POLITECNICO
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Manufacturing Systems Mining: Generation of Real-time Discrete Event Simulation Models

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Andrea Matta

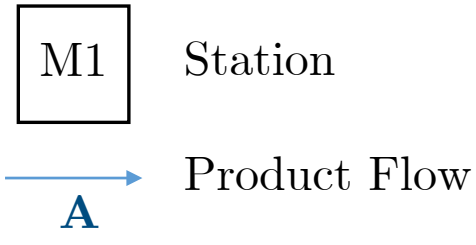
Contents

- A new method that generates the Petri Net model of a manufacturing system.
- Starting point is an **event log** with three data labels.
- The user decides the number of maximum events to be mapped to control the model level of detail.
- **Test case** shows potential applicability to a manufacturing environment.

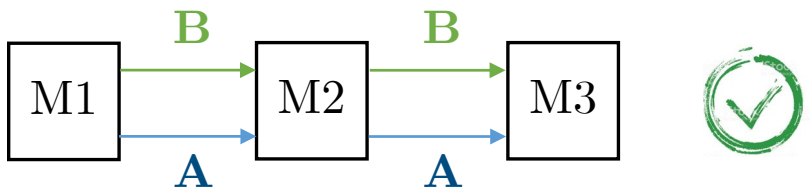
Table of contents

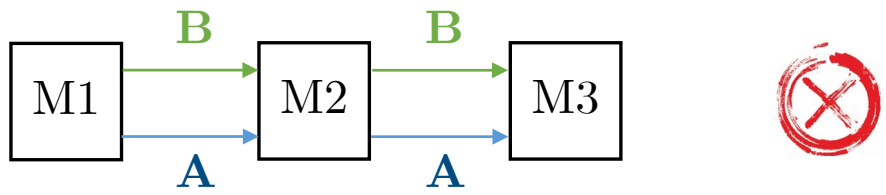
Industrial Scenario

At the time the physical manufacturing system changes, the simulator might be out of date.

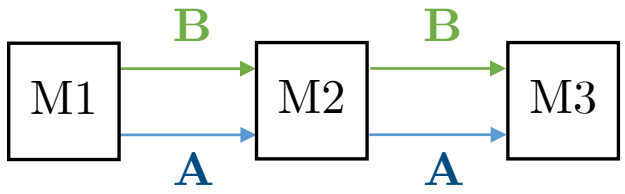


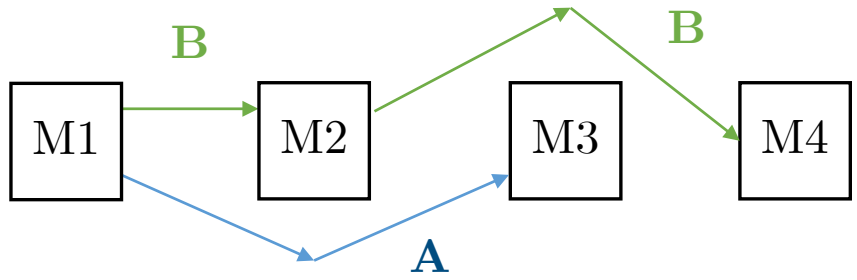
Simulator





Manufacturing System

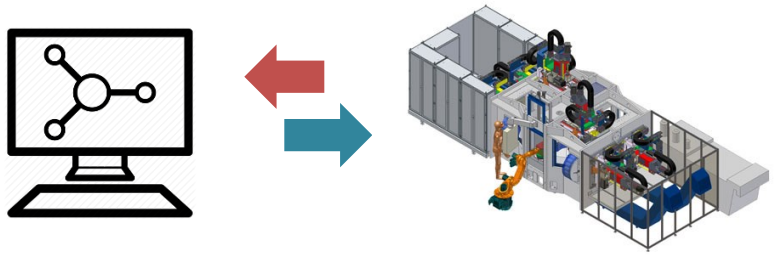




Industrial Scenario

- Manufacturing systems frequently change due to external drivers (e.g. demand, price uncertainty)
- New resources are available (e.g. *Plug and Produce*)
- Strong push towards *customization*
- Industry 4.0 and Cyber Physical Systems (CPS)

Creation/Update of SIMULATORS



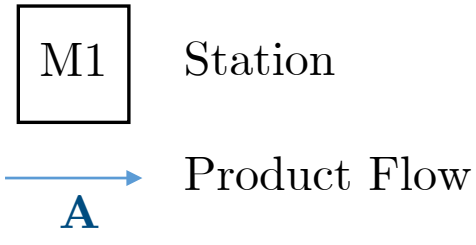
Use SIMULATORS to act on the system

New Application Scenarios:

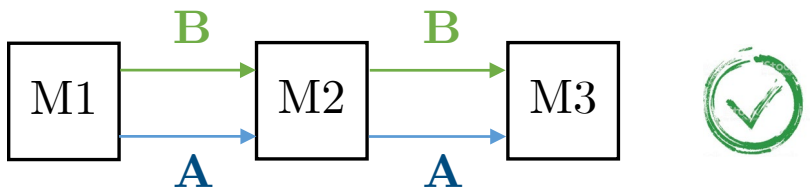
- Collecting information from the system with high frequency
- Understanding emerging behaviors studying systems' data logs
- Evaluating alternative scenarios and their related risk
- Performing data analytics in affordable time and cost

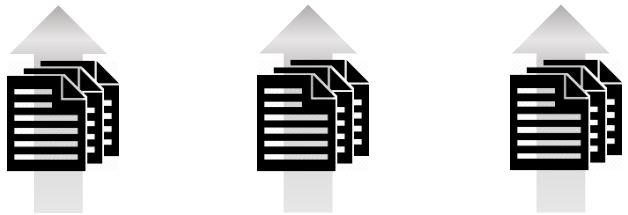
Industrial Scenario

At the time the physical manufacturing system changes, the simulator might be out of date.

