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Applicability aspects of workload control in job shop production

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Chapter 5 Semi-interchangeable machines: implications for workload control

Submitted for publication in Production Planning and Control, with Martin Land and Gerard Gaalman as co-authors.

Abstract

Workload control (WLC) is developed as a production planning and control (PPC) concept for make-to-order job shops. Order release is an important instrument to control the workloads on the floor and to realise the performance objectives. The release of new orders to the shop floor is allowed as long as workload norms for capacity groups are not exceeded.

Effective WLC requires a profound decision regarding order release to allow balancing the workload across capacity groups, preventing a temporary overload of work at the machines. WLC design has to reflect the company characteristics, especially machine characteristics. In practice, machines that perform the same type of operations (e.g. boring, drilling, milling) are often semi-interchangeable. This means, that those machines are neither identical (i.e. completely interchangeable) nor totally different (i.e. non-interchangeable). The importance of the load balancing function within WLC requires careful consideration of semi-interchangeability.

This paper investigates and compares the implications of semi-interchangeable machines within a workload controlled make-to-order job shop. Different control alternatives are developed and tested in a simulation study. The control alternatives relate to: (a) the grouping of semi-interchangeable machines into capacity groups, and (b) the routing of orders across semi-interchangeable machines. We illustrate that the grouping choice cannot be seen independent of the selected routing mechanism and the degree of interchangeability.

The results of the simulation study indicate that the most intuitive control option – grouping semi-interchangeable machines into a single capacity group and making the routing decision at dispatching - does not give the best performance, despite the advantages of pooling synergy. Especially for a low degree of interchangeability another option is more attractive: placing semi-interchangeable machines in separate capacity groups and a routing decision at order release. This enables more detailed load balancing resulting in shorter throughput times. Remarkably, it is shown that even postponing the final routing decision until dispatching and considering separate capacity groups for a preliminary routing decision at the time of release is generally advantageous.

Table 5.2 Job shop characteristics

Number of machines:	7 (Machine 1A, 1B, 2, 3, 4, 5, and 6)
Number of different operations types	6 (Machine 1 A and 1B perform the same type of operations)
Operations per order:	Discrete uniformly distributed [1,6]
Routeing sequence:	Random, no return visits (pure job shop)
Inter-arrival time:	Negative exponentially distributed
Operation processing time:	2-Erlang distributed
Machine 1A and 1B	Mean: 2 time units
Machine 2 to 6	Mean: 1 time unit
Steady state utilisation	90% (at each machine)

The simulated shop consists of seven machines that can perform six types of operations. Machine 1A and machine 1B perform the same type of operation and are semi-interchangeable. The 5 remaining machines (2 to 6) are related to a specific type of operation and non-interchangeable. Routeing length varies between 1 and 6 according to a discrete uniform distribution, with equal probabilities for each operation type to occur. To create a balanced job shop, the steady state utilisation of all machines is set equal to 90%.

Figure 5.4 shows a rough sketch of the simulated production environment. Orders that arrive at the production system are collected in a so-called order pool before they are considered periodically (every 5 time units) for release to the shop.

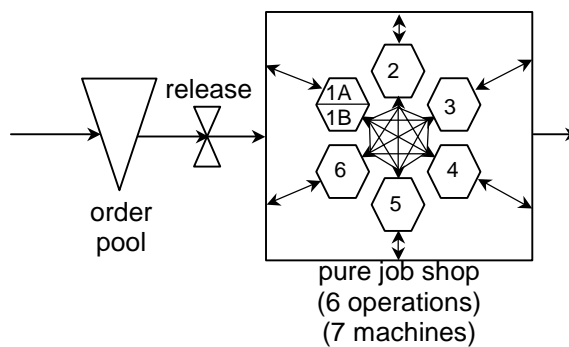


Figure 5.4 Simulated production environment

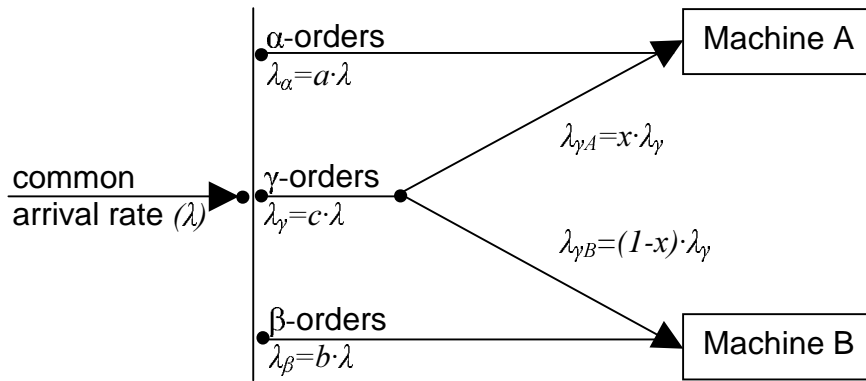
The selection process goes on until all orders in the pool have been considered. An order is released if the workload of each operation does not exceed the workload norm of the related capacity group. The workload calculation is based on the WLC approach using 'corrected aggregate loads' developed by Land and Gaalman (1996A).

In practice, semi-interchangeable machines can often be found when new machines have been bought while older (already depreciated) machines have remained in use. The new and old machines may be able to handle partly overlapping and partly non-overlapping product ranges. Typical reasons are: (a) the fact that technological developments make it impossible to buy exactly the same machines as earlier; (b) the decision to increase the range of products, while technological characteristics make alternative machines necessary; (c) different (e.g. more automated or faster) machines become necessary because of a growth in product volume.

For similar reasons semi-interchangeable machines may also differ with respect to operational characteristics like operation processing times, set ups, operator requirements, or the environmental influences like noise or waste. In order to keep the transparency, this paper focuses on an elementary shop floor situation, considering semi-interchangeable machines that are equal with respect to the operational characteristics.

