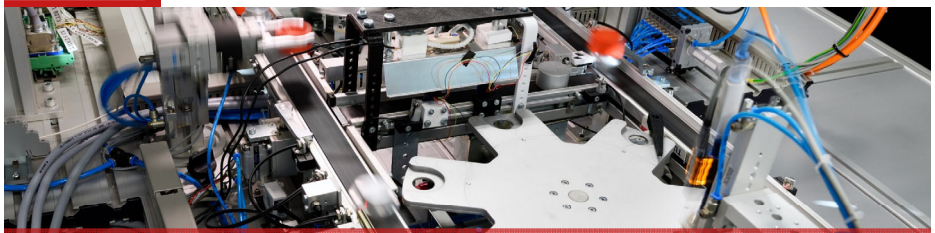


Model-driven Performance Engineering of FMS

About saving time …

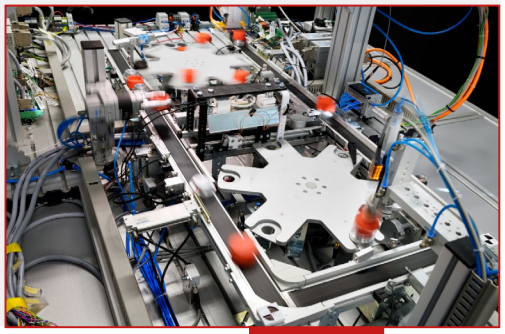
Twan Basten, João Bastos, Róbinson Medina, Bram van der Sanden,
Marc Geilen, Dip Goswami, Michel Reniers, Sander Stuijk, Jeroen Voeten

Robust CPS, projects 12694, 12697

Just a few questions …

- What is the productivity of this machine?
- Optimal production schedule?
- Productivity bottlenecks?
- Optimal controllers?
- Design alternatives?

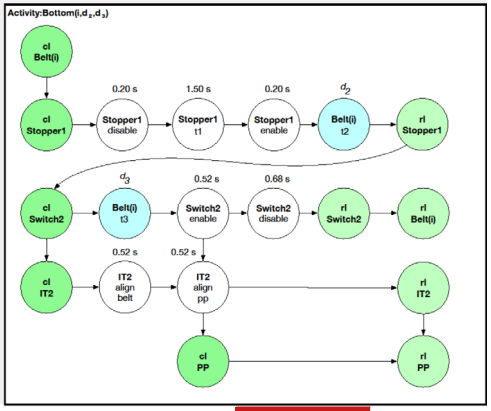
How would you approach this?



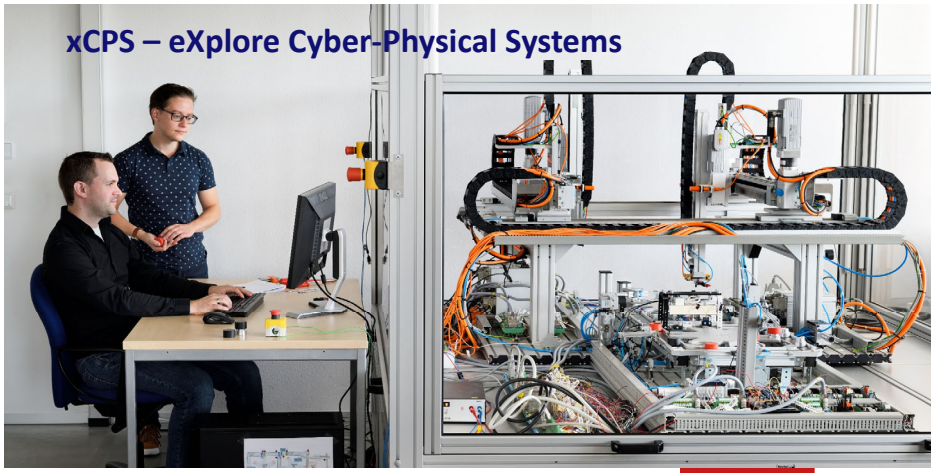
Activity Modeling

Activity – Deterministic, Atomic Functionality

- Actions, precedences
- (Worst-case) action execution times
- Resource claims, releases
- Consistent



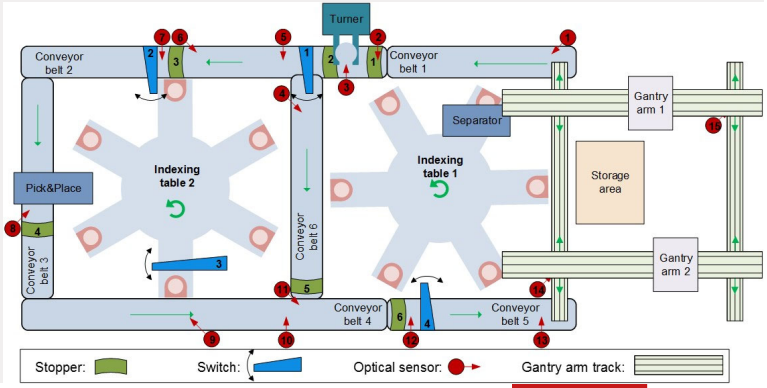
xCPS – eXplore Cyber-Physical Systems



5 xcps.info

ES ELECTRONIC SYSTEMS TU/e

xCPS – Case Study



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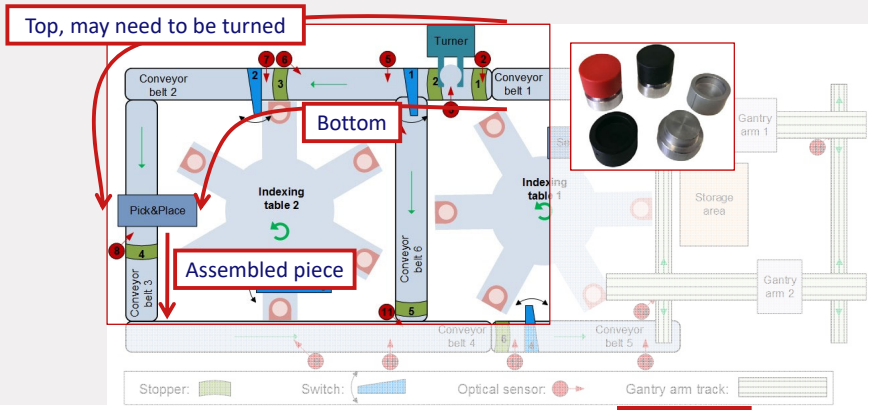
ES ELECTRONIC SYSTEMS TU/e

