Towards the Physical Internet with Coloured Petri Nets

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Abstract: *Coloured Petri Nets can be a valuable and powerful tool to design, analyse, and control the subsystems composing the Physical Internet, as they are able to capture the precedence relations and interactions among events which characterize the facilities and infrastructures (multimodal logistics centres and hubs, transit centres, roads and railways) through which π-containers are delivered. In this paper, the use of Coloured Petri Nets in the field of the Physical Internet is discussed and an example of the application of such a modelling tool to a multimodal hub in the PI is provided. The multimodal hub consists of four areas: a port area at which vessels arrive and depart, a train terminal for rail transportation, a road terminal for truck-to-X (and vice-versa) transhipment, and a storage area. The storage area and the road terminal are considered in detail, and two nets representing a section of a π-conveyor and a π-sorter/π-composer are proposed to illustrate the applicability of the CPN formalism to the Physical Internet paradigm.*

Keywords: *multimodal hubs; π-containers management; modelling tools; coloured Petri nets; simulation tools*

1 Introduction

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2 The model of the multimodal hub

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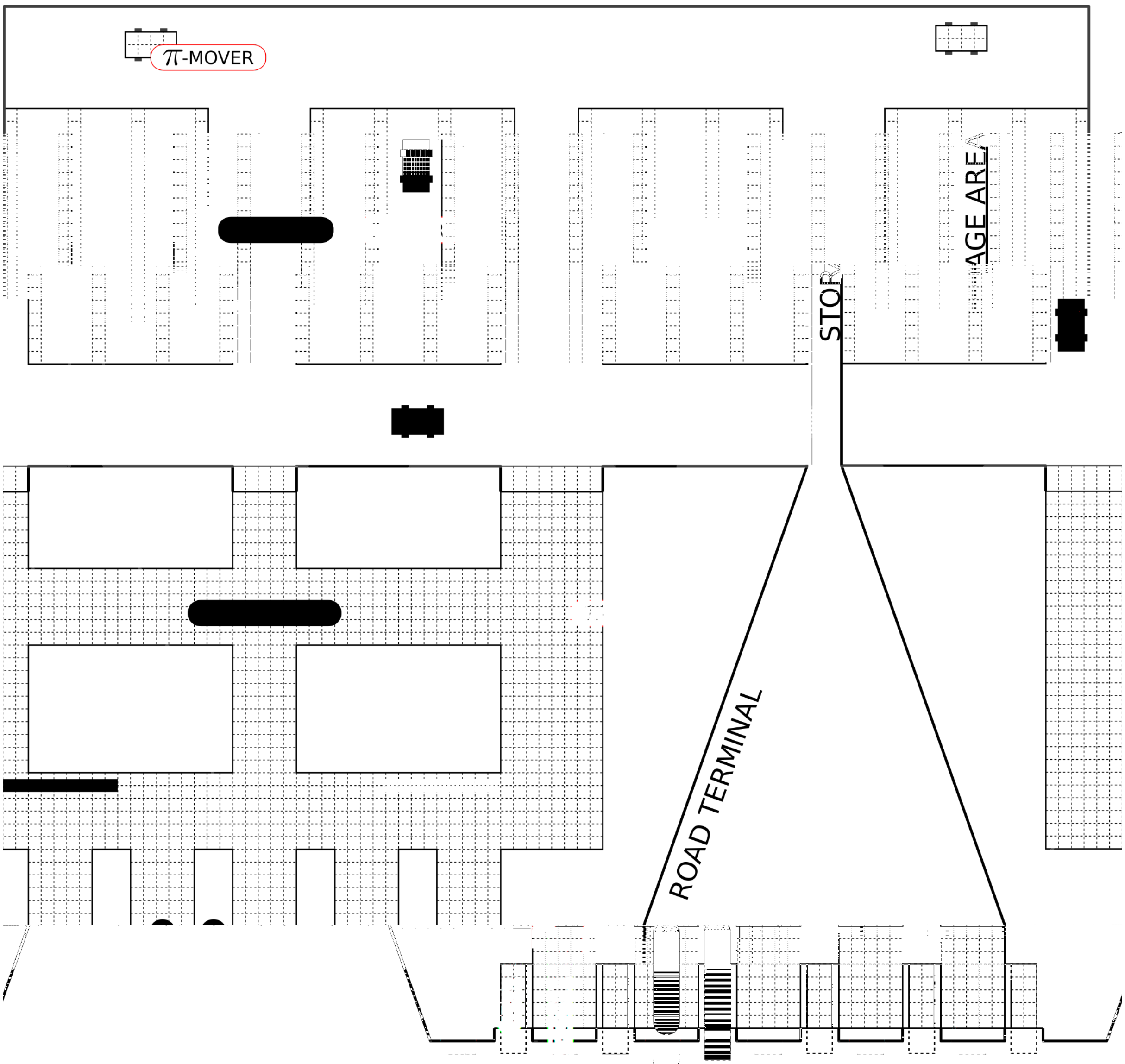

Figure 1: Sketch of the system layout.

