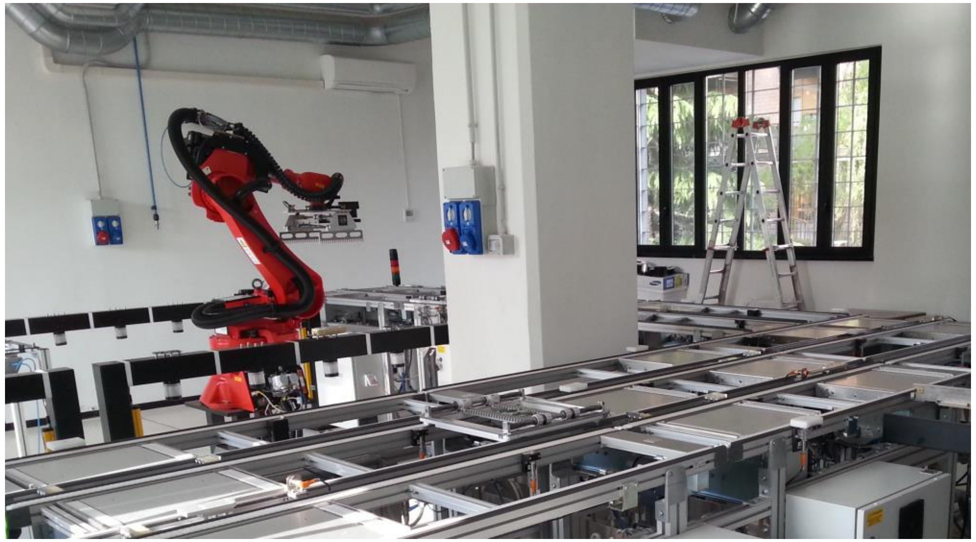
Motivation

Research in advanced manufacturing solutions is motivated by several trends:

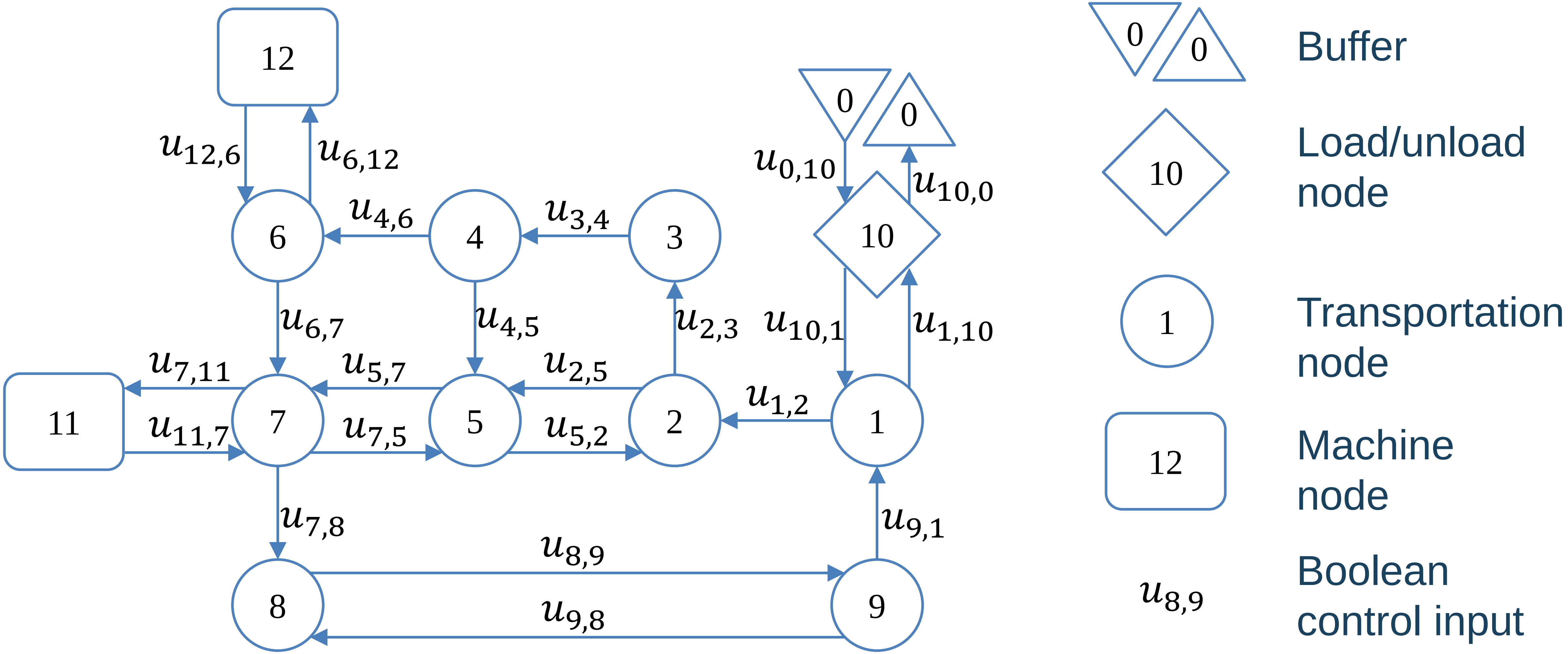
- higher product customization
- more agile supply chains
- higher environmental sustainability



