NATIONAL RESEARCH COUNCIL
INSTITUTE OF INDUSTRIAL TECHNOLOGY AND AUTOMATION

AUTOMATION: MODEL PREDICTIVE CONTROL IN MANUFACTURING PLANTS

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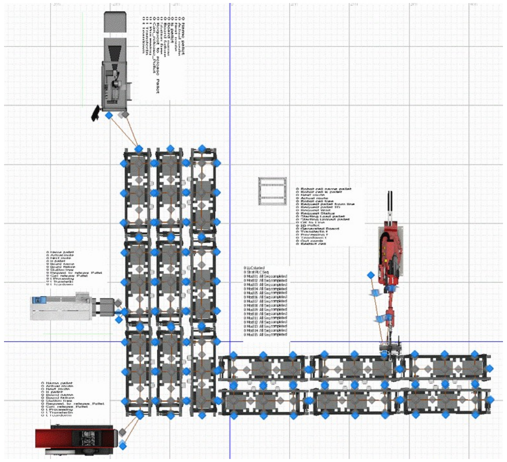


•ABB Corporate Research Italy (Industrial researcher)

•Foster Wheeler Italiana (Control engineer)

Outline

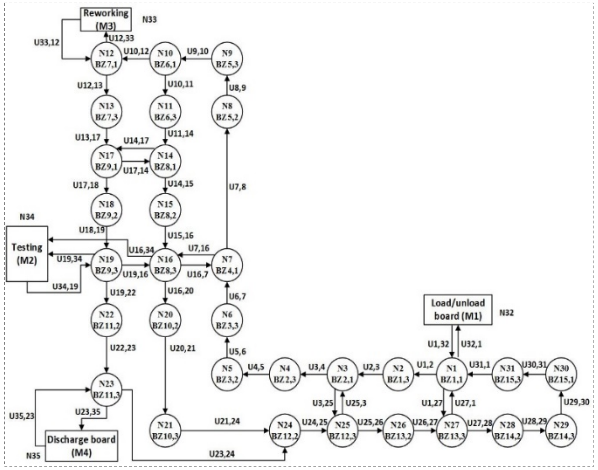
- What does Automation mean?
- Who is a Control Engineer? What does he do?
- Advanced Control System: a case study

What does Automation mean?

Who is a Control Engineer? What does he do?

Real Plant

Mathematical Model



Analysis

Modelling

Control method

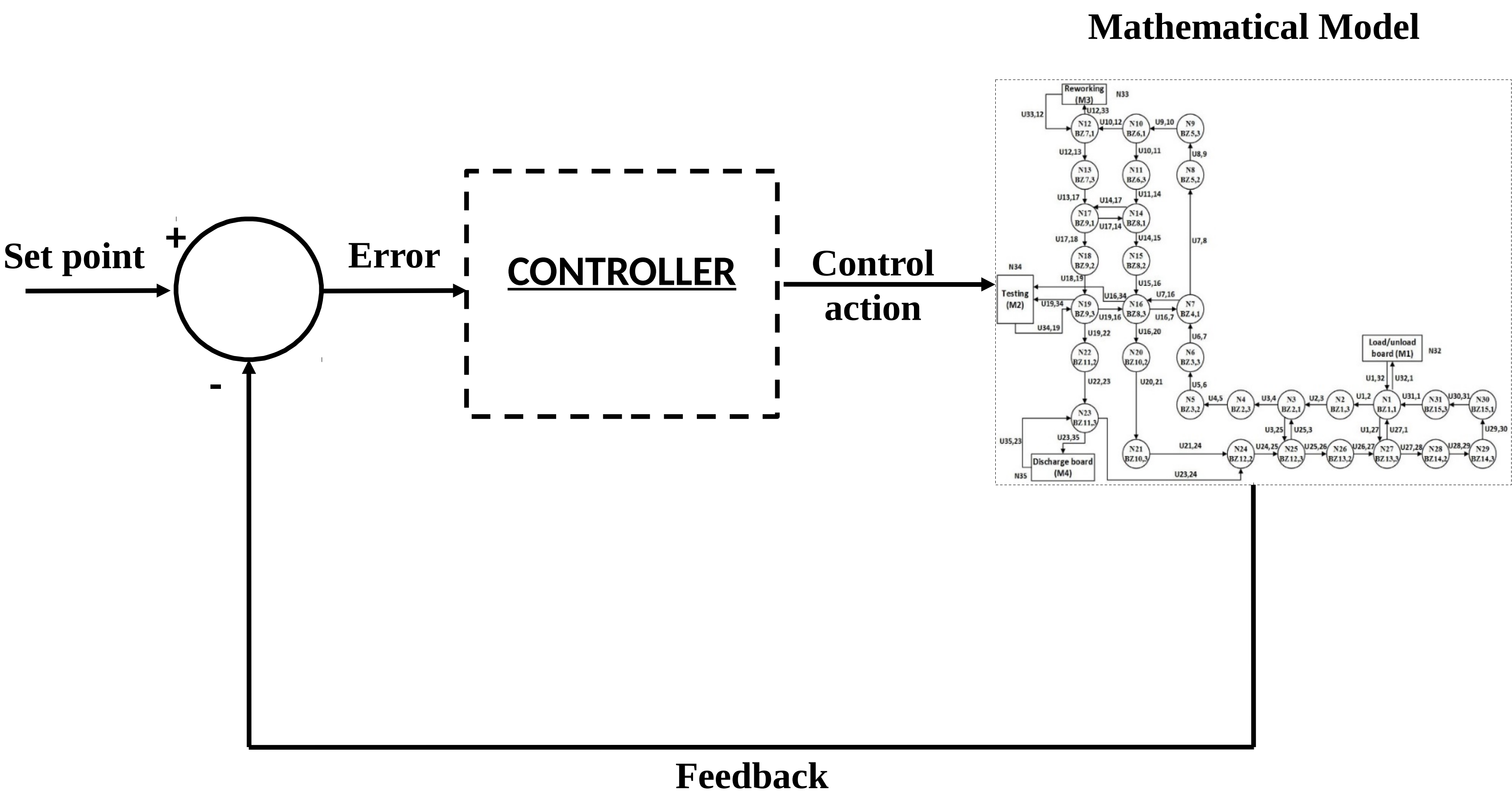
+

CONTROLLER

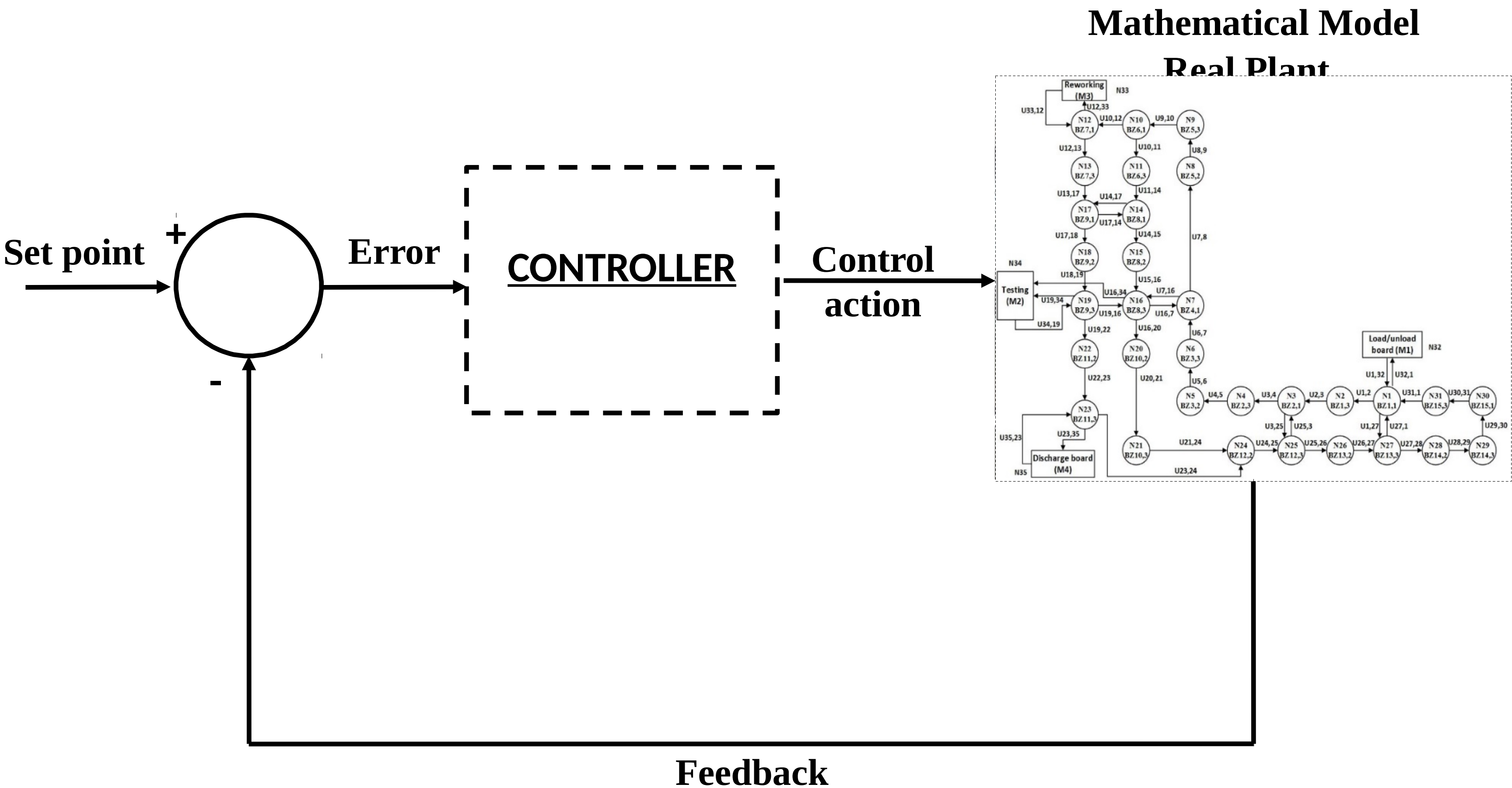
synthesis

Who is a Control Engineer? What does he do?

