Scheduling of a real world filter production with lot-size 1

REGENSBURG

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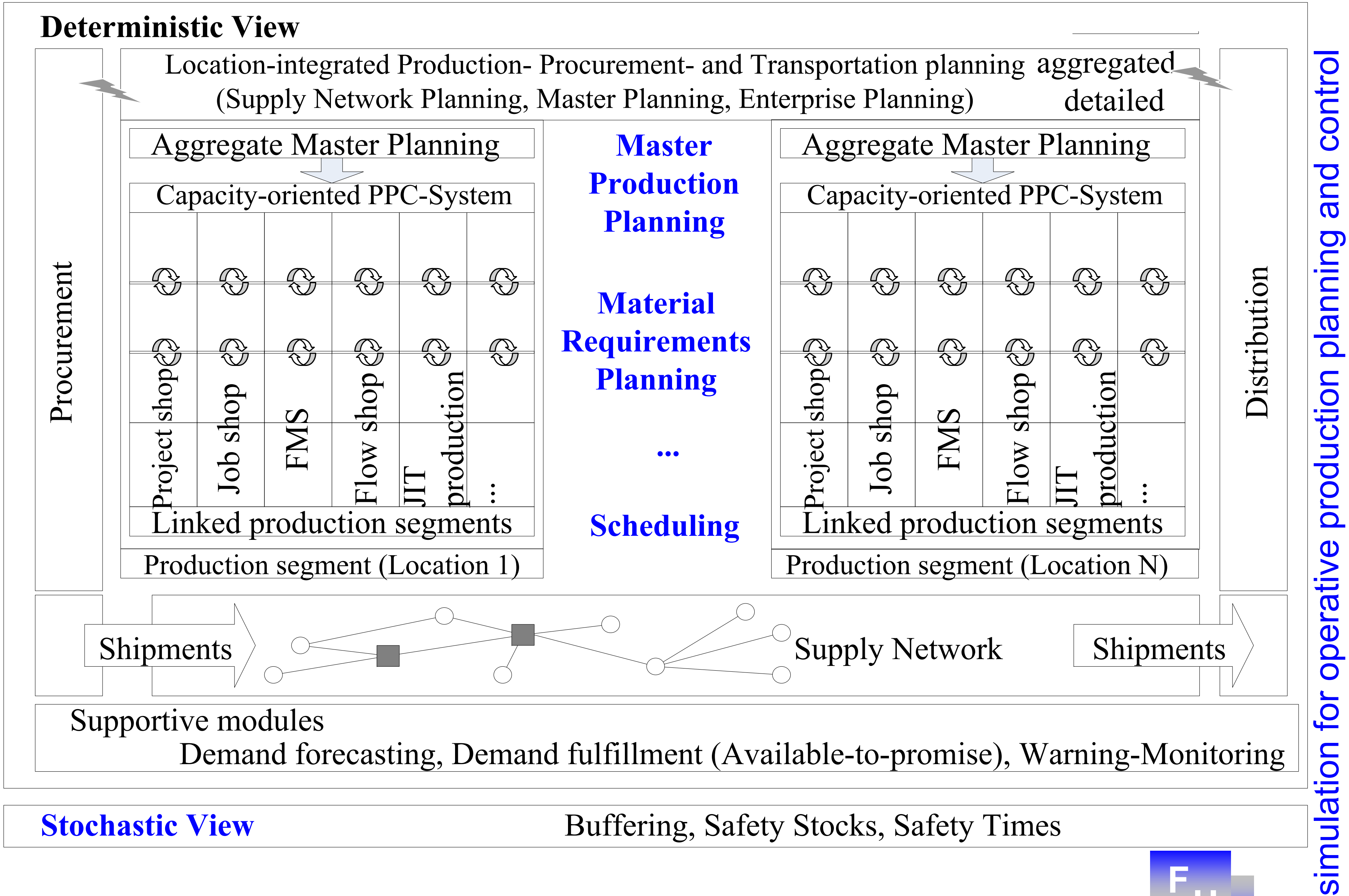
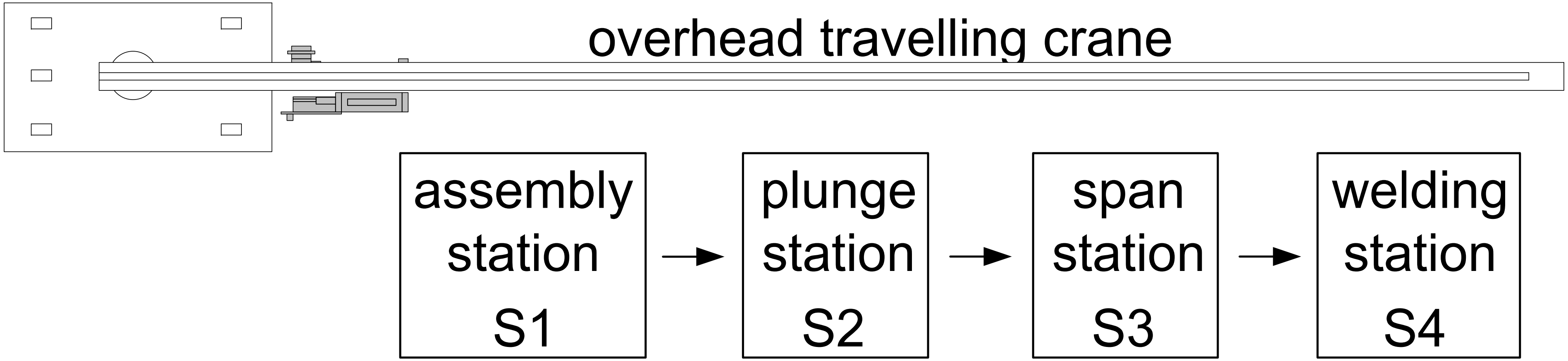
Professor Dr. Frank Herrmann – Curriculum Vitae