The problem of **routing control in discrete manufacturing plants** is considered in this paper.

Problem description

Control problem with large number of integer variables and temporal logic constraints



Literature
Optimality vs. Scalability

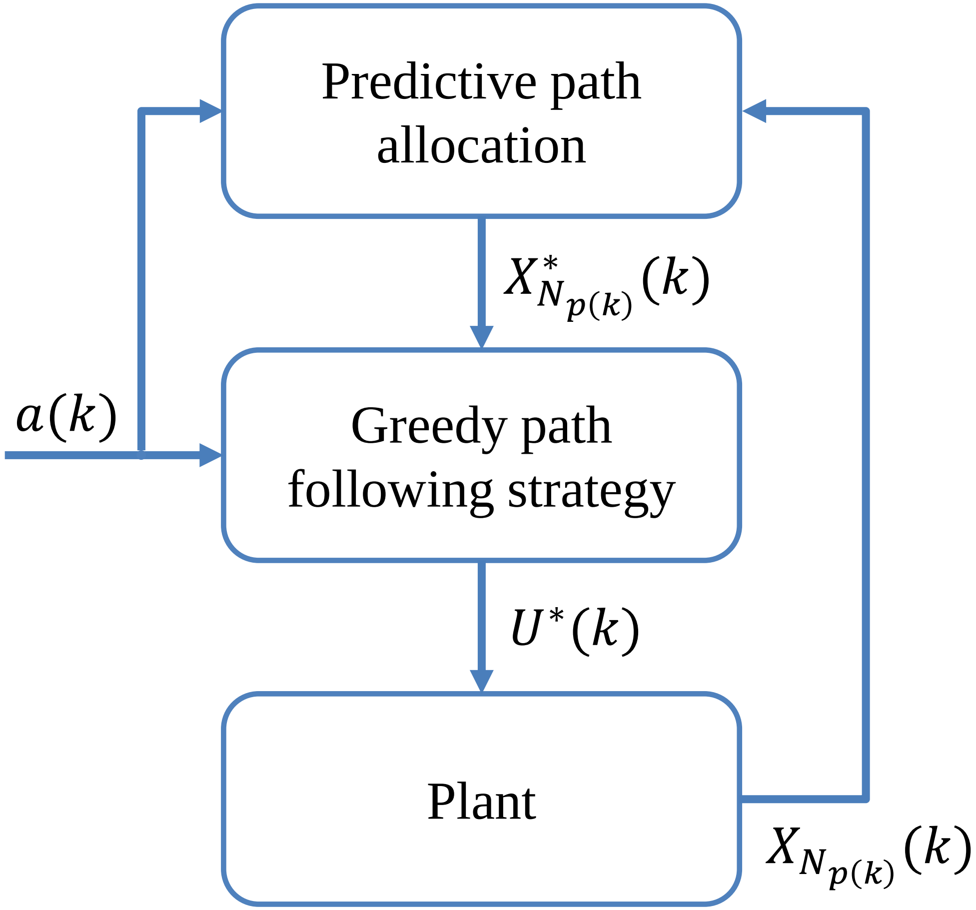
Approaches in the literature include:

- Rule-based techniques (**Gupta et al., 1989, Byrne et al., 1997, Saygin et al., 2001, Bucki et al., 2015, Souier et al., 2010**);
- Integer programming (**Das et al., 1997**);
- Multi-agent architectures (**Kouiss et al., 1997**);
- Heuristic search combined with Petri nets (**Moro et al., 2002**);
- MPC (**Cataldo and Scattolini, 2016**)

Tradeoff between optimality and scalability

Contribution

Scalable predictive approach with hierarchical problem decomposition



"Lagrangian" model of the plant
A change of perspective

"Eulerian" model (most common framework):

- Each binary state corresponds to a node (1=part is present)
- Each binary input is a transition (1=transition occurs from time k to time $k+1$)
- Results in rather large-scale MILP or MIQP

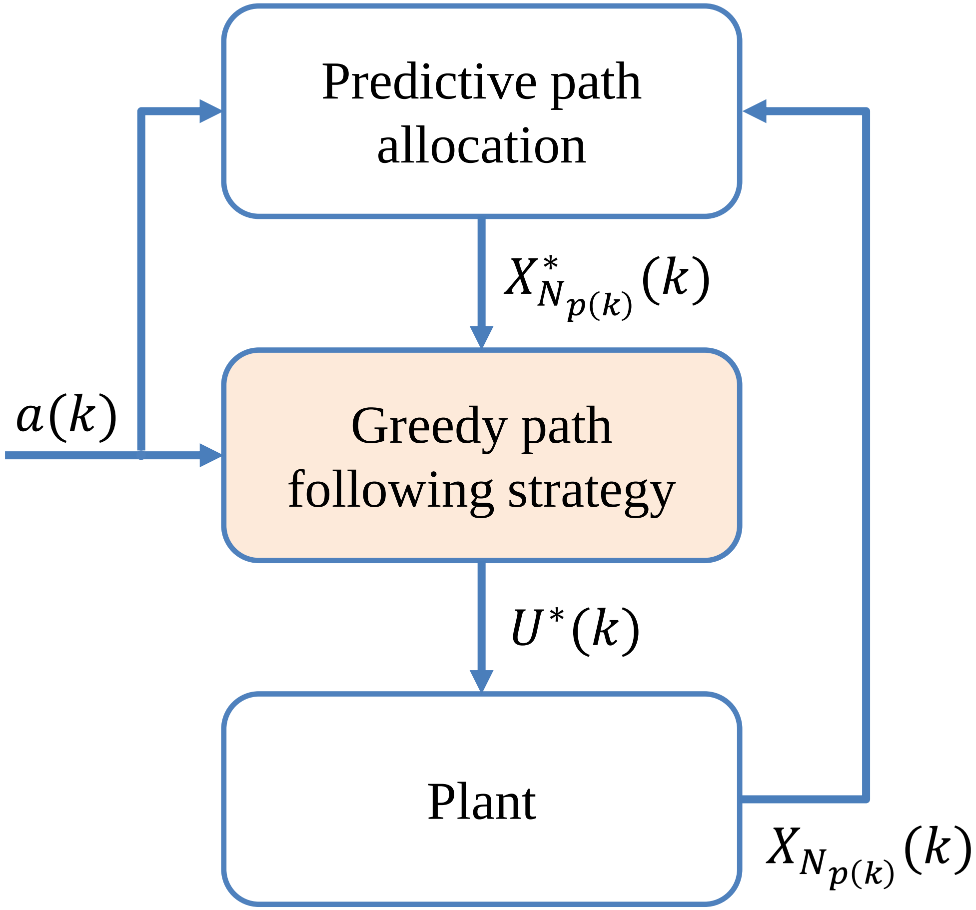
"Lagrangian" model (introduced in this paper):

- Each state is linked to a part on the plant
- States for each part i :
  - Current *sequence* s_i,
  - *Position* p_i along the sequence;
  - *Elapsed time* t_i since the part entered the plant.

