Integration of Production Scheduling and Automation Logic

Venkatachalam Avadiappan
Department of Chemical and Biological Engineering
University of Wisconsin – Madison

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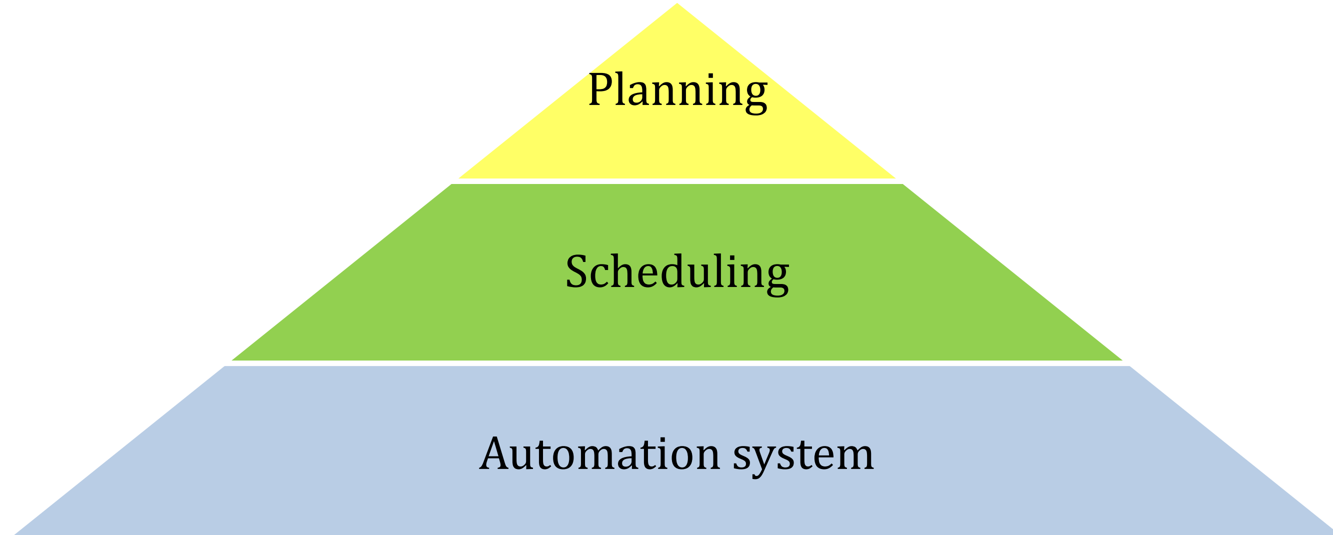
Motivation

Hierarchy of process operation



- Mismatch between model of plant in scheduling layer and actual plant dynamics driven by automation system
- Computed schedule may not be feasible when executed in plant
- Develop methodology to incorporate automation derived information in scheduling layer[1]
- Potential to achieve significant economic benefits in various industries

Engell et al., *Comp. and Chem. Eng.* (2012)
[1]B.C. Rawlings, V. Avadiappan et al., Accepted for PSE 2018 conference

Chemical production scheduling

Given:

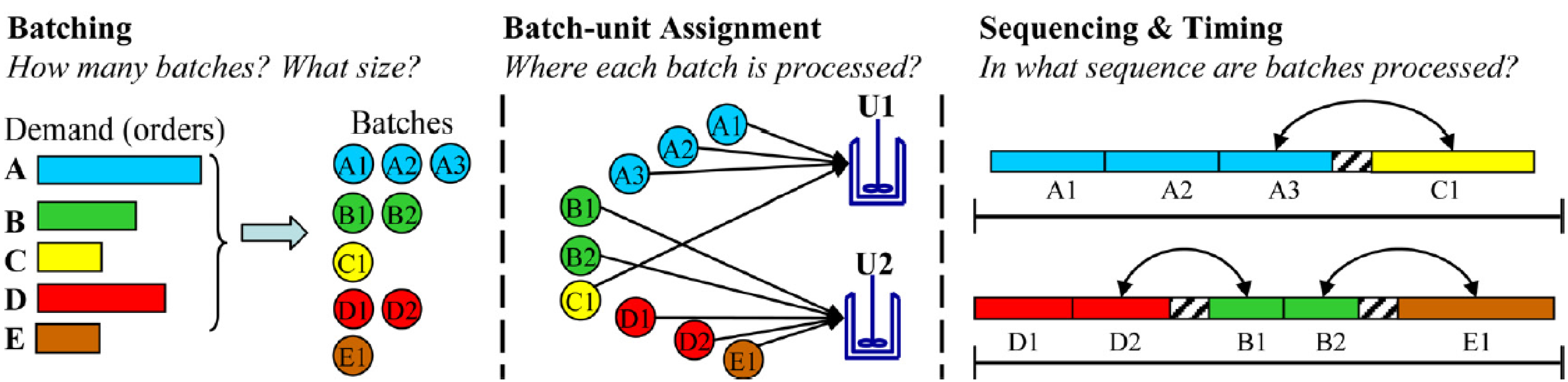
- Production facility data (e.g. plant topology, unit capacities)
- Production recipes (e.g. mixing rules, processing times)
- Resource availability (e.g. raw materials, utility)
- Production targets (e.g. due dates and amounts)