xCPS – Case Study

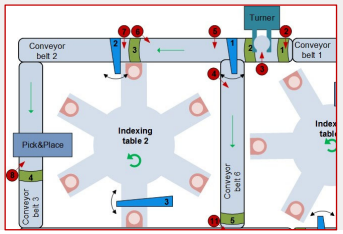


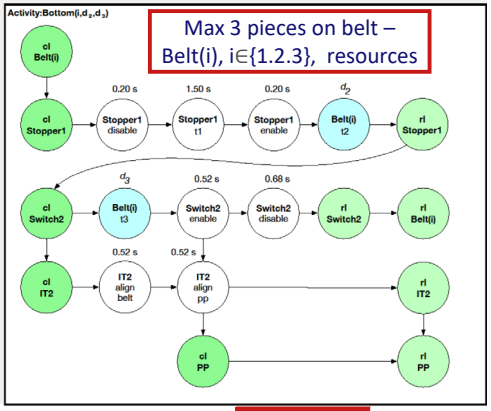
7

ES ELECTRONIC SYSTEMS TU/e

Activity – Deterministic, Atomic Functionality

- Actions, precedences
- (Worst-case) action execution times
- Resource claims, releases
- Consistent

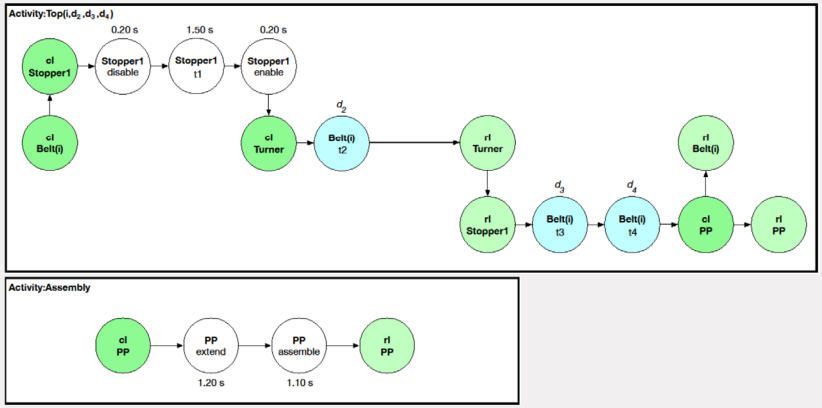




8

ES ELECTRONIC SYSTEMS TU/e

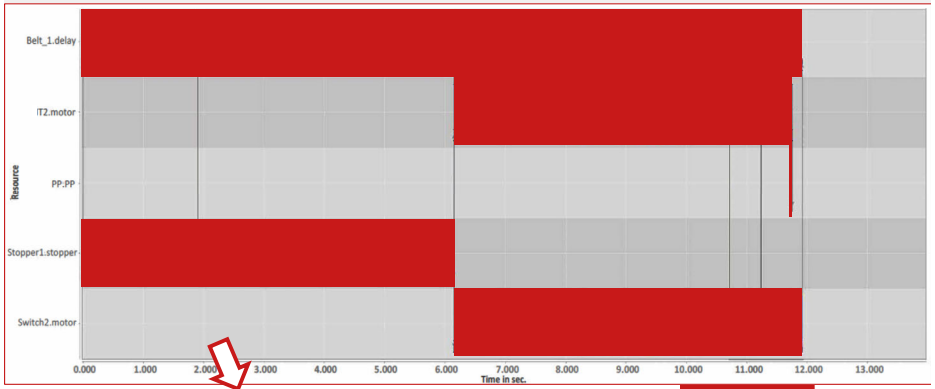
Activity – Deterministic, Atomic Functionality



Action Execution – Bottom(1,4.24,4.57)

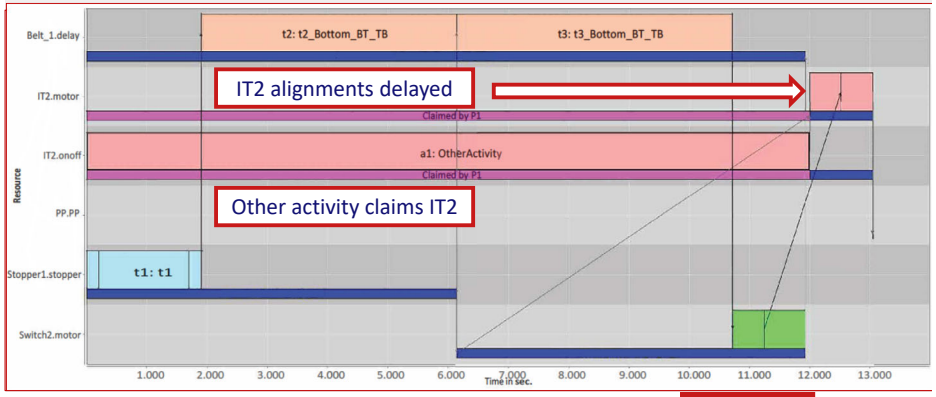
Looks a bit like a tetris block

Action Execution – Bottom(1,4.24,4.57)