- born in Münster, Germany
- studied computer science at the RWTH Aachen University, Germany.
- at the Fraunhofer Institute IITB in Karlsruhe, Germany: worked primarily on algorithms for production control and received in this field a PhD.
- at SAP AG: several positions (Germany, Japan and USA), at the last as director.
- as a Professor for Production Logistics at the University of Applied Sciences in Regensburg, Germany: work mainly on planning algorithms, optimisation and simulation for operative production planning and control at companies.

Improvement of procedures and parameters for planning in ERP systems used in industrial practice



Real world application



Overhead travelling crane lifts a filter basket out of a station, transports it to the next station and **inserts it directly** in this station. This is just possible if this station is free.

- **No buffer** in the production line
- Feasible schedule of jobs is a **permutation** of these jobs.
- Other operational issues: **Move** of **crane** if all **stations** are **inactive**.
- No interruption of an operation: **transport after completion of all operations** - also for first and last operation. ⇒ **“load”-restriction**
- A **station** may be **empty**.

Routings for the real world application

Part type	Station 1	Station 2	Station 3	Station 4	Sum of times
P1	100.5 min.	50 min.	53.5 min.	9 min.	213 min.
P2	256.5 min.	50 min.	53.5 min.	9 min.	369 min.
P3	122 min.	135 min.	90 min.	75 min.	422 min.
P4	256.5 min.	50 min.	267 min.	9 min.	582.5 min.
P5	182 min.	200 min.	135.5 min.	140 min.	657.5 min.
P6	100.5 min.	300 min.	53.5 min.	300 min.	754 min.
P7	223 min.	250 min.	196 min.	220 min.	889 min.
P8	223 min.	250 min.	206.5 min.	220 min.	899.5 min.
P9	100.5 min.	300 min.	267 min.	300 min.	967.5 min.
P10	256.5 min.	300 min.	267 min.	300 min.	11235 min.

Set-up times and all other times, especially for load and unload, are **included in operation times** or **negligible**.

minutes (min.)