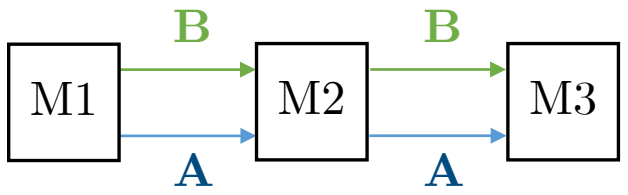


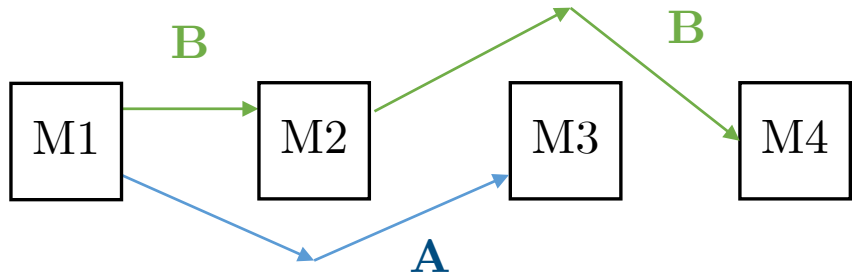
Simulator





Manufacturing System





Industrial Scenario

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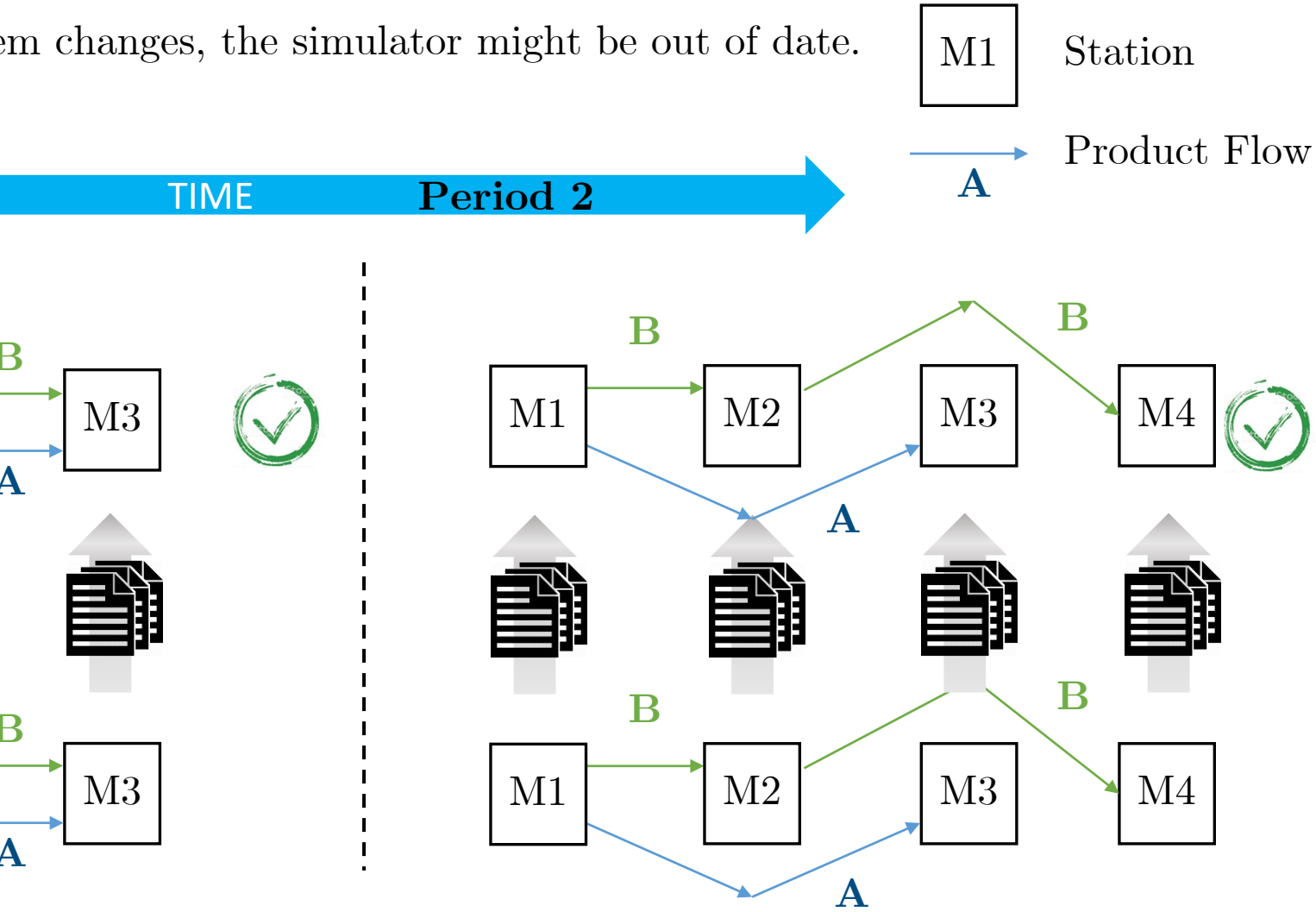
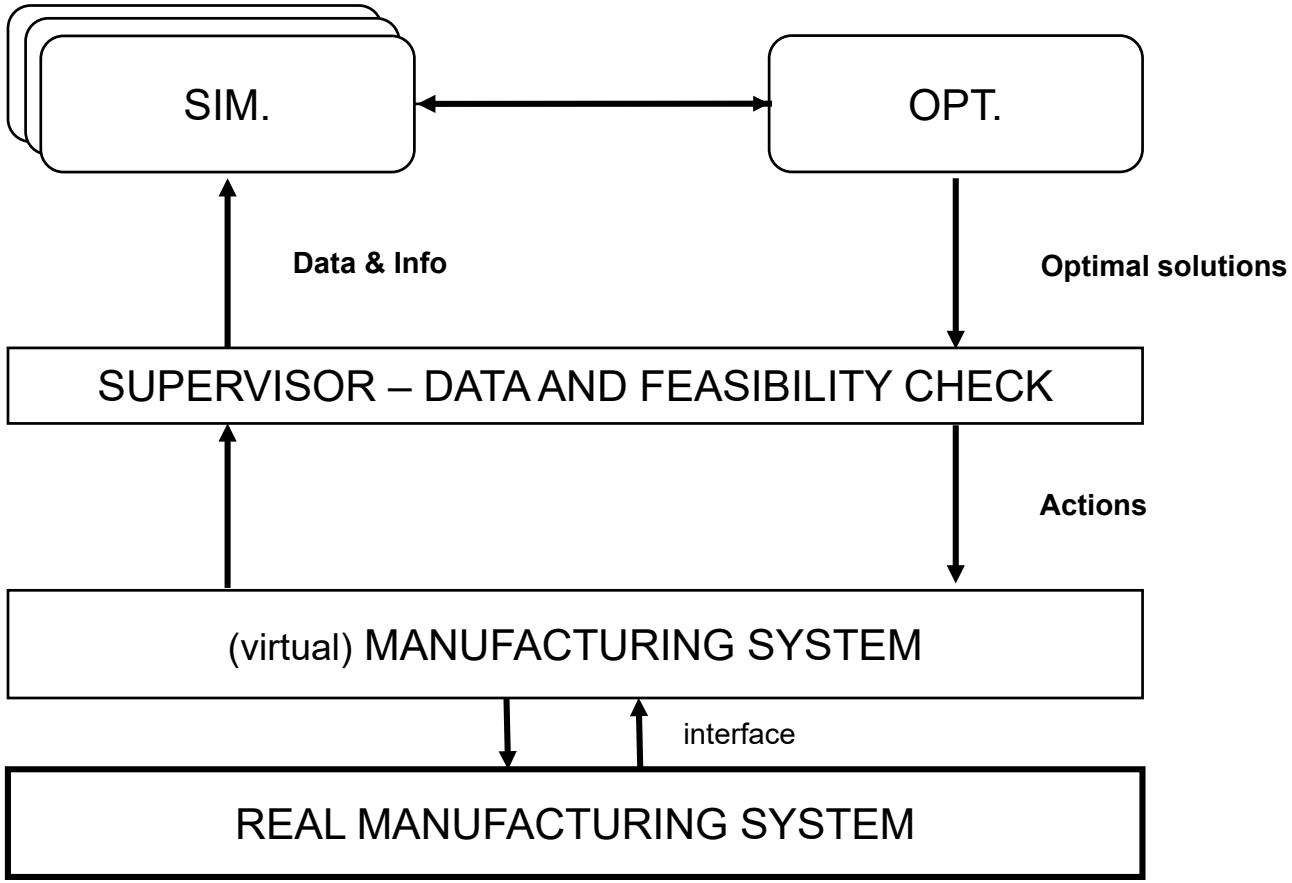
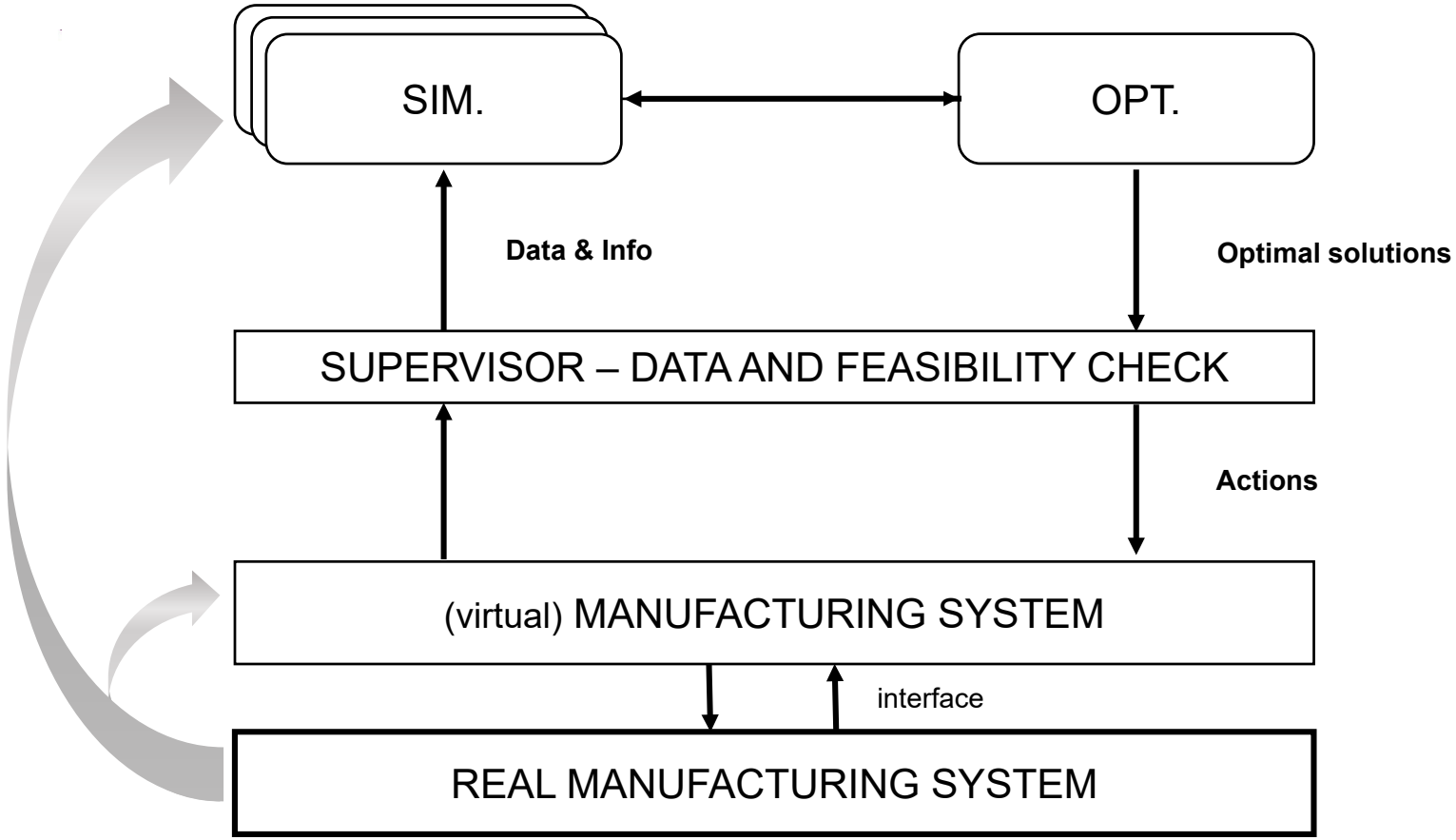