Modelling semi-interchangeable machines

Semi-interchangeability only becomes important if there is any demand for all product ranges - the overlapping and the non-overlapping ones. This is shown in Figure 5.2 by modelling the stream of orders arriving for two machines, A and B. λ is the arrival rate of all orders that have to be operated on machine A or B. This order stream is subdivided into the stream of α -, β -, and γ -orders. α -orders can only be operated on machine A, β -orders only on machine B, and γ -orders on both machines A and B. The relative sizes of the order streams depend on the technical possibility to produce different product ranges. And they depend on the demand for different products. The fraction of orders that can be operated on both machines is called the degree of interchangeability. It is indicated by c in Figure 5.2. While the streams of α -, β -, and γ -orders result from external demand for products within the distinct product ranges, the fractions x and $(1-x)$ of γ -orders that are respectively sent to machine A and B result from a control decision within the company.



constraints:
 $a+b+c=1$
 $0 \leq x \leq 1$

Figure 5.2 Arriving orders at two semi-interchangeable machines A and B

Notice that $c=0$ and $c=1$ represents respectively non-interchangeability and full interchangeability. All of the following semi-interchangeability situations can be found in practice:

- 1) *Specialization* $\rightarrow a > 0, b > 0, c > 0$: Machine A is specialized to produce α -orders, machine B is specialized to produce β -orders. Some orders (γ -orders) can be produced on both machines.
- 2) *Dominance* $\rightarrow a > 0, b = 0, c > 0$: No orders can be produced exclusively on machine B.

Essentially, the degree of interchangeability c and the relative sizes of a and b are necessary to model the semi-interchangeability of the two machines A and B. Considering more machines would successively lead to a multi-dimensional approach with more alternatives.

The order release function within WLC

The WLC concept has to consider the characteristics of semi-interchangeable machines to realise the pre-set company objectives (e.g. predictable and short throughput times). The decision to release orders to the shop floor is important in realizing these objectives within the WLC concept (Henrich et al. 2004B)[⊗]:

[⊗] Chapter 2.

Before orders are allowed to enter the shop floor they are collected in a so-called order pool. The decision to release orders from the pool to the shop, centrally taken, aims at load balancing, besides considering the urgency of jobs. Therefore, order release requires a view of the shop floor situation. This view is realized by depicting the workloads per capacity group as shown in Figure 5.3. Most workload definitions count up the processing times of orders waiting in front of a capacity group (direct load) and those of orders upstream (indirect load). For each capacity group a workload and a norm level is defined. This holds both for capacity groups containing a single machine and for capacity groups that are based on a group of machines. The workload norm (expressed in time units) should guarantee a small but stable buffer of work in front of the machines within the capacity groups. Orders are released as long as their release will not exceed any workload norm. Otherwise the order will have to wait in the pool until the next release opportunity. After this procedure is completed, selected orders are sent to the capacity groups performing the first operation and remain on the shop floor until all operations have been finished. For a more detailed description of the order release mechanism see Land and Gaalman (1998).

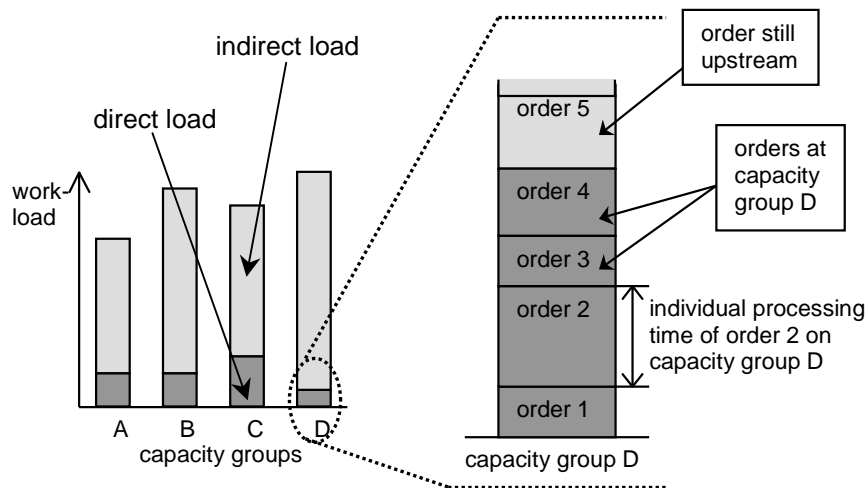


Figure 5.3 Calculating workloads per capacity group

Control alternatives and expected shop performance

The functioning of the above described release function will be influenced by the semi-interchangeability of the machines forming capacity groups. Consider two semi-interchangeable machines A and B (as defined in the Figures 5.1 and 5.2), there are two alternatives for capacity group formation: (a) each machine (A and B) is an independent capacity group with its own workload and workload norm (i.e. non-grouping); (b) the machines are grouped into one (common) capacity group, with a single workload norm for both machines at order release (i.e. grouping).

Additionally, for all γ -orders (see Figure 5.2) an individual routing decision has to be taken. Taking a routing decision means to decide whether a γ -order is operated on either machine A or B. These individual routing decisions lead to the fraction x of γ -orders that are sent to machine A, and the fraction $(1-x)$ that are sent to machine B (see Figure 5.2). In this paper we refer to two alternative positions within the order flow to take a routing decision: (a) the routing decision is taken at the order release, or (b) the routing decision is taken at the time of the dispatching (in front of the machines A and B).

The grouping decision cannot be seen independently from the routing decision for semi-interchangeable machines (Table 5.1) as both may affect the functioning of order release. As described above, the release procedure has a timing and a load balancing function (Land, 2004A/2004B). Centrally balancing the loads, by fitting the orders from the pool into workload norms, aims at smoothing the inflow of work at the individual machines on the floor and at realising shorter and stable throughput times per machine. The different control alternatives that result by combining routing and grouping decision may affect, especially, the balancing function of the order release mechanism. The balancing of load (i.e. determining the release moment of each individual order) depends on the grouping decision of machine A and B, since distinguishing two capacity groups allows for a more detailed shop floor view and a more stable load for each of the machines than e.g. grouping machine A and B. Allowing a routing decision for γ -orders at release may further support the balancing function of the order release.