Decide:

- How much material to produce?
- Which equipment to use?
- When to begin each task?

Objectives:

- Minimize cost to meet demand
- Meet demand in shortest time
- Maximize profit over given time



Harjunkoski et al., *Comp. and Chem. Eng.* (2014)

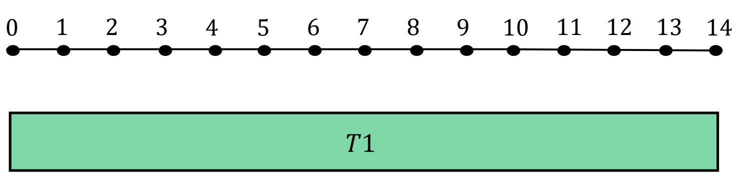
Automation system

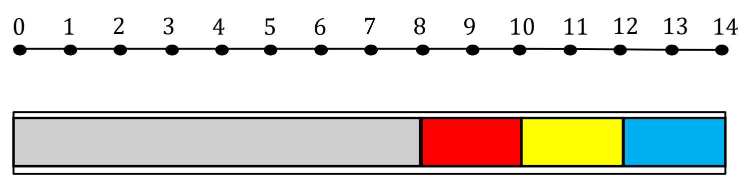
- Discrete control or automation system of plant makes discrete decisions guided by automation logic[1]
- Manipulates process and continuous control system (e.g. as alarm turns on when level in tank violates the threshold, inlet flow rate is reduced)
- Restricts plant dynamics in ways not accounted for in scheduling layer
- Operates at finer resolution than scheduling layer

Example, for batch reaction

Scheduling layer: single task with fixed duration

Automation system: sequence of steps with transitions guided by automation logic

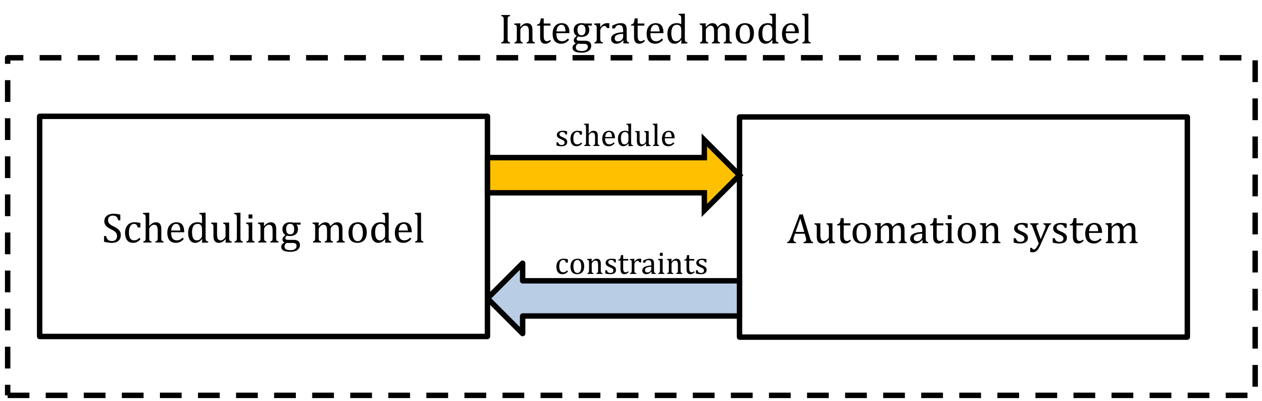




[1]Rawlings et al., *Comp. and Chem. Eng.* (2017)

