Models for Performance Analysis of Manufacturing Systems

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Background

The Systems Engineering group aims to use quantitative methods for the analysis, design and implementation of manufacturing systems and embedded systems exhibiting concurrent behavior.

The objectives are to develop theory and techniques, and to build computational tools, inspired by mechanical engineering science, computer science and mathematics, and to apply these to industrial cases.

Levels in manufacturing systems

- supply chain

  The subsystems are factories and warehouses.

- factory

  The subsystems are areas and (groups of) machines.

- area

  The subsystems are cells or individual machines.

- cell

  The subsystems are groups of machines (typically scheduled as one entity).

- machine

  The subsystems are machine components.

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Key performance indicators

- raw (effective) process time t_0 (t_e):

  The net (effective) time a system needs to process an item.

- throughput δ:

  The number of items per time-unit leaving the system.

- flow time φ:

  The time it takes for an item to travel through the system.

- utilization u:

  The fraction of time a system is processing items.

- work in process w:

  The number of items in the system.

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Effective Process Time

Process time consists of

- raw (natural) process time t_0 (mean)
- variability c_0 (standard deviation /mean)

Process disturbances

- setup times t_s and c_s
- time between failure t_f and c_f,
- time between repair t_r and c_r
- operator delays
- rework of items
- . . . (!)

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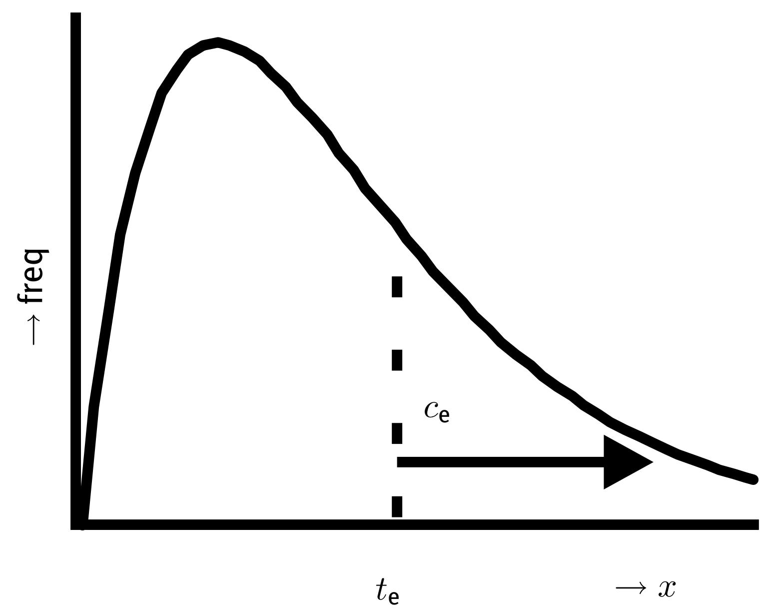
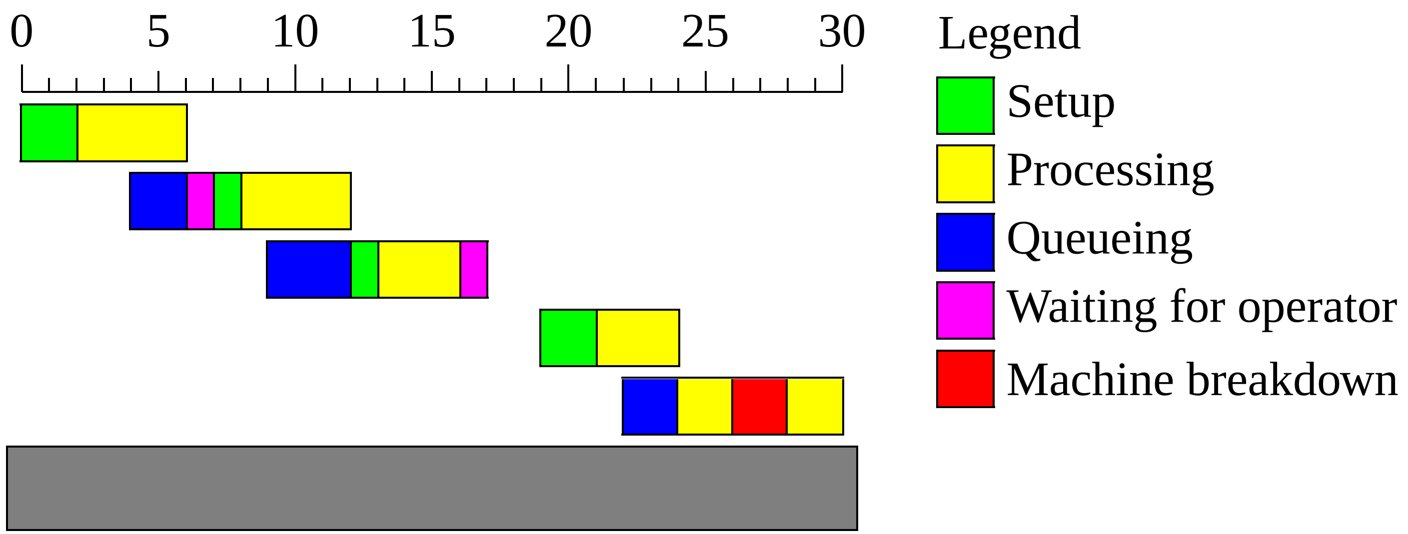
The effective process time idea

Combine all disturbances in one single EPT probability density function.