Table 5.1 Control alternatives by combining routing and grouping decisions

		Grouping decision	
		1 capacity group (1 norm)	2 capacity groups (2 norms)
Routing decision	At order release	(I)	(III)
	At dispatching	(II)	(IV)

Table 5.1 shows four grouping and routing alternatives for two semi-interchangeable machines. These four alternatives have different implications for shop floor control and performance. These are interpreted from the results of Henrich et al. (2004A):

- (I) *Routing decision at order release/Grouping (1 capacity group)*: To take a well-considered routing decision at order release it is necessary to have workload information for the individual machines A and B. By grouping the machines A and B into a single capacity group such detailed load overview is not facilitated. In addition, the possibility to balance at release, i.e. smoothing the inflow of work per individual machine is weakened: A single workload norm for two machines may lead to a temporary over- or underload for one of the machines. The common workload norm may be filled with orders for machine A only, while machine B becomes idle, or vice versa. Earlier research (Henrich et al. 2004A) showed that this combination of grouping and routing decision leads to unacceptable performance losses relative to alternative (II) and (III). Therefore we do not consider this control alternative of being relevant in this study.
- (II) *Routing decision at dispatching/Grouping (1 capacity group)*: Similar to the above described control alternative (I) the load balancing possibilities are weak: It is possible to release too much α -orders, and respectively too little β -orders. However, by postponing the routing decision for γ -orders a temporary overload or underload of the machines can be avoided. The routing decision is taken on the floor: all orders are collected in a common queue in front of the semi-interchangeable machines, so that each machine that becomes available starts processing the first suitable order waiting in the queue (e.g. sequenced by the first-come first-serve (FCFS) rule). Such an approach may have a favourable effect on waiting times, because it prevents γ -orders from waiting in front of machine A while machine B is idle, and vice versa. This effect is called pooling synergy and should be strongest with a larger fraction of γ -orders. This control alternative can be described as the most intuitive approach: First, while grouping the semi-interchangeable machines A and B into a single capacity group a limited set of workloads and workload norms have to be considered. This enables a simple release decision, i.e. less information requirements. Second, the routing decision is postponed to the time of dispatching, and thus under the responsibility of the operators on the floor. Third, a common queue may lead to pooling synergy.
- (III) *Routing decision at order release/Non-grouping (2 capacity groups)*: In contrast to the two control alternatives described above, this alternative allows detailed balancing of workloads across machines, as a separate workload norm per machine is defined. In addition, a routing decision at release can be based on the actual workload per machine. Earlier research showed that the so-called largest-load-gap-first routing decision rule (LLGF-rule) performs well: It tries to allocate the orders to machines with the least workload, i.e. the largest gap in between actual workload and workload norm. By taking the routing decision at

order release, all γ -orders are converted into α - or β -orders before entering the floor. This control alternative can be seen as the most centralised one, as the routing decision is combined with the centrally performed release decision. This combination makes it easier to select a set of orders that obeys the workload norms and supports balancing of workload across machines. It is expected that this may only require a limited degree of interchangeability.

(IV) *Routing decision at dispatching/Non-grouping (2 capacity groups)*: This control alternative is quite similar to control alternative (III). To balance the workloads across the machines A and B, the workloads of the α -, β -, and γ -orders have to be fitted into the respective workload norms at the time of order release. Therefore, each γ -order has to be assigned preliminary to a capacity group (e.g. by the LLGF-rule). The difference with alternative (III) arises, as the final routing decision is done at dispatching. In fact the order routing chosen at release can be reconsidered. With a lower degree of interchangeability combined with low levels of workload, this control alternative will be comparable to alternative (III), because the additional routing decision at dispatching (on the floor) might be of minor influence, as only a few orders can be produced on more than one machine. For a higher degree of interchangeability the balancing possibilities at release are combined with the pooling synergy effects on the floor. How this affects the performance is yet unknown.

In the next section a simulation study is described to investigate the considerations above.

5.3 Simulation Study

The previous section has shown that the grouping decision for semi-interchangeable machines, the routing decision for γ -orders, and the degree of interchangeability are expected to influence the functioning of the WLC concept, especially the order release. To investigate the effects of the different alternatives discussed in Section 5.2 we set up a simulation study. Since these alternatives mainly influence the balancing qualities of release we compare the resulting total throughput times, which is the best for reflecting balancing performance.

The simulation model is an extension of an earlier model by Henrich et al. (2004A). An overview of the job shop characteristics is given in Table 5.2.

In this approach the load contribution of the order is not the full operation time, but corrected by depreciating it with a factor $1/n$ with n being the serial number of the operation within the routing. Oosterman et al. (2000) show that this WLC approach is more suited for pure job shops than using ‘uncorrected aggregate loads’.

Table 5.3 Experimental settings

Experimental variables	Levels	
(1) Grouping decision	Grouping (1 capacity group/1 norm)	Non-grouping (2 capacity groups/2 norms)
(2) Routeing decision	At order release: LLGF-rule	At dispatching: FCFS-rule (with common queue)
(3) Degree of interchangeability	$c \in \{0, 0.025, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.5, 1\}$	
(4) Workload norm (WLN)	Stepwise down from infinity	

We distinguish four experimental variables (see Table 5.3). The first three variables (1) *grouping decision*, (2) *routeing decision*, and (3) *degree of interchangeability*, are directly related to the two semi-interchangeable machines 1A and 1B. The fourth variable (4) *workload norm (WLN)* affects all machines on the floor:

- (1) The *grouping decision* relates to the semi-interchangeable machines 1A and 1B. Two alternatives are considered: (a) Both machines are grouped into a single capacity group; a single workload norm is used for both machines. (b) The machines 1A and 1B are considered to be a single capacity group each (non-grouping) with individual workload norms.
- (2) Two different kinds of *routeing decisions* for γ -orders are considered: (a) The routeing decision is made at order release according to the largest-load-gap-first (LLGF) rule. (b) The routeing decision is made at dispatching with a first-come first-serve (FCFS) selection from the common queue of the two machines.
- (3) The machines 1A and 1B are semi-interchangeable. The *degree of interchangeability* c is used as experimental variable taking levels between 0 and 1. An increase in c leads to a simultaneous decrease in a and b , and vice versa (see Figure 5.2). To keep the job shop balanced the fraction of α - and β -orders is varied according the following relationship: $a=b=(1-c)/2$, and $a+b+c=1$.
- (4) The *workload norm* level is varied, going stepwise down from infinity. For each capacity group an individual workload norm level has to be derived. In this study

they are related by fixed ratios. These ratios are determined in several pre runs. This allows the workload norm levels to be set as a single experimental variable.