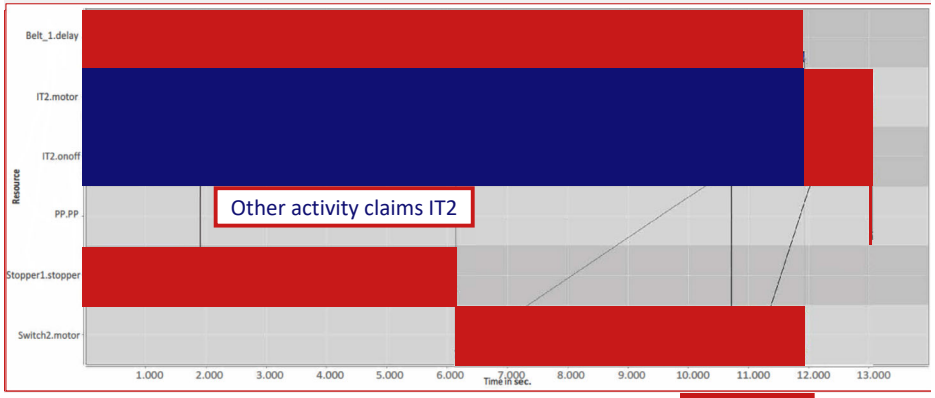
Looks a bit like a tetris block

Action Execution – Bottom(1,4.24,4.57)



Looks a bit like a tetris block

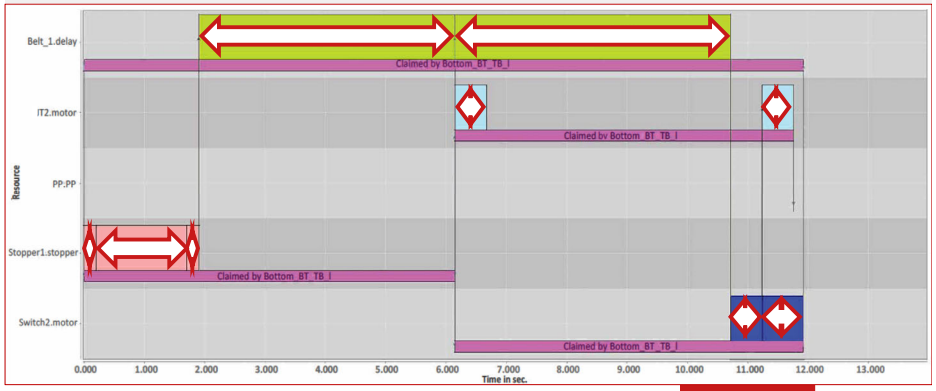
Action Execution – Bottom(1,4.24,4.57)



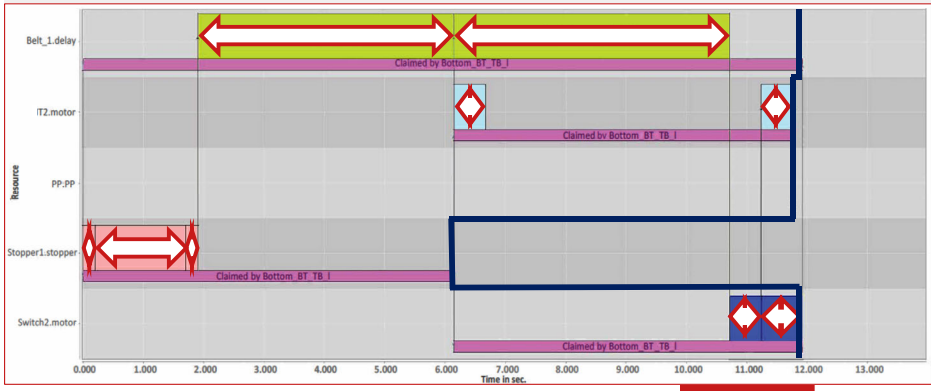
Looks a bit like a tetris block

But flexible !

The Constant – Action Execution Times

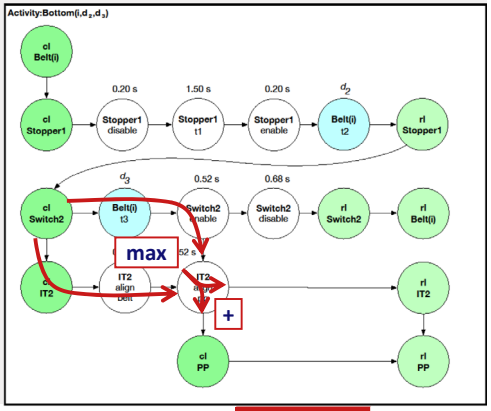


The Variable – Resource Availability Times



Activity – Computing Resource Release Times

- Actions, precedences
- (Worst-case) action execution times
- Resource claims, releases
- Consistent



(max,+) algebra

Semiring $(R \cup \{-\infty\}, \oplus, \otimes)$ with

$x \oplus y = \max(x,y)$

$x \otimes y = x+y$

(max,+) tetris

courtesy Marc Geilen

a
b
dependencies
rotate
clear

ES ELECTRONIC SYSTEMS TU/e

(max,+) Matrix Characterization of Activity Timing

Bottom(1,d_2,d_3)