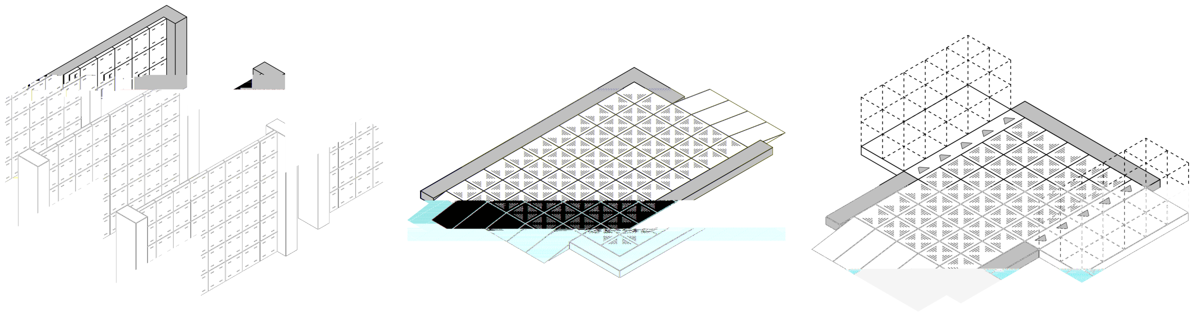

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Figure 2: Details of the physical model of (a) π-store, (b) π-conveyor, and (c) π-sorter.

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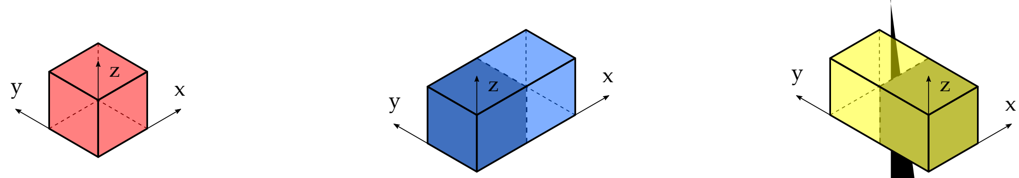

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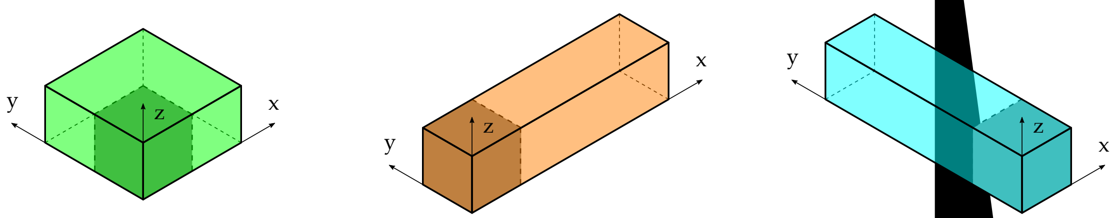
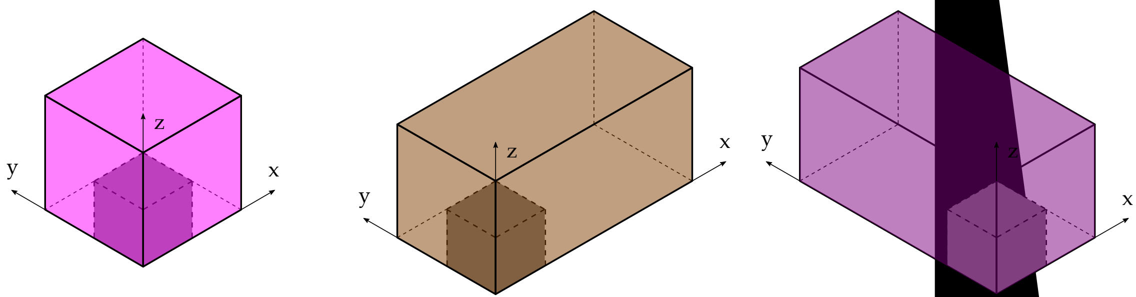


( ) 221 . . 2. ( ) 11 . 2. 2. ( ) 1 1 . 2.



( ) 222 . . . ( ) 22 . . . ( ) 2 2 .

Figure 3: Types of π-containers.