As the combination of ‘grouping machine 1A and 1B’ with a ‘routeing decision at order release’ is of little relevance, this combination is not considered.

For each experiment 100 independent replications are performed. The replication length is 13000 time units, with observations from the first 3000 time units being deleted to avoid start-up effects. Common random numbers are used as a variance reduction technique across all experiments (see e.g. Law and Kelton 2000). The simulation model is built in *eM-Plant* (Tecnomatix 2001).

5.4 Results and Analysis

The simulation study helps us to compare the different combinations of routeing- and grouping alternatives for semi-interchangeable machines, as presented in Table 5.1. The design of the simulation study (Section 5.3) leads to four sets of experiments (I to IV), from which three have been tested extensively (see Table 5.4). These results are presented in the Figures 5.5 to 5.7, wherein each tested degree of interchangeability (*c*-value) leads to a separate performance curve.

Table 5.4 Presentation of the simulation results in figures

Routeing decision \ Grouping decision	1 capacity group (1 norm)	2 capacity groups (2 norms)
At order release	(I) Not relevant	(III) Figure 5.6
At dispatching	(II) Figure 5.5	(IV) Figure 5.7

First we give an overview of the simulation results (Figures 5.5 to 5.7). Here, the representation method and the used performance criteria are presented. Later, the simulation results are discussed to enable a well-considered choice in between the different control alternatives.

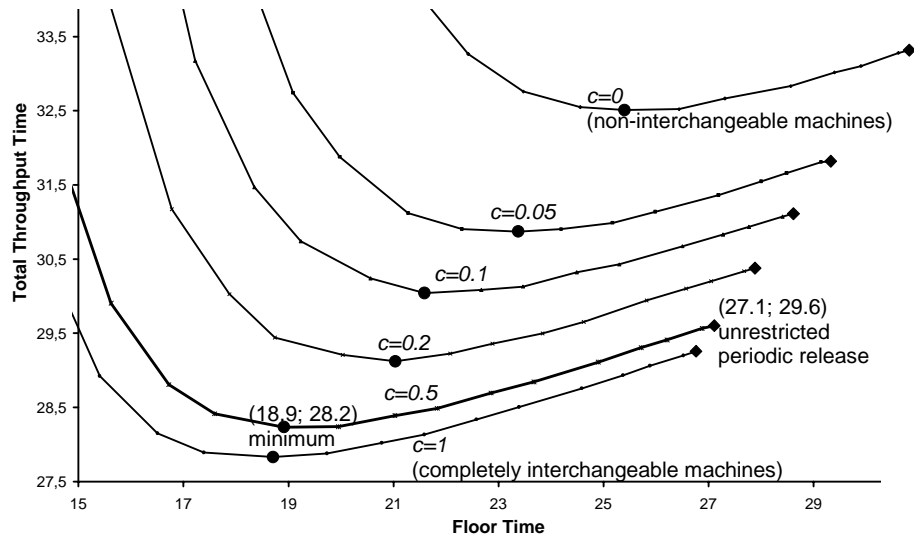


Figure 5.5 Performance curves based on 'Routeing at dispatching/Grouping (1 capacity group)' (II)

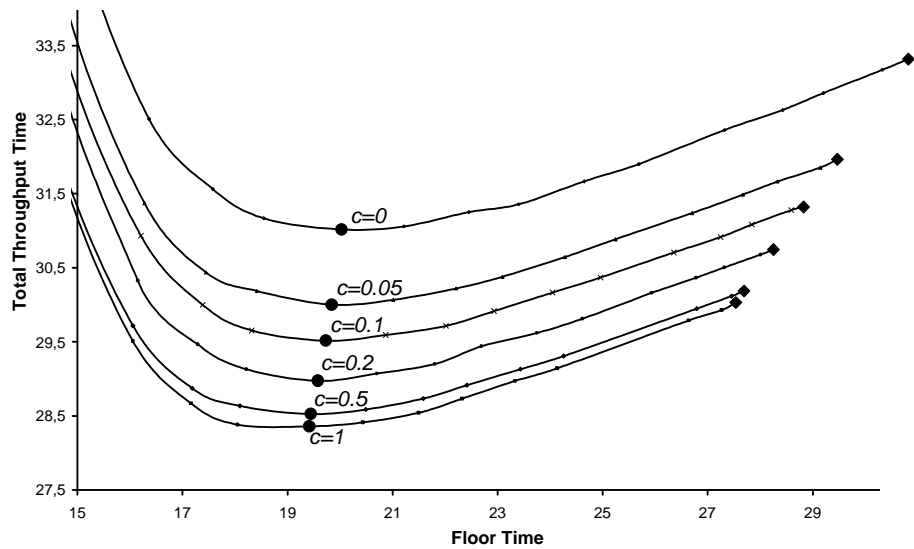


Figure 5.6 Performance curves based on 'Routeing at order release/Non-grouping (2 capacity groups)' (III)