Simulation



Implementation

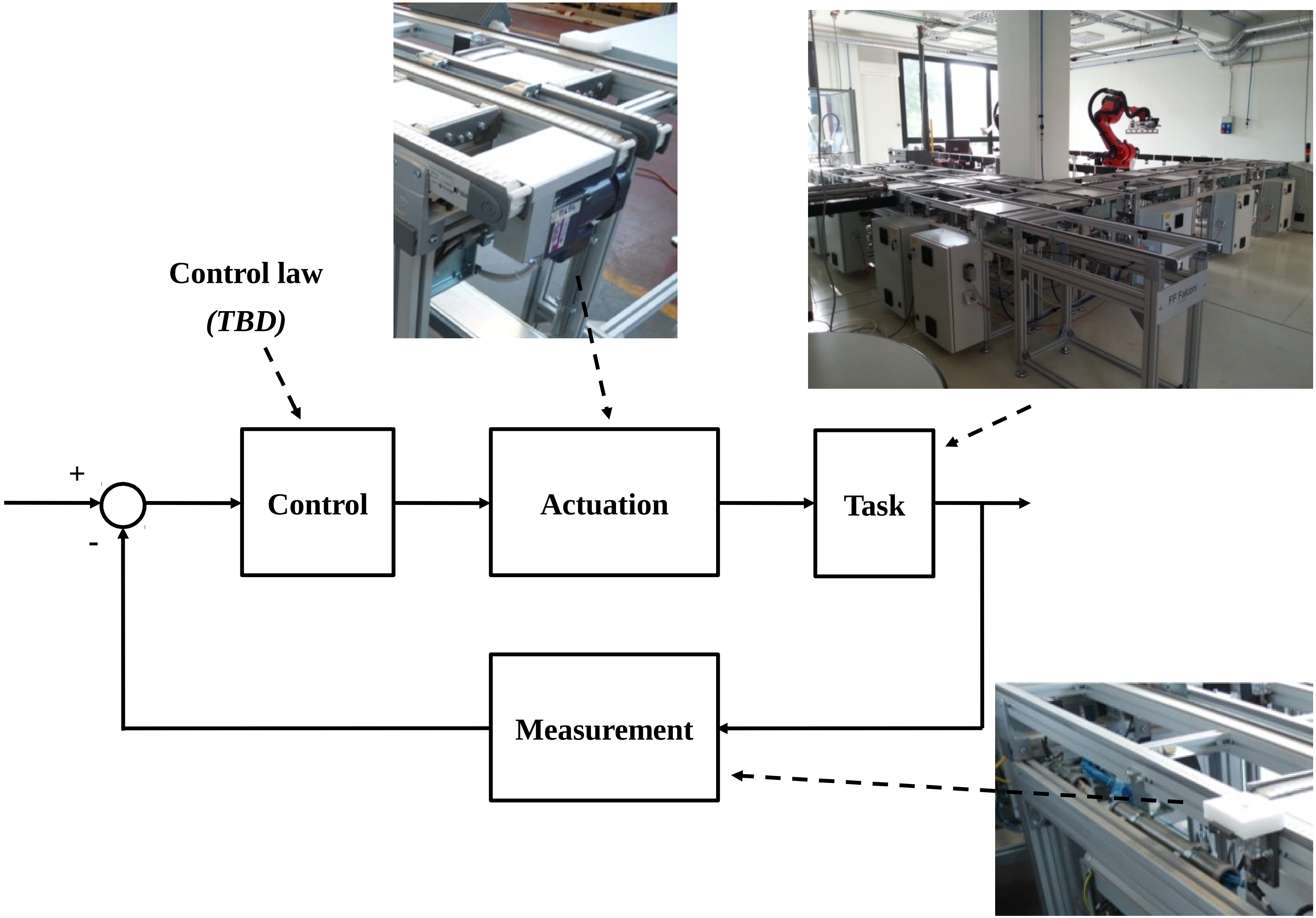


Advanced Control System: a case study

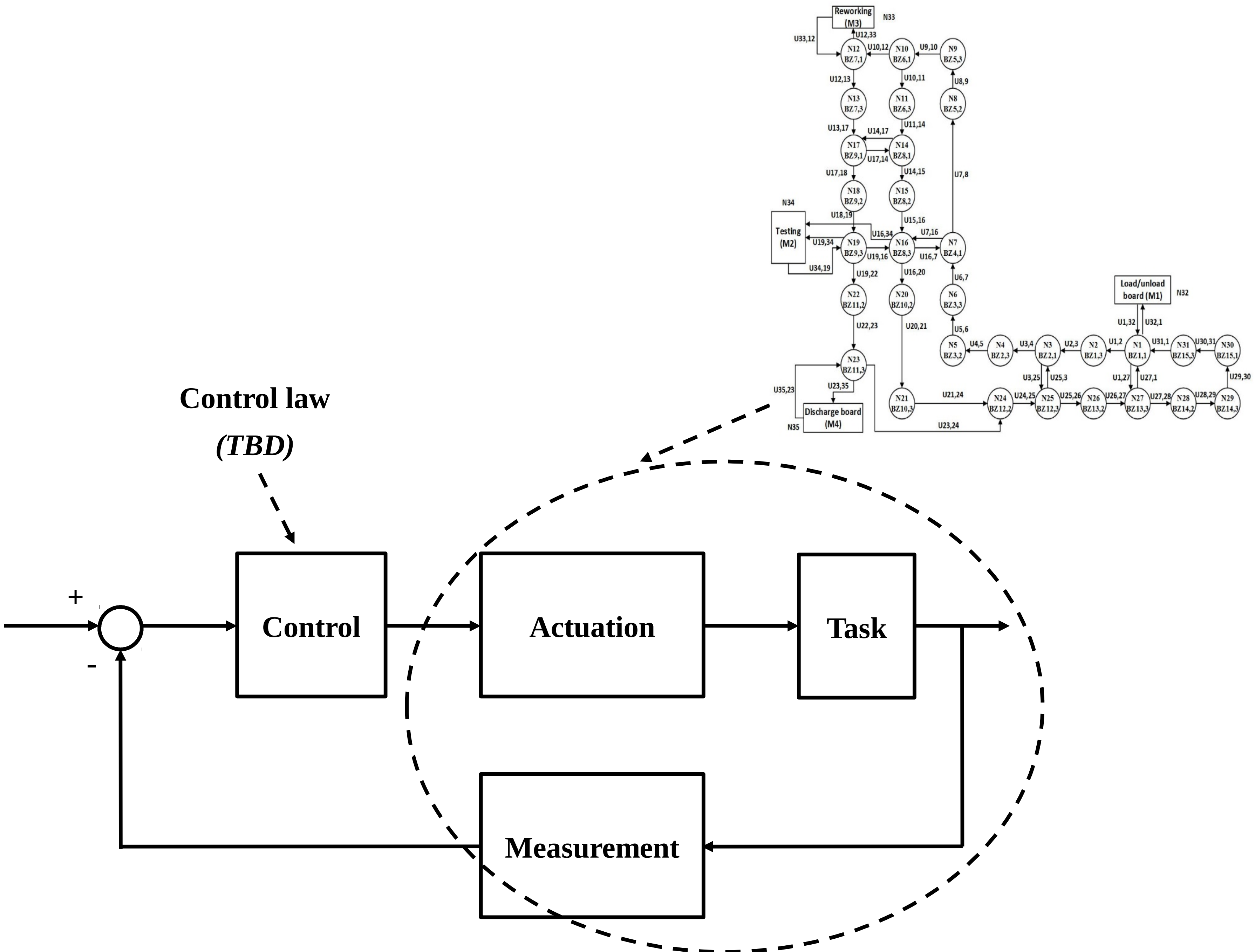
(Dynamic pallet routing in a manufacturing transport line)

De-manufacturing pilot plant – ITIA CNR, Via A. Corti 12, Milan (Italy)