From availability …

… till release

	Stopper1	Switch2	IT2	PP	Turner	Belt(1)	Belt(2)	Belt(3)
Stopper1	$1.9+d_2$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$1.9+d_2$	$-\infty$	$-\infty$
Switch2	$3.1+d_2+d_3$	$d_3+1.2$	$-\infty$	$-\infty$	$-\infty$	$3.1+d_2+d_3$	$-\infty$	$-\infty$
IT2	$2.94+d_2+d_3$	$d_3+1.04$	1.04	0	$-\infty$	$2.94+d_2+d_3$	$-\infty$	$-\infty$
PP	$2.94+d_2+d_3$	$d_3+1.04$	1.04	0	$-\infty$	$2.94+d_2+d_3$	$-\infty$	$-\infty$
Turner	$-\infty$	$-\infty$	$-\infty$	$-\infty$	0	$-\infty$	$-\infty$	$-\infty$
Belt(1)	$3.1+d_2+d_3$	$d_3+1.2$	$-\infty$	$-\infty$	$-\infty$	$3.1+d_2+d_3$	$-\infty$	$-\infty$
Belt(2)	$-\infty$	$-\infty$	$-\infty$	∞	$-\infty$	$-\infty$	0	$-\infty$
Belt(3)	$-\infty$	$-\infty$	$-\infty$	∞	$-\infty$	$-\infty$	$-\infty$	0

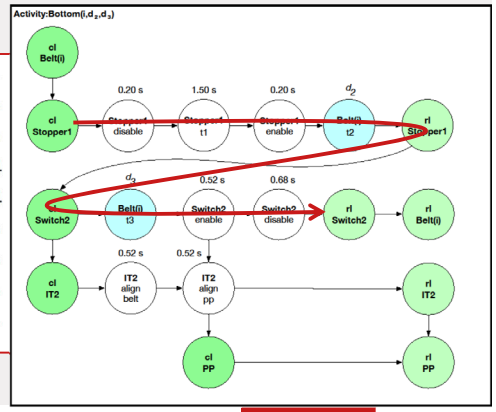
ES ELECTRONIC SYSTEMS TU/e

(max,+) Matrix Characterization of Activity Timing

From availability …

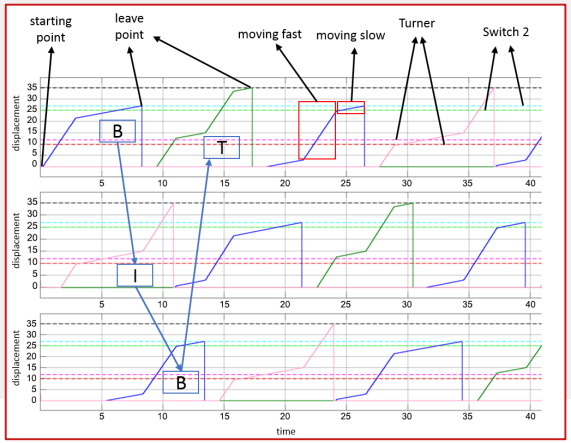
… till release

	Stopper1	Switch2	IT2
Stopper1	$1.9+d_2$	$-\infty$	$-\infty$
Switch2	$3.1+d_2+d_3$	$d_3+1.2$	$-\infty$
IT2	$2.94+d_2+d_3$	$d_3+1.04$	1.04
PP	$2.94+d_2+d_3$	$d_3+1.04$	1.04
Turner	$-\infty$	$-\infty$	$-\infty$
Belt(1)	no dependency	$+1.2$	$-\infty$
Belt(2)	$-\infty$	$-\infty$	$-\infty$
Belt(3)	$-\infty$	$-\infty$	$-\infty$



ES ELECTRONIC SYSTEMS TU/e

Action Execution Times – Simulations, Measurements, …



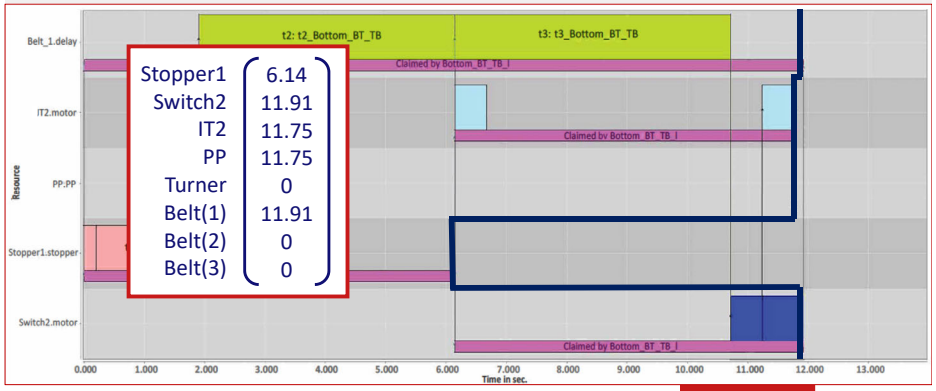
ES ELECTRONIC SYSTEMS TU/e

Timing of Activity Execution – (max,+) Matrix Multiplication

Bottom(1,4.24,4.57)

$$\begin{matrix}\text{Stopper1}\\ \text{Switch2}\\ \text{IT2}\\ \text{PP}\\ \text{Turner}\\ \text{Belt(1)}\\ \text{Belt(2)}\\ \text{Belt(3)}\end{matrix}\begin{pmatrix}6.14\\ 11.91\\ 11.75\\ 11.75\\ 0\\ 11.91\\ 0\\ 0\end{pmatrix} = \begin{pmatrix}6.14 & -\infty & -\infty & \dots\\ 11.91 & 5.77 & \dots & \\ 11.75 & \dots & & \\ \dots & & & \\ & & & \\ & & & \\ & & & \\ & & & \end{pmatrix}\begin{pmatrix}0\\0\\0\\0\\0\\0\\0\\0\end{pmatrix}\begin{matrix}\text{Stopper1}\\ \text{Switch2}\\ \text{IT2}\\ \text{PP}\\ \text{Turner}\\ \text{Belt(1)}\\ \text{Belt(2)}\\ \text{Belt(3)}\end{matrix}$$

Timing of Activity Execution – Bottom(1,4.24,4.57)