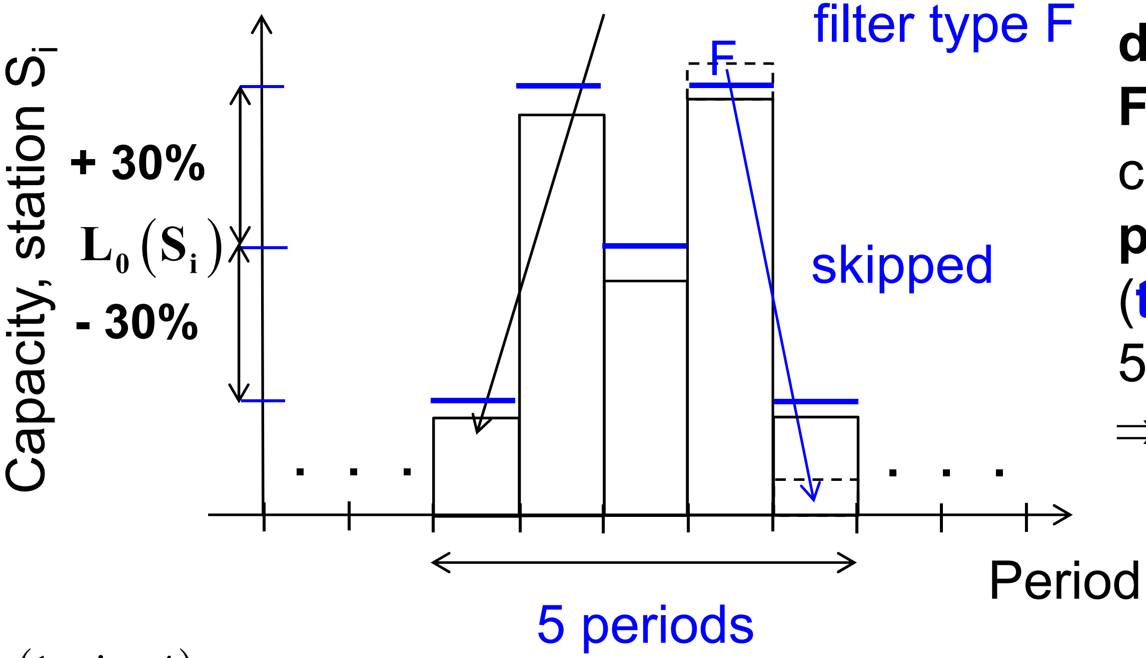
Orders / jobs

Reality

- Jobs comes from an SAP system for a period about seven days with three 8 hour shifts, released at the beginning of a period.
- Large numbers of periods with (very) high number of late jobs and numbers of periods with a low number of late jobs.

Investigation

Set of orders, randomly generated



$(1 \leq i \leq 4)$

Determination of **due dates**: **scheduling** with **FIFO rule** (first-in-first-out) causes a **specific percentage of late jobs** (**time pressure**) of 30%, 50%, 70% and 85%.

⇒ Due date – release date on average in [2 days, 3.5 days].

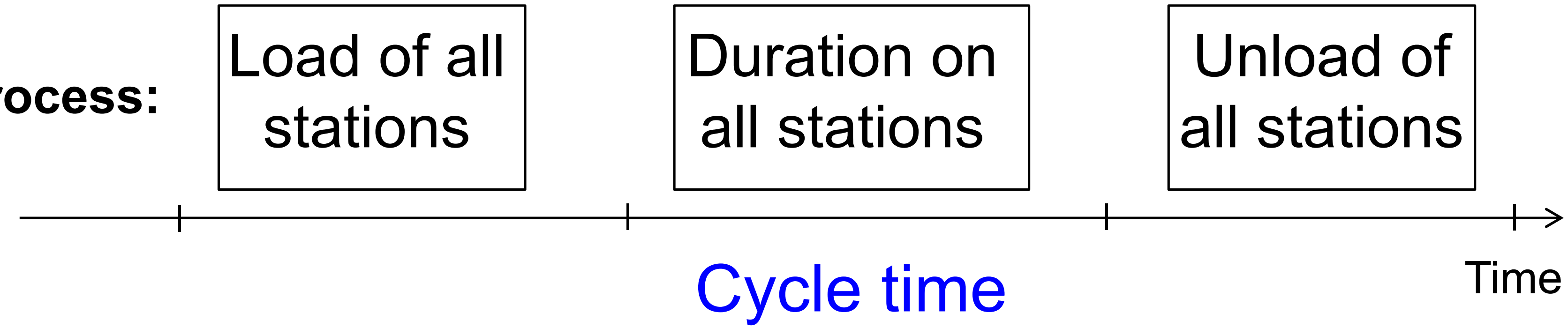
Parameters

- M stations,
- N jobs, which may change at any time,
- Release dates $a_i \ (1 \le i \le N)$,
- Due dates $f_i \ (1 \le i \le N)$ and
- Duration $t_{i,j}$ of operation j $(1 \le i \le M)$ of job i $(1 \le i \le N)$ on station j.

