Оценка структурной сложности моделей потоков работ: асинхронное взаимодействие агентов в мультиагентных системах

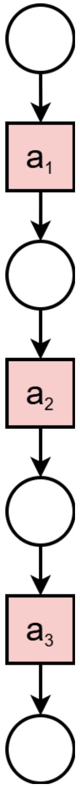
Егор Земляной, Роман Нестеров

Agenda

Process mining

Action
a_1
a_2
a_3

Event log



Model

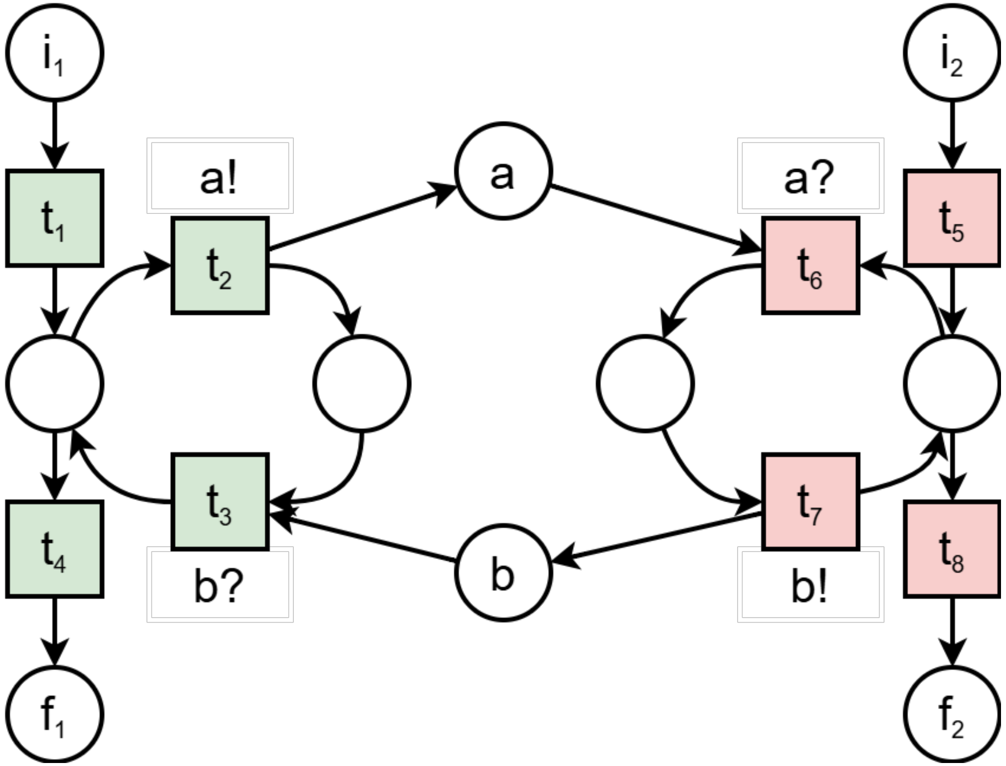
Approaches to generate models:

- Inductive miner (Leemans et al., 2013)
- Fuzzy miner (Günther and Aalst, 2007)
- Region theory-based miner (Werf et al., 2008)

Problems to overcome:

- Incompleteness of event logs
- Noise in event logs
- Understandability of the model

Workflow (WF) net



Two asynchronously communicating agents

Key aspects:

Each transitions corresponds to an agent

Labeled communication channels

! – sending message to channel

? – receiving message from channel

Set of initial and final states

Event log of a Multi-Agent System (MAS)

Timestamp	Action	Agent
2025-03-25 14:07:46.58	a_1	Agent 1
2025-03-25 14:08:32.67	a_2	Agent 1
2025-03-25 14:09:12.56	b_1	Agent 2
2025-03-25 14:10:54.09	b_2	Agent 2
2025-03-25 14:11:32.07	b_3	Agent 2
2025-03-25 14:12:11.02	a_3	Agent 1

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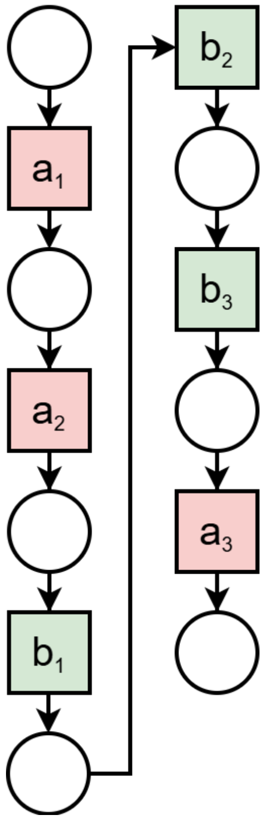
Directly discovered model



fitness = 1.

precision = 1.

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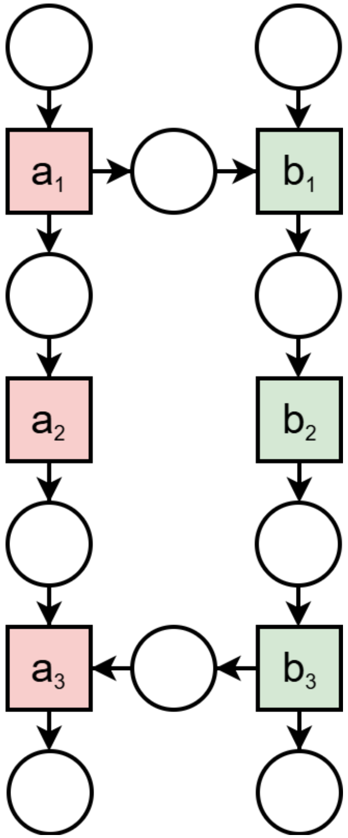
Architecture-Aware Model*



fitness = 1.

precision =0.85

*R. Nesterov, L. Bernardinello, I. Lomazova, and P. L., "Discovering architecture-aware and sound process models of multi-agent systems: a compositional approach," Software and Systems Modeling, vol. 22, pp. 351–375, 2023.