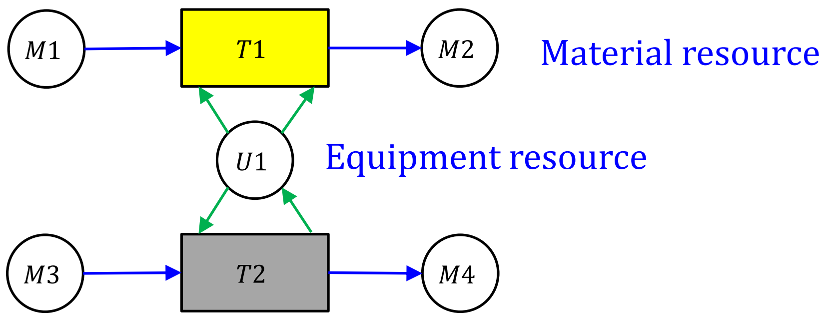
Automation system

- Schedule computed without considering information from automation system maybe inefficient
- Decisions taken by automation system come as surprise to scheduling layer
- Using automation system, infeasibility of nominal schedule can be detected at earlier time
- Recompute schedule after adding constraints to scheduling model that account for detected infeasibility



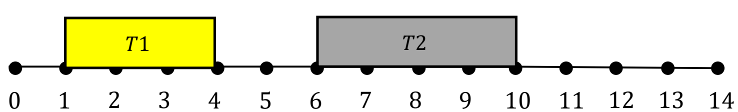
Resource task network (RTN)

- Pantelides[1] proposed resource task network (RTN) framework
- RTN representation has two components: resources and tasks
- Materials, equipment and utilities are uniformly described as resources
- Task is an operation that consumes and generates resources



Example RTN representation

- Time horizon is discretized into periods of uniform length



Discrete time grid

[1]Pantelides, Conference on foundations of computer aided operations (1994)

State-space model

- General form of state-evolution and input-state constraints in state-space model:

$$x(t+1) = Ax(t) + Bu(t) + B_d d(t)$$

$$E_x x(t) + E_u u(t) + E_d d(t) \leq 0$$

- Subramanian et al.[1] transformed scheduling model into state-space form

Inputs: whether to start a new task, batch size and amount of material to ship

States: amount of inventory, backlog of materials and resource levels

Disturbances: task delays, unit breakdowns and yield losses

[1]Subramanian et al., *Comp. and Chem. Eng.* (2012)

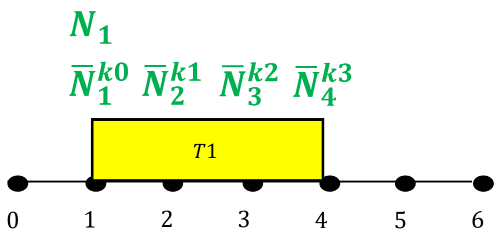
State-space RTN scheduling model

Decision variables

N_{it} equals 1 if task i starts at time t

$\bar{N}_{it}^{k}$ equals 1 if task i has progress status k at time t

Task $T1$ has processing time of $\tau_i = 3\ h$



Progress status of a task i varies from $k = 0$ to $k = \tau_i$

Model constraints

$\bar{N}_{it}^{0} = N_{it} \qquad \forall\ i, t$

$\bar{N}_{i(t+1)}^{k} = \bar{N}_{it}^{k-1} \qquad \forall\ i, t, k \in \{1,2, \dots \tau_i\}$

Lifting equations

State-space RTN scheduling model

$$\beta_i^{min} N_{it} \leq B_{it} \leq \beta_i^{max} N_{it} \qquad \forall\, i, t$$

Batch size

Batch size limits

$$S_{rt} = S_{r(t-1)} + \sum_{i \in \mathbf{I}} \sum_{k=0}^{\tau_i} (\mu_{irk} \bar{N}_{it}^k + \nu_{irk} \bar{B}_{it}^k) - D_{rt} \qquad \forall\, r, t$$