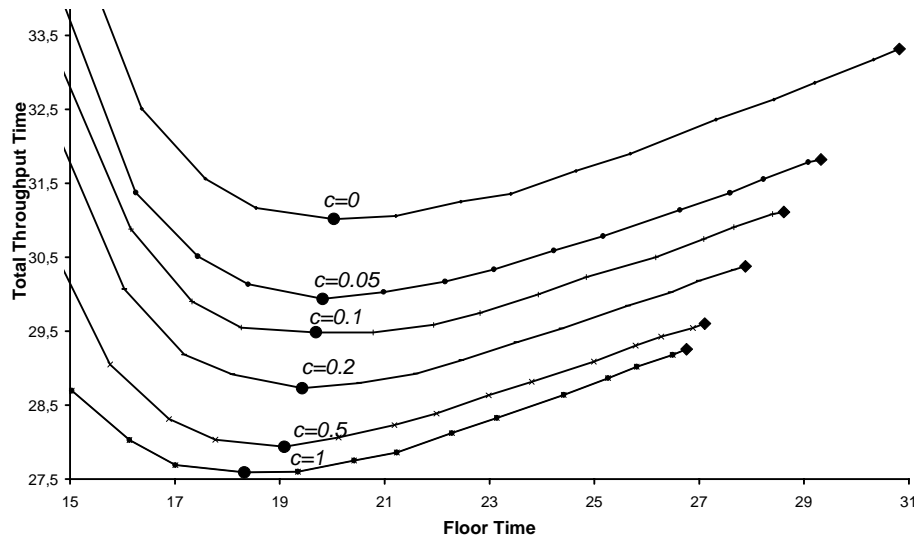


Figure 5.7 Performance curves based on 'Routeing at dispatching/Non-grouping (2 capacity groups)' (IV)

The presentation method used to depict the simulation outcomes in the Figures 5.5 to 5.7 is similar to that used in earlier research (e.g. Oosterman et al. 2000). The curves are the performance curves. The horizontal axis shows the average time an order stays on the shop floor (floor time): it is the time in between order release and order completion. It is used as an instrumental variable to indicate the tightness of workload norms (WLN). The vertical axis shows the average total throughput time. To determine total throughput time, the pool waiting time (i.e. the time an order is waiting in the order pool) is added to the floor time. Thus, total throughput time performance is indicated for different levels of norm tightness.

Let us describe the second curve from below in Figure 5.5 in detail for a better understanding: This performance curve is based on grouping the machine 1A and 1B while taking the routeing decision at dispatching. It is based on $c=0.5$. This means that 50% of all arriving orders are γ -orders. According to the experimental settings, respectively 25% of the orders that arrive for machine A and B are α -orders, and 25% are β -orders. The curve has its right-hand end point at (27.1; 29.6), depicted by a rhombus. This is the point using 'infinite' norms, resulting in an unrestricted periodic release. The average total throughput time is 2.5 time units longer than the floor time; exactly halve the length of a release period. The different workload norm levels, going stepwise down from infinity, are depicted as points connected by lines to construct the performance curve. Narrowing the norm results in a point more to the left, i.e. a shorter average floor time. The shortest measured total throughput time of

28.2 time units, realised at a floor time of 18.9 time units, is indicated on the curve as a minimum (circle). Decreasing the workload norm level even more (i.e. left from the minimum) leads to a trade off: floor time decreases, but at the costs of increasing total throughput time, which is the result of more than proportionally increasing pool waiting times.

The performance curves in the Figures 5.5 to 5.7 are based on different degrees of interchangeability. Going down from top to bottom, the curves are based on the c -values 0, 0.05, 0.1, 0.2, 0.5, and 1, respectively. To keep the figures clear, not all intermediate c -values, as summed up in Table 5.2, are depicted. Obviously a higher degree of interchangeability always improves overall performance. Already a small c -value ($c=0.05$) leads to a relatively large performance improvement in comparison to non-interchangeable machines ($c=0$). A further increase in interchangeability leads to a marginal improvement of overall performance. For instance the distance between the curves for $c=0.5$ and $c=1$ is smaller than for the curves for $c=0$ and $c=0.05$. However, the distances strongly differ among the control alternatives, which means that not all control alternatives are equally sensitive to the degree of interchangeability. Particularly the performance curves of the control alternative based on grouping semi-interchangeable machines into a single capacity group (Figure 5.5) are sensitive to the degree of interchangeability: With non-interchangeable machines ($c=0$), it is only possible to realise relatively large average total throughput times, larger c -values lead to a strong decrease in average total throughput times. The performance outcomes of the other two tested control alternatives (Figures 5.6 and 5.7) are less sensitive to the degree of interchangeability.

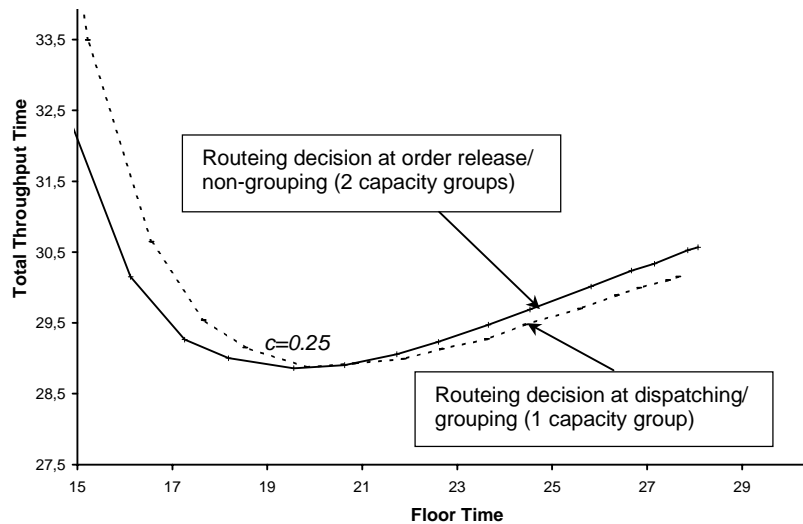


Figure 5.8 Comparison of two performance curves at $c=0.25$

The different control alternatives as depicted by the performance curves in the Figures 5.5 to 5.7 notably differ in sensitivity towards the degree of interchangeability, but also towards the tightness of workload norms. To facilitate a discussion of the latter aspect we have to compare performance curves with equal degrees of interchangeability. This is done in Figure 5.8. The performance curves for two alternatives and a value of $c=0.25$ are shown. The solid curve is based on a routeing decision at order release combined with non-grouping, the dotted one on a routeing decision at dispatching combined with grouping. The two performance curves cross each other. With looser norms (i.e. on the right part of the curve) the dotted curve (grouping) outperforms the solid curve (non-grouping), with tighter norms it is the other way around. This shows that at this degree of interchangeability the selection of the right control alternatives depends on the chosen workload norm level (WLN), as well.