Performance criteria

- Tardiness $T_i = \max\{F_i - f_i, 0\}$ with F_i is the realized completion time.
- Average tardiness $\left(T_{Mean} = \frac{T_i}{N} \right)$ and
- Root mean square of tardiness $\left(T_{RMS} = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} T_i^2} \right)$ (similar to standard deviation)

Process:



Main restrictions:

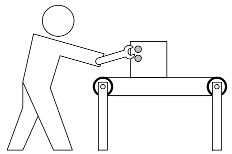
- This “load”-restriction.
- The no-buffer condition.
- The capacity of the stations.
- Relaxation of the “load”-restriction ⇒ no-buffer problem which is **NP-hard in the strong sense** for more than two stations.

Heuristic solution with priority rules

Priority (dispatching) rule

Sorted by criterion
(**earliest due date** (**EDD rule**))

A_2	A_7	A_9



Free

Occupy order
with highest priority

Priority rules **reacts on real time events** like **station failure**, **tool breakage**, **arrival of new jobs with high priority**, **changes of due dates** etc. immediately. **Used in real application**; priority rules in this investigation assigns an order in 1 milli-second.

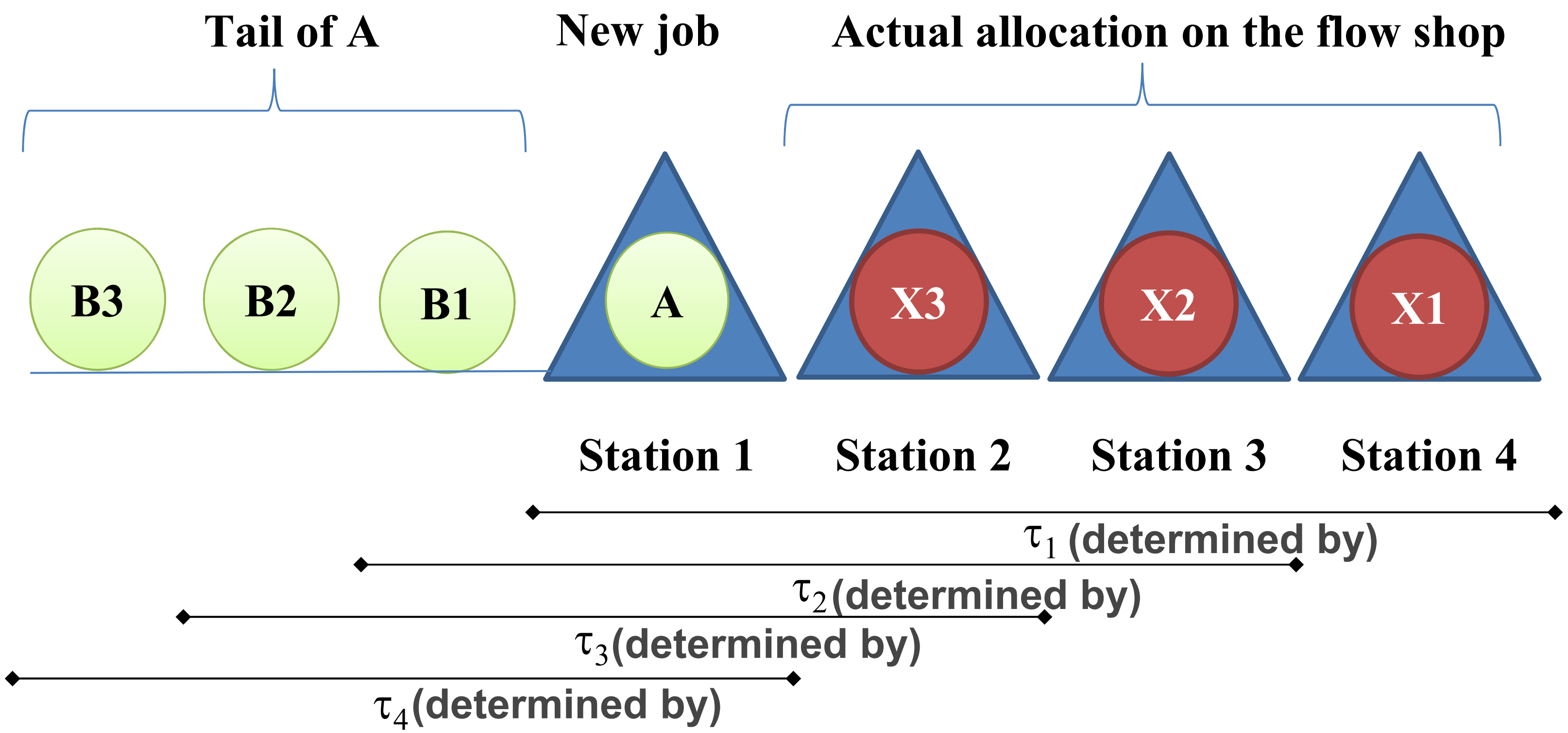
Scheduling with priority rules **still investigated**: see e.g. Rajendran and Holthaus (1999), Swaminathan et al. (2007), Rajendran and Alicke (2007), Mouelhi-Chibani and Pierreval (2010), Chiang and Fu (2009), El-Bouri (2012) or Chiang and Fu (2012).