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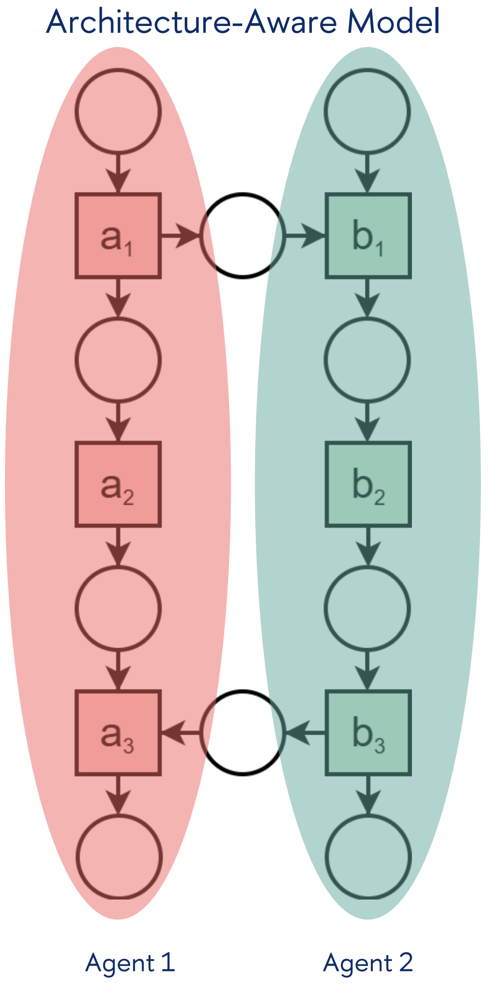
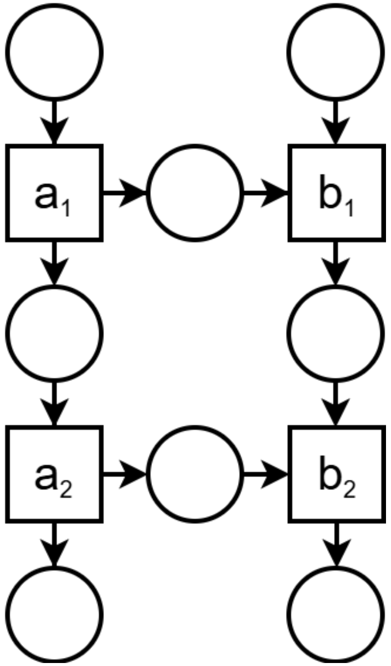


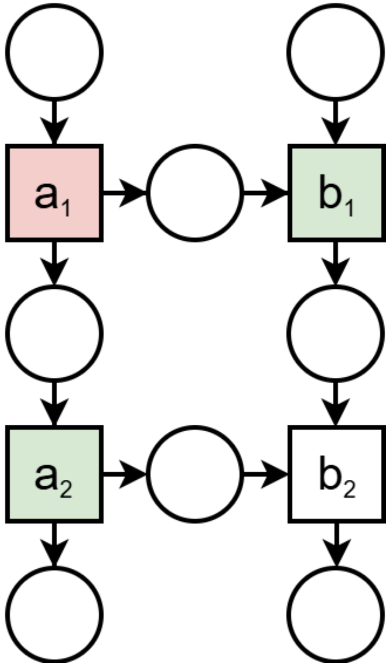
Neighboring Transitions



all(t) – set of all neighbors of transition t

diff(t) ⊆ **all**(t) – set of neighbors of transition t whose agent is different from the agent of t

Neighboring Transitions



all(t) – set of all neighbors of transition t

$$\mathbf{all}(a_1) = \{a_2, b_1\}$$

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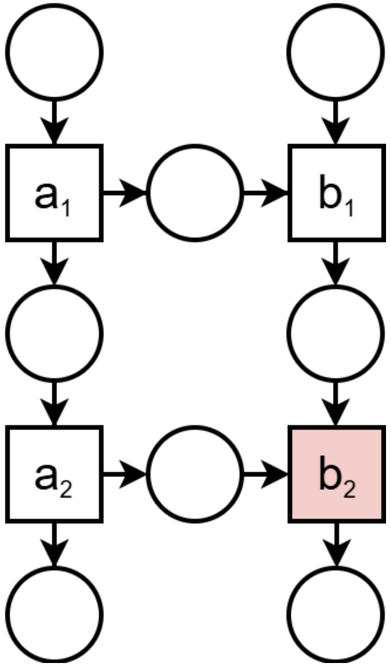
$$\mathbf{diff}(a_1) = \{b_1\}$$

Neighboring Transitions



all(t) – set of all neighbors of transition t

$\textbf{all}(a_1) = \{a_2, b_1\}$

$\textbf{all}(b_2) = \emptyset$

diff(t) ⊆ **all**(t) – set of neighbors of transition t whose agent is different from the agent of t

$\textbf{diff}(a_1) = \{b_1\}$

$\textbf{diff}(b_2) = \emptyset$

Neighbor Independence

Different aggregation of the ratio of **diff** to **all**

- **0** if all neighbors of each transition are from different agents
- **1** if agents are not connected