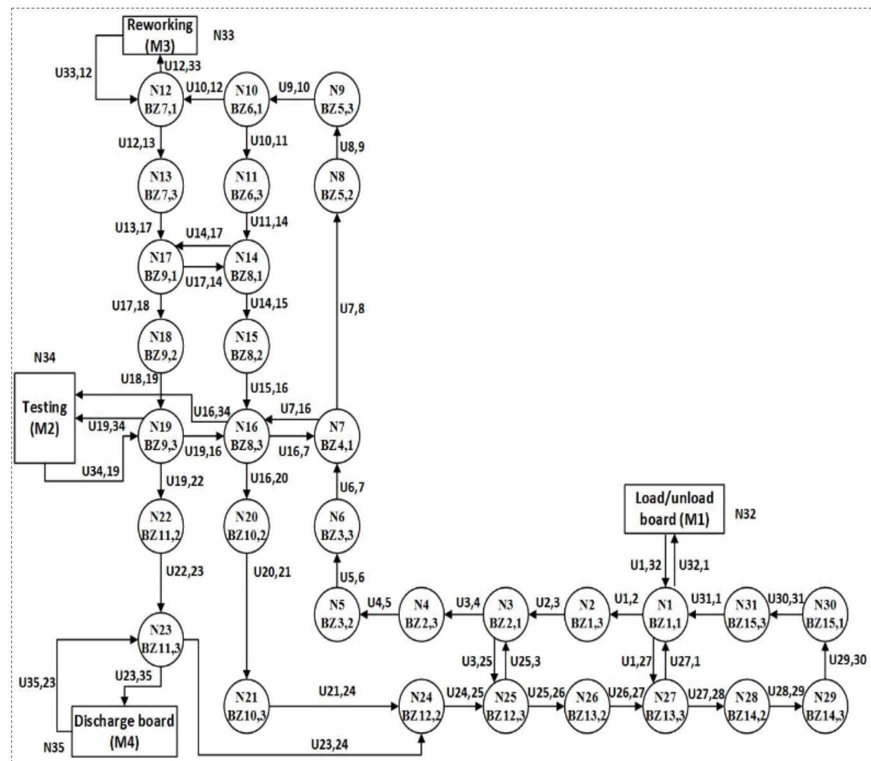
Control Systems Design



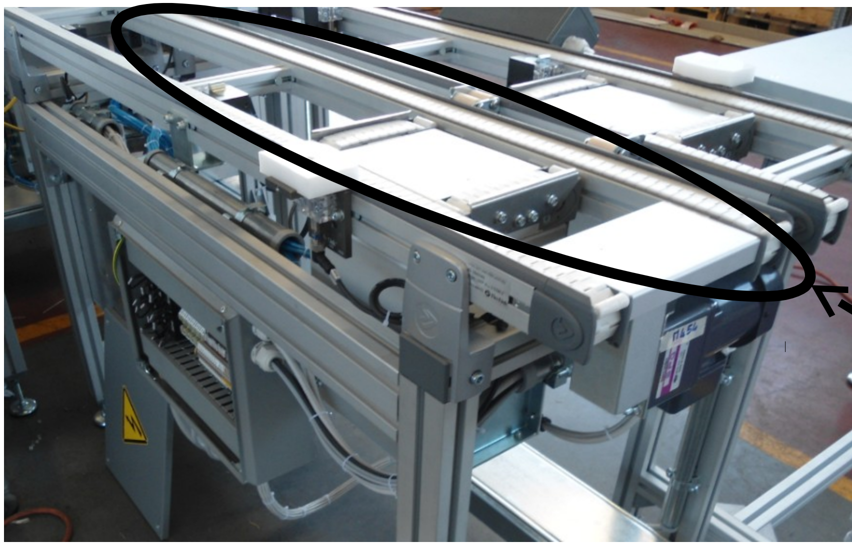
Control Systems Design



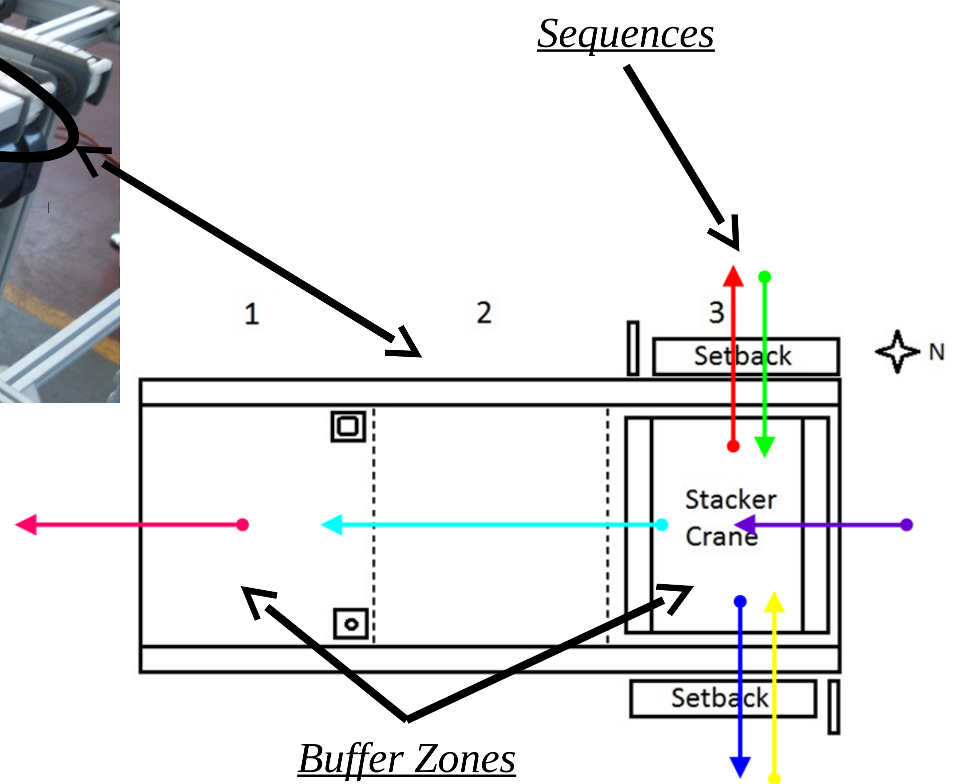
System Modelling



Buffer Zones and control Sequences



The generic pallet transport module

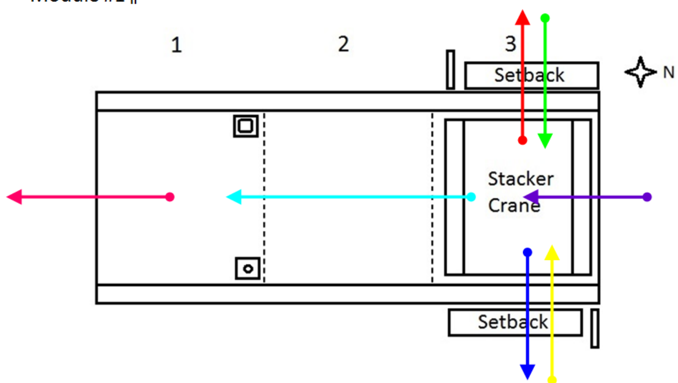


Sequences:

- S2: from Stacker crane #1 to Piston lock
- S3: from Piston lock to Next Module
- S28: from External Right (Setback Right) to Stacker crane #1 (Setback Left)
- S27: from External Left (Setback Left) to Stacker crane #1 (Setback Right)
- S6: from Stacker crane #1 to External Right
- S26: from Stacker crane #1 (Setback Right) to External left (Setback Left)
- S19: from Previous Module to Setback Right

The Sequences technique implementation

Module #1

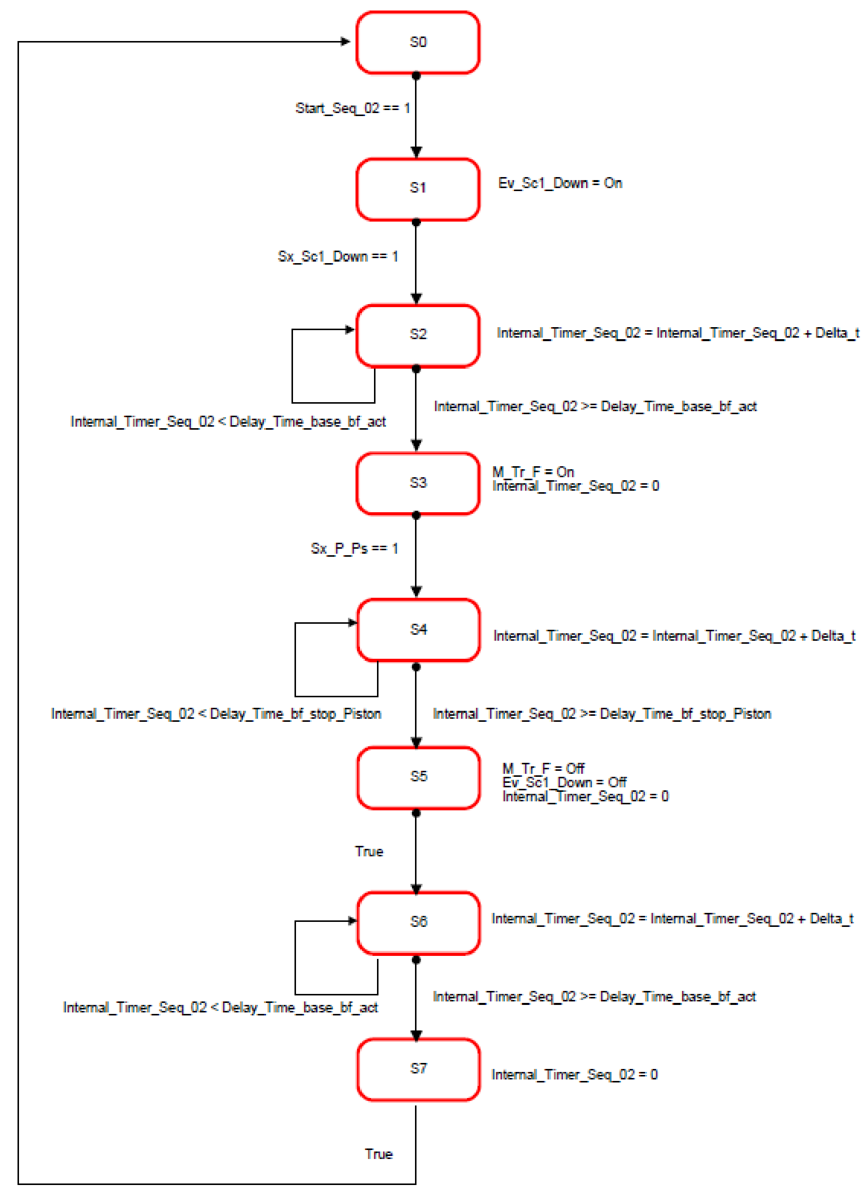


Sequences:

- S2: from Stacker crane #1 → to Piston lock
- S3: from Piston lock → to Next Module
- S28: from External Right (Setback Right) → to Stacker crane #1 (Setback Left)
- S27: from External Left (Setback Left) → to Stacker crane #1 (Setback Right)
- S6: from Stacker crane #1 → to External Right
- S26: from Stacker crane #1 (Setback Right) → to External left (Setback Left)
- S19: from Previous Module → to Setback Right

36 different *Sequences* - - - - - - >

Seq 2: Stacker Crane 1 - Piston lock



Finite State Machines – Automata

(Hybrid systems course – Prof. Prandini)

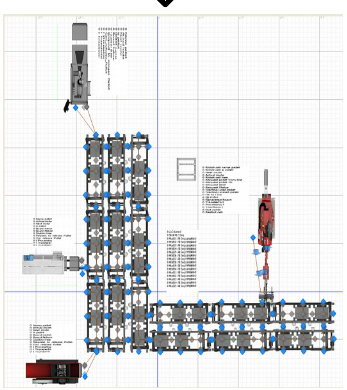
A. Cataldo, M. Taisch, B. Stahl, Modelling, simulation and evaluation of energy consumptions for a manufacturing production line, IECON 2013 - Wien

The Sequences technique implementation

SIMIO simulation platform

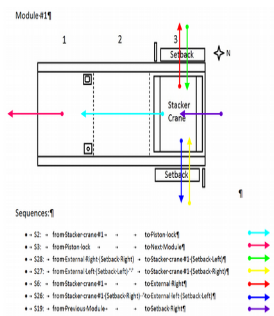
```
// → Arc Transitions
// → ***************
  switch (M4_FSM_variable_state) {

  case 0 : {
    //From State 0 to State 1
    if (FTC_In == true) {
      M4_FSM_variable_state = 1;
    }
  } break;

  case 1 : {
    From State 1 to State 2
    if (Drilling processed == true) {
      M4_FSM_variable_state = 2;
    }
  } break;

  case 2 : {
    From State 2 to State 0
    if (FTC_Out == true) {
      M4_FSM_variable_state = 0;
    }
  } break;

}//switch


//Output
//******
switch (M4_FSM_variable_state) {

  case 0 : {
    //Output State 0

  } break;

  case 1 : {
    //Output State 1
    Start drilling = true;
  } break;

  case 2 : {
    //Output State 2

  } break;

}//switch
```

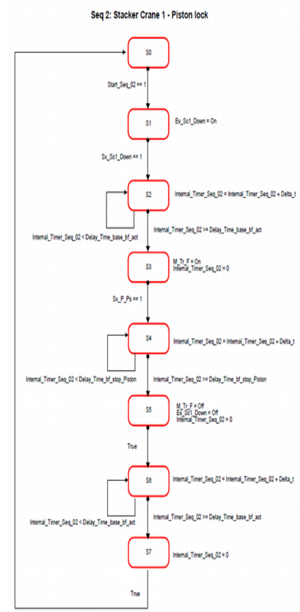
C# Sw code



Dynamic Discrete Event simulation model (SIMIO)

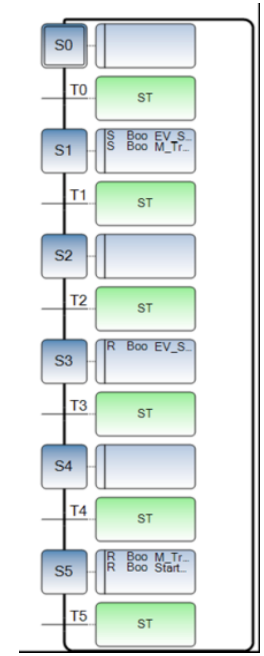
The methodological aspect





Transport line shop floor

(Low level control implementation)



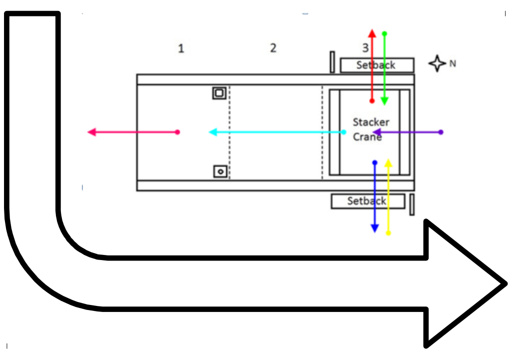
IEC 61131-3 standard

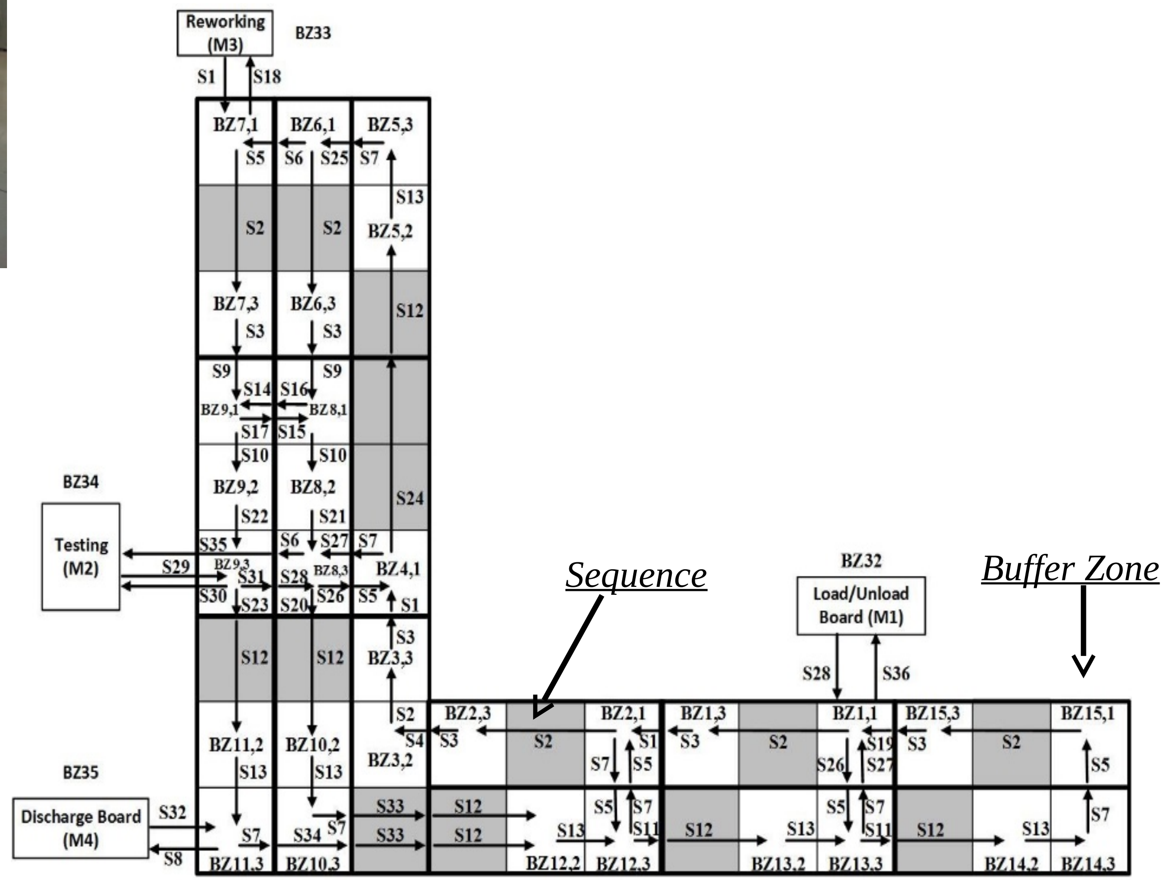
(Sequential Functional Chart)

PLC

(Isagraf - Rockwell)