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2.1 π-core

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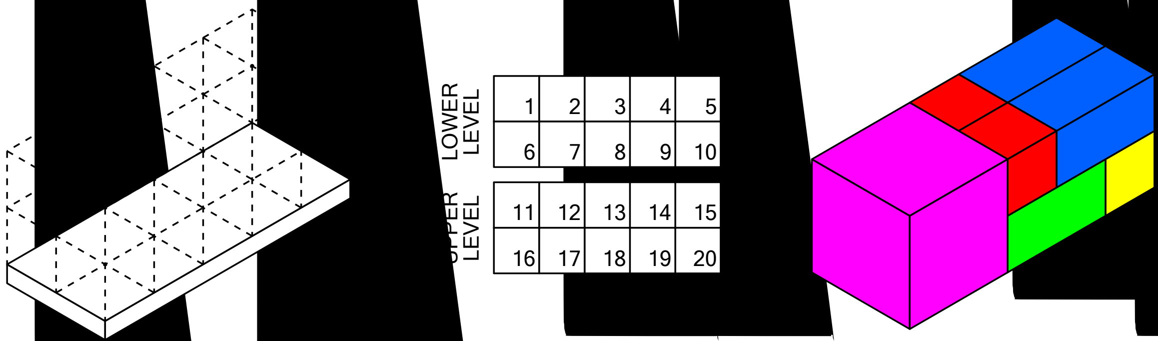

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π-con): (a) structure, (b) logical scheme, and (c) example.

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221, 121, 111, 211 .

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$$(0,0,0,0,0,222,0,221,0,121,0,0,111,211,0,0,0,111,211,0)$$

0	0	0	0	0
222	0	221	0	121

(#1÷#10)

0	0	111	211	0
0	0	111	211	0

(#11÷#20)

π- 222 π- # ( ),
π- 221 π- # ( ), π-
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3 CPN rep[redacted]sentation

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Definition 1 (Je[redacted]d Kristensen, 2009) – (-) -
$CPN = ($[redacted]$\Sigma, \mathcal{V}, \mathcal{C}, G, E, I)$,
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$$\Sigma = \{\text{BSIZE},\text{BSIZE0},\text{STRUCT}\} \qquad (1)$$

$$\text{BSIZE} = \{111,211,121,221,411,141,222,4\ 2,242 \qquad (2)$$

$$\text{BSIZE0} = \text{BSIZE} \cup \{0\} \qquad (\ )$$

$$\text{STRUCT} = BSIZE0^{20} = \text{BSIZE0}\times\text{BSIZE0}\times\ \ \text{ZE0}\ \ .\times\text{BSIZE0}\times\text{BSIZE0}\ (20\ \ ) \qquad (\ )$$

3.1 π-conveyor

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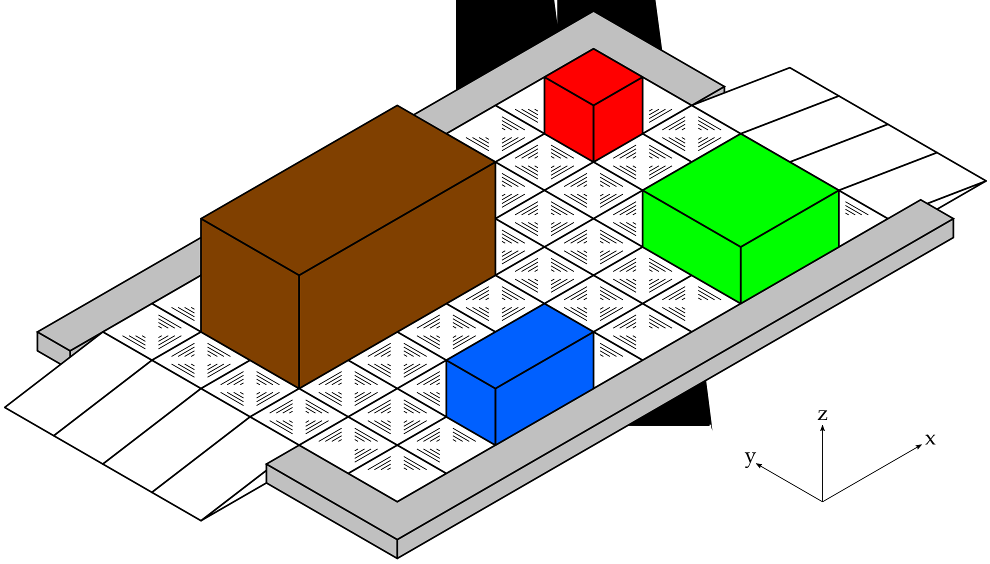

Figure 5: Physical model of a section of the π-conveyor.

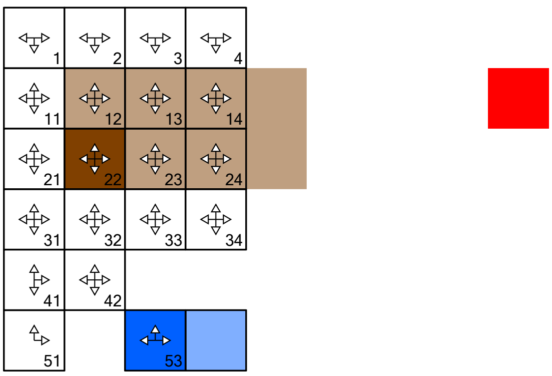

Figure 6: Logical representation of a section of the π-conveyor.