Comparing all control alternatives for each degree of interchangeability one-by-one is possible but not shown. Instead we focus on the comparison of two points: (1) The point of 'unrestricted periodic release' (depicted as rhombus in the Figures 5.5 to 5.7); this can be seen as a reference scenario where all arriving orders will be released immediately to the floor, representing the uncontrolled situation. (2) The 'minimum point' of each curve (depicted as circle); it depicts the minimum simulated total throughput time resulting from an appropriate workload norm level (WLN) choice, representing the (workload) controlled situation.

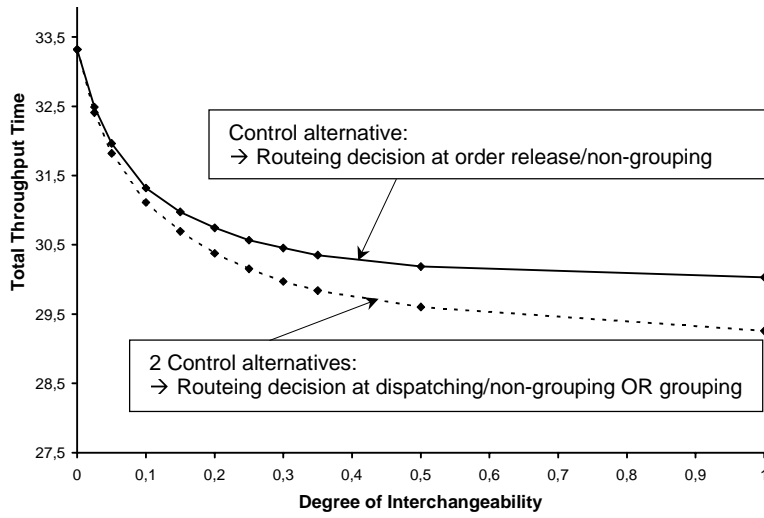


Figure 5.9 Total throughput time at unrestricted periodic release at different degrees of interchangeability (based on the Figures 5.5 to 5.7)

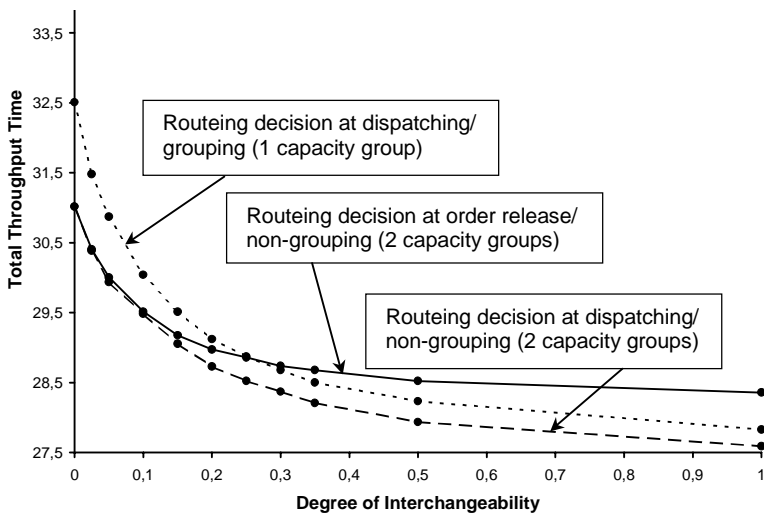


Figure 5.10 Minimum total throughput time at different degrees of interchangeability (based on the Figures 5.5 to 5.7)

The comparisons are visualised by the Figures 5.9 and 5.10 respectively. The Figures 5.9 and 5.10 relate the different degrees of interchangeability on the x-axis to the average total throughput time on the y-axis. The solid curve links all those points as depicted in Figure 5.6 that are based on 'routeing decision at order release/non-grouping'. The dotted curve is based on Figure 5.5 (routeing decision at dispatching level/grouping), and the dashed curve on Figure 5.7 (routeing decision at dispatching/non-grouping). In Figure 5.9 the last two curves are equal, because the grouping/non-grouping decision has no influence on total throughput time for unrestricted release: all orders are released immediately, independent of the grouping choice and the related workload norm(s).

In both curves of Figure 5.9 (unrestricted release) an increase in the degree of interchangeability leads to a decrease in total throughput time as already observed from the Figures 5.5 to 5.7, this means that both tested routeing decisions show a better performance with a larger fraction of interchangeable orders. Both curves start on the left hand side at the same total throughput time, because with non-interchangeable machines ($c=0$) for none of the orders a routeing decision has to be taken. Moving from left to right the dotted curve outperforms the solid one. The distance in between the both curves must result from the differences in routeing decision. The lower (dotted) curve is based on a routeing decision at dispatching, selecting from a common queue. This leads to the pooling synergy effect. More interchangeable orders (i.e. moving from left to right in Figure 5.9) lead to a relatively stronger pooling synergy effect which causes the larger performance differences in between the two routeing decisions. Thus, according to the results in Figure 5.9, it can be concluded that, if the workload is not controlled during order release, the grouping/non-grouping decision is of no influence and the routeing decision should be done as late as possible – at the time of dispatching.