0 → 1

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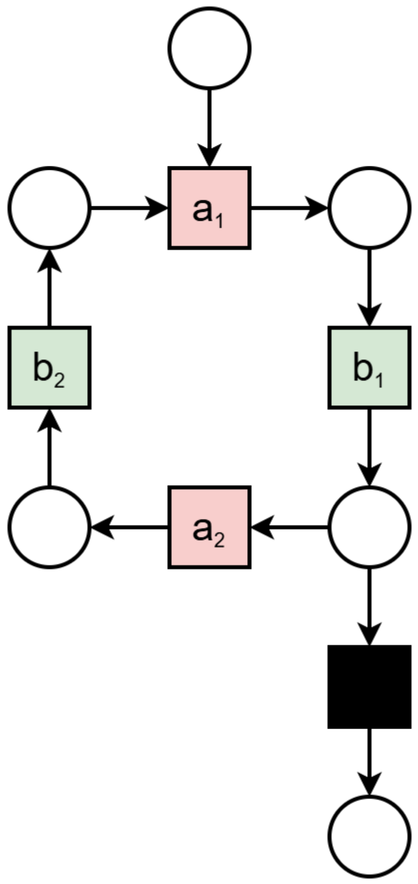

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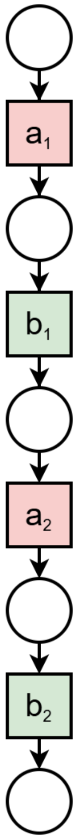

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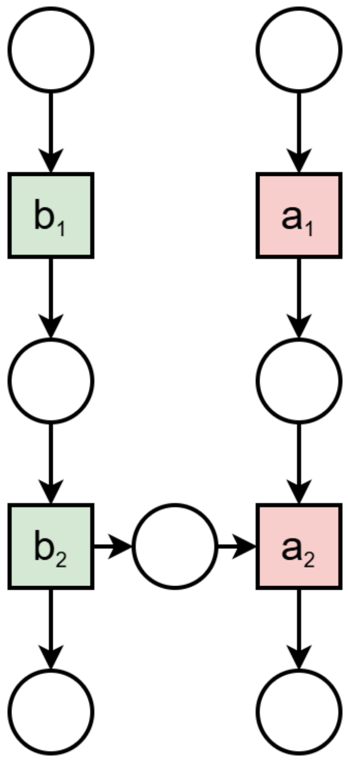

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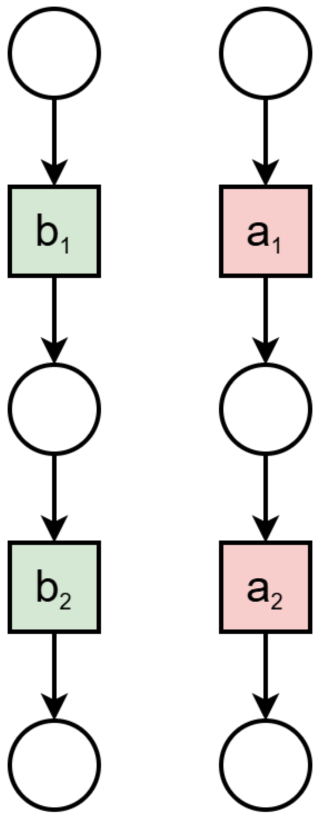


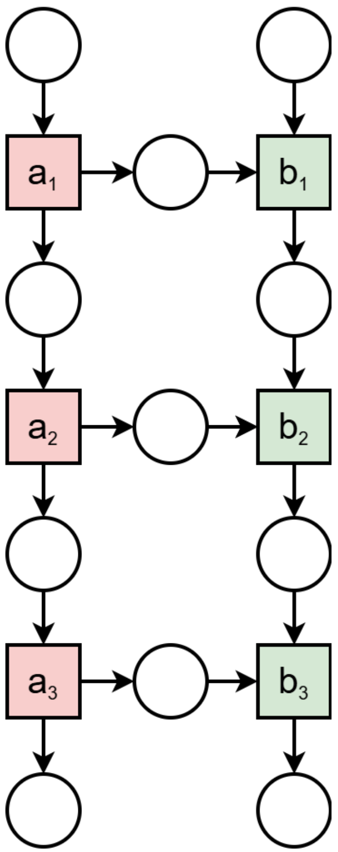
0 → 1

Global Neighbor Independence (GNI)

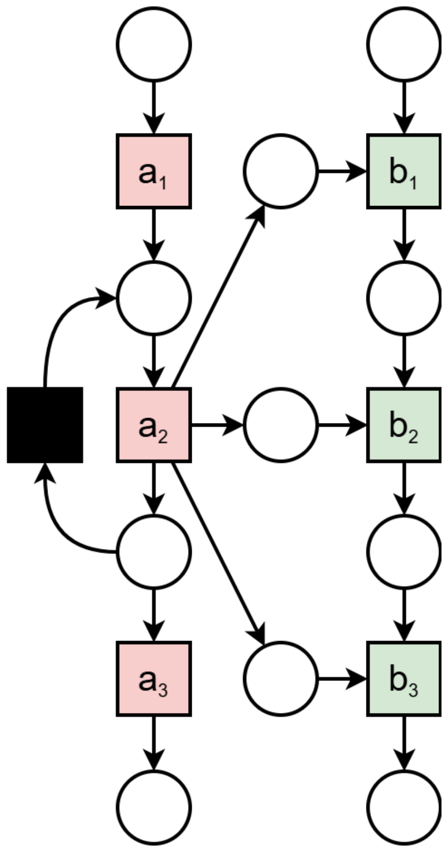
$$\mathrm{GNI}(N) = 1 - \frac{\sum_{t\in T}|\mathrm{diff}(t)|}{\sum_{t\in T}|\mathrm{all}(t)|}$$