Run time (hours) for **solving** the **optimisation model** is **too large for industrial application in real time**.

Simulation of processing times in priority rules

"Load"-restriction ⇒ processing time of job A significantly larger than sum of processing times of its single operations (**net processing time** (t_A)).

Processing of job A:



Cycle times $(\tau_1, \ldots, \tau_4)$ depend on the 3 jobs (X1, X2, and X3) on the flow shop, and the 3 jobs (B1, B2, and B3) will follow A in the sequence (**tail of A**). $\tau_1 + \tau_2 + \tau_3 + \tau_4$ is the (total) (**simulated**) **processing time** (tt_A) of A.

(Deviation of) **Tardiness** is **improved** by assigning **jobs with a small slack** $sl_i = f_i - t - tt_i$, with current time t.

Investigations by the author (see also Engell et al. (1994)) show: rules

$$\textbf{CR+SPT} = \begin{cases} \dfrac{f_i - t}{tt_i}, & f_i - t - tt_i > 0 \\ tt_i, & f_i - t - tt_i \le 0 \end{cases}$$

(tt_i is the shortest processing time (SPT) rule), **ODD** (here identical with the EDD-rule) and $\textbf{SL/OPN} = \dfrac{f_i - t - tt_i}{M}$

(a low value is always preferred) are **pareto optimal** to the **average**, the **variance** and the **maximum tardiness for many job shop problems**.

SL/OPN and **CR+SPT often** used as **benchmark**; Raghu and Rajendran (1993): other combinations deliver worse results for flow shop problems.

⇒ **Restriction to these pareto optimal rules; justified by some sample simulations.**

In addition: more recent rules are adapted to the class of problems regarded here. One is the rule **RR** of Raghu and Rajendran (1993) – **minimises** both **mean flow time** and **mean tardiness** of jobs; originally defined for job shop problems.

Adaption to flow shop problems:

- **remaining work content** is tt_i.
- **probable waiting time** of the **successor** of an **operation** (in job i) at the (**next**) **station** is integrated **in cycle times**; due to Rajendran and Holthaus (1999) this seems to be **less effective** in flow shops for **minimising mean flow time**.
- **utilisation level** of the entire flow shop $\eta = \frac{b}{b+j}$ with busy time b and idle time j of the entire flow shop.

Priority index is $\underbrace{(f_i - t - tt_i)}_{\text{slack } (sl_i)} \cdot e^{-\eta} + e^{\eta} \cdot tt_i$ (note: a low value is preferred).

Optimal solution for the **single-station weighted tardiness scheduling** problem $\Rightarrow$ Rachamadugu and Morton (1982): **weighted slack-based scheduling rule RM**. Analysis (Rachamadugu and Morton 1982): **near optimal** results to the **one station** problem can be assumed and modifications: very good for flow shop and job shop problems with weighted tardiness criteria (see (Vepsatainen and Morton 1987)). Rule successfully adapted to resource constrained project scheduling problems (RCPSP) in (Voß and Witt 2007) – following based on this.