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Figu… N representing the section of the π-conveyor.

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$\mathcal{C}(p_h) = \text{BSIZE}, \forall h = 1$ ( )

$\mathcal{V} = \{b_h:\text{BSIZE}; h = 1, ..$ ( )

$\text{E}(p_h, t_{h-k}) = 1'b_h, \forall h,$ 0 ( )

$\text{E}(t_{h-k}, p_k) = 1'b_h, \forall h,$ 0 ( )

$\text{G}(t_{h-k}) = [(b_h = 111) \wedge (\text{C}_{h-k-111})] \vee [(b_h = 211) \wedge (\text{C}_{h-k-211})] \vee [(b_h = 121) \wedge (\text{C}_{h-k-121})] \vee [(b_h = 221) \wedge (\text{C}_{h-k-221}$

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s p_h.

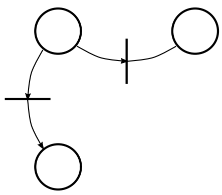

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Figure 8: Detail of the CPN representing the section of the π-conveyor: movement from cell #22 to cells #23 (eastbound) and #32 (southbound).

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p_{22}, p_{23}, p_{32} t_{22-23}, t_{22-32}, ( ) ( ) ,
( ) 22 (π-) 211 (
π-). $C_{22-23-422}$ #1
#2 , , p_{16} p_{26}
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p_{32}, p_{33}, p_{34}, p_{35} .
$C_{22-23-211}$ $C_{22-32-211}$ p_{24}, p_{32}, p_{33}, ,
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$$C_{22-23-422} = [(b_{16} \neq 111) \vee (b_{16} \neq 121) \vee (b_{16} \neq 211) \vee (b_{16} \neq 221) \vee (b_{16} \neq 411) \vee (b_{16} \neq 222) \vee (b_{16} \neq 422)] \wedge [(b_{26} \neq 111) \vee (b_{26} \neq 121) \vee (b_{26} \neq 211) \vee (b_{26} \neq 221) \vee (b_{26} \neq 411) \vee (b_{26} \neq 222) \vee (b_{26} \neq 422)] \wedge [(b_{36} \neq 121) \vee (b_{36} \neq 221) \vee (b_{36} \neq 141) \vee (b_{36} \neq 222) \vee (b_{36} \neq 422) \vee (b_{36} \neq 242)] \wedge [(b_{46} \neq 141) \vee (b_{46} \neq 242)] \wedge [(b_{56} \neq 141) \vee (b_{56} \neq 242)] \quad (10)$$

$$C_{22-32-422} = [(b_{31} \neq 211) \vee (b_{31} \neq 411)] \wedge [(b_{32} \neq 111) \vee (b_{32} \neq 211) \vee (b_{32} \neq 411)] \wedge [(b_{33} \neq 111) \vee (b_{33} \neq 211) \vee (b_{33} \neq 411)] \wedge [(b_{34} \neq 111) \vee (b_{34} \neq 211) \vee (b_{34} \neq 411)] \wedge [(b_{35} \neq 111) \vee (b_{35} \neq 211) \vee (b_{35} \neq 411)] \wedge [(b_{41} \neq 221) \vee (b_{41} \neq 222) \vee (b_{41} \neq 422)] \wedge [(b_{42} \neq 121) \vee (b_{42} \neq 221) \vee (b_{42} \neq 222) \vee (b_{42} \neq 422)] \wedge [(b_{43} \neq 121) \vee (b_{43} \neq 221) \vee (b_{43} \neq 222) \vee (b_{43} \neq 422)] \wedge [(b_{44} \neq 121) \vee (b_{44} \neq 221) \vee (b_{44} \neq 222) \vee (b_{44} \neq 422)] \wedge [(b_{45} \neq 121) \vee (b_{45} \neq 221) \vee (b_{45} \neq 222) \vee (b_{45} \neq 422)] \quad (11)$$

$$C_{22-23-211} = [(b_{24} \neq 111) \vee (b_{24} \neq 121) \vee (b_{24} \neq 211) \vee (b_{24} \neq 221) \vee (b_{24} \neq 411) \vee (b_{24} \neq 222) \vee (b_{24} \neq 422)] \wedge [(b_{34} \neq 121) \vee (b_{34} \neq 221) \vee (b_{34} \neq 141) \vee (b_{34} \neq 222) \vee (b_{34} \neq 422) \vee (b_{34} \neq 242)] \wedge [(b_{44} \neq 141) \vee (b_{44} \neq 242)] \wedge [(b_{54} \neq 141) \vee (b_{54} \neq 242)] \quad (12)$$