Lot-time diagram



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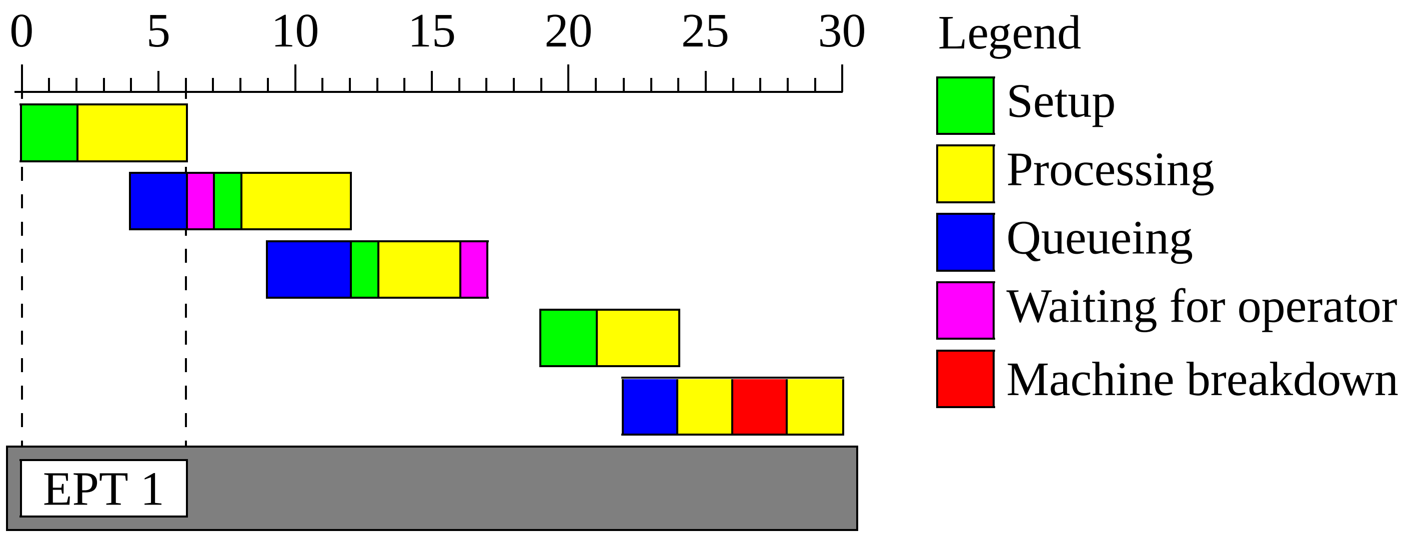

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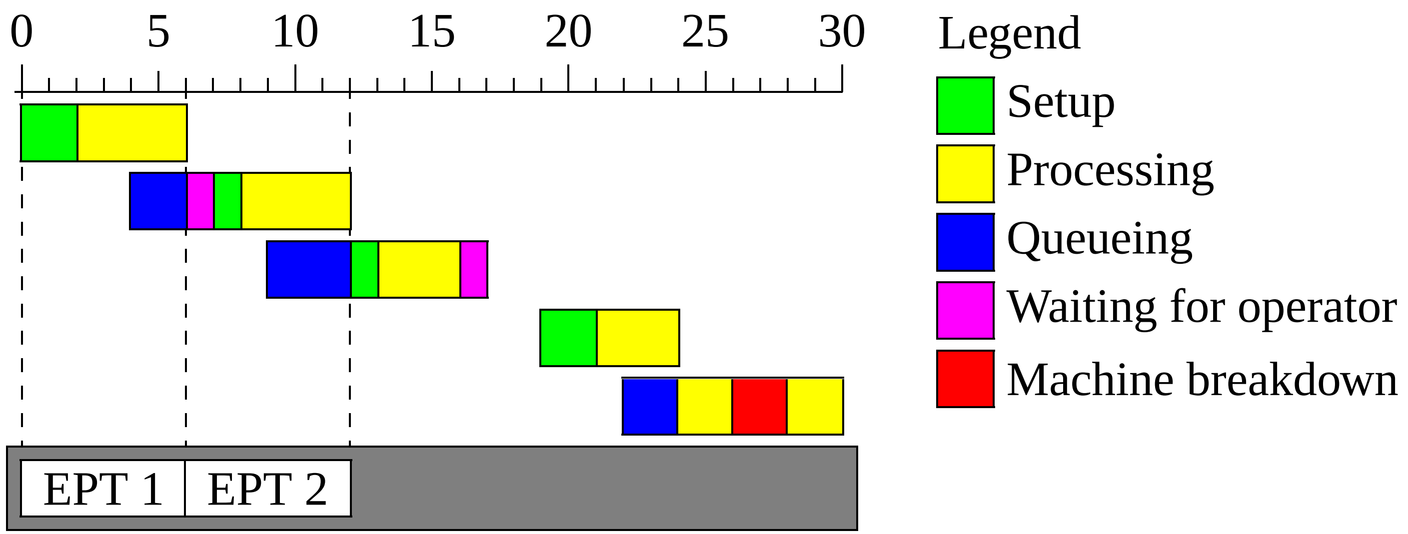