Greedy path following strategy

The Lagrangian state $X_{N_{p(k)}}(k)$ is conveniently used by a low-level strategy that ensures satisfaction of all constraints:

1. Try to propagate forward all parts according to their current sequences;
2. Detect and resolve any conflicts
   - Parts held in place have highest priority
   - Parts that are more advanced in their sequence have 2nd highest priority;
   - Parts with higher t_i values have 3rd highest priority
3. Compute accordingly the plant inputs



Model Predictive Path Allocation
Finite Horizon Optimal Control Problem

$$\min_{(\sigma_i,\pi_i),\, i=1,\ldots,N_p(k)} \sum_{o=0}^{N} \ell_{N_p(o|k)}\left(X_{N_p(o|k)}(o|k)\right)$$

Economic cost over horizon N_p

All equivalent states

subject to

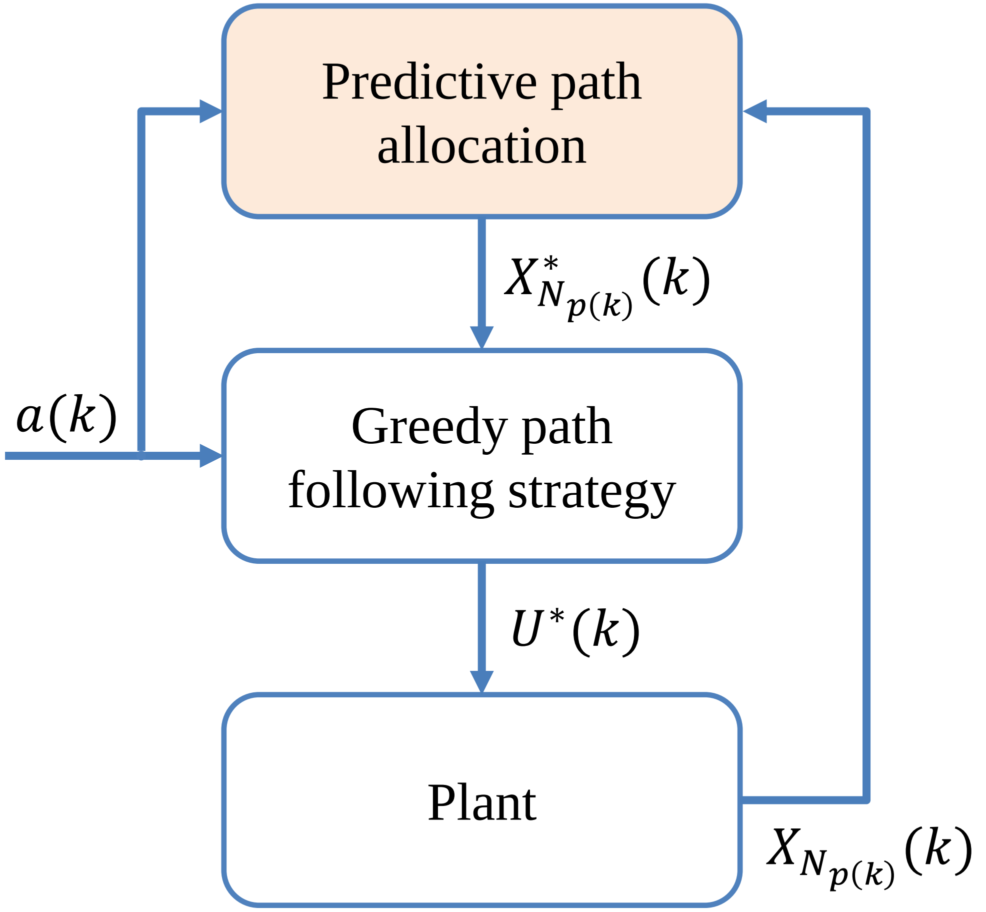
$$x_i(0|k) = [\sigma_i, \pi_i, t_i(k)]^T,\ i = 1, \ldots, N_p(k)$$