$$C_{22-32-211} = [(b_{31} \neq 211) \vee (b_{31} \neq 411)] \wedge [(b_{32} \neq 111) \vee (b_{32} \neq 211) \vee (b_{32} \neq 411)] \wedge [(b_{33} \neq 111) \vee (b_{33} \neq 211) \vee (b_{33} \neq 411)] \wedge [(b_{41} \neq 221) \vee (b_{41} \neq 222) \vee (b_{41} \neq 422)] \wedge [(b_{42} \neq 121) \vee (b_{42} \neq 221) \vee (b_{42} \neq 222) \vee (b_{42} \neq 422)] \wedge [(b_{43} \neq 121) \vee (b_{43} \neq 221) \vee (b_{43} \neq 222) \vee (b_{43} \neq 422)] \quad (13)$$

C_{h-k-s} (, , $C_{h-k-s} = 0$) π-
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π- 1 1 2 2, $C_{22-k-141} = 0$
$C_{22-k-242} = 0$ $k = 12,21,23,32$.

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3.2 π-sorter/π-composer

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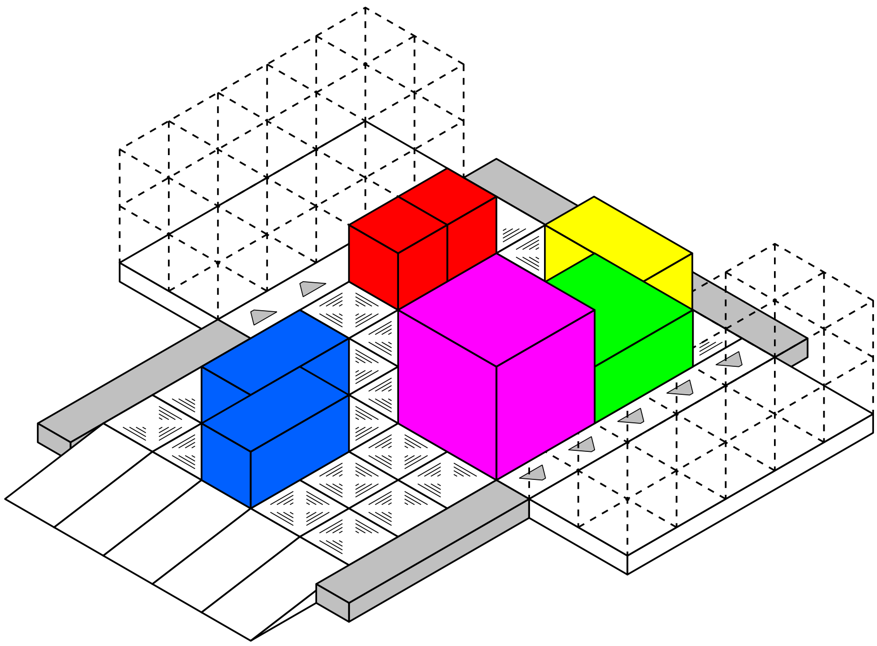

Figure 9: Physical model of a π-sorter with two π-composers.

Table 1: Loading sequence of the π-containers in Figure 9.

	π-	π-	(#)	π- (#)
1	222 ( )			
2	221 ( )			
	121 ( )	0		10
	111 ( )			1
	111 ( )			1
	211 ( )			1
	211 ( )			1

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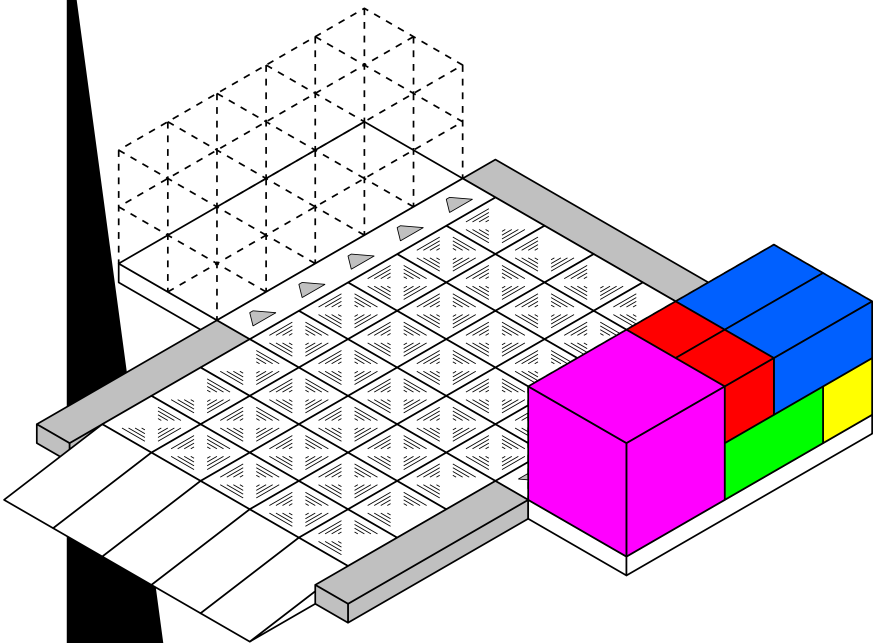

Fig[redacted]π-sorter/π-composer after the composition of a container.