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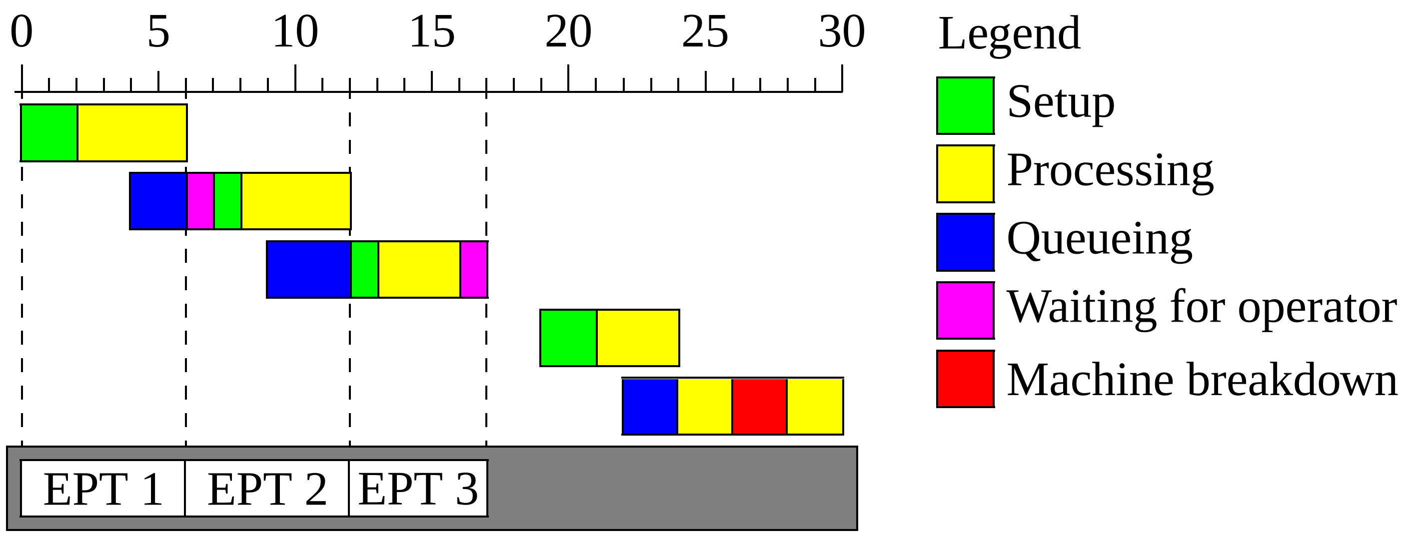

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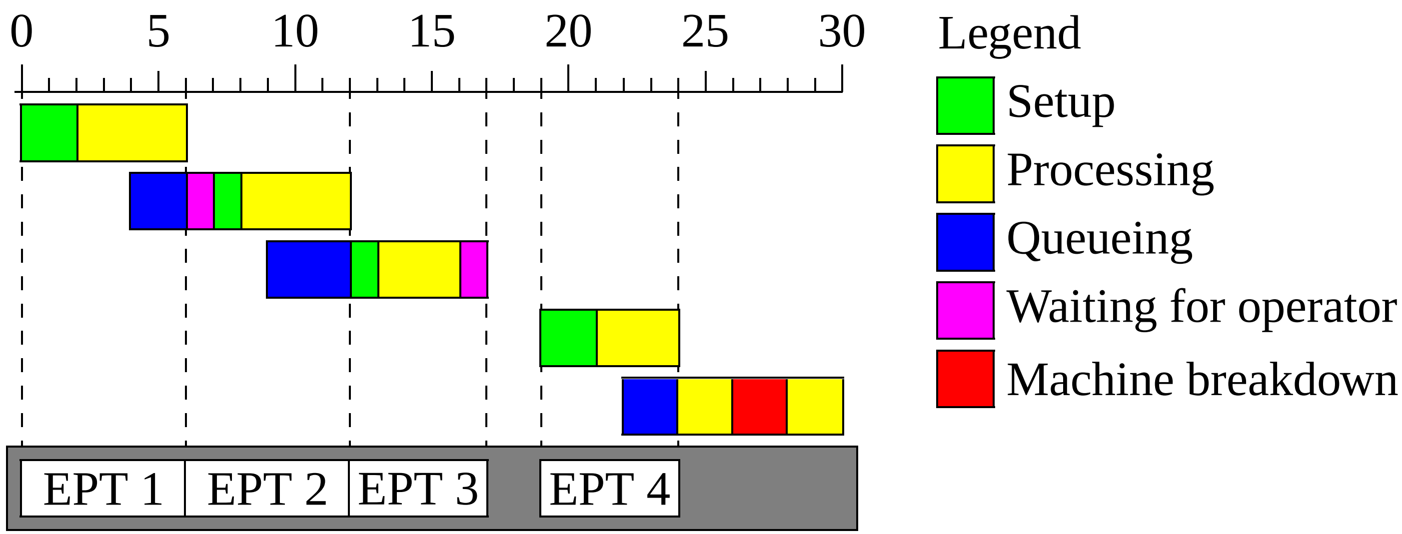
Lot-time diagram