General relation of **diff** to **all**

Does not capture local changes



GNI=0.57



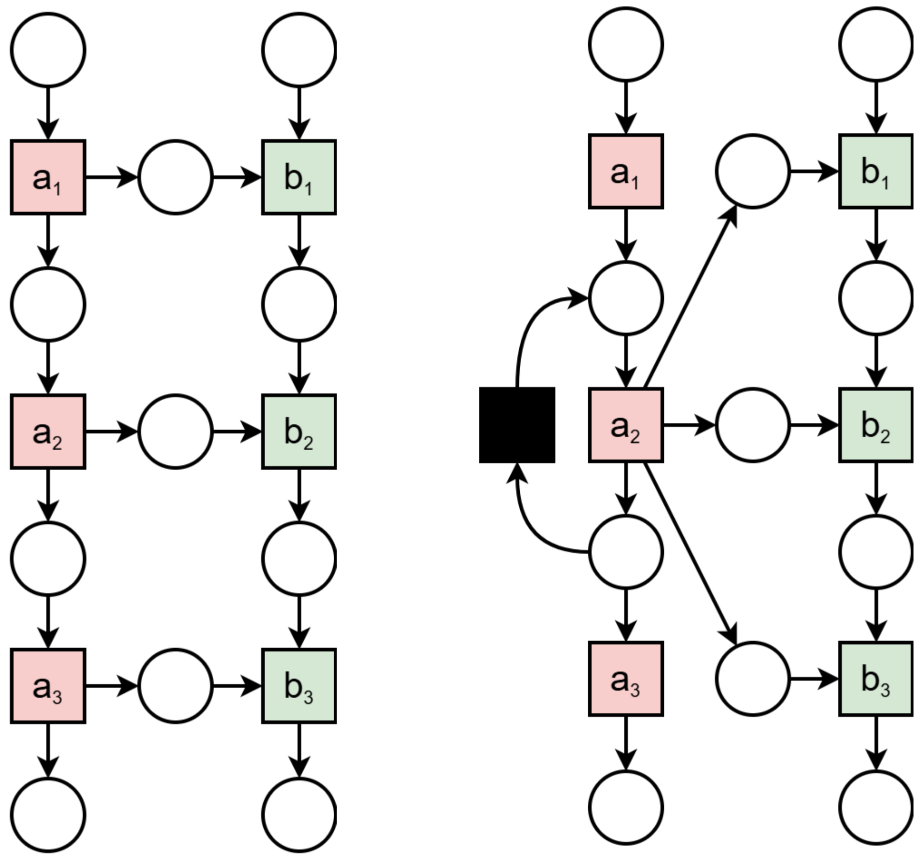
GNI=0.57

Local Neighbor Independence (GNI)

$$\mathrm{LNI}(N) = 1 - \frac{1}{T_{VIS}} \sum_{t \in T_{WN}} \frac{|\mathrm{diff}(t)|}{|\mathrm{all}(t)|}$$