Priority index is: $\frac{1}{\pi_i} \cdot e^{-\frac{k}{\bar{t}} \cdot \max\{f_i - t - tt_i, 0\}}$

with slack $f_i - t - tt_i$ as usual, k is an empirically determ8i7unined "look-ahead" parameter π_i are processing time costing, namely

local: $\pi_i^l = tt_i$ (RM local) and

global: $\pi_i^g = \sum_{i \in U_t} tt_i$, U_t set of unfinished jobs, excluding job i (RM global).

Computational results – Basic settings

Real world application is realised in the simulation tool “Plant Simulation” together with an implementation of the above mentioned hierarchical planning as realised in commercial ERP systems.

- products' distribution among routing

1	2	3	4	5	6	7	8	9	10
5%	5%	15%	15%	5%	10%	10%	15%	5%	15%

- Station with largest work load (i.e. bottleneck)

Station	1	2	3	4
	22%	31%	23%	24%

- Time-dependent course of work load on stations and urgency of jobs are identical (≈**stationary stochastically process**).

  ⇒ **performance criteria** reach a **steady state** by a **simulation horizon of 3000 periods** – without first / last 10 periods.

- Preliminary studies: parameter k has a significant impact on the performance of the local and the global **RM** rule and the **best** results are achieved with **k = 1**.

Impact of the simulated processing time 1/2

- Dependency from the (3) jobs on the flow shop and the (3) jobs following.

  ⇒ Independent from the priority rules and the time pressure.

- The rules prefer permutations of jobs in a cycle. Mean, the standard deviation, the minimum and the maximum of the simulated processing times for all part types and all rules are between those for the SPT rule and the SL; see following table.

Net processing time (NET) and simulated processing time in minutes for the rules SPT and SL 1/2

Part type	SPT				
	Mean	Net	Standard deviation	Minimum	Maximum
P1	1116.5	213	151.8	885	1349.5
P2	1159.8	369	100.45	1061	1349.5
P3	1088.6	422	138.1	929	1349.5
P4	1151.7	582.5	96.4	1061	1349.5
P5	1162.9	657.5	88.5	1063.5	1349.5
P6	1233.3	754	95.3	1098.5	1376
P7	1228.1	889	60.1	1164.5	1349.5
P8	1225.5	889.5	57.8	1164.5	1349.5
P9	1237.2	967.5	93.9	1098.5	1376
P10	1322.8	1123.5	27.9	1098.5	1376

Net processing time (NET) and simulated processing time in minutes for the rules SPT and SL 2/2

Part type	SL				
	Mean	Net	Standard deviation	Minimum	Maximum
P1	1179	213	126.5	885	1349.5
P2	1192.6	369	112.3	885	1349.5
P3	1179.3	422	118.1	885	1349.5
P4	1181.7	582.5	111.5	885	1349.5
P5	1184.6	657.5	106.5	885	1349.5
P6	1198.3	754	106.1	885	1376
P7	1203.8	889	101.7	885	1376
P8	1207.9	889.5	98.2	885	1376
P9	1215.9	967.5	98.1	885	1376
P10	1225.9	1123.5	97.5	885	1376

Impact of the simulated processing time 1/2

- Dependency from the (3) jobs on the flow shop and the (3) jobs following.

  ⇒ Independent from the priority rules and the time pressure.

- The rules prefer permutations of jobs in a cycle.

- **No best tail** for **each** priority **rule**: Study: tails of part types with similar net processing times and those with significantly different net processing times ⇒ **both significant and minor deviations** – not exceptions, deviation is almost one-third (or even more).
- **Best tail**: jobs of part type P4 only (i.e. P4, P4, P4); used in the following. Accidently tail is a very good alternative.