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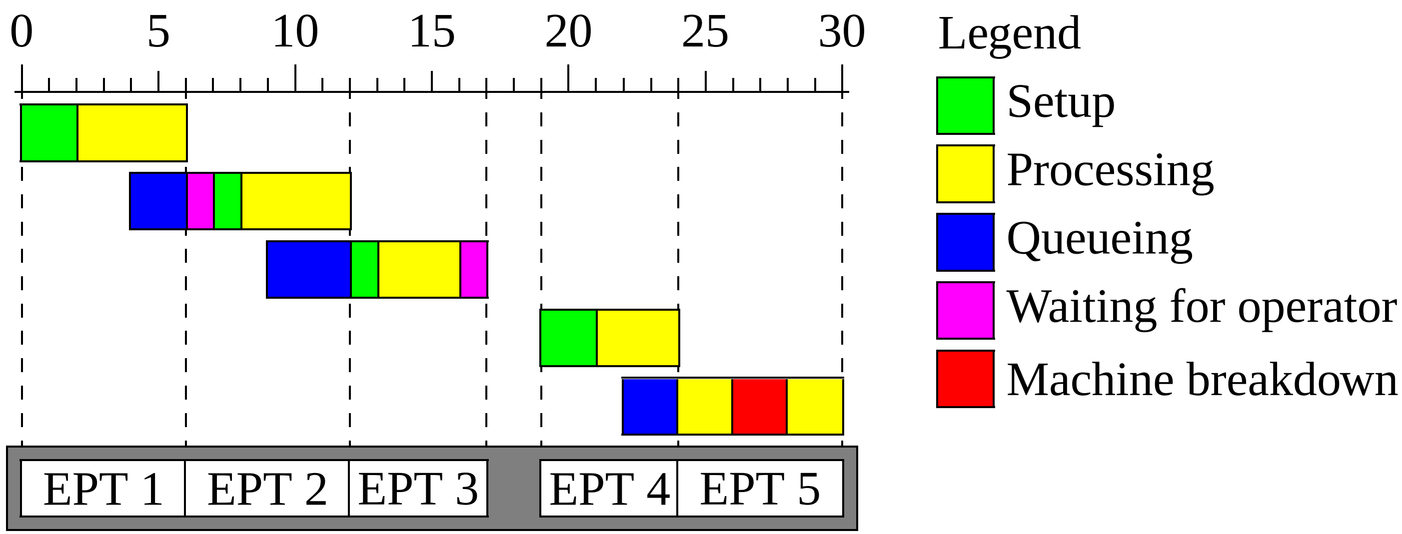
Lot-time diagram



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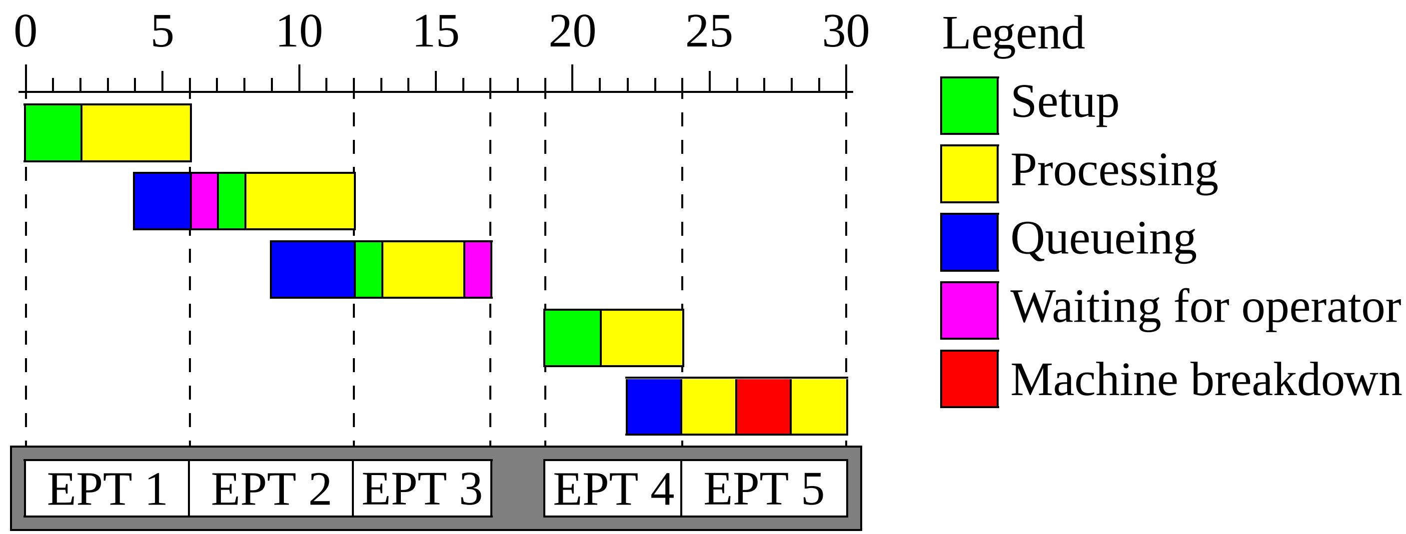

Formula (no overtake):