Averaging local relations of **diff** to **all**

Captures local changes



LNI=0.67

LNI=0.88

Pathology of LNI – Neighbor Explosion Problem

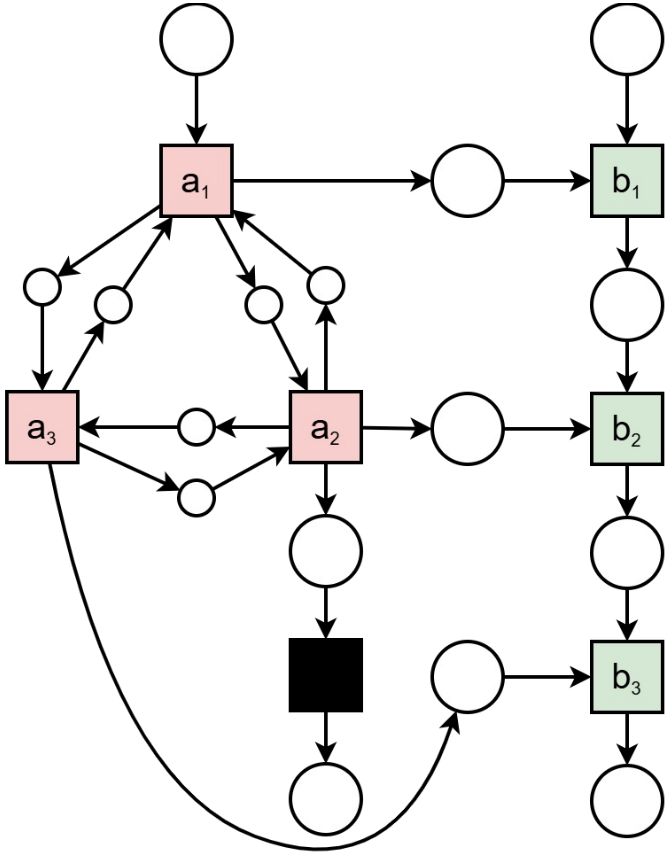
Very dense model case

$\sum_{t \in T} |\text{all}(t)|$ grows as $O(n^2)$

$\sum_{t \in T} |\text{diff}(t)|$ grows as $O(n)$

LNI $\rightarrow 1$

GNI $\rightarrow 1$



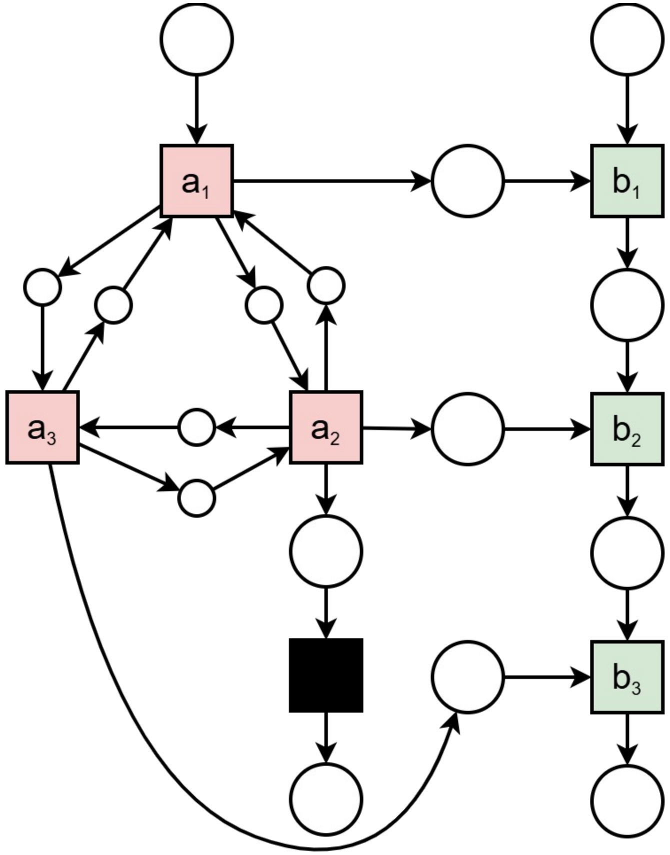
Balanced Local Neighbor Independence (BLNI)

$$\mathrm{BLNI}(N) = 1 - \sum_{i=1}^{k} \frac{w_i}{|T_i|} \sum_{t \in T_i} \frac{|\mathrm{diff}(t)|}{|\mathrm{all}(t)|}$$

Weighted averaging local relations of **diff** to **all**

Weights are crucial

	$w_R = 0.5$ $w_G = 0.5$	$w_R = 0.7$ $w_G = 0.3$	$w_R = 1$ $w_G = 0$
BLNI	0.83	0.77	0.67



Comparison

Statement	**GNI**	**LNI**	**BLNI**
Conformance with the basic principles		Partial	
Sensitivity to the communication structure			
Sensitivity to *changes* in the communication structure			
Locality of recalculation			

Comparison

Statement	GNI	LNI	BLNI
Conformance with the basic principles		Partial	
Sensitivity to the communication structure	No	Yes	Yes
Sensitivity to *changes* in the communication structure			
Locality of recalculation			

Comparison

Statement	**GNI**	**LNI**	**BLNI**
Conformance with the basic principles		Partial	
Sensitivity to the communication structure	No	Yes	Yes
Sensitivity to *changes* in the communication structure	Yes	Yes	Yes
Locality of recalculation			

Comparison

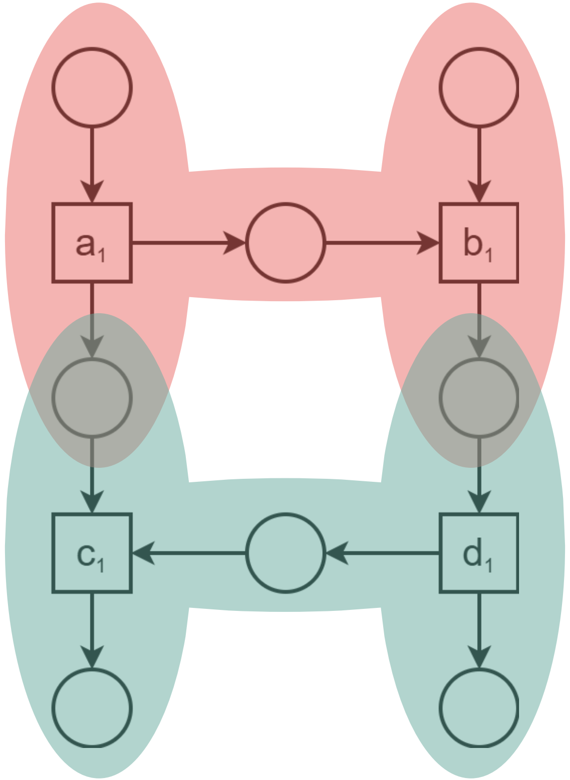
Statement	GNI	LNI	BLNI
Conformance with the basic principles		Partial	
Sensitivity to the communication structure	No	Yes	Yes
Sensitivity to *changes* in the communication structure	Yes	Yes	Yes
Locality of recalculation	No	Yes	Yes

Comparison

Statement	**GNI**	**LNI**	**BLNI**
Conformance with the basic principles		Partial	
Sensitivity to the communication structure		Yes	
Sensitivity to *changes* in the communication structure		Yes	
Locality of recalculation		Yes	