Real Time Simulation Framework

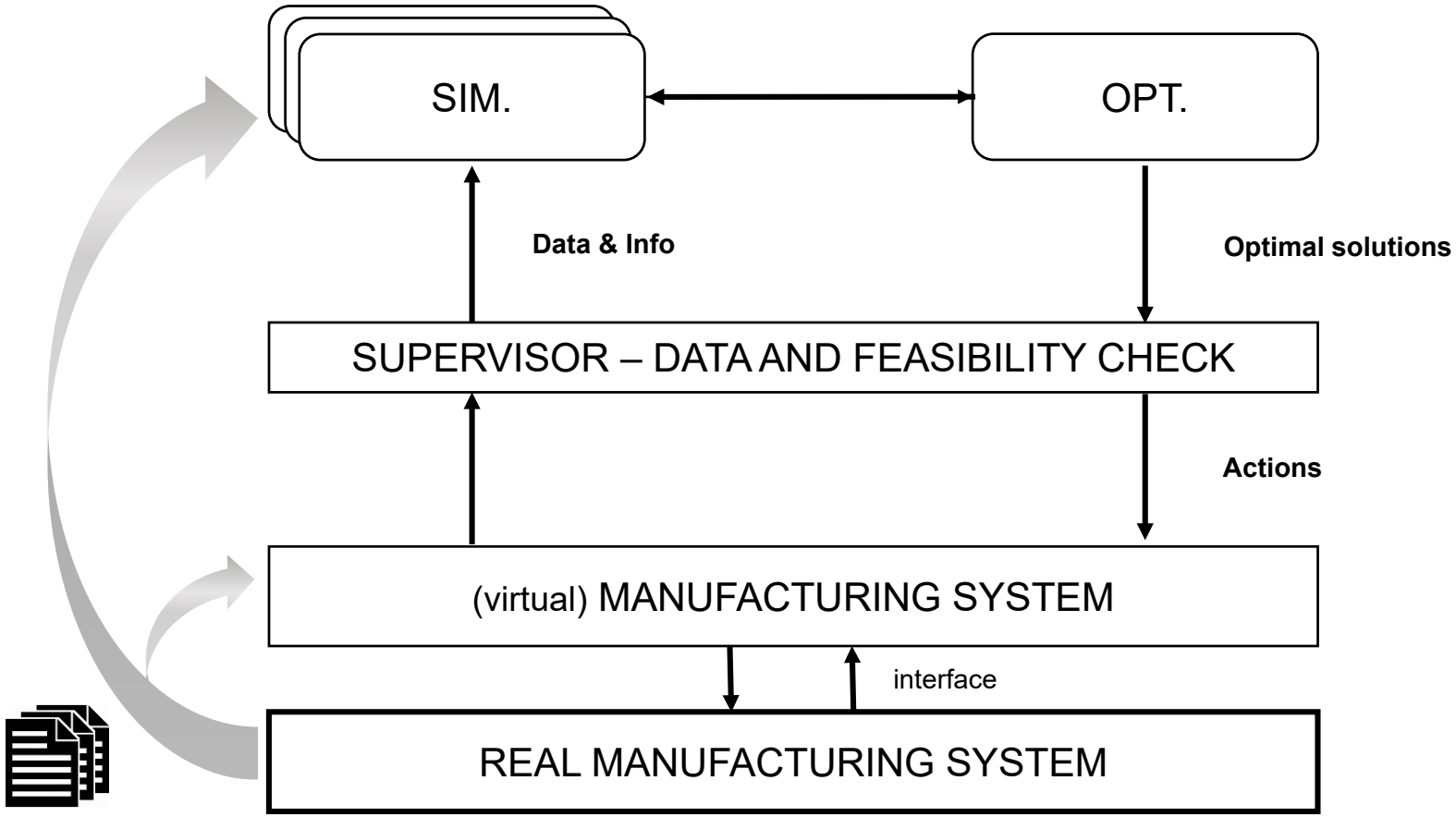


Real Time Simulation Framework

We need to generate models!