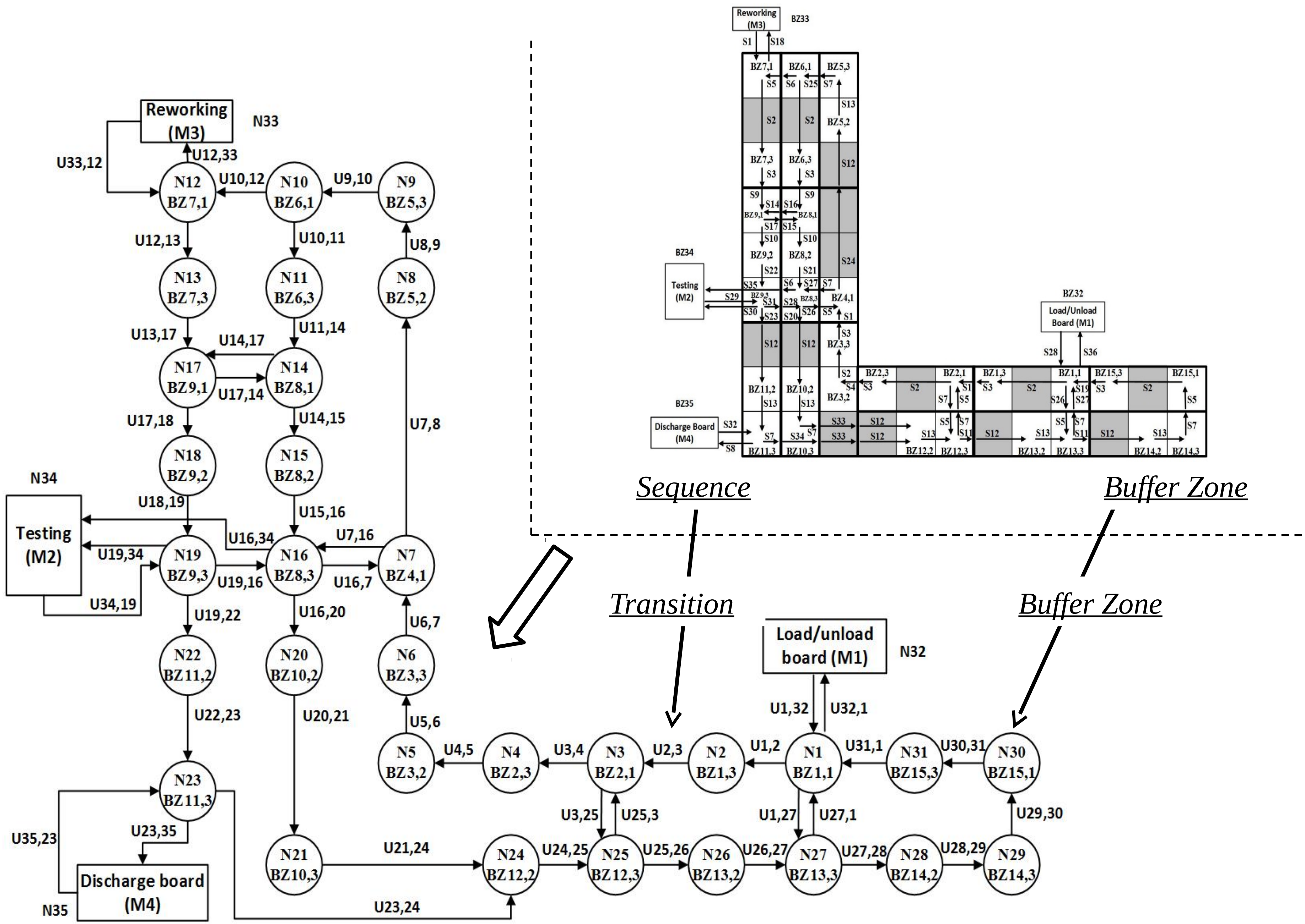
The Buffer Zones model



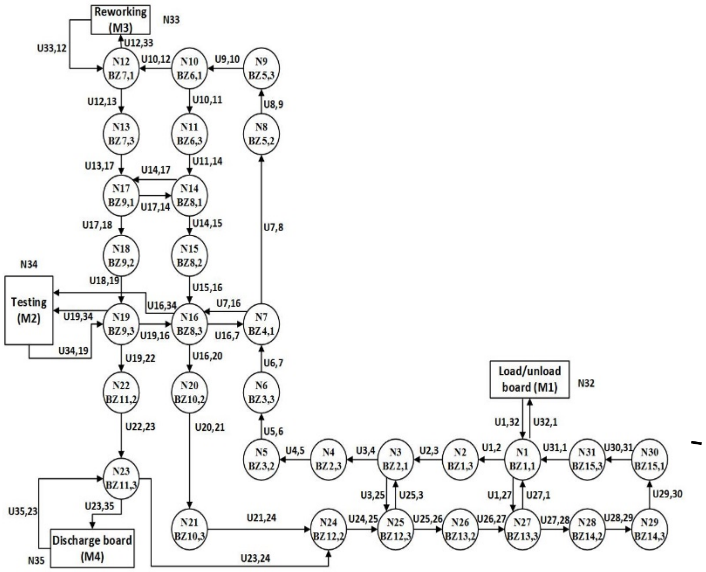


Buffer Zones model

The transport line abstract description



The High Level Control System design: main concepts



Input: pallet Target

Output: Transition

Propositional calculus

$$
\begin{aligned}
x(t+1) &= Ax(t) + B_1 u(t) + B_2 \delta(t) + B_3 z(t) + B_5 \\
y(t) &= Cx(t) + D_1 u(t) + D_2 \delta(t) + D_3 z(t) + D_5 \\
E_2 \delta(t) + E_3 z(t) &\leq E_4 x(t) + E_1 u(t) + E_5
\end{aligned}
$$

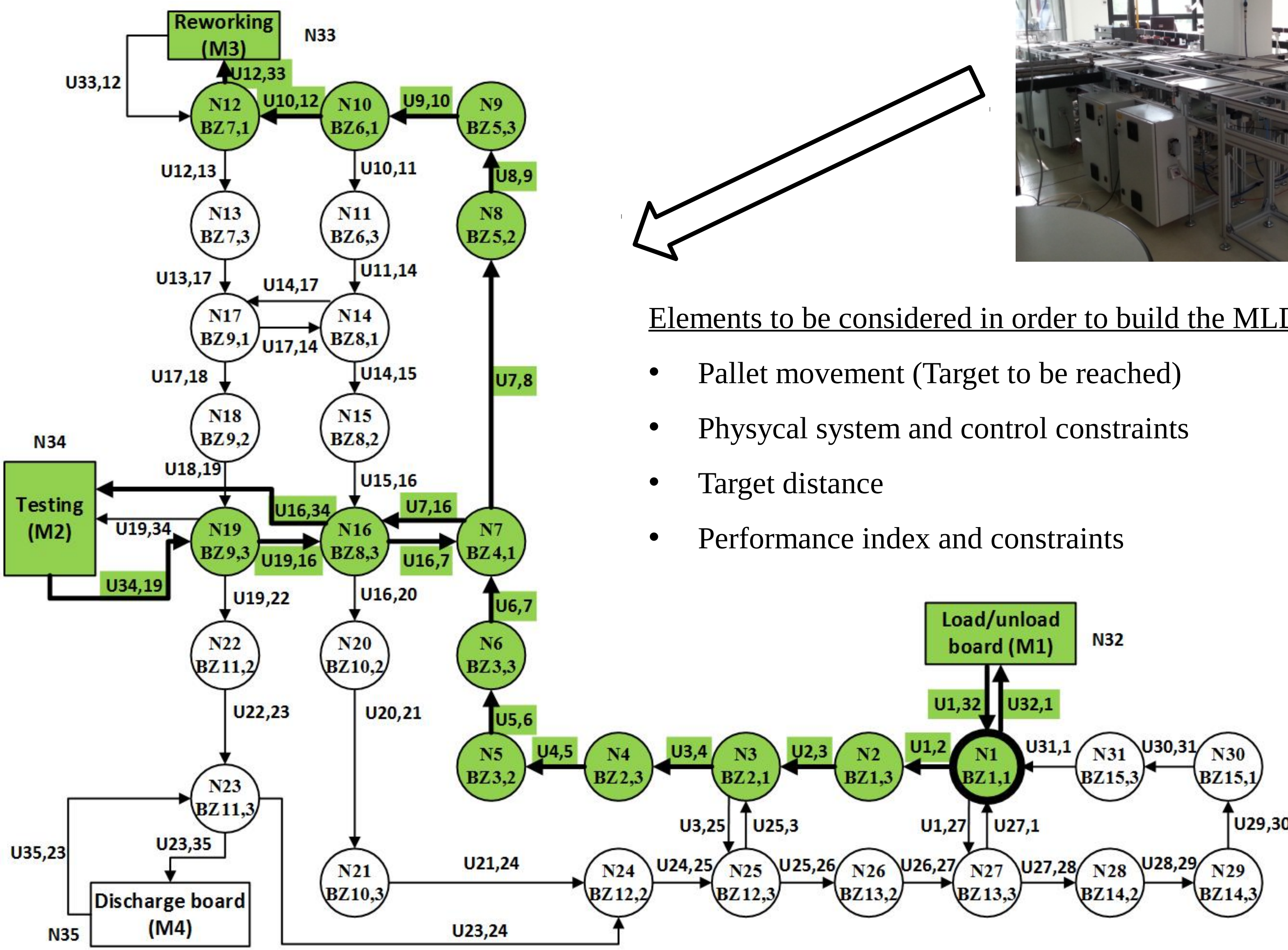
Continuous and binary variables

$$
\begin{aligned}
& x \in \mathbb{R}^{n_r} \times \{0,1\}^{n_b}, \; u \in \mathbb{R}^{m_r} \times \{0,1\}^{m_b} \\
& y \in \mathbb{R}^{p_r} \times \{0,1\}^{p_b}, \; \delta \in \{0,1\}^{r_b}, \; z \in \mathbb{R}^{r_r}
\end{aligned}
$$