Resource level · Resource task interactions · Shipment

Resource balance

$$\omega_r^{min} \leq S_{rt} \leq \omega_r^{max} \qquad \forall\, r, t$$

Resource limits

$$BO_{rt} = BO_{r(t-1)} - D_{rt} + \alpha_{rt} \qquad \forall\, r, t$$

Backlog level · Demand

Backlog balance

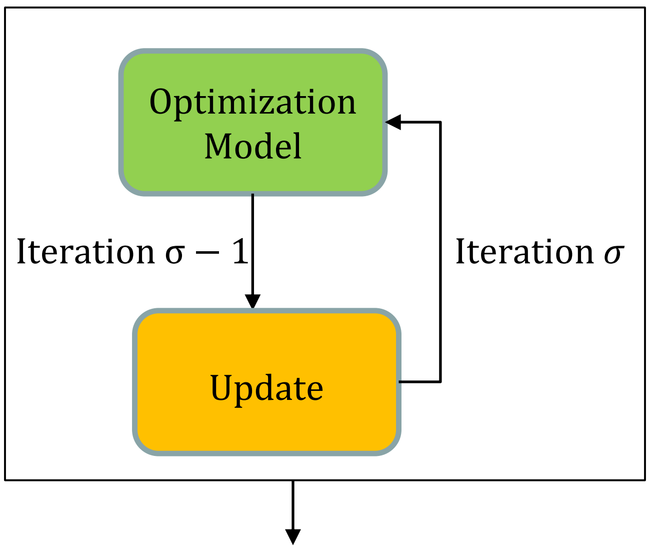
Objective function

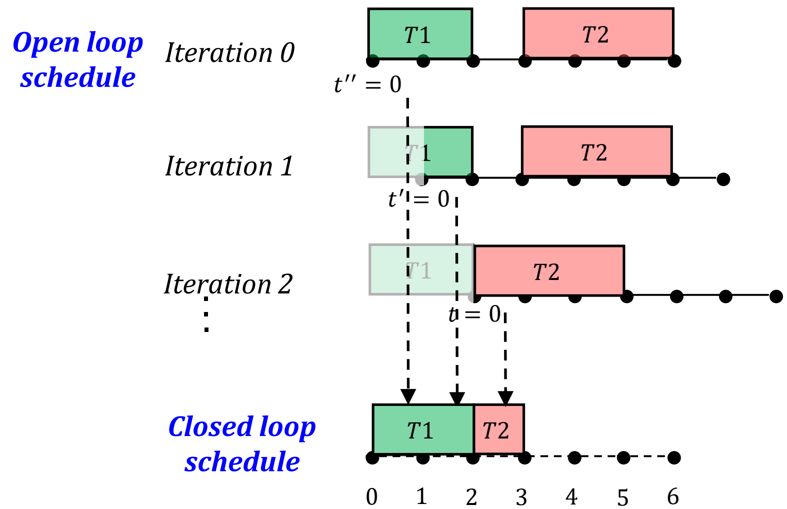
$$\min \sum_{r \in \mathbf{R}^{\mathrm{P}}} \sum_{t \in \mathbf{T}} \left(\gamma_r^{Inv} S_{rt} + \gamma_r^{BO} BO_{rt} \right) + \varepsilon \sum_{i \in \mathbf{I}} \sum_{t \in \mathbf{T}} N_{it}$$

Inventory cost · Backlog cost · Fixed cost

Online scheduling

- Information is carried from iteration $\sigma - 1$ to next iteration σ using update equations
- Optimization model is kept identical in each iteration





Closed loop schedule

$$_{\sigma}\bar{N}^{k}_{i(t=0)} = {}_{\sigma-1}\bar{N}^{k-1}_{i(t'=0)} \qquad \forall\, i, k \in \{1,2, \dots \tau_i\}$$ Task state update

$$_{\sigma}BO_{r(t=0)} = {}_{\sigma-1}BO_{r(t'=0)} - D_{r(t=0)} + \alpha_{r(t=0)} \qquad \forall\, r$$ Backlog update