$$e_i = d_i - \max(a_i, d_{i-1})$$

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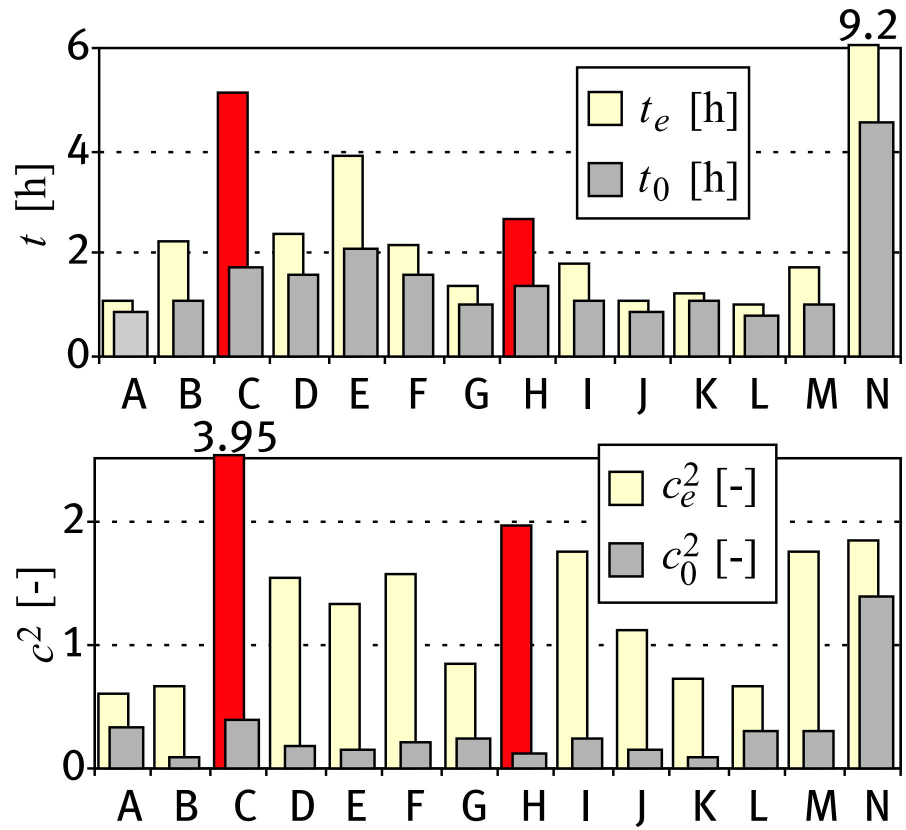
Algorithm (with overtake)

- a is triggered by arrival of an item in the buffer.
- d is triggered by departure of an item (not necessarily the same one).
- C sends the value of e_i of departed item i via r to its environment.

$$\begin{array}{l}
\text{proc } C(\text{chan } a?,\ d! : \text{void},\ r! : \text{real}) = \\
[\![\ \text{var } n : \text{nat} = 0,\ s : \text{real} \\
::\ *(\ a? \\
\qquad ;\ (n = 0 \rightarrow s := \text{time} \ [\!]\ n > 0 \rightarrow \text{skip}) \\
\qquad ;\ n := n + 1 \\
\quad [\!]\ d? \\
\qquad ;\ r!\text{time} - s \\
\qquad ;\ n := n - 1 \\
\qquad ;\ (n > 0 \rightarrow s := \text{time} \ [\!]\ n = 0 \rightarrow \text{skip}) \\
\quad) \\
]\!]
\end{array}$$

Case, Philips Nijmegen fabricator



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Available algorithms

- Infinite buffer and one machine (previous case)
- Infinite buffer and more (equal) machines
- Finite buffer and one machine
- Finite buffer and more (equal) machines
- Batch machines (e.g. furnaces)
- Cascade machines (e.g. litho machines)
- Assembly machines

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Type of models

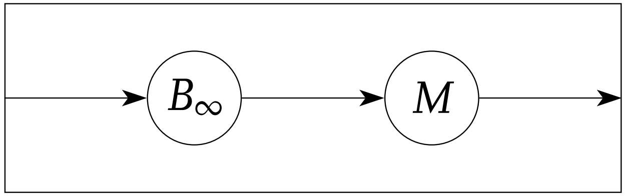
- deterministic: mass conservation models
- stochastic: queueing models

- steady state
- transient: ODE (fluid models), PDE (flow models)

Examples:

- analytical: Kingman's equation
- numerical: process algebra
- enumeration: automata

Kingman's approximation for φ, 1961



$$\varphi = \left(\frac{c_a^2 + c_e^2}{2} \cdot \frac{u}{1-u} + 1\right) \cdot t_e \qquad u = \frac{t_e}{t_a}$$

φ mean flow time

c_a coefficient of variation of mean inter-arrival time t_a

c_e coefficient of variation of mean effective process time t_e

u utilization

t_e mean effective process time

t_a mean inter-arrival time

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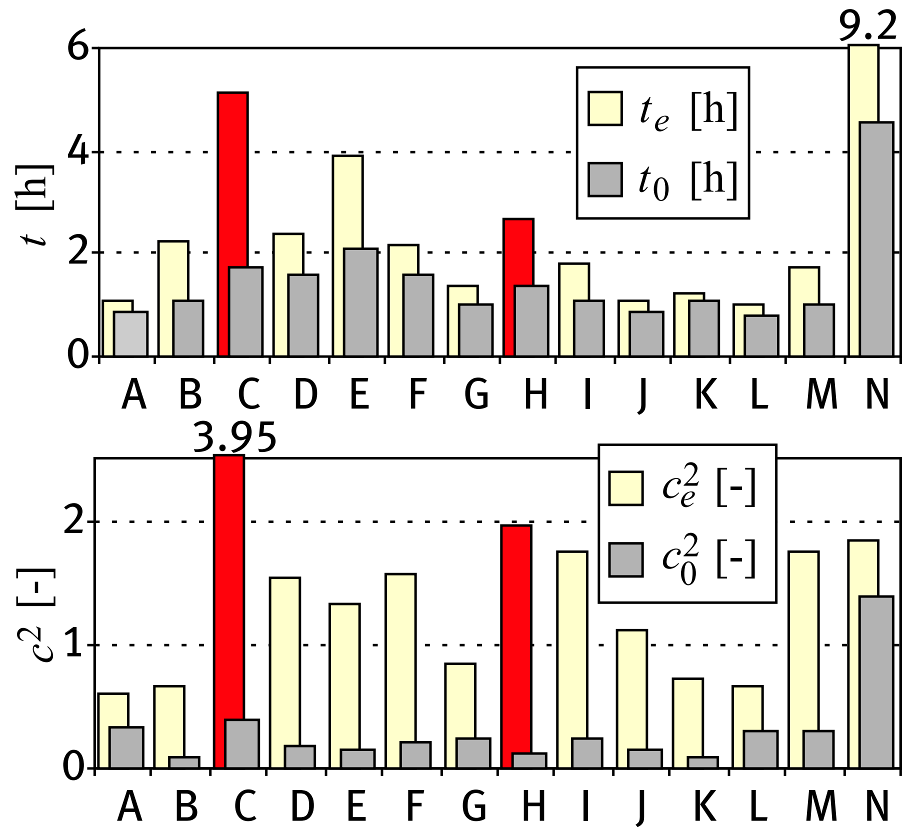