Impact of the simulated processing time 2/2

- Significant impact by the tail, listed values are representative for many tails. Exceptions: tail only consists of jobs with a small net processing time, e.g. P1, or a high one, e.g. P10.
  First case: small simulated processing times, e.g. 901.1 minutes for P1 and 1067.6 minutes for P10 .
  Second case: large mean values are large, e.g. 1248.5 minutes for P1 and 1269.2 minutes for P10.
  Standard deviations: huge in first case, e.g. for P1 173.1 minutes and for P10 187.6 minutes, and low in second case, e.g., P1 77.4 minutes and P10 61.3 minutes.
- Performance of a priority rule: influenced by concrete tail. Study: tails of part types with similar net processing times and those with significantly different net processing times ⇒ both significant and minor deviations – not exceptions, reduction is almost one-third (or even more).
- Best tail: jobs of part type P4 only (i.e. P4, P4, P4); used in the following. Accidently tail is a very good alternative.

Simulated versus net processing time

Change by using simulated processing time (a) instead of net processing time (b), compared to the result with net processing time; i.e. (b-a)/b*100%.

Rule	Time pressure			
T_{Mean}	30 %	50 %	70 %	85 %
SPT	57.6 %	10.3 %	12.3 %	25.8 %
SL	-41.2 %	-2.3 %	0.23 %	-17 %
CR+SPT	-4 %	-10.3 %	-7.4 %	8.9 %
RR	75.3 %	4.2 %	3.9 %	11.9 %
RM local	48.9 %	10.4 %	11.7 %	21.5 %
RM global	3.3 %	-10.9 %	-4 %	-5.8 %
T_{σ}	30%	50%	70%	85%
SPT	68.65 %	31.3 %	27.2 %	48.11 %
SL	-20.1 %	1.2 %	3.4 %	-19 %
CR+SPT	51.4 %	34.1 %	37.1 %	48.6 %
RR	69.8 %	14.3 %	14.4 %	23.6 %
RM local	68.3 %	-21.2 %	-25.5 %	-242.8 %
RM global	50 %	-10.1 %	10.4 %	67.9 %

Simulated versus net processing time 2/3

- SPT rule benefits most from a more realistic processing time.
- SL rule just small improvements but often significant deteriorations.

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- CR+SPT rule:
  - deteriorations for T_{Mean} due to CR (some kind of slack).
  - net processing time is much smaller than simulated processing time: CR+SPT rule with simulated processing time decides earlier according to SPT – explains **improvement**.

Simulated versus net processing time 1/3

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- RR and RM: combination of slack and SPT.
- RR rule benefits from a more precise processing time. Smaller than SPT rule due to already better values if net processing is used and the impact of slack; see time pressure of 85%.
- RR rule prefers critical jobs with positive slack much better than the SPT rule.

Simulated versus net processing time 2/3

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Simulated versus net processing time 3/3

- RR rule prefers critical jobs with positive slack much better than the SPT rule: see T_{Mean} in case of a small time pressure.

- RM rule prefers small jobs if there is no slack and otherwise jobs with small slack.
  ⇒ Changes: between those of the rules SL and CR+SPT – depending on the degree of influence of the slack on the priority confirmed for RM global.
- RM local: percental improvements for both criteria with small time pressure are comparable to the ones of the SPT rule.
  T_σ better processing time causes an increase of the (absolute) values on the level of the values of the SPT rule, except for a low time pressure.

Absolute performance measures for priority rules with simulated processing time 1/5

Rule	Time pressure			
T_{Mean}	30 %	50 %	70 %	85 %
SPT	99.1	323.3	326.2	646.9
SL	161.6	321.5	344.7	1149.8
CR+SPT	581.97	575.7	574.6	1032.7
RR	40.7	279.5	313.5	823.1
RM local	55.3	267.1	278.6	626.2
RM global	134.9	346.7	359.2	1008.5
T_{σ}	30%	50%	70%	85%
SPT	314.5	449.2	473.4	99.1
SL	353.4	315.3	326.6	161.6
CR+SPT	2023.9	916.4	901.2	1464.1
RR	125.1	282.8	305.7	564.6
RM local	235.9	425.8	454.1	1187.4
RM global	395.5	456.2	464.6	890.04

Values in minutes

Absolute performance measures for priority rules with simulated processing time 2/5

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Values in minutes.