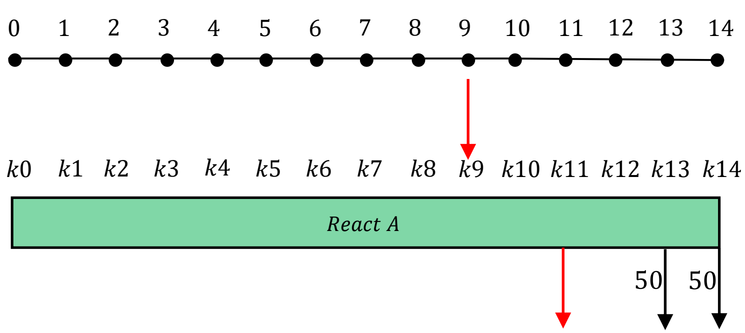
$$_{\sigma}S_{r(t=0)} = {}_{\sigma-1}S_{r(t'=0)} + \sum_{i \in \mathbf{I}} \sum_{k=0}^{\tau_i} \left(\mu_{irk}\bar{N}^{k}_{i(t=0)} + \nu_{irk}\bar{B}^{k}_{i(t=0)}\right) - D_{r(t=0)} \qquad \forall\, r$$ Inventory update

Delays

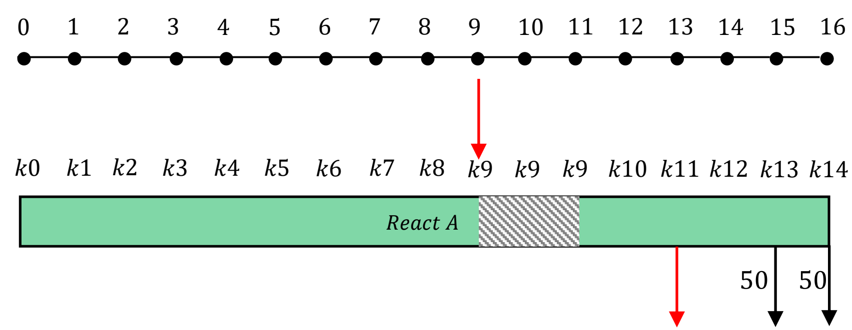
- Can handle multi-period task delays
- Lifting and task state update equations are modified using delay parameters
- For φ hour delay, progress status remains constant for next $\varphi - 1$ hours

Example

- Operator is needed between 9 and 11 h when task *React A* is being executed
- A 2 h delay is observed at $t = 10$ due to operator inefficiency



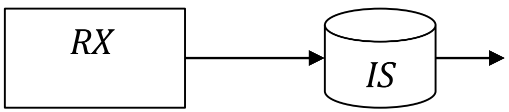
Nominal case



With delay

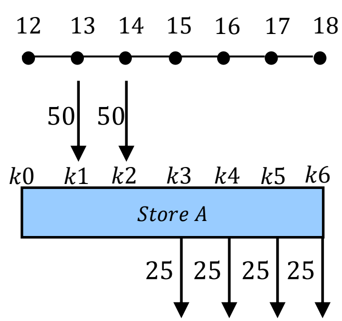
Disturbance in flow rates

- When observed flow rates are less than nominal, task maybe delayed
- Modify parameters in resource balance equations

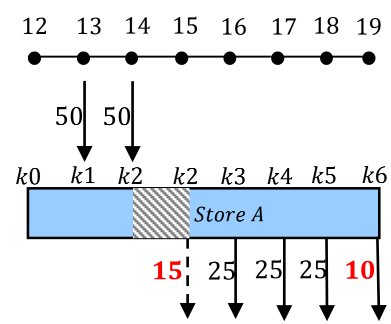


Example

- Max. flow rate out of RX is 50 lbs/h and batch size is 100 lbs, it takes at least 2 h to empty RX and fill in IS
- Max. flow rate out of IS is 25 lbs/h, so it requires at least 4 h to empty IS
- Suppose, outflow occurring at $t = 15$, is 15 lbs instead of the nominal 25 lbs