Real Time Simulation Framework



State of the Art

Mining approaches:

- Alpha-mining [1]
- Others:
  - Heuristic Miners [2]
  - Genetic Miners [3]
  - Fuzzy Miners [4]
  - Hybrid frameworks [5]

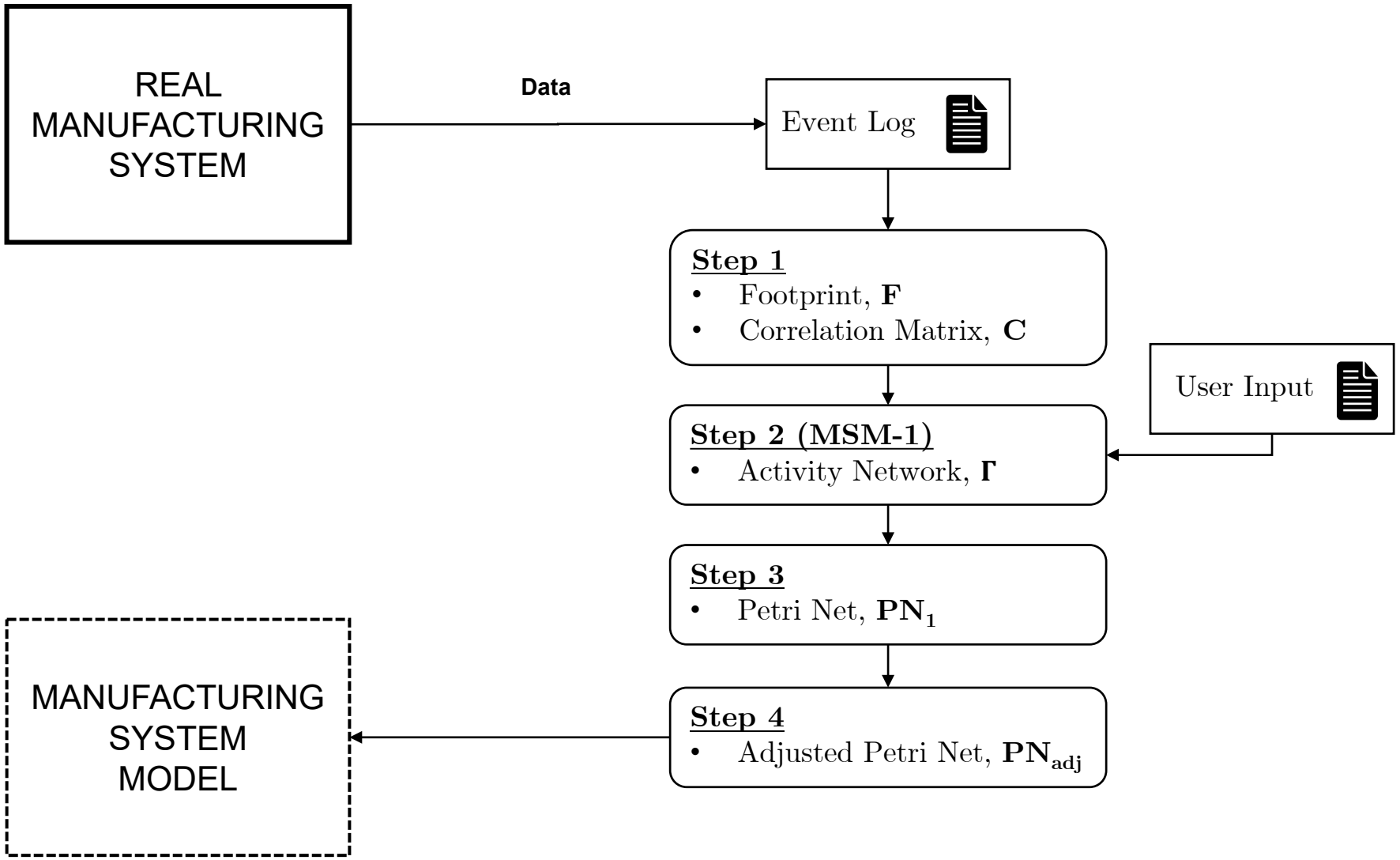
✓ based on **the logical relationships** among activities;
the **activities** can be mined;
the **logical framework** of the system can be created.

✗ **Finite capacity resources** cannot be recognized automatically;
Mining algorithms cannot recognize **rare or wrong sequences of events**;

NOTE: several frameworks can be found starting from an initial conceptual model of the system.

[1] W. V. der Aalst. *Process Mining - Data Science in Action*. Springer, second edition ed., 2016.
[2] A. A. d. M. A.J.M.M. Weijters, W.M.P. Van der Aalst, "Process mining with the heuristic miner algorithm," BETA publications : working papers, vol. 166, 2006.
[3] A. W. J.E. Cook, "Automatic process discovery through event-data analysis," International Conference in Software Engineering, 1995.
[4] C. W. Gunther and W. M. Van Der Aalst, "Fuzzy mining–adaptive process simplification based on multi-perspective metrics," in International conference on business process management, pp. 328–343, Springer, 2007.
[5] M. Mesabbah and S. McKeever Presenting a hybrid processing mining framework for automated simulation model generation. Winter Simulation Conference, pp. 1370–1381, IEEE, 2018.

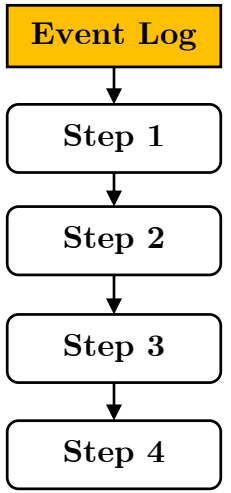
Methodology



The event log

Activity	Meaning
999	Entrance in S1
998	Exit from S1
997	Entrance in S2
996	Exit from S2

Timestamp	ID	Activity
68559	1	999
68569	1	998



The event log

Activity	Meaning
999	Entrance in S1
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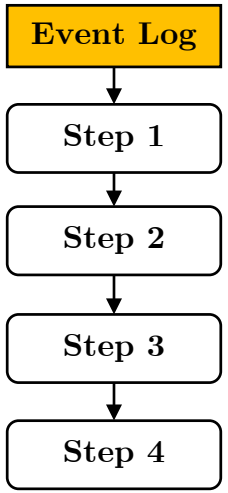
997	Entrance in S2
996	Exit from S2

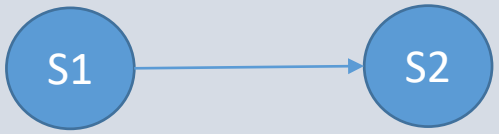
Timestamp	ID	Activity
68559	1	999
68569	1	998
68577	1	997
68580	2	999
68581	2	998
68581	1	996
…	…	…



Methodology

- The first step consists in the dataset loading, used to generate the footprint and a correlation matrix.