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p_1 p_{40} π-
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p_{41} p_{60} p_A (π-
) [redacted] p_{60} p_B (π-). $p_{41} \div p_{60}$ $p_{61} \div p_{80}$
π- -
[redacted] 10. 11,
$p_4 \div p_8$ $p_{36} \div p_{40}$, ,
. p_A p_B

t_A t_B, ,
$p_{41} \div p_{60}$ $p_{61} \div p_{80}$
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$$\mathcal{C}(p_h) = \mathrm{BSIZE}\,, \forall h = 1, \dots, 80 \quad (1\ )$$

$$\mathcal{C}(p_l) = \mathrm{STRUCT}\,, \forall l = \mathrm{A,B} \quad (1\ )$$

$$\mathcal{V} = \{b_h\text{:BSIZE}; h = 1, \dots, 80\} \quad (1\ )$$

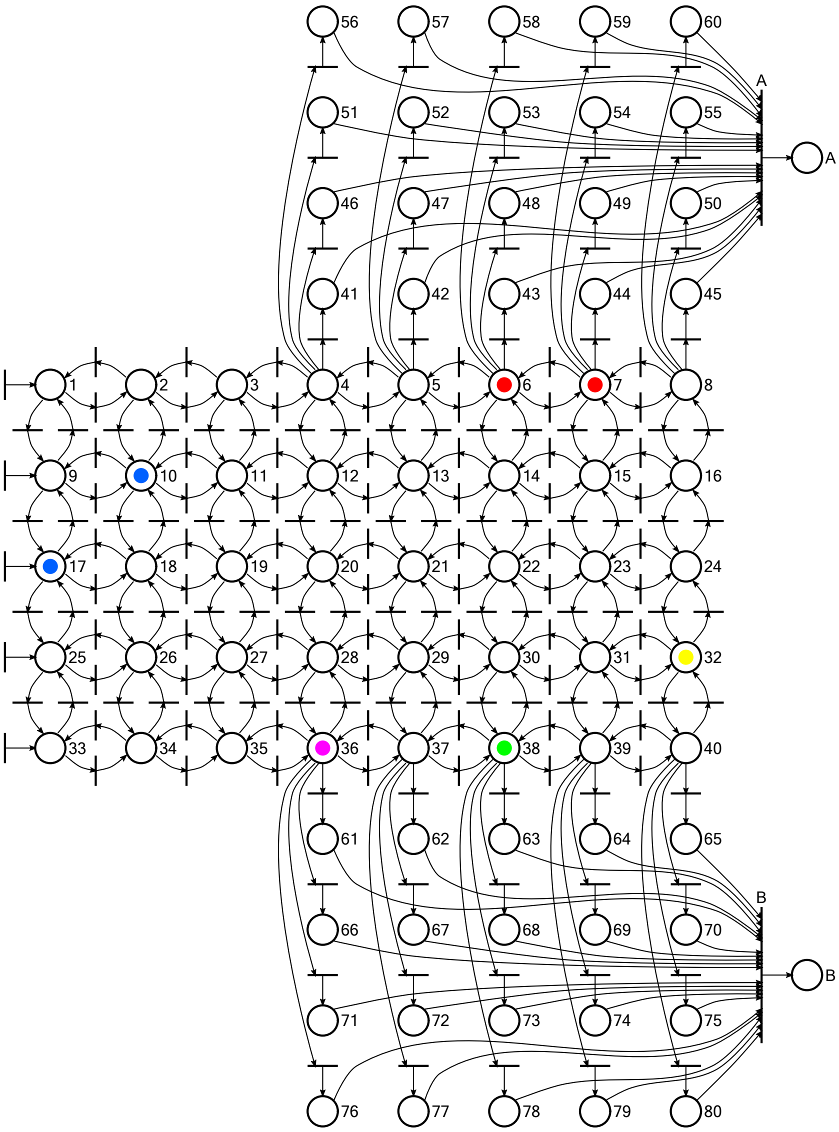

Figure 11: CPN representing the π-sorter with two π-composers.