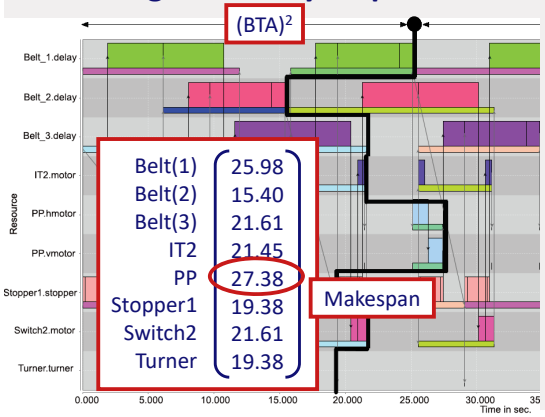


$$\begin{matrix}\text{Stopper1}\\ \text{Switch2}\\ \text{IT2}\\ \text{PP}\\ \text{Turner}\\ \text{Belt(1)}\\ \text{Belt(2)}\\ \text{Belt(3)}\end{matrix}\begin{pmatrix}6.14\\ 11.91\\ 11.75\\ 11.75\\ 0\\ 11.91\\ 0\\ 0\end{pmatrix}$$

Worst-case timing analysis of distributed systems: (max,+) algebra

Timing Analysis

Timing of Activity Sequences – BTABTABTA…



Belt(1)	25.98
Belt(2)	15.40
Belt(3)	21.61
IT2	21.45
PP	27.38
Stopper1	19.38
Switch2	21.61
Turner	19.38

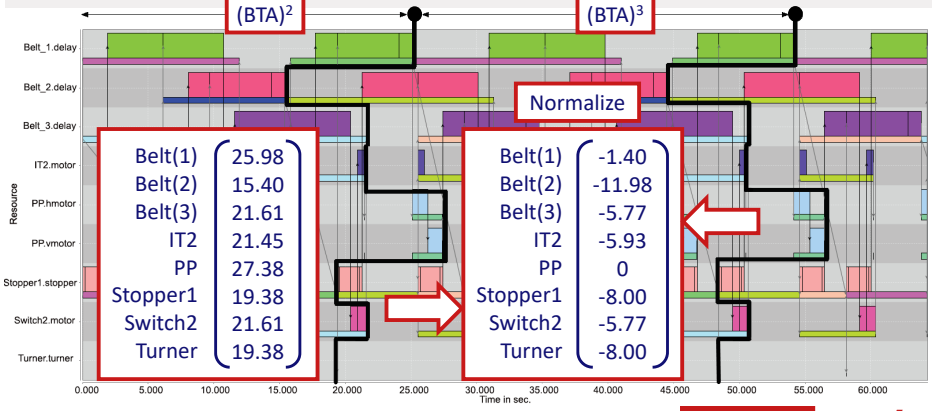
Makespan

Repeated matrix multiplication

ES ELECTRONIC SYSTEMS TU/e

Timing of Activity Sequences – BTABTABTA…

Recurrent?



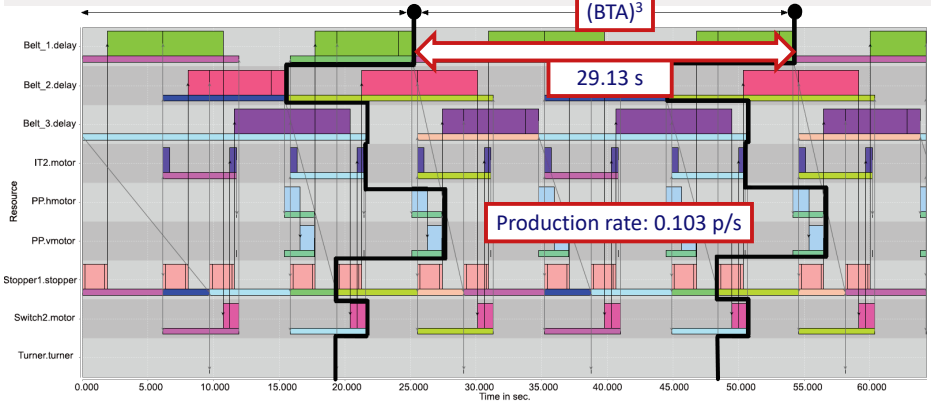
Belt(1)	25.98	Belt(1)	-1.40
Belt(2)	15.40	Belt(2)	-11.98
Belt(3)	21.61	Belt(3)	-5.77
IT2	21.45	IT2	-5.93
PP	27.38	PP	0
Stopper1	19.38	Stopper1	-8.00
Switch2	21.61	Switch2	-5.77
Turner	19.38	Turner	-8.00

Normalize

ES ELECTRONIC SYSTEMS TU/e

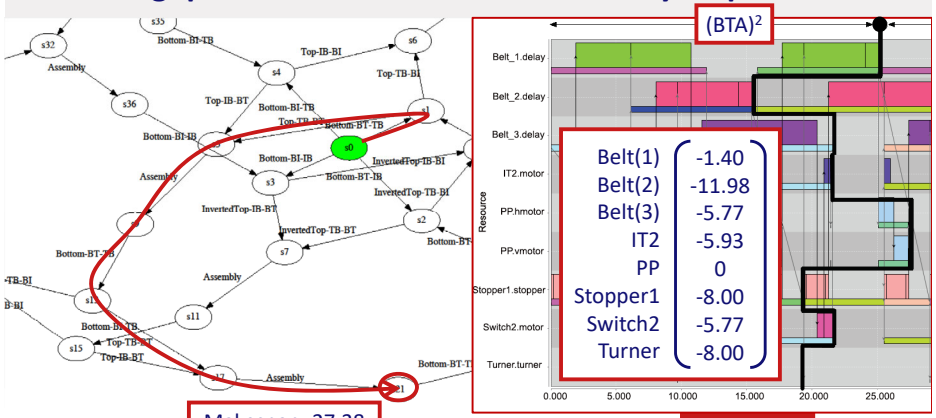
Timing of Activity Sequences – BTABTABTA…

Recurrent!