The transport line Mixed Logical Dynamic (MLD) model

The transport line Model Predictive Controller (MPC)

From the manufacturing plant to the MPC design: main concepts



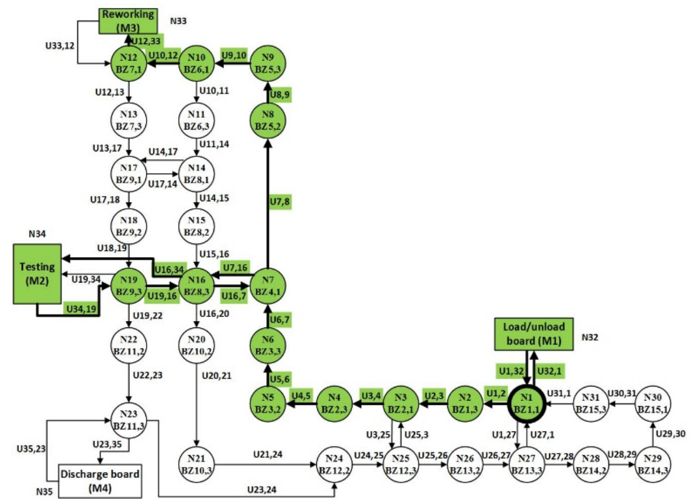
Elements to be considered in order to build the MLD model

- Pallet movement (Target to be reached)
- Physycal system and control constraints
- Target distance
- Performance index and constraints

The MPC design: system modelling and MLD formulation

Pallet movement (Target to be reached)

$$Tp_i(k+1) = Tp_i(k) + \sum_{j \in I_{i,in}} Tp_i(k) \cdot u_{j,i}(k) - \sum_{j \in I_{i,out}} Tp_i(k) \cdot u_{i,j}(k), i = 1,..,31$$



Physycal system and control constraints

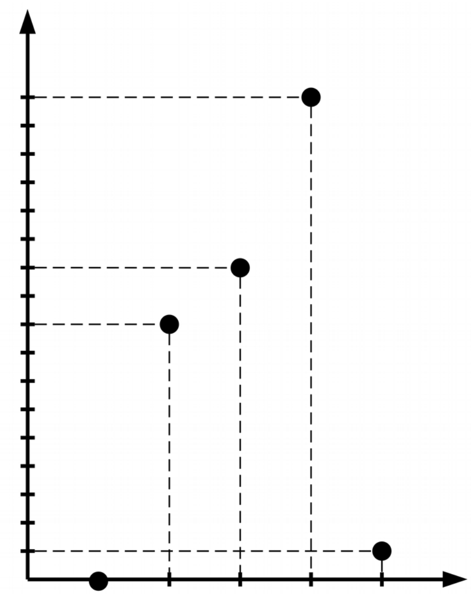
$$X_{i1}(k) \wedge \prod_{\forall j \in I_{i,in}} (u_{i,j}(k)) \rightarrow X_{i1}(k+1) = 0 \qquad U_n(k) + U_m(k) \leq 1$$

Target distance

$$x_i(k) = f(Tp_i(k))$$

$$Tp_i(k) \xrightarrow{\text{Pallet distance}} x_i(k)$$

(Linear function - H. Paul Williams, pag. 182; Sherali 2001)



Performance index

$$y_i(k) = C_i \cdot x_i(k)$$

Pallet distance from the Target

$$J = \sum_{h=1}^{RH} \left[\sum_{i=1}^{35} (Q_y \cdot y_i(k+h)) + \sum_{i=32}^{35} (Q_x \cdot x_i(k+h)) + \sum_{(i,j) \in I_u} Q_u \cdot u_{i,j}(k+h-1) \right]$$

$$\begin{aligned} x(k+1) &= Ax(k) + B_u u(k) + B_{aux} w(k) + B_{aff} \\ y(k) &= Cx(k) + D_u u(k) + D_{aux} w(k) + D_{aff} \\ & E_x x(k) + E_u u(k) + E_{aux} w(k) \leq E_{aff} \end{aligned}$$

The de-manufacturing transport line: MILP formulation

By re-arranging into the canonical form it comes:

$$J = \min C' x'$$

s. t.

$$\left.\begin{array}{l} A' x' \le b' \end{array}\right\} x' = [x_z' x_b']^T \in Z_+^n$$

$$x_z' \ge 0$$

$$x_z' \text{ int .}$$

$$x_b' \in \{0,1\}$$

IP problem formulation

$$\min\{ c' x' : A' x' \le b', x' \in Z_+^n \}$$

$$\Downarrow$$

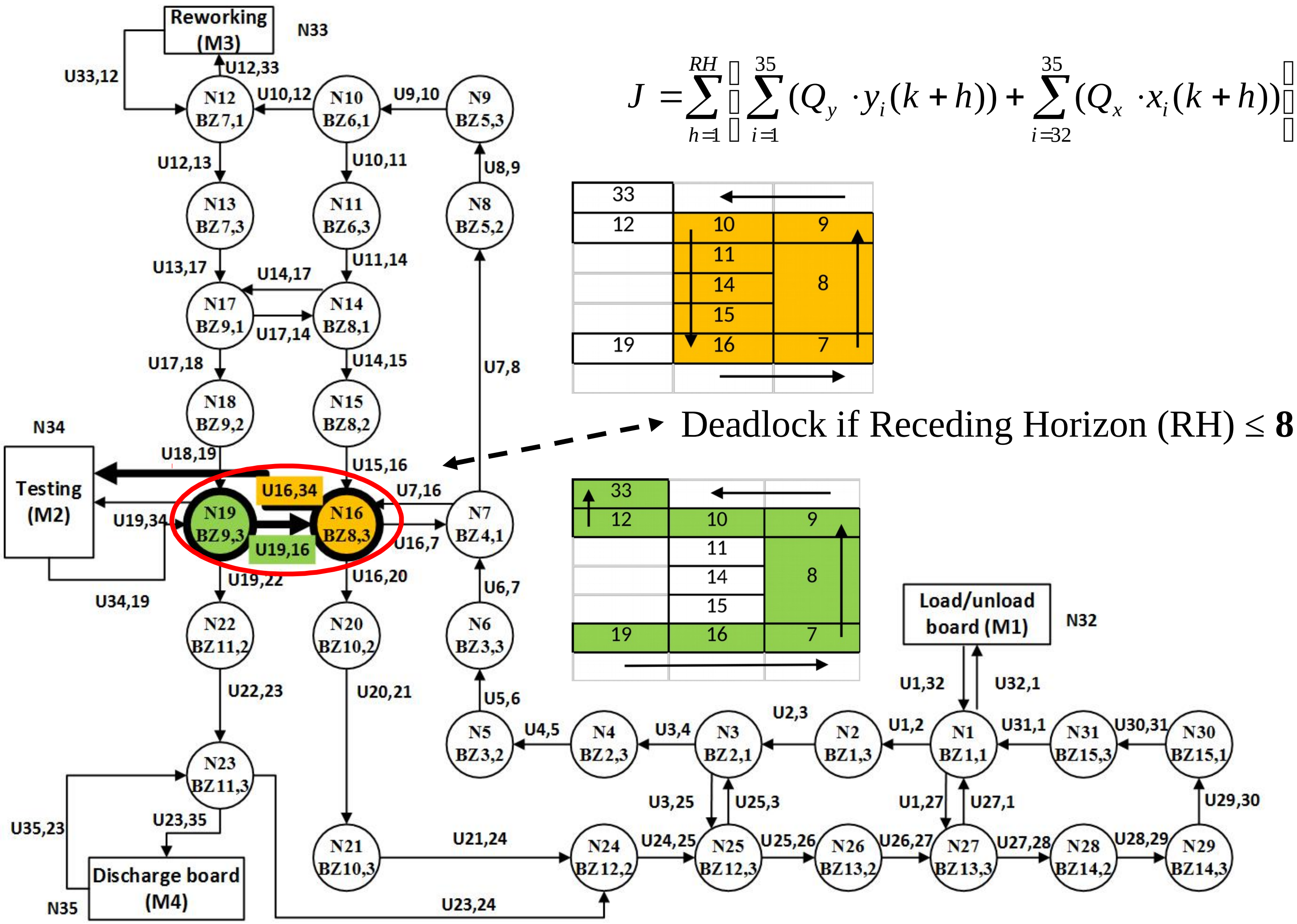
$$u(t) = v_t^*(0)$$

Optimal solution

(Receding horizon philosophy)