- Differ partially from the results published in other papers – note: very special problem structure.
- Expectation: small T_{Mean} but large T_{σ} by SPT rule and opposite by SL rule – is fulfilled.
- CR+SPT rule outperforms SPT and the SL rule often – here much worse (1 exception).
  Reason: too late switch from pre-ferring small slack to small SPT.
  Compared to other rules:
  Misguided decision ⇒ long cycles.
  ⇒ more reduction remaining slack; cause long idle times.

Absolute performance measures for priority rules with simulated processing time 3/5

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T_{Mean}	30 %	50 %	70 %	85 %
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RR rules compared to (Rajendran and Holthaus 1999):
In (Rajendran and Holthaus 1999): RR rule delivers **better results** than other rules except for 1 case – improvements: less significant (partially much less) and sequences of rules according are different.

Reason: **Different work load**.

- **Rajendran and Holthaus** (1999): utilisation level of 80% and 95%.
- Here: **significant fluctuation of the load in periods – much higher / lower than 95% / 80%.**

⇒ **tighter due date has more significant effect**.

Absolute performance measures for priority rules with simulated processing time 3/5

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T_{Mean}	30 %	50 %	70 %	85 %
SPT	99.1	323.3	326.2	646.9
SL	161.6	321.5	344.7	1149.8
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RR	125.1	282.8	305.7	564.6
RM local	235.9	425.8	454.1	1187.4
RM global	395.5	456.2	464.6	890.04

Values in minutes.

Poor results of RM global compared with RM local (1 exception) contradicts results in (Lawrence et al. 1993) - same to investigation (Voß and Witt 2007).

- Local processing time costing prefers more often jobs with short processing times than the global processing time costing. Cause much better absolute results with time pressures: SPT rule delivers a much better T_{Mean} than to the SL.
- Other cases: RM local is beneficial if many tardy jobs are waiting in front of the production line.

Absolute performance measures for priority rules with simulated processing time 5/5

Rule	Time pressure			
T_{Mean}	30 %	50 %	70 %	85 %
SPT	99.1	323.3	326.2	646.9
SL	161.6	321.5	344.7	1149.8
CR+SPT	581.97	575.7	574.6	1032.7
RR	40.7	279.5	313.5	823.1
RM local	55.3	267.1	278.6	626.2
RM global	134.9	346.7	359.2	1008.5
T_{σ}	30%	50%	70%	85%
SPT	314.5	449.2	473.4	99.1
SL	353.4	315.3	326.6	161.6
CR+SPT	2023.9	916.4	901.2	1464.1
RR	125.1	282.8	305.7	564.6
RM local	235.9	425.8	454.1	1187.4
RM global	395.5	456.2	464.6	890.04

Values in minutes.

Sequence in the **performance criteria** of the priority rules are **in accordance to** the **results** shown in **many publications** (Lawrence and Morton (1993), Engell et al. (1994), Raghu and Rajendran (1993) as well as in Rajendran and Holthaus (1999)).

Differences of **results** of the rules:

- Flow shop problem in (Voß and Witt 2007) with parallel resources and setup states: **differences** are **smaller** than in this investigation.
- General problem structure in (Rajendran and Holthaus (1999) and Raghu and Rajendran (1993): **Differences** are **larger**.

Absolute performance measures for priority rules with simulated processing time 5/5

Rule	Time pressure			
T_{Mean}	30 %	50 %	70 %	85 %
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Values in minutes.

Overall:

- **Simulated processing times should** be **used** in **rules**.
- Then, **RR** and **RM local** deliver the **best mean tardiness**.
- **RR** is **beneficial** with **low** and **RM local** with (**very**) **high time pressure**.
- **RR** rule delivers the **best standard deviation** of the **tardiness** (for **all time pressures**).

Summary

- **Real world** flow shop scheduling problem with **specific restrictions**, which are **not covered** by **restrictions** in **standard classification**.

- **Simulated processing times should** be **used** in **rules**. Then, **RR** and **RM local** deliver the **best mean tardiness**.
  - **RR** is **beneficial** with **low** and **RM local** with (**very**) **high time pressure**.
  - **RR** rule delivers the **best standard deviation** of the **tardiness** (for **all time pressures**).

Future investigations

- Scheduling of workers.

- Limited resources - number of coils or assembly ground plates.

- Efficient improvement procedure – based on behaviour of priority rules.