$$X_{N_p(0|k)}(0|k) = [x_1(0|k)^T, \ldots, x_{N_p(k)}(0|k)^T]^T$$

Move blocking

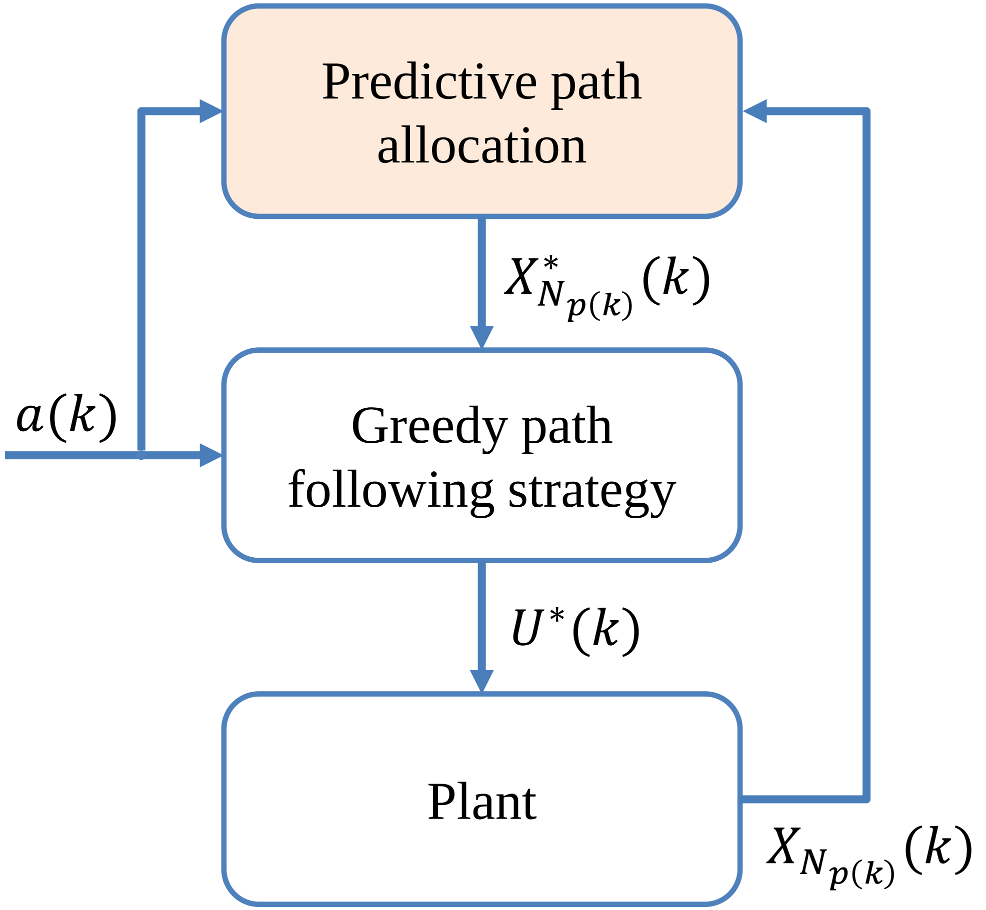
$$X_{N_p(o+1|k)}(o+1|k) = f_{(N_p(o+1|k), N_p(o|k))}(X_{N_p(o|k)}(k), a(o|k)),\quad o = 0, \ldots, N-1$$