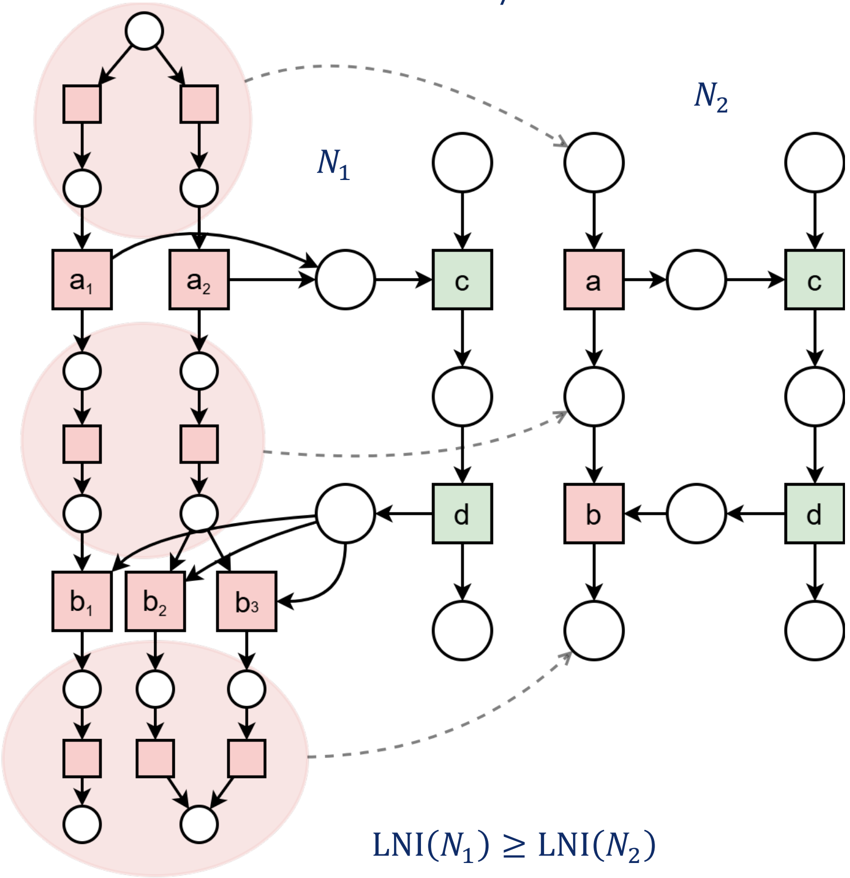
Properties of LNI

Compositionality



$\mathrm{LNI}(N) = w_1 \mathrm{LNI}(N_1) + w_2 \mathrm{LNI}(N_2)$

Monotonicity*



$\mathrm{LNI}(N_1) \geq \mathrm{LNI}(N_2)$

* under certain conditions

Experimental Evaluation. Random WF-Net Generation

h1: increasing the number of channels between unchanged agents lowers the values of GNI and LNI (within the random WF-net generation)

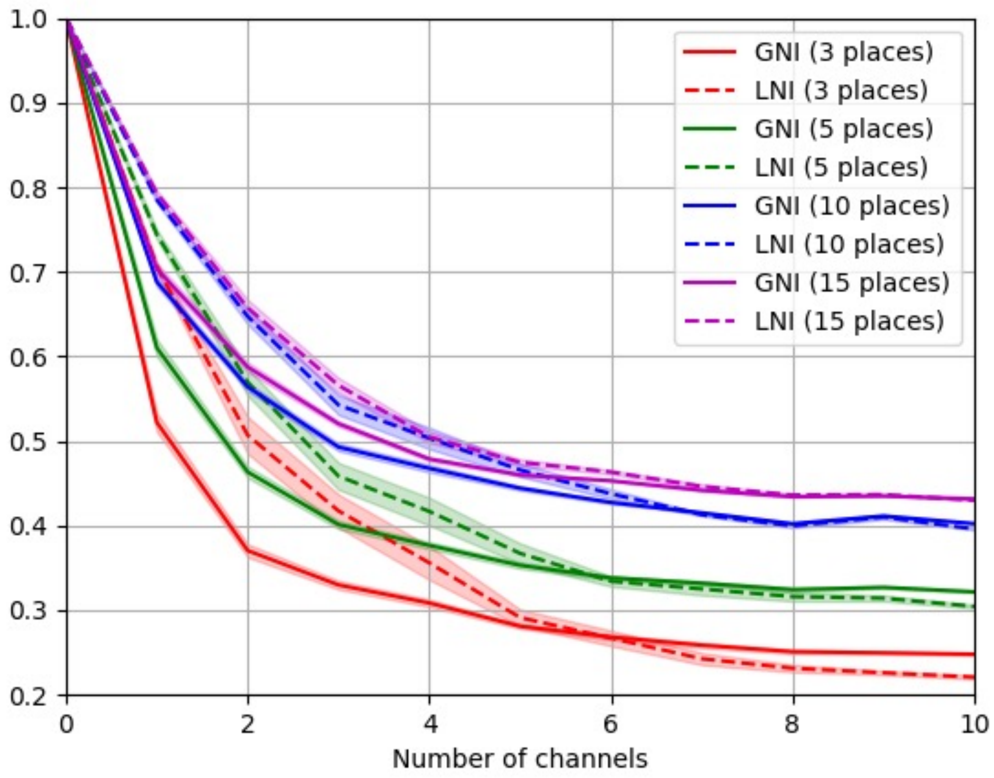
h2: increasing the number of places in agents with unchanged channels increases the values of GNI and LNI (within the random WF-net generation)

h3: the application of refinement rules can confirm the monotonicity of LNI (within the rule-based WF-net generation).

Parameters for modeling

- the number of agents
- the number of places within each agent
- transitions within each agent
- the number of places used for agent interactions
- the density of arcs within each agent and between them