Timestamp	ID	Activity
68559	1	999
68569	1	998
68577	1	997
68580	2	999
68581	2	998
68581	1	996
…	…	…



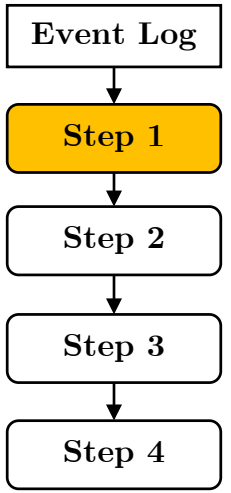
Activity	Meaning
999	Entrance in S1
998	Exit from S1
997	Entrance in S2
996	Exit from S2

Footprint, F

$$F = \{999, 998, 997, 996\}$$

Correlation Matrix, C

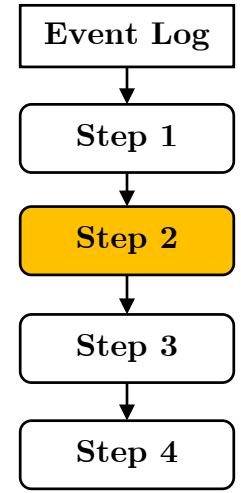
$$C = \begin{matrix} \\ 999 \\ 998 \\ 997 \\ 996 \end{matrix} \begin{matrix} \begin{matrix} 999 & 998 & 997 & 996 \end{matrix} \\ \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

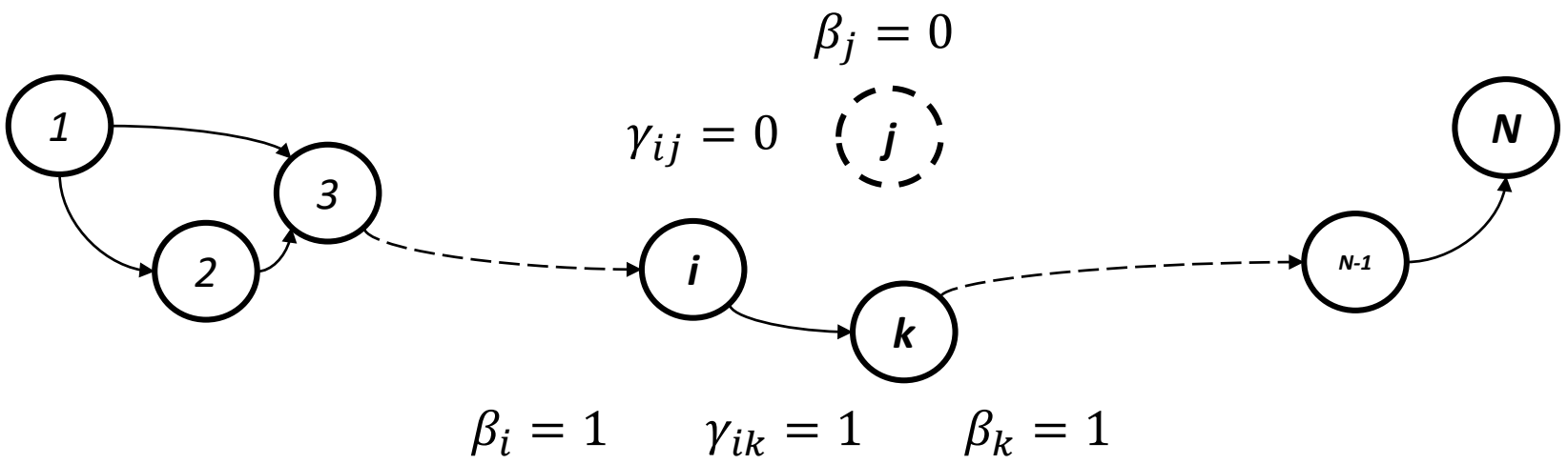


Methodology

INPUT DATA	
n	Number of event types in the log.
E	Number of event types the user wishes to map.
M	Vector of occurrences.
A	Matrix of frequencies of connection between activities i and j.
C	Boolean reflection of A.
k_{max}	Maximum number of iterations allowed.

DECISION VARIABLES	
β	Boolean vector such that $\beta_i = 1$ if the *i*-th activity is considered for the inclusion in the network, $\beta_i = 0$ otherwise; it represents the list of activities that are used in the network.
Γ	Symmetric, Boolean matrix representing the activity, its elements are $\gamma_{ij} = 1$ if event type I is followed by event type *j*.





Methodology

Optimization problem (MSM-1)

$$\max\left(\sum_{i=1}^{n}\beta_i\, m_i + \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}\,\gamma_{ij}\right) \quad (1)$$

$$\sum_{i=1}^{n}\beta_i \;=\; E \quad (2)$$

$$\gamma_{ij} = \min\left(\beta_i\, c_{ij};\ \beta_j\, c_{ij}\right) \qquad \forall i = 1\ldots n, \quad (3)$$

$$\forall j = 1\ldots n,$$

$$\beta_i \in \{0,1\} \qquad \forall i = 1\ldots n, \quad (4)$$

$$\gamma_{ij} \in \{0,1\} \qquad \forall i = 1\ldots n, \quad (5)$$

$$\forall j = 1\ldots n.$$

The MSM-1 problem is solved with a local search heuristic.

INPUT DATA	
n	Number of event types in the log.
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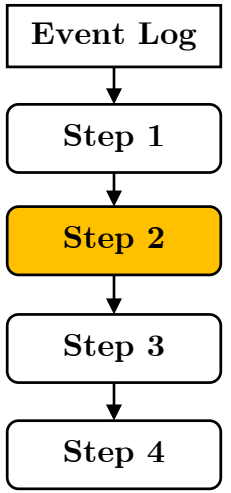
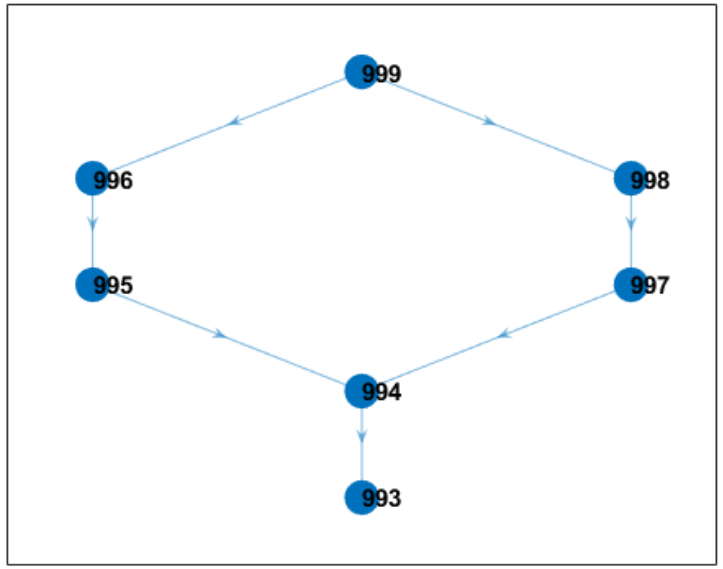
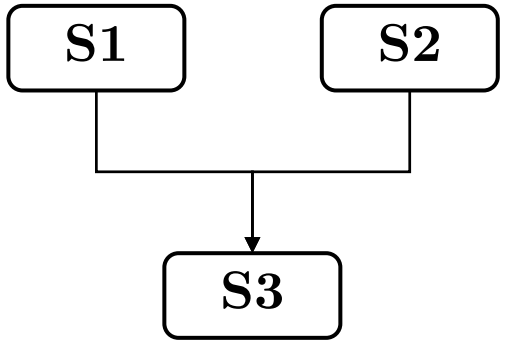