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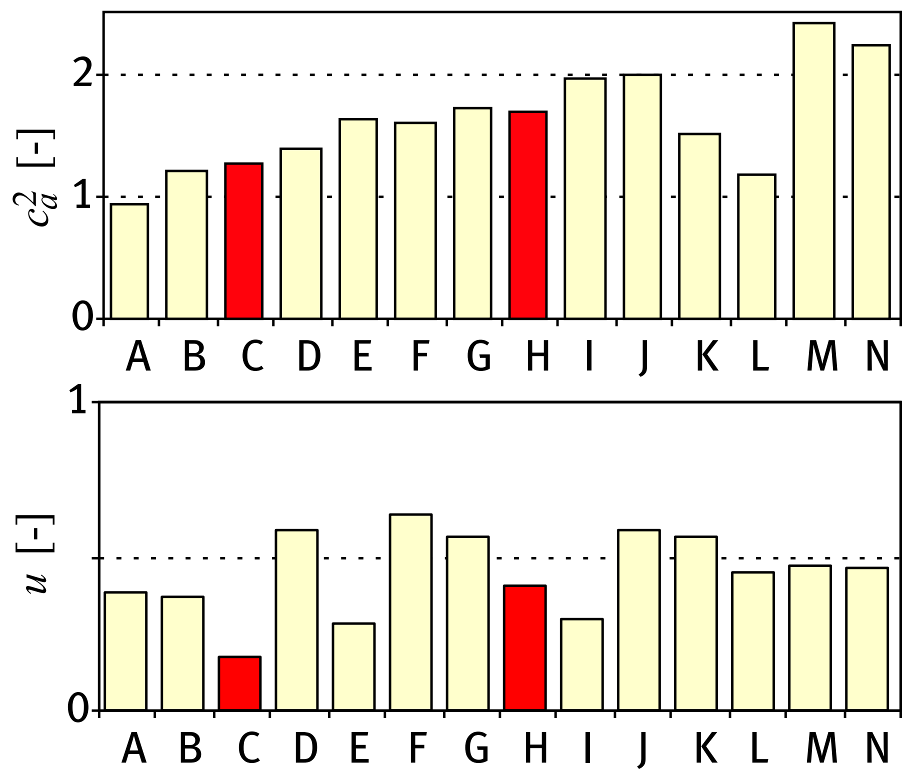

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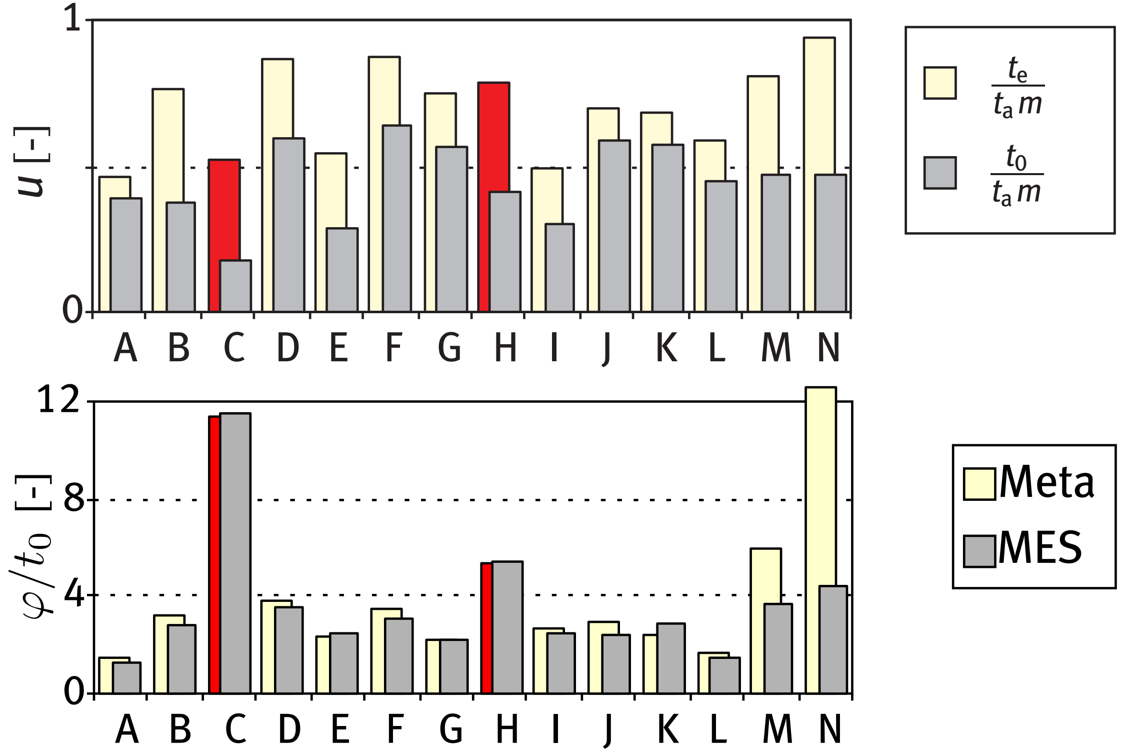

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Process algebra

Informal definition

- A system contains components.
- The components execute concurrently (in parallel).
- The components interact via channels, which support various data types.