ES ELECTRONIC SYSTEMS TU/e

Throughput Bounds – Consider All Activity Sequences

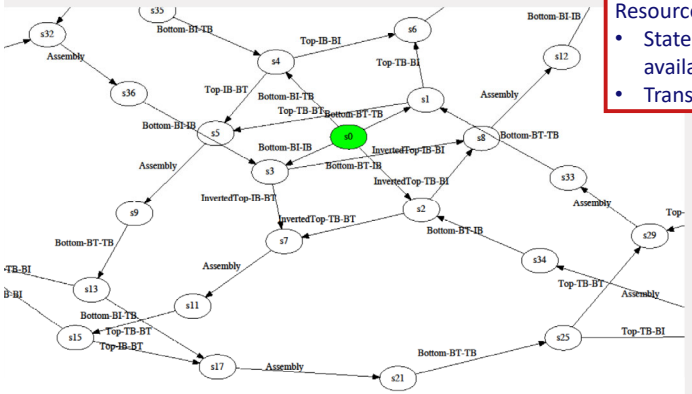


Belt(1)	-1.40
Belt(2)	-11.98
Belt(3)	-5.77
IT2	-5.93
PP	0
Stopper1	-8.00
Switch2	-5.77
Turner	-8.00

Makespan: 27.38

ES ELECTRONIC SYSTEMS TU/e

Throughput Lower and Upper Bounds



Resource-availability state space
- States: Normalized resource-availability vectors
- Transitions: Delay

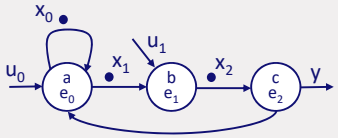
Max/Min Cycle Mean provide bounds (and schedules)

Max: 0.103 p/s
Min: 0.080 p/s

Analysis time: < 9 ms

Other advanced techniques available

In General: (max,+) Linear Systems



A dataflow graph
- Actors a,b,c
- Actor execution times e_i
- Channels
  - inputs u_i
  - output y
- Tokens x_i

Timing semantics: (max,+) linear system

$x[k+1] = A \otimes x[k] \oplus B \otimes u[k]$

$y[k] = C \otimes x[k] \oplus D \otimes u[k]$

A,B,C,D can be obtained by 'executing the graph once'

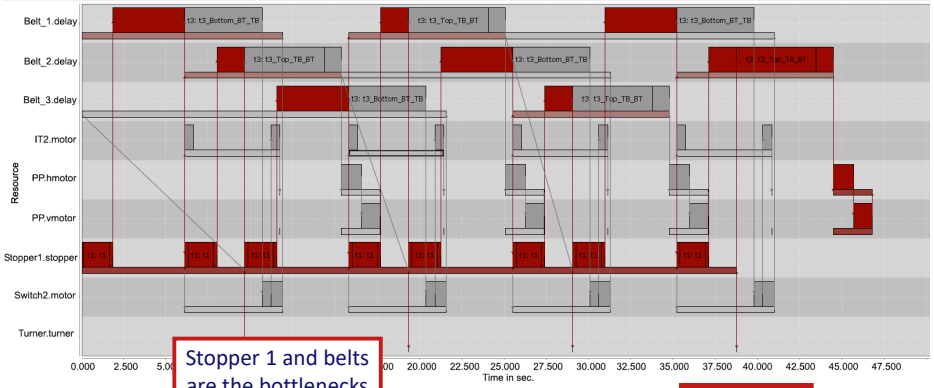
Earlier: closed system, x[k+1] = Ax[k]

Worst-case timing of distributed systems:

(max,+) linear system

Bottleneck Analysis and Redesign

Critical Path in BTA$^{\omega}$

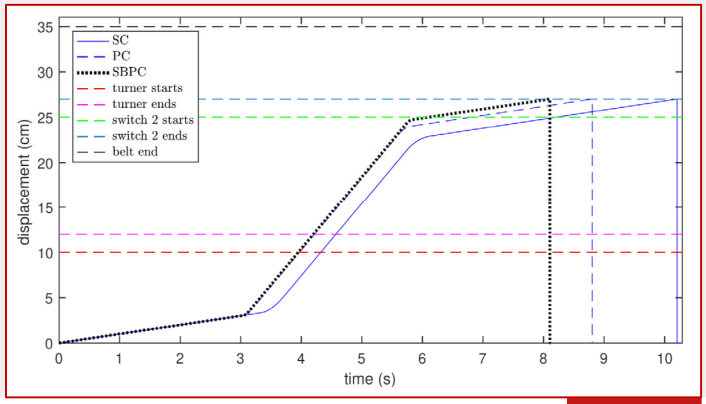


Stopper 1 and belts are the bottlenecks

Redesigning Critical Resources – Belt Controller

	Sequential Controller	Pipelined Controller	Switched Pipelined Controller
d_2	4.55	4.21	4.19
d_3	5.62	4.57	3.89

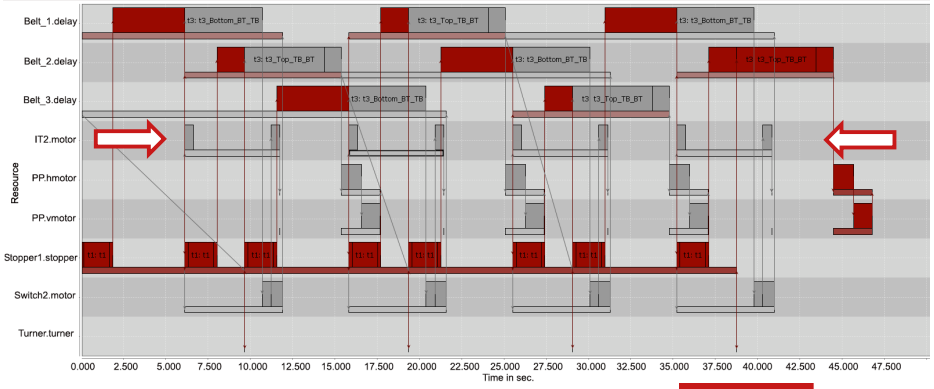
Redesigning Critical Resources – Belt Controller