Illustrative example

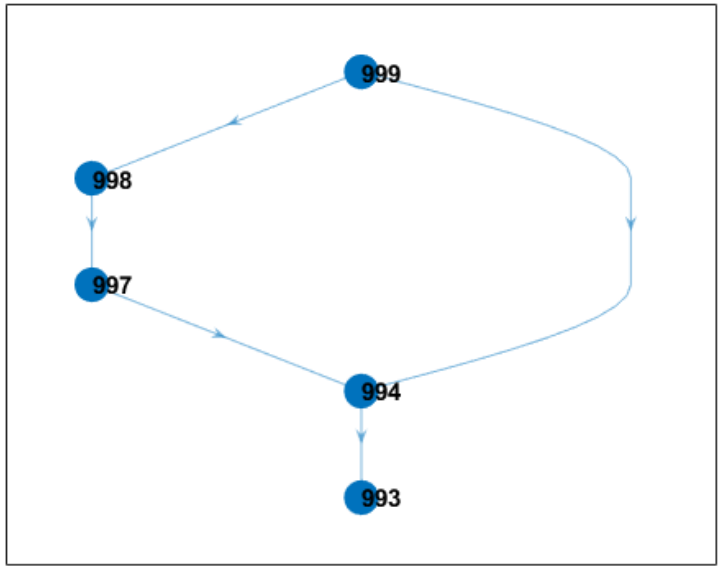
E	**Number of event types the user wishes to map.**
N	Number of event types in the event log.



E = 7



N = 7

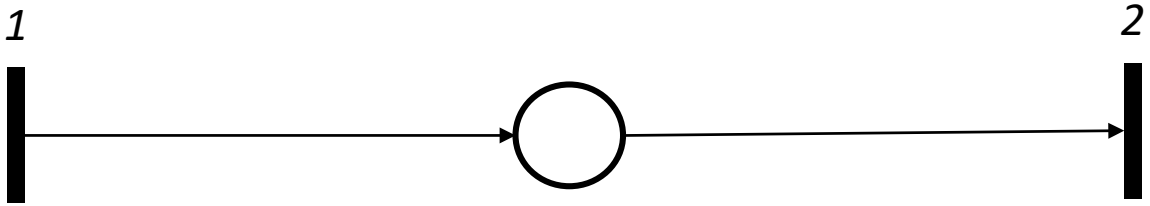


E = 5

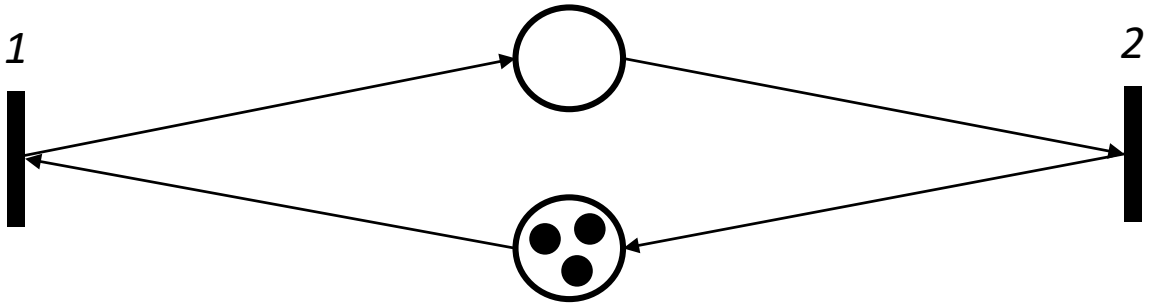
PN modeling

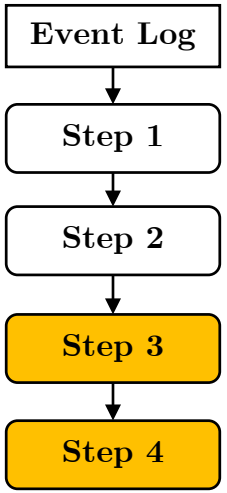
Process Model

Activity Network (step 2)

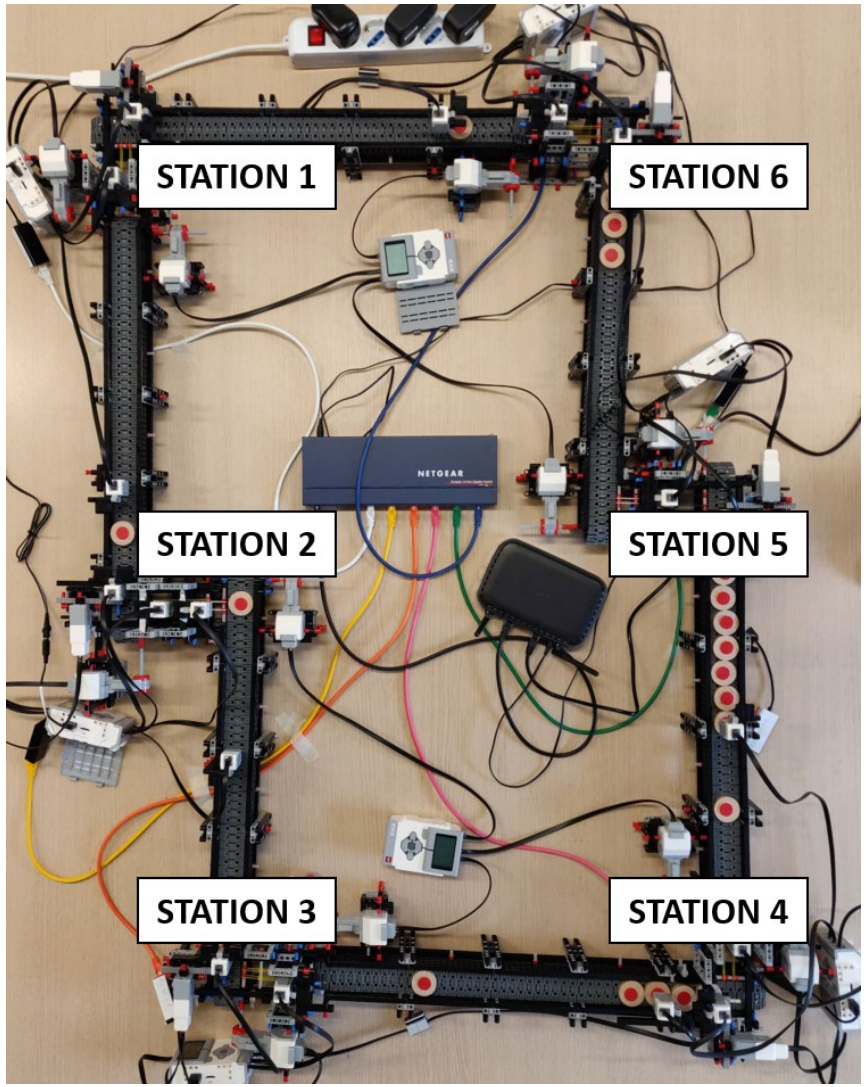


Petri Net Model (adjusted)