$\mathrm{E}(p_h, t_{h-k}) = 1'b_h \,, \forall h, k = 1, \dots, 40$ (1)

$\mathrm{E}(t_{h-k}, p_k) = 1'b_h \,, \forall h, k = 1, \dots, 40$ (1)

$\mathrm{E}(p_h, t_{\mathrm{A}k}) = 1'b_h \,, \forall h, k\colon (p_h, t_{\mathrm{A}k}) \in \mathcal{A} \,, h \in \{4, \dots, 8\} \,, k \in \{41, \dots, 60\}$ (1)

$\mathrm{E}(t_{\mathrm{A}k}, p_k) = 1'b_h \,, \forall h, k\colon (p_h, t_{\mathrm{A}k}) \in \mathcal{A} \,, h \in \{4, \dots, 8\} \,, k \in \{41, \dots, 60\}$ (20)

$\mathrm{E}(p_h, t_{\mathrm{B}k}) = 1'b_h \,, \forall h, k\colon (p_h, t_{\mathrm{B}k}) \in \mathcal{A} \,, h \in \{36, \dots, 40\} \,, k \in \{61, \dots, 80\}$ (21)

$\mathrm{E}(t_{\mathrm{B}k}, p_k) = 1'b_h \,, \forall h, k\colon (p_h, t_{\mathrm{B}k}) \in \mathcal{A} \,, h \in \{36, \dots, 40\} \,, k \in \{61, \dots, 80\}$ (22)

$\mathrm{E}(p_h, t_l) = 1'b_h \,, \forall h = 41, \dots, 60 \text{ when } l = \mathrm{A} \,, \forall h = 61, \dots, 80 \text{ when } l = \mathrm{B}$ (2)

$\mathrm{E}(t_{\mathrm{A}}, p_{\mathrm{A}}) = 1'(b_{41}, \dots, b_{60})$ (2)

$\mathrm{E}(t_{\mathrm{B}}, p_{\mathrm{B}}) = 1'(b_{61}, \dots, b_{80})$ (2)

$\mathrm{G}(t_{h-k}) = [(b_h = 111) \wedge (\mathrm{C}_{h-k-111})] \vee [(b_h = 211) \wedge (\mathrm{C}_{h-k-211})] \vee [(b_h = 121) \wedge (\mathrm{C}_{h-k-121})] \vee [(b_h = 221) \wedge (\mathrm{C}_{h-k-221})] \vee [(b_h = 411) \wedge (\mathrm{C}_{h-k-411})] \vee [(b_h = 141) \wedge (\mathrm{C}_{h-k-141})] \vee [(b_h = 222) \wedge (\mathrm{C}_{h-k-222})] \vee [(b_h = 422) \wedge (\mathrm{C}_{h-k-422})] \vee [(b_h = 242) \wedge (\mathrm{C}_{h-k-242})] \,, \forall h, k = 1, \dots, 60$ (2

$$\mathrm{G}(t_{\mathrm{A}k}) = f_{\mathrm{LS}}(b_4, \dots, b_8, b_{41}, \dots, b_{60}) \quad (2\ \ )$$

$$\mathrm{G}(t_{\mathrm{B}k}) = f_{\mathrm{LS}}(b_{36}, \dots, b_{40}, b_{61}, \dots, b_{80}) \quad (2\ \ )$$

$$\mathrm{G}(t_{\mathrm{A}}) = g_{\mathrm{LS}}(b_{41}, \dots, b_{60}) \quad (2\ \ )$$

$$\mathrm{G}(t_{\mathrm{B}}) = g_{\mathrm{LS}}(b_{61}, \dots, b_{80}) \quad (\ \ 0)$$

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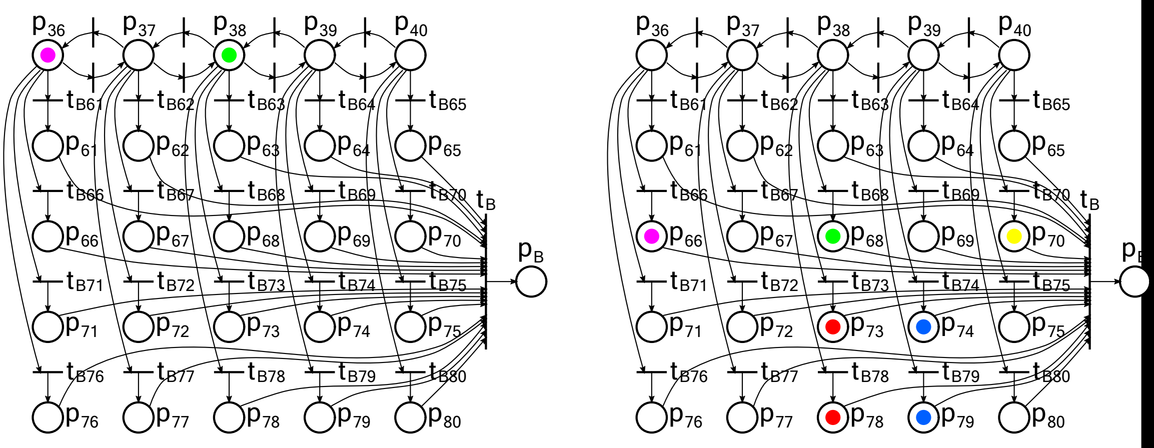

Figure 12: Detail of the CPN representing the π-sorter with two π-composers: (a) start of composit on π-composer B, and (b) end of composition on π-composer B (final marking).