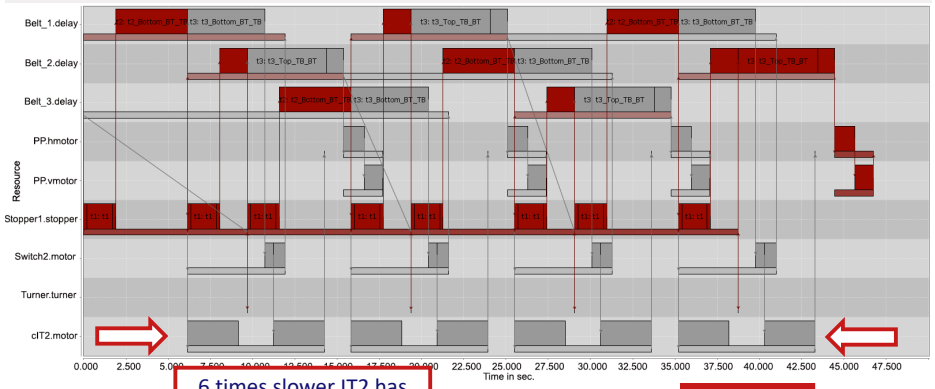
Redesigning Critical Resources – Belt Controller

	Sequential Controller	Pipelined Controller	Switched Pipelined Controller
max throughput	0.091 p/s	0.103 p/s	0.111 p/s

Redesigning Non-Critical Resources – Indexing Table



Redesigning Non-Critical Resources – Indexing Table



6 times slower IT2 has no performance impact

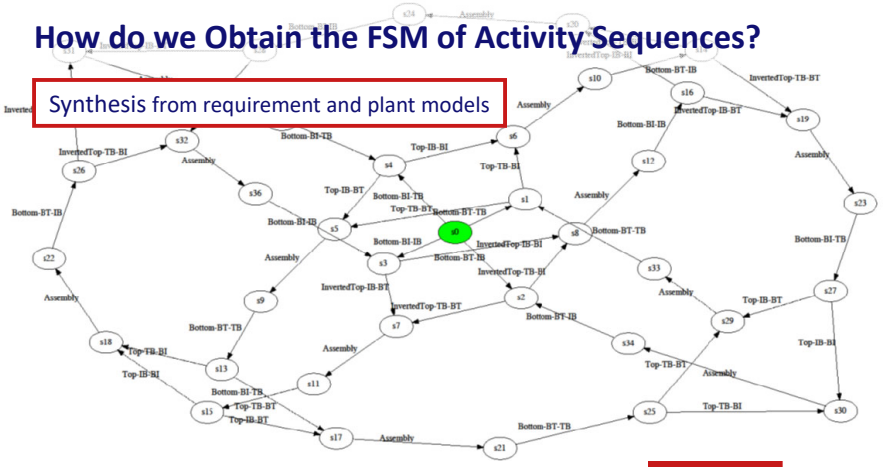
Activity Models allow

Fast Design-Space Exploration

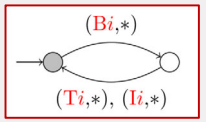
Supervisory Control

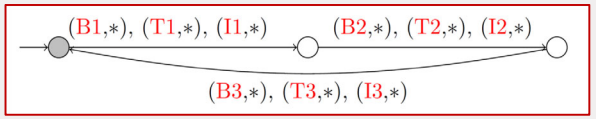
How do we Obtain the FSM of Activity Sequences?

Synthesis from requirement and plant models



Plant Models





+ some context juggling

Requirement Models

$$c = 0 \quad \text{Assembly } \mathbf{do}\ c := c - 1 \quad (Bi,*)\ \mathbf{when}\ c < 1\ \mathbf{do}\ c := c + 1$$

$$c = 0 \quad \text{Assembly } \mathbf{do}\ c := c - 1 \quad (Ti,*),(Ii,*)\ \mathbf{when}\ c < 3\ \mathbf{do}\ c := c + 1$$

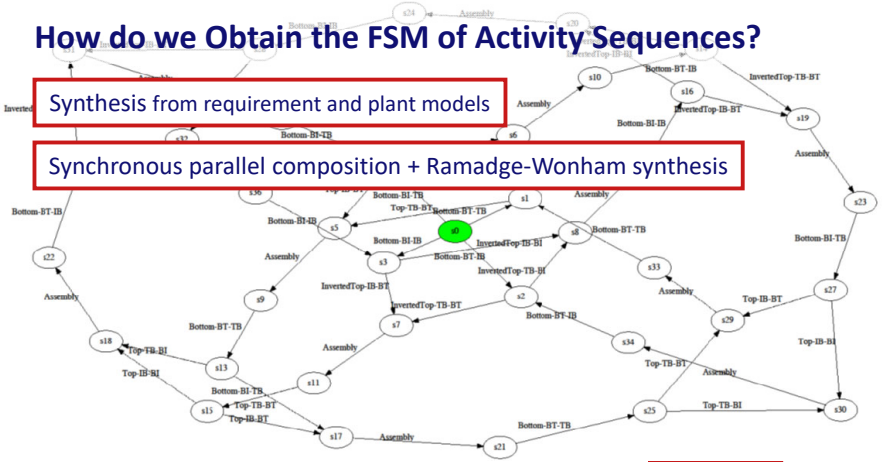
Assembly ⇒

IndexTableBuffer.c > 0 and BeltBuffer.c > 0

How do we Obtain the FSM of Activity Sequences?