In Figure 5.10, the depicted performance differences are not only a result of the routeing decision and the related pooling synergy effect (as in Figure 5.9) but also relate to balancing of loads at order release. As described in section 2, *grouping* semi-interchangeable machines into a single capacity group and taking the *routeing decision at dispatching* on the floor (dotted curve) is the most intuitive control alternative: the order release decision becomes less complex because fewer capacity groups have to be considered, no routeing decisions have to be taken at order release and the operators on the floor have the autonomy to make the routeing decisions themselves. It represents a decentralised control approach, because the control decisions are postponed until dispatching the work at individual capacity groups. In contrast the solid curve (routeing at release/non-grouping) represents a centralised control approach: the release decision and the routeing decision are done centrally, based on a detailed shop floor view. Comparing these two opposite alternatives

(dotted vs. solid curve) shows a trade off between load balancing and pooling synergy effects. While the decentralised control approach (dotted curve) benefits from the pooling synergy the centralised control approach (solid curve) focuses on the effect of load balancing during order release (supported by a detailed shop floor view and the routing decision at release). The two curves cross at $c=0.25$. For a higher degree of interchangeability the influence of load balancing during order release (solid curve) is weaker than by the pooling synergy effect (dotted curve), and vice versa for smaller degrees of interchangeability ($c<0.25$).

Independent of the degree of interchangeability, the combination of ‘*non-grouping*’ and ‘*routing at dispatching*’ as depicted by the dashed curve in Figure 5.10 is always superior to the other control alternatives. The simulation results show that the balancing and the pooling synergy effect can be combined. They show that particularly for a high degree of interchangeability the routing decision should best be taken on the floor, while being supported by a release decision based on a detailed shop floor view (non-grouping). This means that a preliminary routing choice is made as a part of the release decision while the final decision is postponed until the dispatching. However, with a smaller degree of interchangeability ($c<0.15$) the pooling synergy effect seems less relevant: the dashed and the solid lines come close together.

It is widely accepted in WLC research that a dispatching rule does not influence overall performance significantly. Besides the experiments presented in this paper – applying FCFS dispatching - additional experiments have been conducted to investigate the sensitivity of the simulation results relative to the priority dispatching rules on the floor. These experiments show that total throughput time is hardly affected by other order sequencing rules. However, the simulation outcomes in this paper show that the dispatching decision may be important for the allocation of work to semi-interchangeable machines, i.e. important for the routing decision within the WLC concept.

The discussion of the simulation results makes it clear that the grouping and the routing decisions, even for an elementary situation with only two semi-interchangeable machines, require careful consideration. We have seen that the choice of the appropriate control alternative depends on the degree of interchangeability and on the chosen level of norm tightness. With infinite norms only pooling synergy affects overall shop floor performance. Therefore, in situations without workload control, the routing decision should be taken as late as possible, i.e. on the shop floor at dispatching level. The simulation results show that the balancing function of order release, which is supported by distinguishing separate capacity groups for semi-interchangeable machines, becomes less effective with looser norms. Tighter workload norms allow for a better balance of loads across machines, where a separate

5.1 Introduction

The term make-to-order job shop is used to address a manufacturing setting where a large number of different products are produced according to customer specification. Typically, the product differences result in highly variable routings and processing times. In literature (e.g. Melnyk and Ragatz 1989) job shops are often modelled as consisting of multiple machines but a single machine per type of operation (e.g. drilling, milling, turning). However, in practice we encounter groups of machines performing a similar operation type. These machines are not necessarily identical; they may be semi-interchangeable with respect to the range of products that can be handled.

The workload control (WLC) concept is a production planning and control (PPC) approach especially developed for the requirements of make-to-order job shops (e. g. Stevenson et al. 2005). The concept strives to reduce planning complexity by applying basic principles of input/output control (as defined in Plossl and Wight 1973). The aim is to control the work in process (WIP) on the floor to realise short and predictable throughput times. This requires balancing the orders on the floor to avoid temporary over- and underloading of the individual machines. Order release is the main instrument for the load balancing. The release of orders to the shop floor is allowed as long as the work in process does not exceed the preset workload norms per capacity group. Once released, the orders remain on the shop floor. Simple priority dispatching rules direct the orders along their downstream capacity groups.

In WLC research, capacity groups are commonly considered to consist of a single machine or sometimes a group of identical machines (e.g. Kingsman and Hendry 2002). Capacity groups are the smallest units to be controlled centrally since one workload norm is specified per group. Distinguishing a large number of capacity groups on the floor (e.g. one capacity group per machine) allows for a detailed shop floor view, and detailed balancing of workloads during order release. Obviously, a lesser number of capacity groups decreases the load balancing capabilities during order release, but reduces the control complexity, too.

Nyhuis and Wiendahl (1999) give some rules on grouping machines into capacity groups, but the grouping decision itself and the related performance implications are not addressed explicitly. Henrich et al. (2004A)[∅] investigate the grouping of non-interchangeable and interchangeable machines and show that non-interchangeable and interchangeable machines should be treated completely different regarding the grouping decision.

Semi-interchangeable machines allow for options in forming capacity groups that are not covered in current literature. It may be expected that the semi-

[∅] Chapter 4.

interchangeability is of major influence on shop performance and should not be neglected within WLC because of the importance of load balancing.

Semi-interchangeable machines not only ask for a grouping/non-grouping decision but also the routing of orders across those machines has to be defined. For instance, it is possible to set up a common queue in front of semi-interchangeable machines to take the routing decision at the dispatching level on the floor. The resulting so-called ‘pooling synergy’ leads to a waiting time reduction (see e.g. Kleinrock 1975, 1976). Intuitively this option should be combined with grouping the semi-interchangeable machines. On the other hand, taking a routing decision at order release supported by a detailed load overview per machine (i.e. non-grouping), may contribute to balancing. Thus, the routing decisions cannot be seen independently from the formation of capacity groups.

The goal of this paper is to investigate the implications of semi-interchangeable machines within a workload controlled environment. We focus on both of the above mentioned decision areas, namely the grouping of semi-interchangeable machines into capacity groups and on the positioning of the routing decision within the control concept. Different degrees of interchangeability are also considered.