Motivation

- When a component is defined as a process algebra component we can use theory and tools to design and execute concurrent and interacting components, as well as to rewrite to other formalisms.

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Atomic statements

p_{atom} ::=	skip		
	|	$\mathbf{x} := \mathbf{e}$	(multi-)assignment
	|	Δd	delay
	|	$h\,!\,\mathbf{e}$	delayable send
	|	$h\,?\,\mathbf{x}$	delayable receive
	|	$h\,!!\,\mathbf{e}$	send
	|	$h\,??\,\mathbf{x}$	receive

Compound statements

$p ::=$	p_{atom}	atomic
$\mid$	$p;\ p$	sequential composition
$\mid$	$b \to p$	guard operator
$\mid$	$p \talloblong p$	alternative composition
$\mid$	$p \parallel p$	parallel composition
$\mid$	$* p$	loop statement
$\mid$	$b \overset{*}{\to} p$	while statement
$\mid$	$\text{id}(\mathbf{e})$	process instantiation
$\mid$	$[\![\ \text{mode}\ X_1 = p_1$	mode definition
	$\vdots$	
	$,\ \text{mode}\ X_n = p_n$	
	$::\ X_i$	
	$]\!]$	

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Example, simple flow line

proc G(chan $a!$: real) $=$
$[\![$ var d : $\rightarrow$ real $=$ exponential(4.0), x : real, t : real
$::$ $*($ $a\,!\,$time; $t :=$ sample d; Δt $)$
$]\!]$

proc B(chan $a?, b!$: real) $=$
$[\![$ var *xs* : [real] $= []$, x : real
$::$ $*($ $a\,?\,x$; *xs* $:=$ *xs* $++[x]$
$[\!]$ len(*xs*) $> 0 \rightarrow b\,!\,$hd(*xs*); *xs* $:=$ tl(*xs*)
$)$
$]\!]$

proc M(chan $a?, b!$: real) $=$
$[\![$ var x : real $::$ $*($ $a\,?\,x$; $\Delta 3.0$; $b\,!\,x$ $)]\!]$

proc E(chan $a?$: real) $=$
$[\![$ var x : real $::$ $*($ $a\,?\,x$; !!time, "\t", x, "\n" $)]\!]$

model *GME*() $=$ $[\![$ chan a, b, c : real $::$ $G(a) \parallel B(a,b) \parallel M(b,c) \parallel E(c)$ $]\!]$

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Example, some machines M

Break-down

$$
\begin{array}{l}
\text{proc } M(\text{chan } a?, b!, l! : \text{void}) = \\
[\![\text{ var } t_\text{p}, t_\text{f}, t_\text{r} : \text{real} \\
:: [\![\text{ mode idle} \quad = (\ a\,?;\ \text{working}\ ) \\
\quad , \text{ mode working} = (\ \Delta t_\text{p};\ b\,!;\ \text{idle} \\
\qquad\qquad\qquad\qquad [\,]\ \Delta t_\text{f};\ l\,!;\ \text{down} \\
\qquad\qquad\qquad\qquad) \\
\quad , \text{ mode down} \quad = (\ \Delta t_\text{r};\ \text{idle}\ ) \\
\quad :: \text{ idle} \\
\quad]\!] \\
]\!]
\end{array}
$$

Assembly

$$
\begin{array}{l}
\text{proc } M(\text{chan } a?, b? : \text{item},\ c! : (\text{item}, \text{item})) = \\
[\![\text{ var } x, y : \text{item} :: *(\ (a\,?\,x \parallel b\,?\,y);\ \Delta 3.0;\ c\,!\,(x, y)\ )\ ]\!]
\end{array}
$$

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Automata

Informal definition

- A system is described by the set of states, transitions between states, and actions (events) that occur when in a state or when transitioning between states.
- The system can only be in one of the states at a given time.
- Transitions may be conditioned by (external) variables.

Motivation

- When a component is defined as an automaton we can use theory and tools to derive a correct and optimal controller.

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Automata

Automaton $A = (Q, \Sigma, \delta, q_0, Q_m)$ with

- Q — finite state set
- Σ — alphabet (finite set of event labels)
- δ — (partial) transition function, $\delta : Q \times \Sigma \to Q$
- q_0 — initial state
- Q_m — marker states, $Q_m \subseteq Q$

Supervisory control theory

- Σ_c — finite set of controllable event labels
- Σ_u — finite set of uncontrollable event labels
- partial observation
- ...