Synthesis from requirement and plant models

Synchronous parallel composition + Ramadge-Wonham synthesis



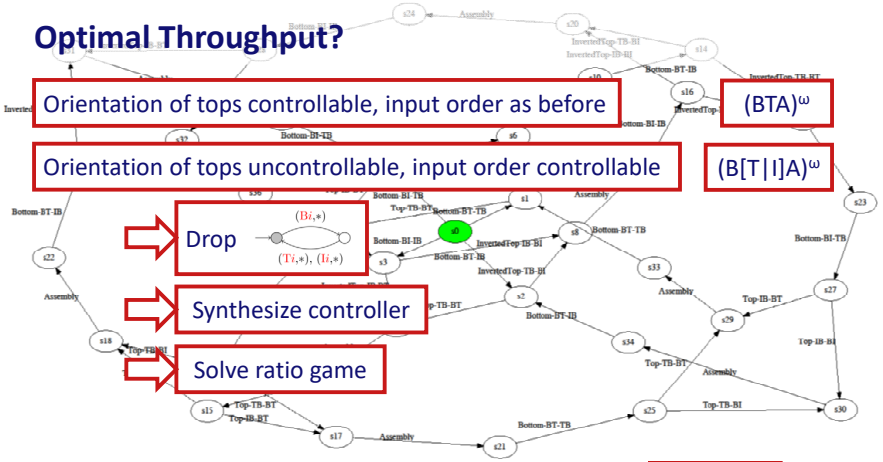
Optimal Throughput?

Orientation of tops controllable, input order as before

$(BTA)^{\omega}$

Orientation of tops uncontrollable, input order controllable

$(B[T|I]A)^{\omega}$



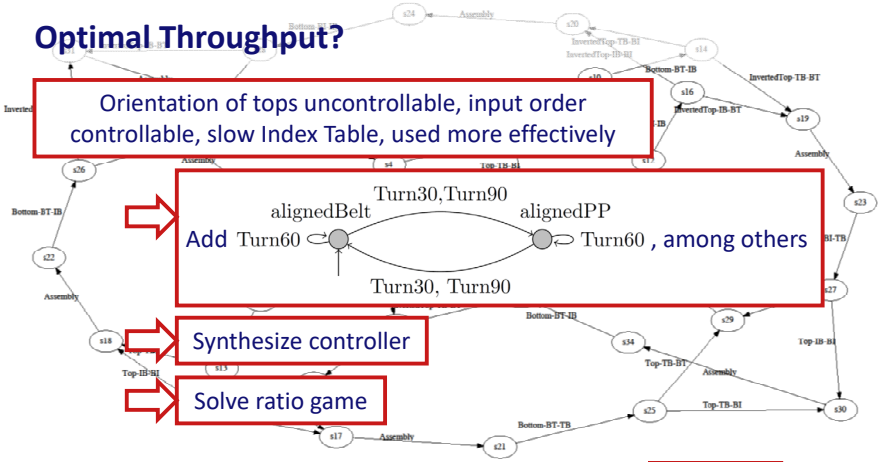
Drop

Synthesize controller

Solve ratio game

Optimal Throughput?

Orientation of tops uncontrollable, input order controllable, slow Index Table, used more effectively



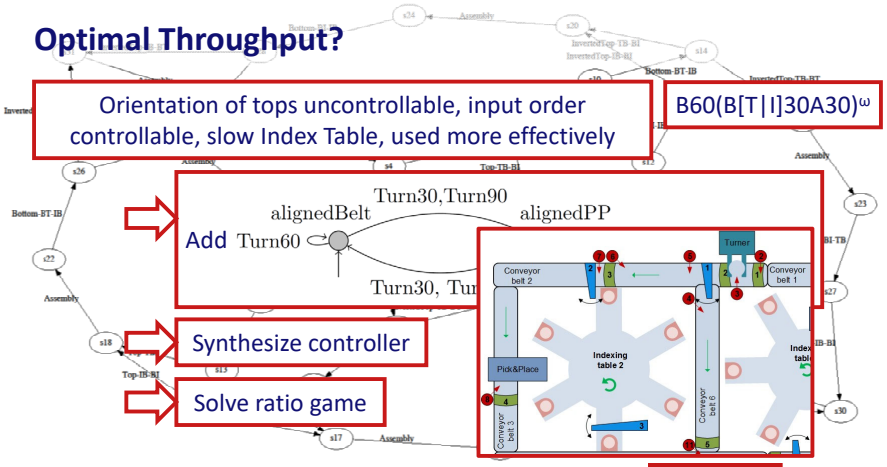
Synthesize controller

Solve ratio game

Optimal Throughput?

Orientation of tops uncontrollable, input order controllable, slow Index Table, used more effectively

$B60(B[T|I]30A30)^{\omega}$



Synthesize controller

Solve ratio game

Supervisory Controller Synthesis from Activity Models

- **scales better than Synthesis from Action Models**
- **allows Performance Optimization**

Conclusions

Remember the Take Aways?

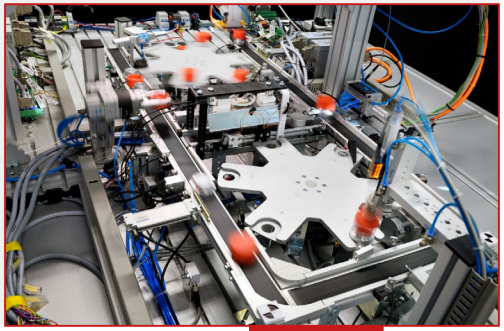
Think (max,+)

Activity models

- improve scalability of performance analysis and controller synthesis
- allow integral supervisory controller synthesis and performance optimization

Questions ?

- What is the productivity of this machine?
- Optimal production schedule?
- Productivity bottlenecks?
- Optimal controllers?
- Design alternatives?



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xcps.info