In Section 5.2, we investigate semi-interchangeable machines in more detail and develop a definition. We review the WLC concept, identify relevant elements for the control of semi-interchangeable machines, and discuss the expected performance implications. A series of simulation experiments is defined in Section 5.3 to gain insights into the effects of the different control alternatives for semi-interchangeable machines. The results of the simulation experiments are analyzed in Section 5.4, and conclusions are summarized in Section 5.5.

5.2 Semi-interchangeable machines within WLC

The implementation of a WLC concept requires considering shop floor characteristics (Gaalman and Perona 2002). In WLC research several shop floor characteristics have been investigated, such as: the routing structure (Oosterman et al. 2000), the appearance of specific bottlenecks (Park and Salegna 1995, Salegna and Park 1996, Enns and Prongué Costa 2002), sequence dependent set up times (Missbauer 1997), or the available information technology for the exchange of production data (Henrich et al. 2004c)[⊕]. Semi-interchangeability of machines in the context of WLC has not been researched, yet.

To discuss the implications for WLC, it is necessary to model the different types of semi-interchangeability. On the one hand this model has to reflect the reality in

[⊕] Chapter 3.

make-to-order job shops and the different types of semi-interchangeability. On the other hand it has to allow for a systematic discussion of all implications for WLC.

Background of semi-interchangeability of machines

Semi-interchangeability relates to the technical ability of the machines to perform similar operations. Even though two machines perform the same type of operations (e.g. drilling, milling, turning, boring), the range of products that can be handled may only be partly overlapping. In that case we speak of semi-interchangeability.

An example for two semi-interchangeable machines A and B with overlapping product ranges is depicted in Figure 5.1. While machine A allows to operate products within a range of 20 and 70 [millimetres], machine B allows a product range in between 5 and 55 [millimetres].

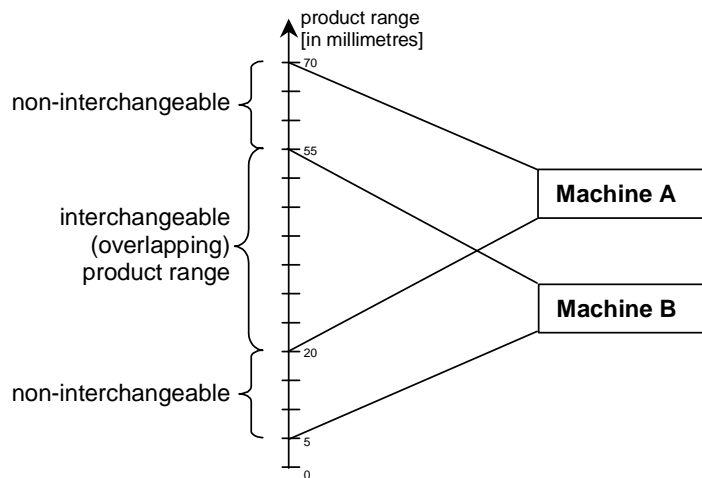


Figure 5.1 Example of two semi-interchangeable machines (A and B) with an overlapping product range

The reason why machines that perform the same operations type are semi-interchangeable, depends on several aspects like, for instance, differences in:

- power,
- size of the table,
- number of axes,
- tool sets (shape, number, material) and fixtures,
- tolerances,
- control mechanism (e.g. CNC, manual).

capacity group is distinguished for each machine. With tighter norms, both effects – pooling synergy and balancing loads – can work simultaneously to reduce total throughput times. The results also show that the pooling effect is more dependent on the degree of interchangeability than the balancing effect.

5.5 Conclusions

The objective of this paper has been to investigate, to develop, and to compare different alternatives for controlling semi-interchangeable machines within a workload controlled environment. We show that the semi-interchangeability of machines is of major influence on shop performance and should not be neglected within WLC.

Semi-interchangeability influences the WLC approach in different ways: (1) *grouping* (respectively non-grouping) semi-interchangeable machines into capacity groups influences the possibility to balance workloads across machines within the release decision; (2) for orders that can be processed on more than one machine a *routing decision* has to be made, i.e. a decision on what machine an order has to be operated. Within WLC this can be done as a part of either the release or the dispatching decision.

The different control alternatives for semi-interchangeable machines are investigated systematically by a simulation study. The main effects on overall performance are identified as a result of (1) the balancing of loads across the machines by a controlled order release and by (2) the so-called pooling synergy effect, emerging in case of a common queue in front of two (semi-)interchangeable machines.

For all control alternatives, it holds that an increase in interchangeability always leads to performance improvements. It has been shown that additional increases in interchangeability result in decreasing marginal performance gains.

The most intuitive control alternative choice (i.e. grouping semi-interchangeable machines together into a single capacity group and making the routing decision at dispatching) does not always result in the best performance. Especially with a low degree of interchangeability (i.e. a low fraction of orders that can be produced on more than one machine) and for situations with limited workload on the shop floor, the underlying pooling synergy loses its effectiveness. In situations with controlled workload a more centralised control alternative becomes attractive: defining a separate capacity group for each (semi-interchangeable) machine and taking the routing decision at release. This leads to a reduction of total throughput times, based on the balancing effect.

However, distinguishing separate capacity groups at release can also be done for just a preliminary routing choice. This allows for improved balancing at release. Still, the final routing decision can be made at dispatching. This combination leads to the best results independent of workload and interchangeability levels.

Though previous research showed limited effectiveness of dispatching rules within a workload controlled environment, this research shows that the dispatching decision may be important for allocating work to semi-interchangeable machines in such environments.

This paper considered the wide spectrum of semi-interchangeable machines. However, the simulation was restricted to a 'symmetric version of semi-interchangeability' in terms of equal order volumes that could be handled on each machine, it was restricted to machines with identical operational characteristics (e.g. operation processing times), and only the machine capacity was considered as a resource constraint for capacity groups. Future work could further investigate these aspects.