The MPC algorithm: Basic formulation

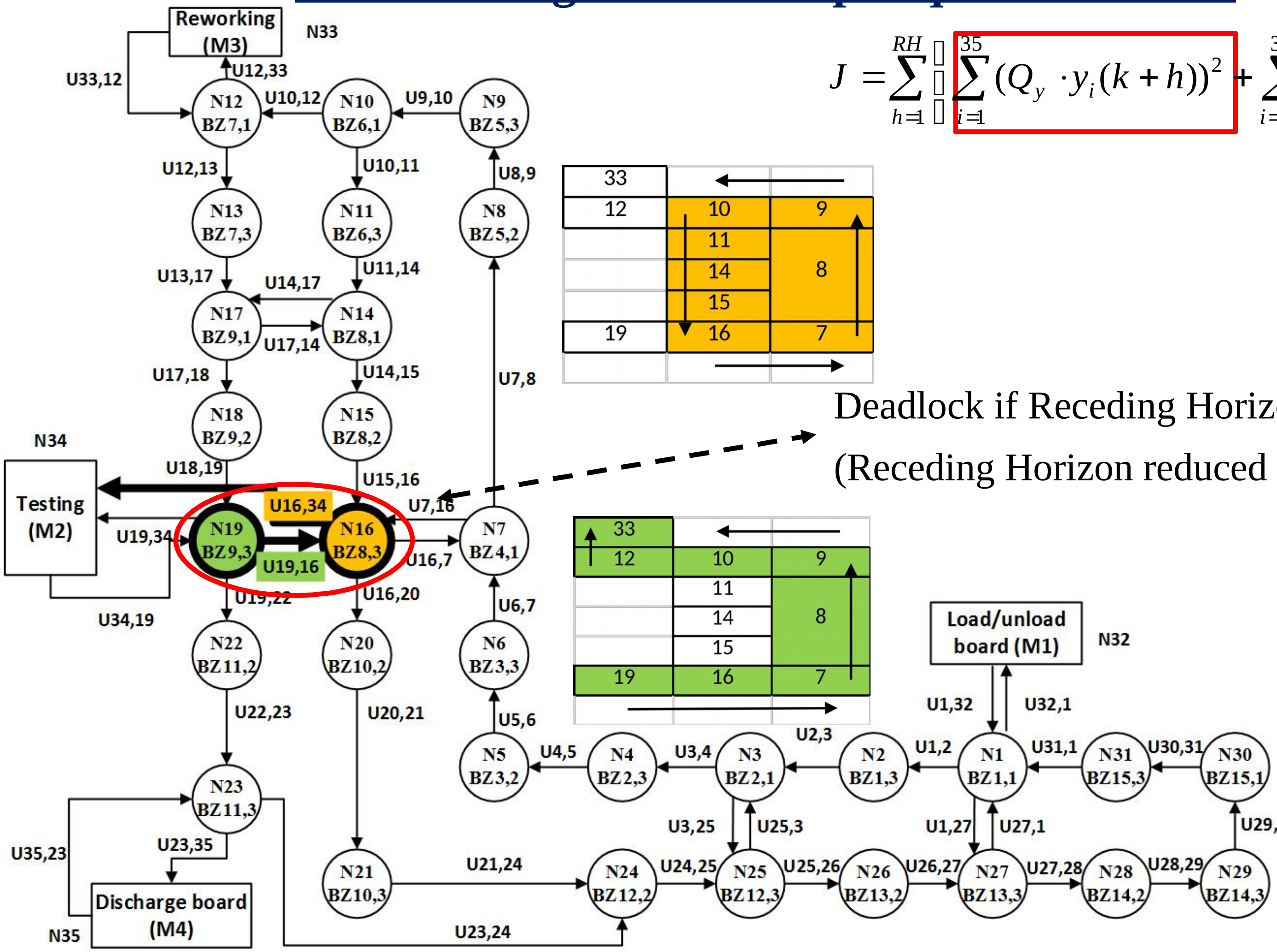
$$J = \sum_{h=1}^{RH} \left[\sum_{i=1}^{35} (Q_y \cdot y_i(k+h)) + \sum_{i=32}^{35} (Q_x \cdot x_i(k+h)) \right]$$



Passi	1		2		3		4		5		6		7		8		9	
Nodi	19	16	19	7	16	8	7	9	8	10	9	11	10	14	12	15	33	16
Obiettivi	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2
Valori distanze dai Target	7	1	7	2	6	7	5	6	4	5	3	4	2	3	1	2	0	1
Valore calcolato nella J Lineare	8		9		13		11		9		7		5		3		1	
Valore calcolato nella J Lineare (con deadlock)	8		8		8		8		8		8		8		8		8	
Progressivo valore J Lineare	8		17		30		41		50		57		62		65		66	
Progressivo valore J Lineare (con deadlock)	8		16		24		32		40		48		56		64		72	

The MPC algorithm: Output quadratic term

$$J=\sum_{h=1}^{RH}\left[\sum_{i=1}^{35}(Q_y\cdot y_i(k+h))^2+\sum_{i=32}^{35}(Q_x\cdot x_i(k+h))\right]$$



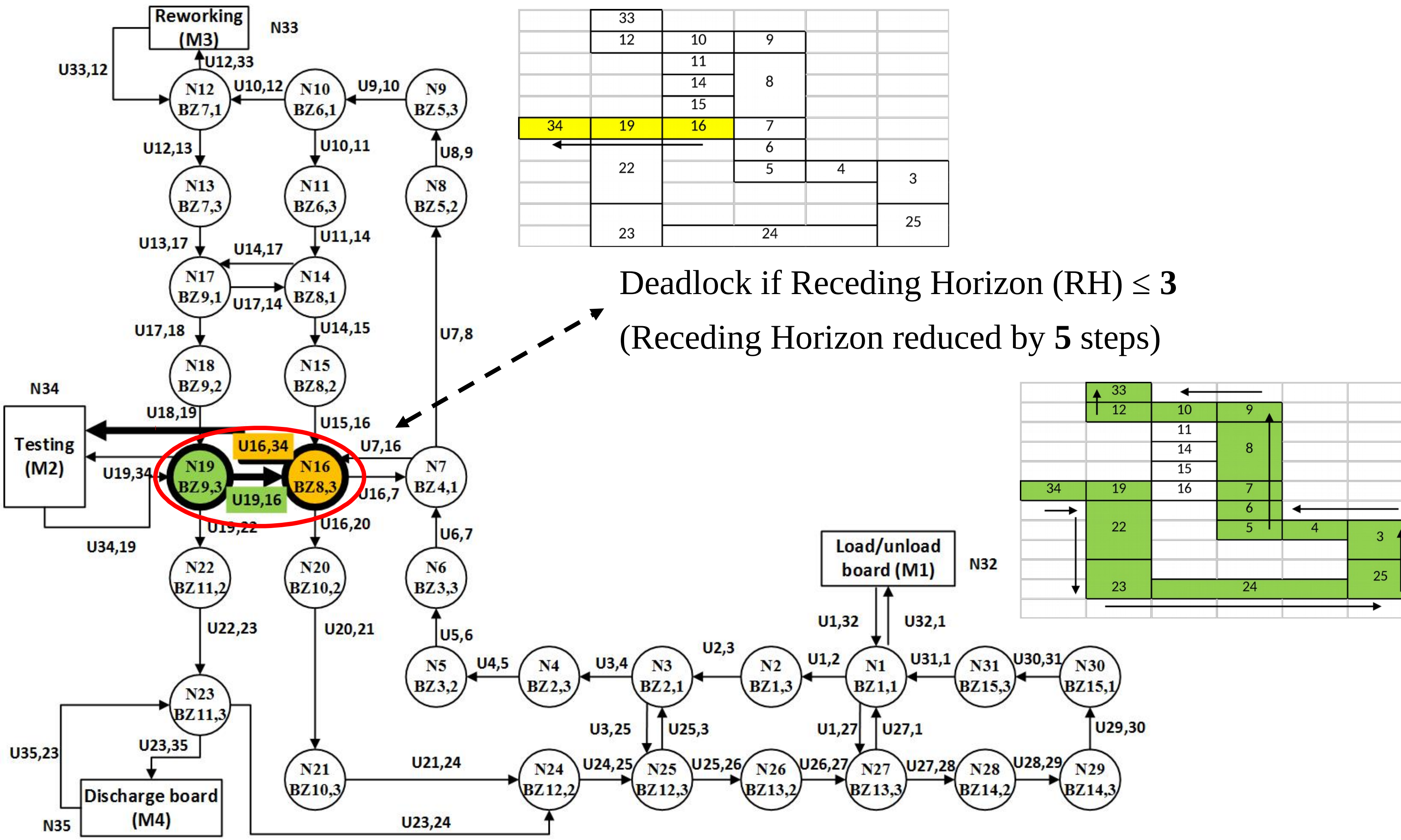
Deadlock if Receding Horizon (RH) ≤ **6**

(Receding Horizon reduced by **2** steps)

Passi	1		2		3		4		5		6		7		8		9	
Nodi	19	16	19	7	16	8	7	9	8	10	9	11	10	14	12	15	33	16
Obiettivi	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2	M3	M2
Valori distanze dai Target	7	1	7	2	6	7	5	6	4	5	3	4	2	3	1	2	0	1
Valore calcolato nella J Lineare	8		9		13		11		9		7		5		3		1	
Valore calcolato nella J Lineare (con deadlock)	8		8		8		8		8		8		8		8		8	
Progressivo valore J Lineare	8		17		30		41		50		57		62		65		66	
Progressivo valore J Lineare (con deadlock)	8		16		24		32		40		48		56		64		72	
Valore calcolato nella J Quadratica	50		53		85		61		41		25		13		5		1	
Valore calcolato nella J Quadratica (con deadlock)	50		50		50		50		50		50		50		50		50	
Progressivo valore J Quadratica	50		103		188		249		290		315		328		333		334	
Progressivo valore J Quadratica (con deadlock)	50		100		150		200		250		300		350		400		450	