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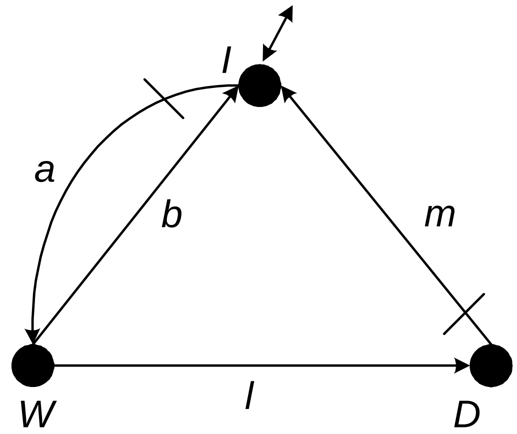
Example, machine with break-down

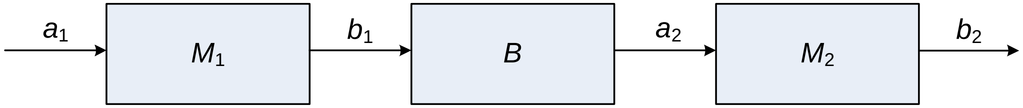


Automaton $M = (Q, \Sigma, \delta, q_0, Q_m)$ with

- $Q = \{I, W, D\}$ — State is Idle, Working or Down
- $\Sigma_c = \{a, m\} \quad \Sigma_u = \{b, l\}$
- δ: $\delta(I, a) = W$, $\delta(D, m) = I$, $\delta(W, b) = I$, $\delta(W, l) = D$
- $q_0 = I$
- $Q_m = \{I\}$

Example, simple flow-line

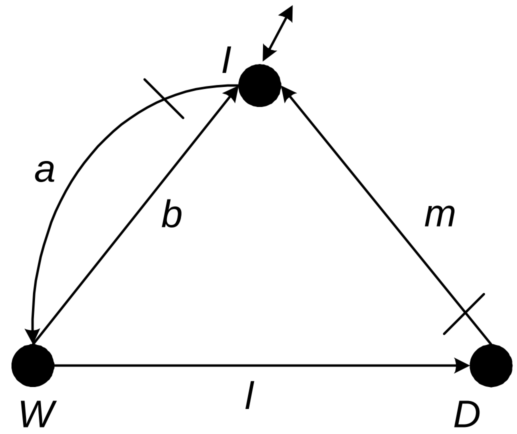
A manufacturing system consists of machine M_1, a one-place buffer B, and machine M_2, where both machines can break down.



Specifications

- Buffer B contains at most one product.
- When both machines break-down, M_2 must be repaired before M_1.

Example, model of machine M_1



Operation

1. (initially empty) takes item from an infinite input bin and enters state $W(a_1)$, go to 2
2. then either breaks down, enters $D(l)$ and on repair returns to $I(m_1)$, or completes its work cycle, deposits the item in the buffer and returns to $I(b_1)$, go to 1

Example, models of buffer B and machine M_2

Operation B

1. (initially empty) tries to receive an item from M_1, go to 2
2. tries to send an item to M_2, go to 1

Operation M_2

- (initially empty) operates similarly as M_1 but it takes an item from buffer B and after completion deposits the item in an infinite bin

Example, goal of simple flow line

We now have:

- An automaton for M_1.
- An automaton for B.
- An automaton for M_2.

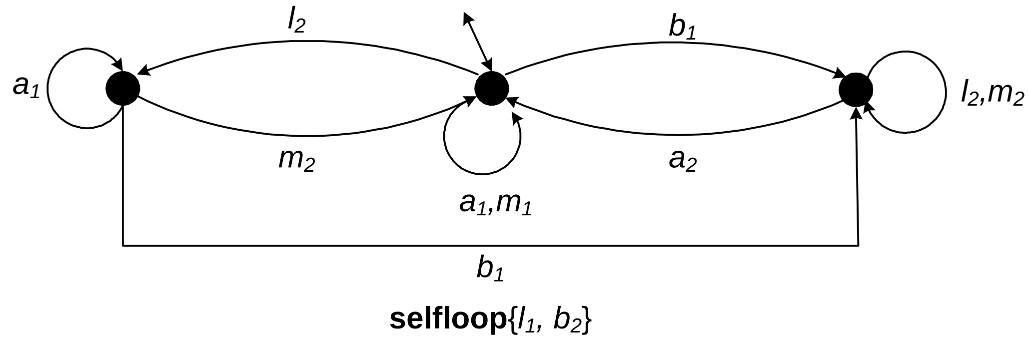
The goal is to derive a controller (supervisor automaton) that forces the system under control (flow-line) to satisfy its constrains (specifications).

Specifications

- Buffer B contains at most one product
- When both machines break-down, M_2 must be repaired before M_1.

Example, simple flow-line supervisor

The trimmed, parallel composition of the machines and the buffer results in the automaton of the supervisor. This automaton contains all flow-line trajectories (evolutionary path) that are admissible with respect to the specifications.



Obtaining optimal performance means that these trajectories have to be evaluated according to some performance criterion.

Case

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Epilogue

Simulation

- only one trajectory is executed
- for stochastic models not a drawback

Verification

- all trajectories are investigated
- for deterministic models required

Epilogue

We use, e.g.:

- analytical approximation models,
- process algebra models, and
- automata

to analyze deterministic and stochastic system in a timed-discrete-event and hybrid setting.

The models are used for throughput and flow-time analysis in factories (e.g. automotive, semiconductor), areas (e.g. body-shop, litho), cells (e.g. track-scanner, cluster machines), and machines (litho scanners, MRI-scanners). Recently we applied our knowledge for the verification of supervisors in cells and machines.

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