Experimental Evaluation. Random WF-Net Generation

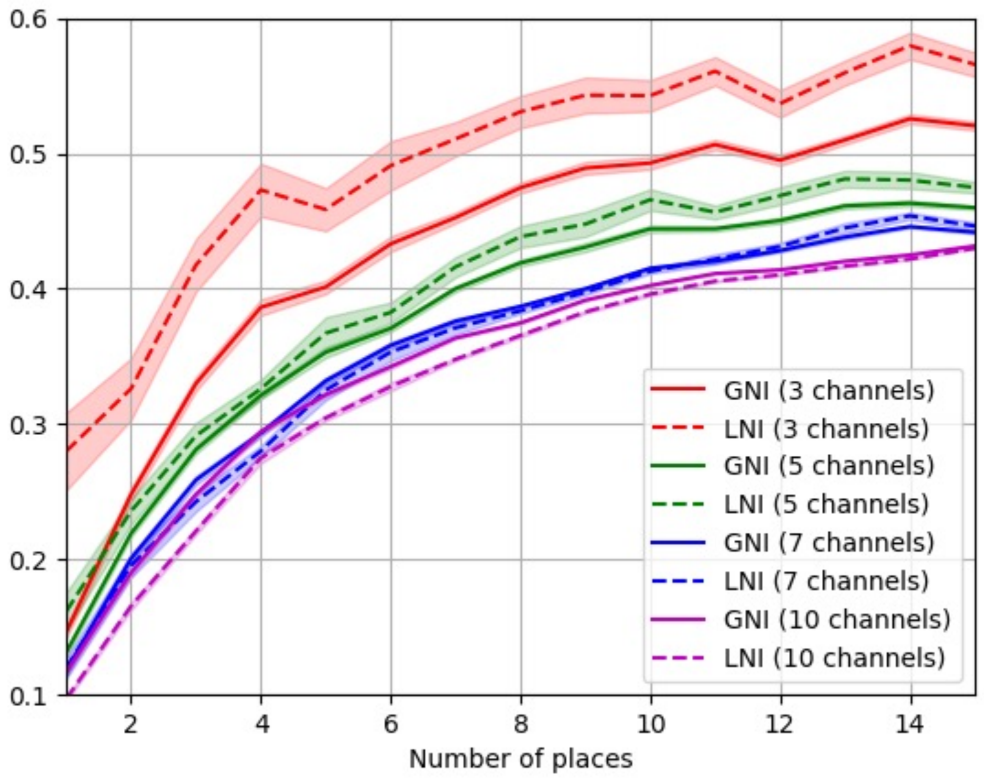


h1: increasing the number of channels between unchanged agents lowers the values of GNI and LNI (within the random WF-net generation)

5 transitions in each agent

100 models generated per each set of parameters

Experimental Evaluation. Random WF-Net Generation



h2: increasing the number of places in agents with unchanged channels increases the values of GNI and LNI (within the random WF-net generation)

5 transitions in each agent

100 models generated per each set of parameters

Experimental Evaluation. Rule-Based WF-Net Generation

h1: Increasing the number of channels between unchanged agents lowers the values of GNI and LNI (within the random WF-net generation)

h2: increasing the number of places in agents with unchanged channels increases the values of GNI and LNI (within the random WF-net generation)

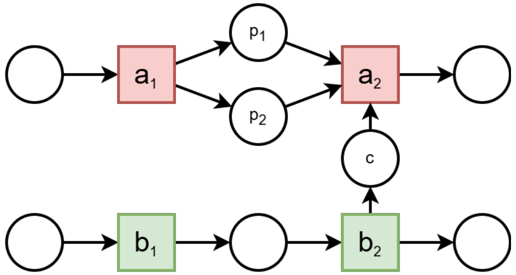
h3: the application of refinement rules can confirm the monotonicity of LNI (within the rule-based WF-net generation).

Parameters for modeling

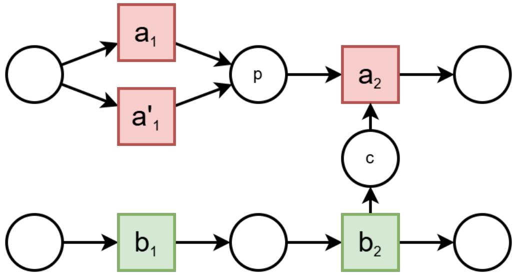
probabilities of refinements

number of refinements

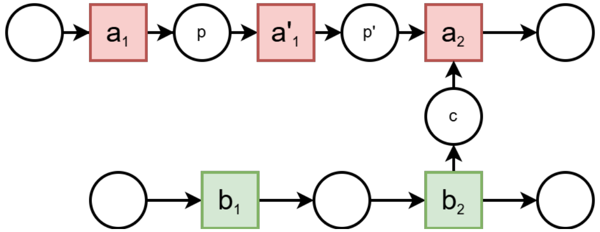
Experimental Evaluation. Rule-Based WF-Net Generation