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222, 221, 121, 111, 211, p_{36} (222), p_{38} (
221 111), p_{39} (211), p_{40} (1
π- .

$p_{66}, p_{68}, p_{70}, p_{73}, p_{74}, p_{78}, p_{79}$ $t_{\mathrm{B}66}, t_{\mathrm{B}68}, t_{\mathrm{B}70}, t_{\mathrm{B}73}, t_{\mathrm{B}74}$, $t_{\mathrm{B}79}$, . ,
1. , $t_{\mathrm{B}66}, t_{\mathrm{B}68}$,
$t_{\mathrm{B}78}, t_{\mathrm{B}73}, t_{\mathrm{B}79}, t_{\mathrm{B}74}$, (
π- $p_{36} \div p_{40}$).

$$\mathrm{G}(t_{\mathrm{B}66}) = (b_{36} = 222) \quad (\ \ 1)$$

$$\mathrm{G}(t_{\mathrm{B}68}) = (b_{38} = 221) \wedge (b_{66} = 222) \quad (\ \ 2)$$

$$\mathrm{G}(t_{\mathrm{B}70}) = (b_{40} = 121) \wedge (b_{68} = 221)$$

$$\mathrm{G}(t_{\mathrm{B}78}) = (b_{38} = 111) \wedge (b_{70} = 121)$$

$$\mathrm{G}(t_{\mathrm{B}73}) = (b_{38} = 111) \wedge (b_{78} = 111)$$

$$\mathrm{G}(t_{\mathrm{B}79}) = (b_{39} = 211) \wedge (b_{73} = 111)$$

$$\mathrm{G}(t_{\mathrm{B}74}) = (b_{39} = 211) \wedge (b_{79} = 211)$$

$$\mathrm{G}(t_{\mathrm{B}k}) = 0\,,\ k = 61,62,63,64,65,67,69,71,72,75,76,77,80$$

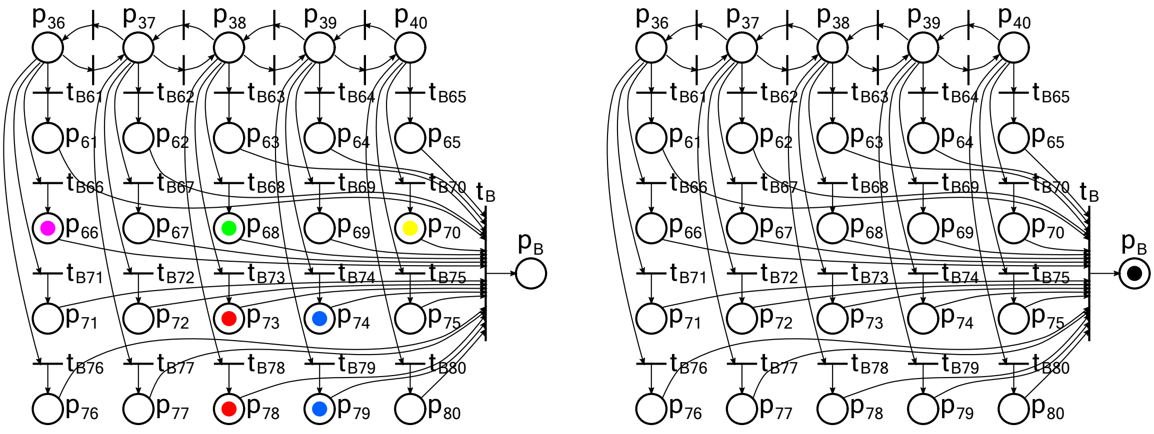

Figure 13: Detail of the CPN representing the π-sorter with two π-composers: (a) end of composition on π-composer B (final marking), and (b) consolidation of the composed container.

$p_{61} \div p_{80}$,
t_B (1),
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$\mathrm{G}(t_\mathrm{B}) = (b_{61} = 0) \wedge (b_{62} = 0) \wedge (b_{63} = 0) \wedge (b_{64} = 0) \wedge (b_{65} =$ [redacted] $) \wedge ($ [redacted] $b_{66} = 222) \wedge (b_{67} = 0) \wedge (b_{68} = 221) \wedge (b_{69} = 0) \wedge (b_{70} = 121) \wedge (b_{71} = 0) \wedge (b_{72} =$ [redacted] $) \wedge ($ [redacted] $b_{73} = 111) \wedge (b_{74} = 211) \wedge (b_{75} = 0) \wedge (b_{76} = 0) \wedge (b_{77} = 0) \wedge (b_{78} = 111) \wedge (b_{79} =$ [redacted] $11)$ [redacted] $\wedge (b_{80} = 0)$ ( )

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4 Conclusions and further research direction

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