Nominal case



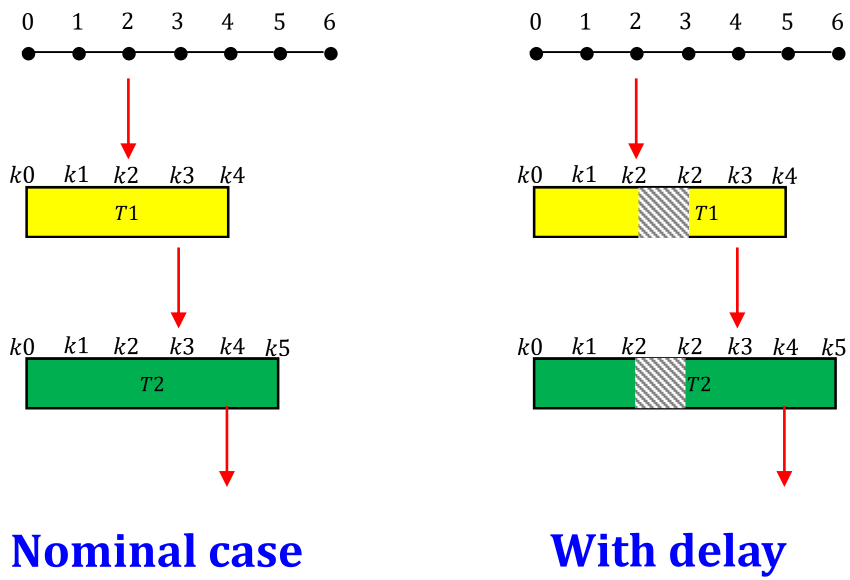
With disturbance in flow

Integrated model development

Delays as decisions

- Delay in a task may induce delay in other task, due to limited resource availability
- When delay of $1\ h$ is observed in task $T1$ at $t = 3$

  Operator is released only at $t = 4$, leading to an infeasible schedule

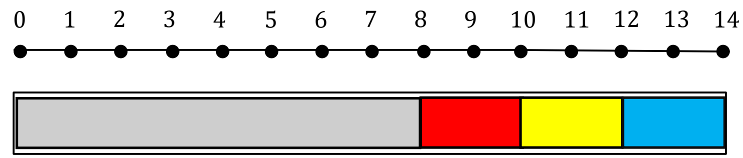


- Introduce binary variables that activate when tasks need to be delayed
- Variables would affect the model similar to delay parameters
- Objective function must include terms that penalize such delays

Infeasibility of schedule

- In the example, *React A* task is composed of 4 steps

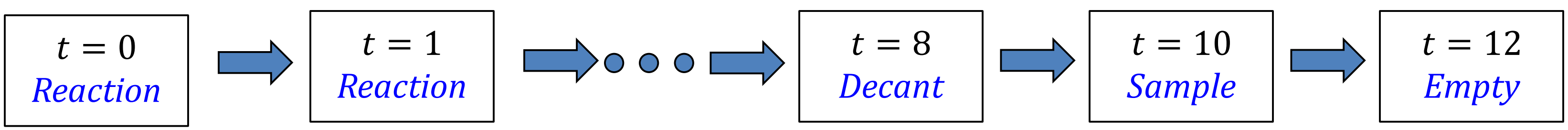
  - *Reaction* step
  - *Decant* step
  - *Sample* step
  - *Empty* step



- Automation system detects step transitions

  Nominal case

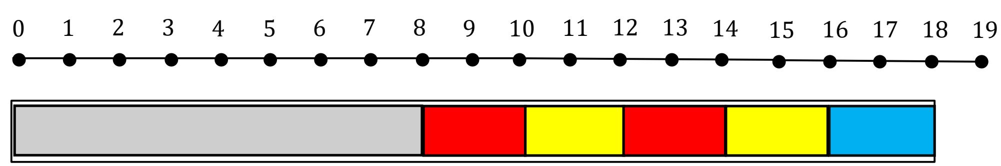
  Evolution of automation-states:



- Receives signal to repeat *Decant* →*Sample* steps at $t = 12$

  Plant's automation-state

  $t = 12$ *Decant*



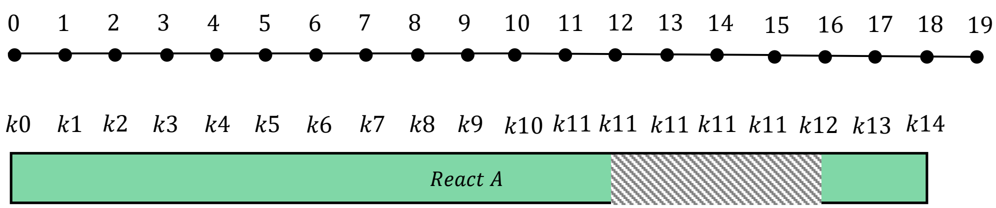
- Nominal schedule: infeasible (not physically realizable)