Experiments



LEGO® Manufacturing System (LMS) installed in the Manufacturing Systems Laboratory from the Department of Mechanical Engineering of Politecnico di Milano:

- 6 STATIONS controlled by EV3® bricks
- Each station has three sensors: entrance, processing, blocking
- Wooden circles tagged with red plates represent pallets
- Closed system, modelled as open

STATION	PROCESSING TIME [s]
1	***9.5***
2	***10***
3	***9.5***
4	***9.5***
5	***9.5***
6	***9***

BUFFER	SLOTS
1	***5***
2	***9***
3	***3***
4	***9***
5	***3***

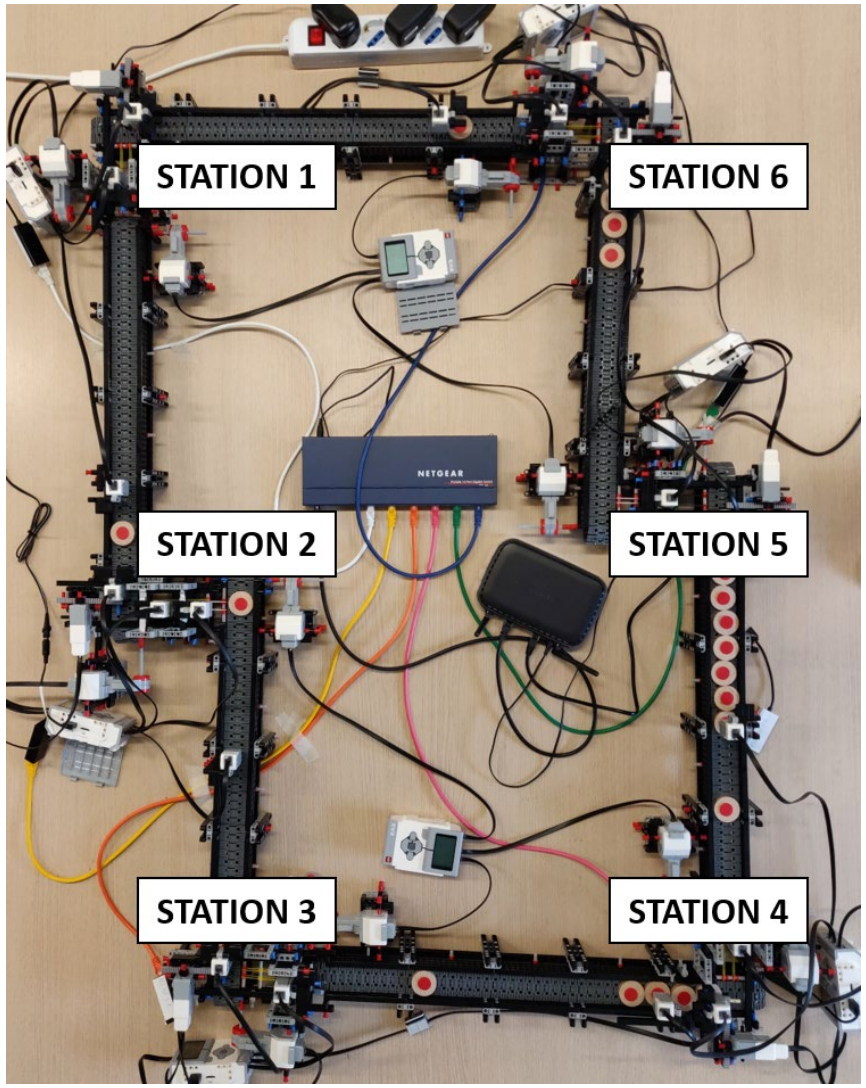
Results

EXPERIMENTS
Three different event logs
Each log represents a run of 40 parts
Each log → Steps 1 – 4 → Simulation model
Each simulation model: **100 replications**

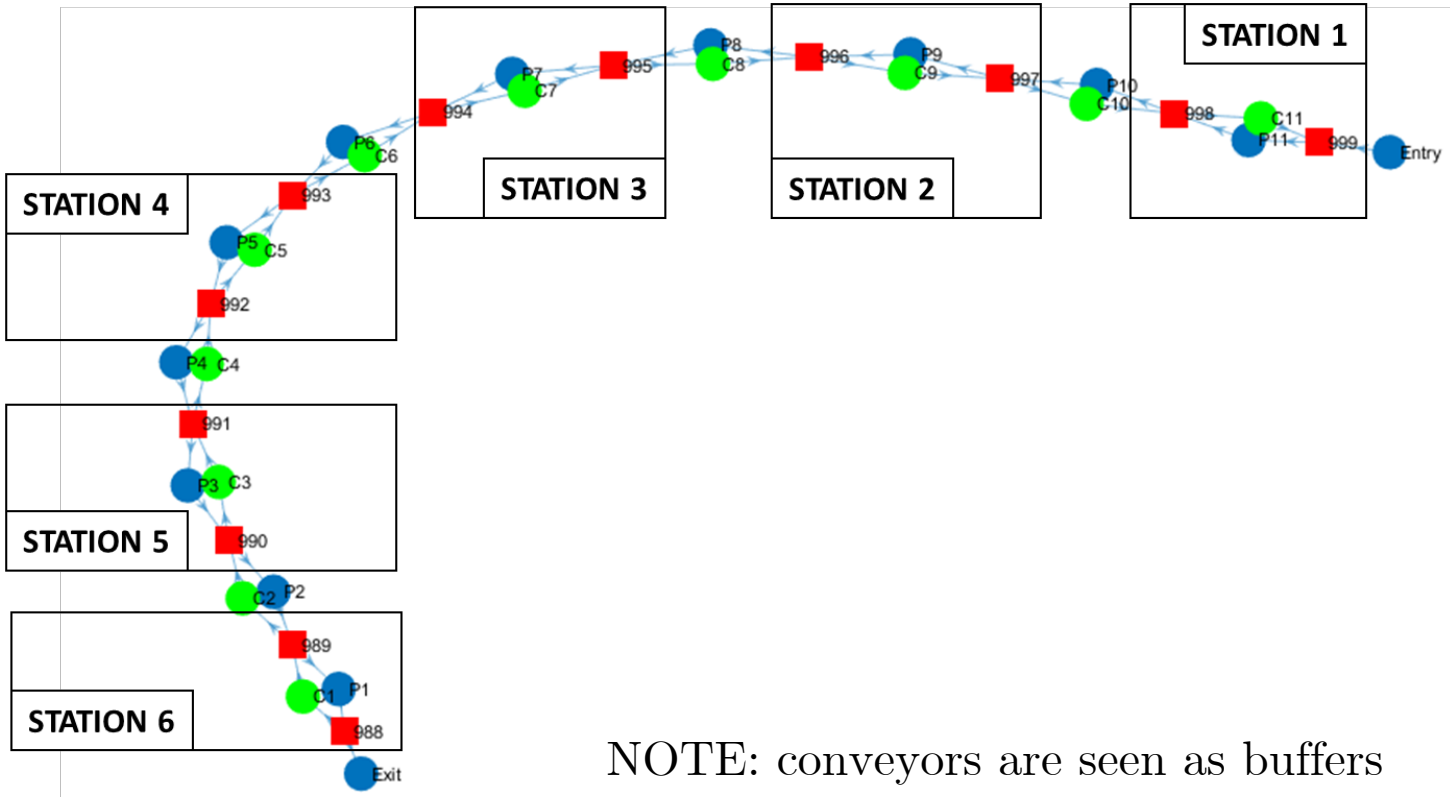
We tested our approach in its ability to recognize the following:

1. Systems's Layout
2. Stations' processing times
3. Buffer slots
4. System performance

Results – (1) LAYOUT



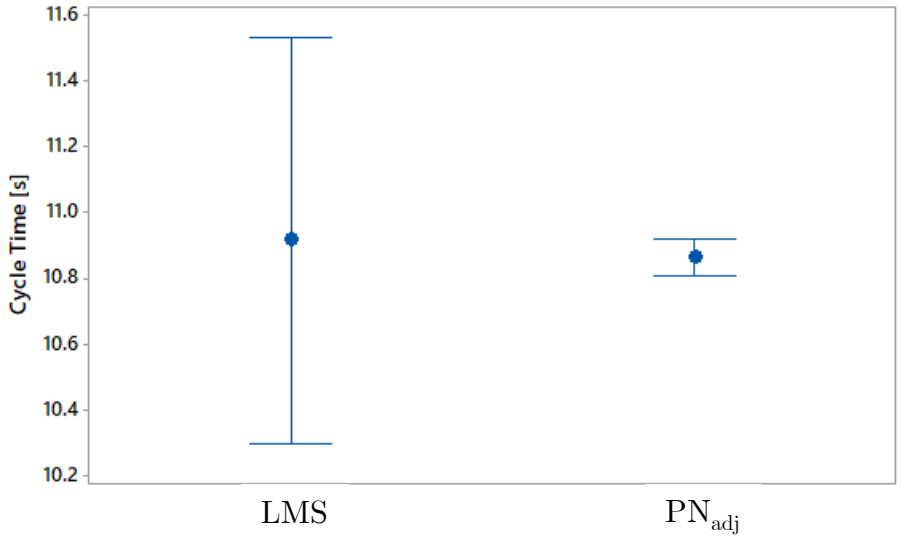
Station	Entrance	Exit
S1	999	998
S2	997	996
S3	995	994
S4	993	992
S5	991	990
S6	989	988



NOTE: conveyors are seen as buffers

Results – (2) PROCESSING TIMES

STATION	PROCESSING TIME [s]	FOUND [s]
1	9.5	N(9.6, 1.6)
2	10	N(10.3, 0.9)
3	9.5	N(9.4, 1.8)
4	9.5	N(8.6, 1.8)
5	9.5	N(10.3, 1.8)
6	9	N(8.5, 1.6)

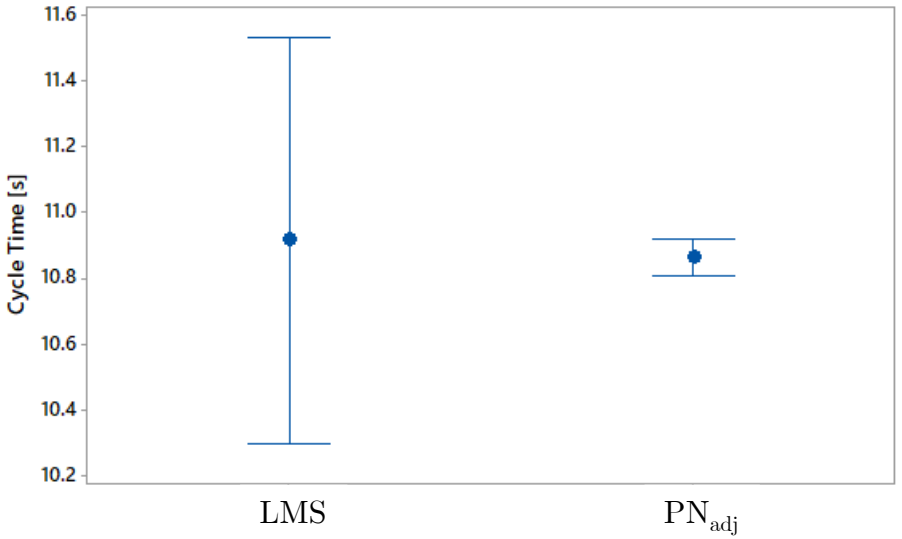


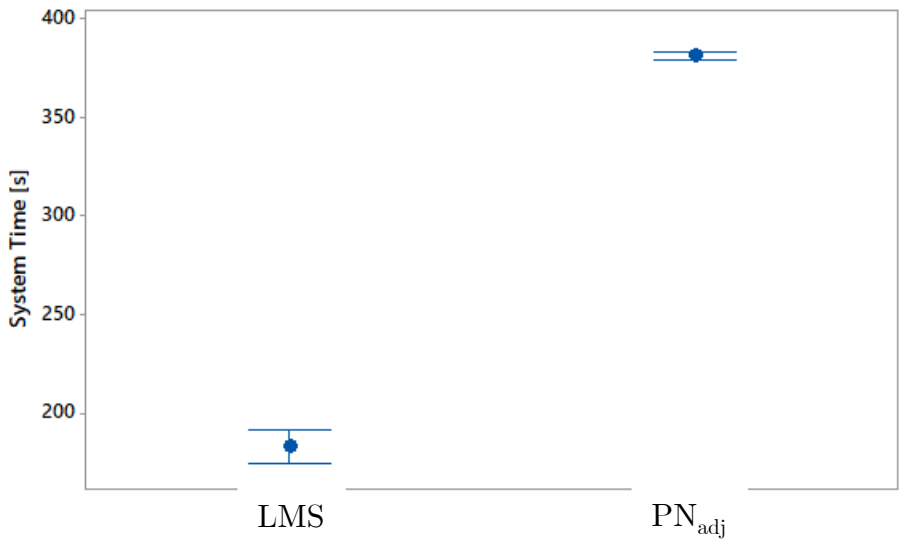
Results – (3) BUFFER SLOTS

BUFFER	LMS	FOUND
1	5	5
2	9	2
3	3	2
4	9	4
5	3	2

Results – (4) SYSTEM PERFORMANCE

Property	System	Mean	St. Dev.	SE Mean	95% CI for Difference	P-Value	Result
Layout	LMS	-	-	-	-	-	- *reference* -
	PN_{adj}	-	-	-	-	-	Correct
Cycle Time [s]	LMS	10.92	4.74	0.31	[-0.56, 0.67]	0.87	- *reference* -
	PN_{adj}	10.86	0.40	0.03			Correct
System Time [s]	LMS	182.8	68.2	4.5	[-207.54, -189.63]	0.00	- *reference* -
	PN_{adj}	381.4	12.4	0.88			Over-estimated
Work-in-Progress [parts]	LMS	16.67	6.67	0.31	[7.69, 8.93]	0.00	- *reference* -
	PN_{adj}	8.35	0.99	0.07			Under-estimated





Final remarks

Conclusions

- A new method that generates the Petri Net model of a manufacturing system.
- Starting point is an **event log** with three data labels.
- The user decides the number of maximum events to be mapped to control the model level of detail.
- **Test case** shows potential applicability to a manufacturing environment.

Further Research

- Complete literature review → working paper on RTS.
- Test on more complex manufacturing systems.
- Investigate how to better model multiple terms in objective function.
- Better mining → improve buffer capacity mining, perhaps with longer experiments?

THANK YOU

Suggested References

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