Closed-loop prediction with greedy path-following



Model Predictive Path Allocation
Close loop strategy

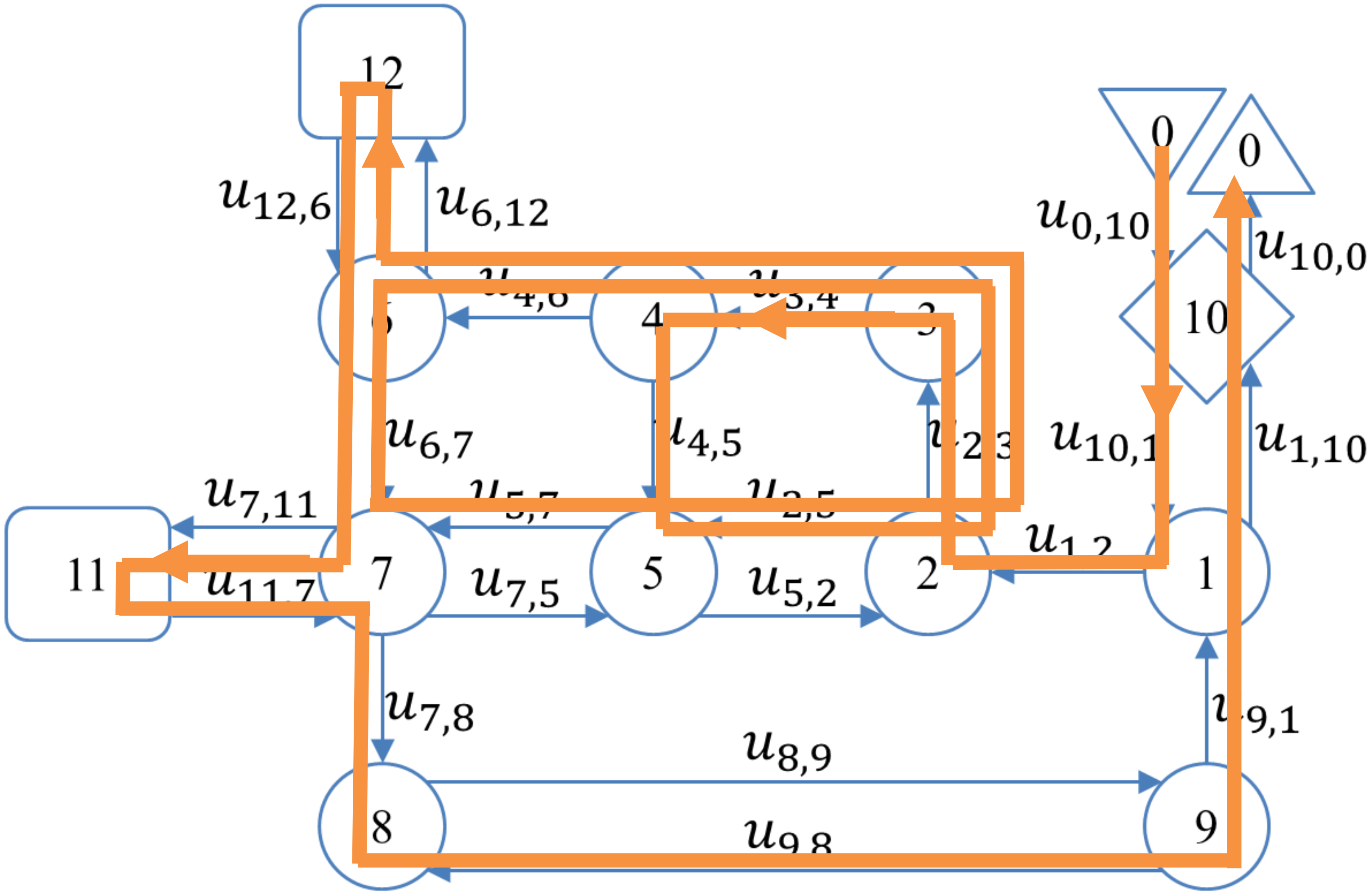
1. At time k, solve the FHOCP (unconstrained integer program of small-medium size)
2. Change the Lagrangian state from the current one to the one obtained as solution to the FHOCP k
3. Apply the greedy path-following strategy
4. Set $k \leftarrow k + 1$, go to 1.