Compute a new schedule

- Generate constraints to guide rescheduling away from detected infeasibility

Constraint: Task not complete before $t = 18$

$\bar{N}_6^{k14} = 1$ (imposed in iteration 12, so relative time $t = 6$)



- Task is automatically delayed by optimization

Scheduling model without considering automation logic:

infeasibility detected at $t \geq 13$

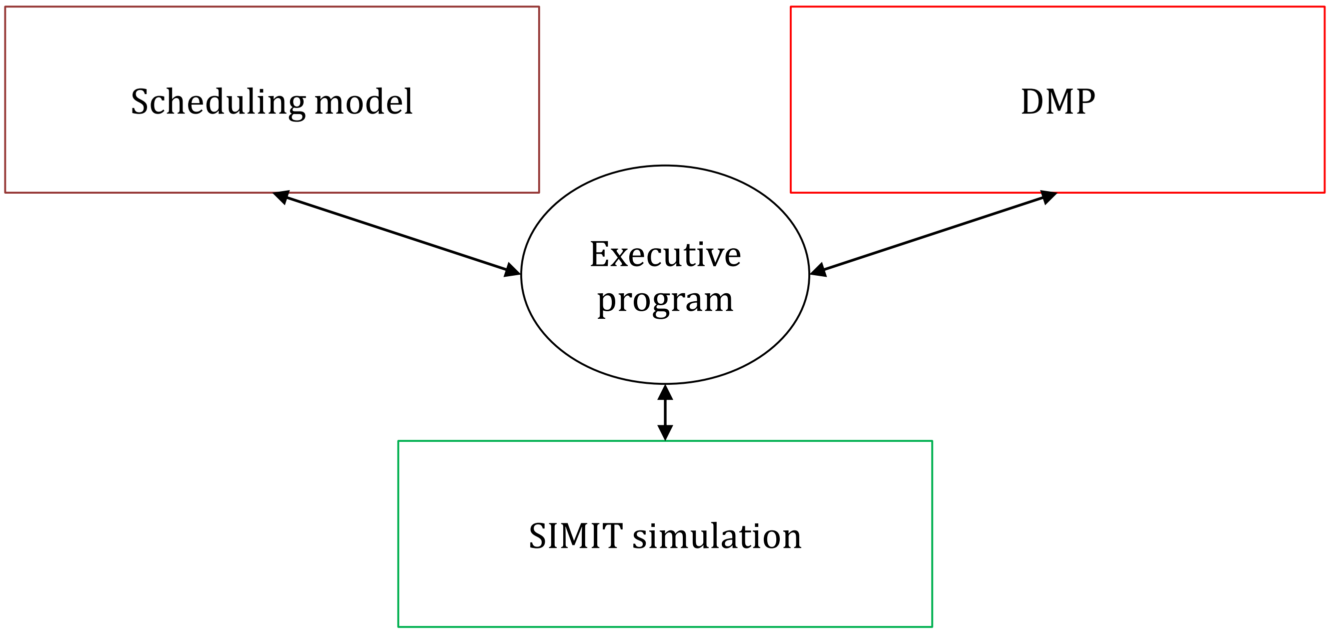
Integrated model:

infeasibility detected at $t = 12$

Integrated model is superior!

Interaction with other modules

- Schedule generated contains information on start and end time of tasks
- This information is communicated to Delay Monitoring Prediction (DMP) module and SIMIT simulation software
- Delays are detected by DMP by analyzing automation logic and schedule is recomputed to account for these disturbances
- Other disturbances such as yield losses or disturbances in flow rates occurring in plant are communicated through SIMIT



Summary

Extensions from traditional RTN

- Altering resource-task interactions using parameter updates
- Considering delays as decisions taken by the optimizer in addition to treating them as disturbances to the schedule
- Incorporating disturbance information from automation system and simulation software into scheduling model
- Including restrictions posed by automation system in form of additional constraints
- Modeling of flow rates and accounting for yield loss disturbances