The MPC algorithm: Integral control action

$$J = \sum_{h=1}^{RH} \left[\sum_{i=1}^{35} (Q_y \cdot y_i(k+h))^2 + \sum_{i=32}^{35} (Q_x \cdot x_i(k+h)) + \sum_{i=1}^{31} (q_{Ni} \cdot N_i(k+h)) \right]$$

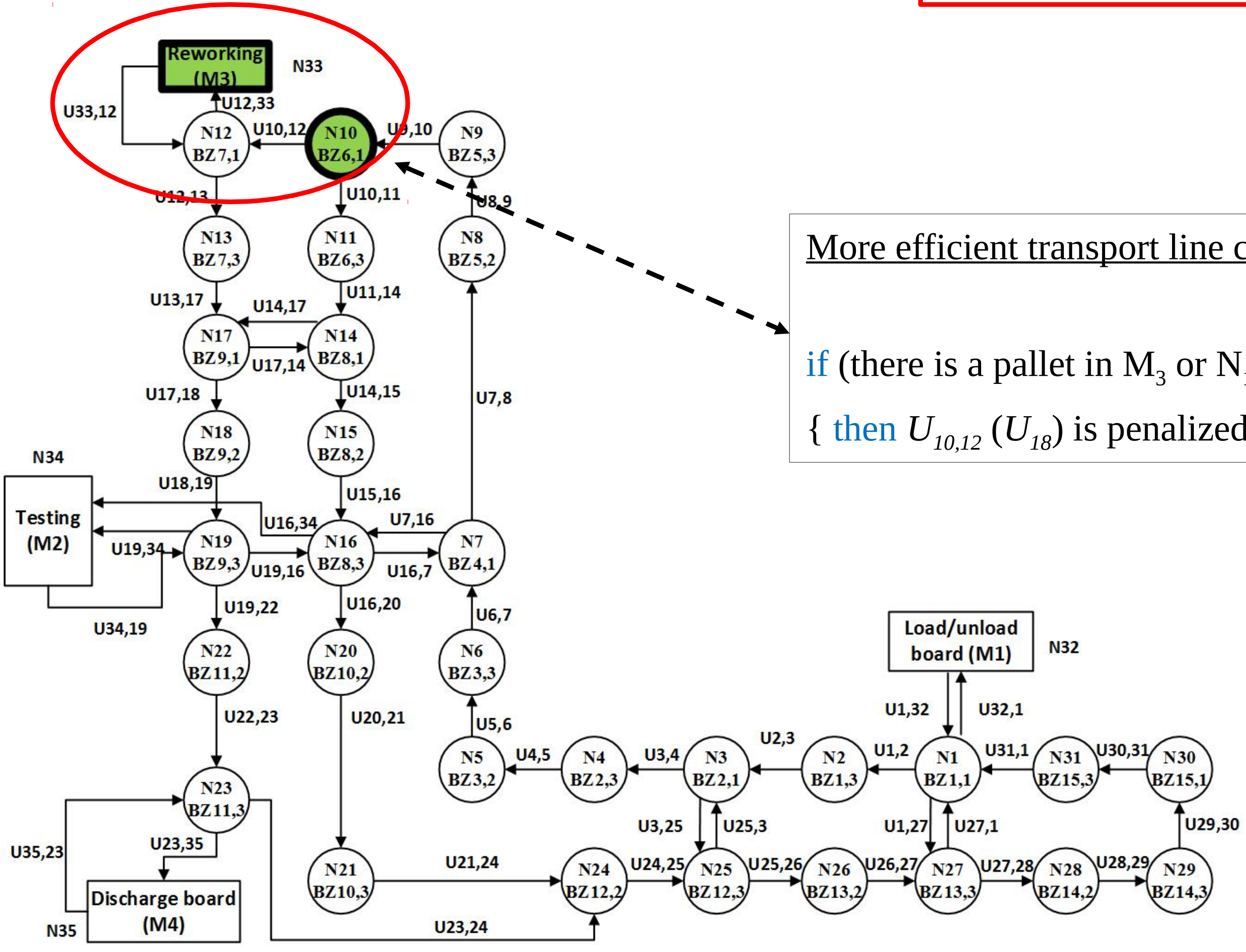


Deadlock if Receding Horizon (RH) ≤ **3**

(Receding Horizon reduced by **5** steps)

The MPC algorithm: Off-limit zone

$$J = \sum_{h=1}^{RH} \left[\sum_{i=1}^{35} (Q_y \cdot y_i(k+h))^2 + \sum_{i=32}^{35} (Q_x \cdot x_i(k+h)) + \sum_{i=1}^{31} (q_{Ni} \cdot N_i(k+h)) + k_1\delta_1 U_{14} + k_1\delta_1 U_{26} + k_1\delta_1 U_{33} + k_2\delta_2 U_{18} + k_3\delta_3 U_{34} \right]$$

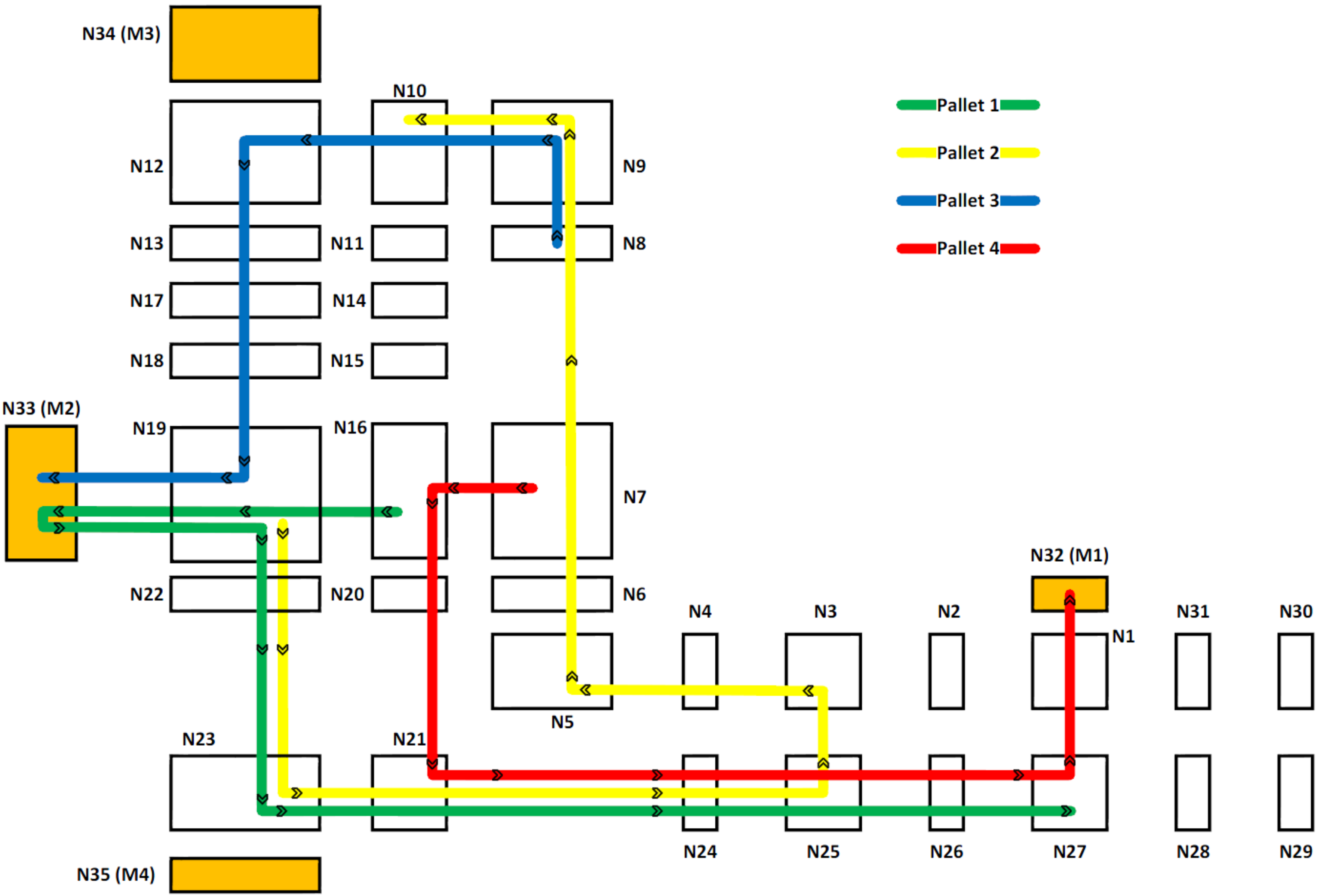


<u>More efficient transport line control</u>

if (there is a pallet in M_3 or N_{12})

{ then $U_{10,12}$ (U_{18}) is penalized in J }

MPC testing



N34 (M3)
N10
N12
N9
N13
N11
N8
N17
N14
N18
N15
N33 (M2)
N19
N16
N7
N32 (M1)
N22
N20
N6
N4
N3
N2
N31
N30
N1
N5
N23
N21
N24
N25
N26
N27
N28
N29
N35 (M4)
Pallet 1
Pallet 2
Pallet 3
Pallet 4

MPC testing