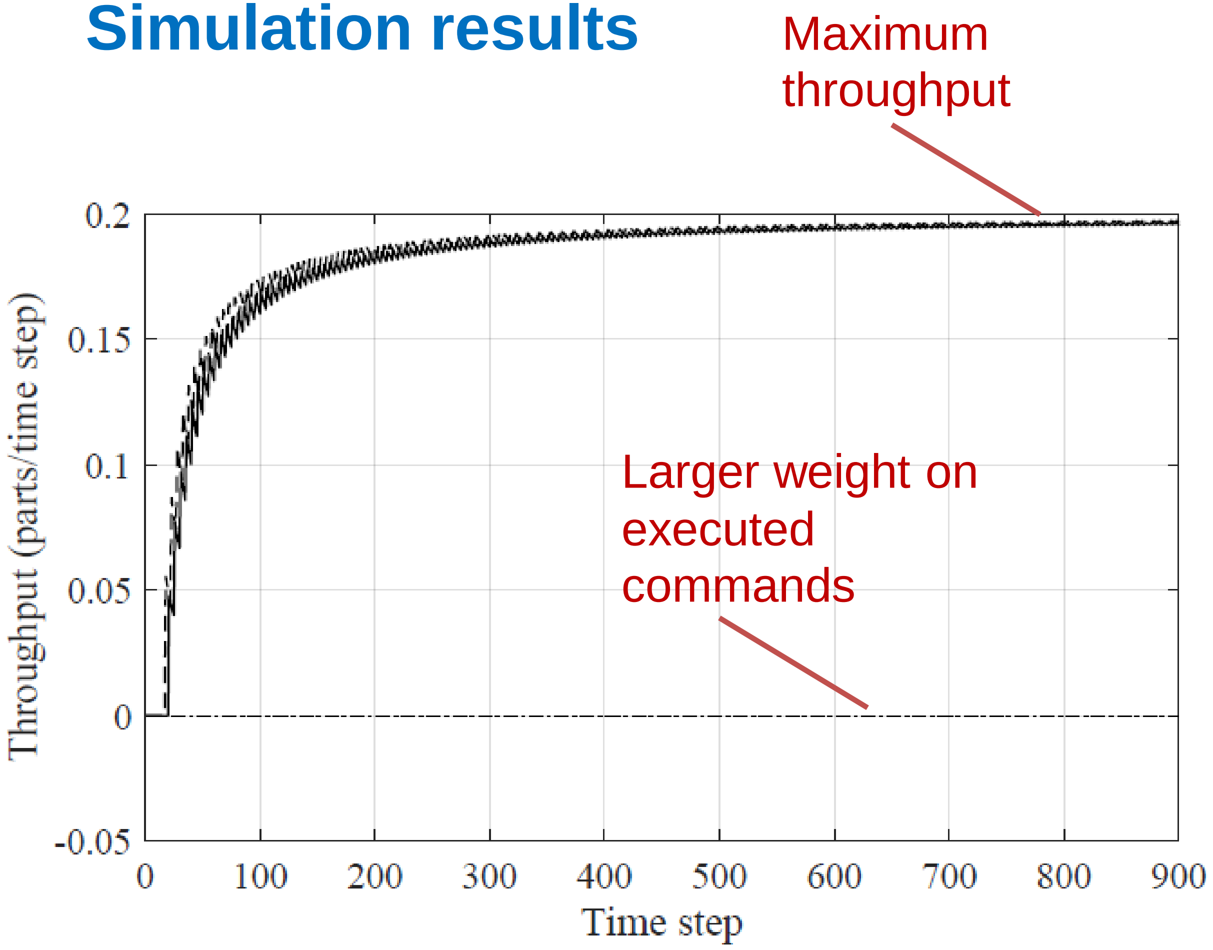
Numerical example

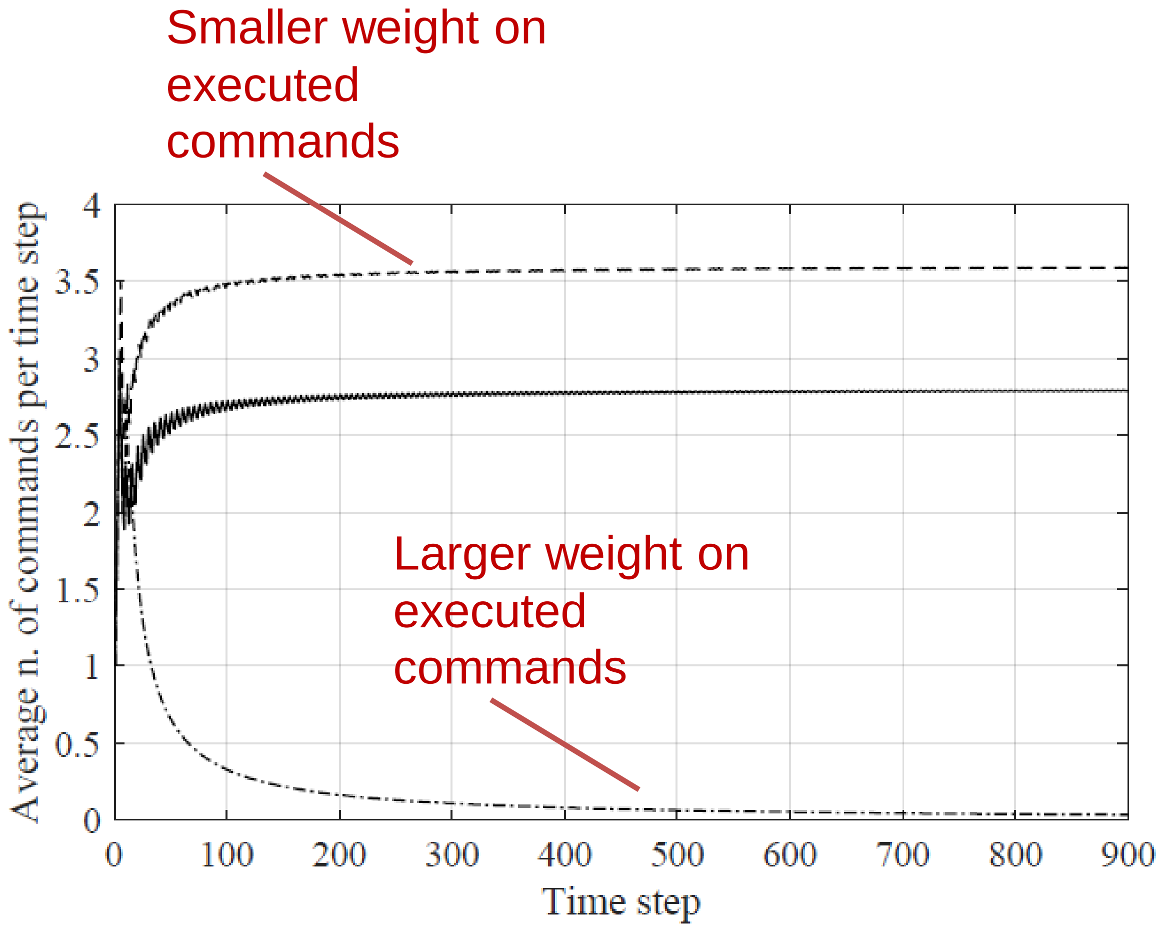
Plant description and employed sequence

- Parts must visit node 12, then 11, then exit
- Lockout may occur due to working time in the machine nodes and conflicts in nodes 6 and 7
- Employ one longer sequence obtained by merging shorter ones



Numerical example
Simulation results





Computational time: approx 0.5 s per time step, with prediction horizon of 50 time steps (impractical with non-hierarchical approach)

Conclusions and next steps

- Novel “Lagrangian” modeling approach and hierarchical control structure shows optimal performance with scalable computation
- Next steps:
  - Apply to a real plant (undergoing);
  - Improve the solution to the predictive path allocation problem (undergoing);
  - Investigate the sequence generation problem;
  - Develop fault tolerant and robust extensions.

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