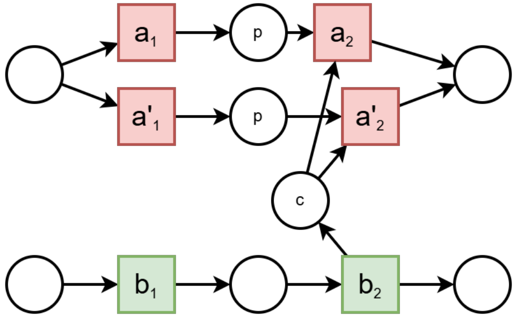
1. Place duplication



2. Transition duplication

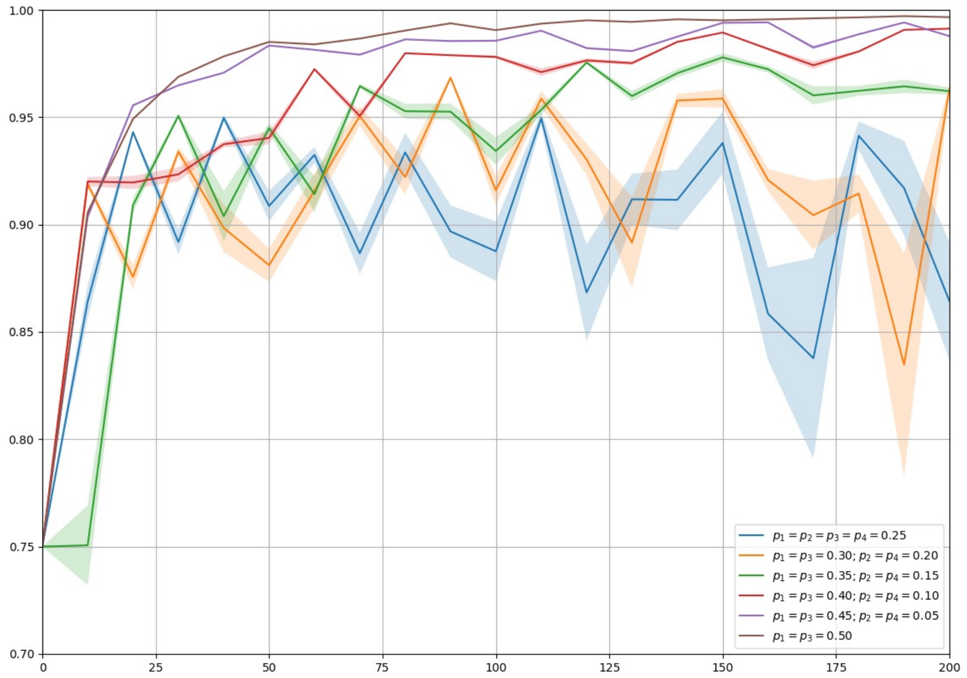


3. Local transition introduction



4. Place split

Experimental Evaluation. Rule-Based WF-Net Generation

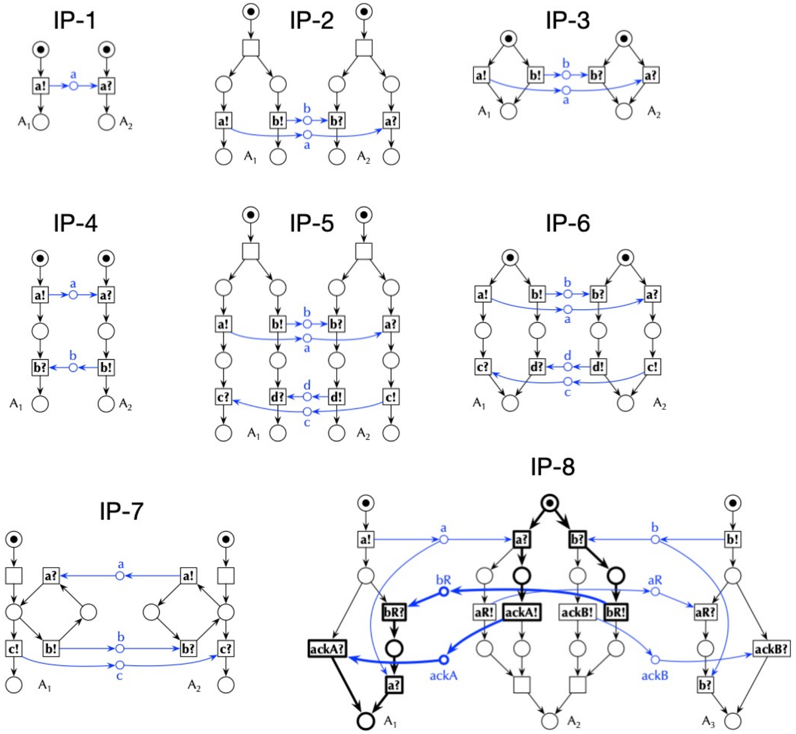


h3: the application of refinement rules can confirm the monotonicity of LNI (within the rule-based WF-net generation).

100 models generated per each set of parameters

Apply Place duplication (1) and Local transition introduction (3) more often

Experimental Evaluation. Compositional Process Discovery

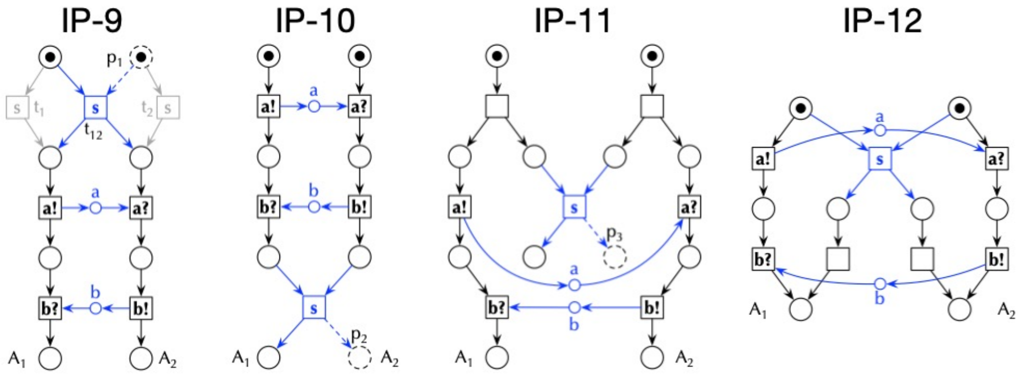


Lowest increase in IP-7 because of loops

Great increase in the rest patterns

	IP-1	IP-2	IP-3	IP-4	IP-5	IP-6	IP-7	IP-8
Direct	0.565	0.561	0.574	0.626	0.632	0.538	0.595	0.495
Compositional	0.957	0.986	0.977	0.943	0.980	0.945	0.867	0.960
Δ, %	69.38	75.76	70.21	50.64	55.06	75.65	45.71	93.94

Experimental Evaluation. Compositional Process Discovery



Synchronization decreases LNI (as it increases diff)

	IP-9	IP-10	IP-11	IP-12
Direct	0.518	0.503	0.516	0.538
Composition	0.808	0.766	0.912	0.911
Δ, %	55.98	52.29	76.74	69.33

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