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Design of a period batch control planning system for cellular manufacturing

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2001

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Riezebos, J. (2001). *Design of a period batch control planning system for cellular manufacturing*. [Thesis fully internal (DIV), University of Groningen]. s.n.

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Chapter 7 Determining a configuration of the PBC system

In Chapter Five we presented a progressive search heuristic for determining a configuration of a PBC system. This heuristic finds both an appropriate period length P and a suitable number of transfer batches at each operation (a variable subbatch strategy). The number of stages N follows from these parameter choices, as they determine the maximum throughput time of any of the products. The throughput time of the proposed PBC system is then equal to N·P.

Chapter Five concluded that the progressive search heuristic performs quite well. The period length found by the heuristic remained in 92% of the experiments unchanged compared with the best solution found. However, the total costs of the configuration that was found by the progressive search heuristic could further be reduced by reconsidering the subbatch strategy.

These results for the progressive search heuristic were obtained for a number of random experiments based on the information from the example problem in § 5.5.1. This example problem has a simple structure, containing two products and a sequence of 8 or 9 operations per product. The example problem did not clearly resemble a cellular manufacturing system situation, as it did not distinguish cells, only operations.

In Chapter Six, we have considered a more complex production situation. We analysed the effects of various configurations of a PBC system with a fixed throughput time of 15 days. This analysis revealed that there are huge differences in performance between configurations with the same throughput time. The number of stages N and the equal subbatch strategy applied are the most important factors. Chapter Six used a time consuming simulation analysis to explore the effect of the various configurations on the amount of overtime work and costs. The simulation model provided a good representation of the production situation. However, it took 30 hours computing time to perform all simulations for the configurations with this single throughput time.

This chapter aims at determining a PBC configuration for a cellular manufacturing system with a more complex production situation than we considered in Chapter Five. Such a configuration includes a throughput time T, a period length P, a number of stages N, a decision about the stage contents, and a suitable subbatch strategy. Due to the complex relationships between the PBC design parameters, this is not an obvious problem. We might want to use the simulation model to evaluate several throughput times and determine appropriate PBC configurations. However, it will probably take too much time to perform such a simulation analysis for many different throughput times. We might also want to consider the possibility of using a search heuristic to determine an initial configuration of the PBC system for more complex production situations. This may require some modifications in the heuristic, as it has to cope with different input data structures. We therefore have to consider both the applicability of the heuristic and the suitability of a configuration that it proposes. We will restrict ourselves to the production situation I, discussed in Chapter Six.

We reformulate the question as follows:

How can we use the progressive search heuristic in PBC system design, and what effect will it have on the performance of the PBC system for production situation I?

The progressive search heuristic has been developed with a different purpose than the simulation model of Chapter Six. The proposed configuration consists of a variable subbatch strategy, while the simulation model allows only equal subbatch strategies. If order to test the outcomes of the heuristic, we will simulate the proposed configuration with our simulation model. Therefore, we need a procedure that translates the proposed configuration to a set of configurations that can be simulated in the model. Furthermore, the cost parameters in the simulation model have to be translated to suitable cost parameters in the progressive search heuristic in order to obtain a cost-effective configuration.

Appendix G proposes several modifications of both the heuristic and the input (cost) data in order to be able to use the results of the progressive search heuristic as input in the simulation model and to compare the results with other simulated configurations.

Section § 7.1 tests the proposed PBC configuration that results from the progressive search heuristic for production situation I. It describes the results of the progressive search heuristic and the application of this configuration in the simulation model of Chapter Six. The performance is compared with configurations that we tested in that chapter.

Section § 7.2 discusses the use of an initial configuration from the progressive search heuristic in the integral design of production and planning system. It uses the insights on the applicability of the progressive search heuristic in determining a configuration for the PBC system and develops a procedure for the integral design of both the production and (PBC) planning system. Finally, it pays attention to the value of the search heuristic in the design process. We present our conclusions in Section § 7.3.

§ 7.1 PBC configuration proposed by progressive search heuristic

We have used the data of production situation I, presented in Table 6.2 and Figure 6.9, as input for the progressive search heuristic. All three end products require 25 operations. The longest path starts for all three products with family B. There are only 12 operations on this longest path. Appendix G provides details on the procedure that we followed.

The 12 operations on the longest path require processing on machines in the sequence:
1 ➔ 2 ➔ 6 ➔ 7 ➔ 8 ➔ 9 ➔ 10 ➔ 11 ➔ 12 ➔ 13 ➔ 14 ➔ 15.

The length of this path varies per product and depends on the batch size q_h. This batch size varies per period only if there is uncertainty of demand (AfwVol>0) and increases with the length of P. If there is no uncertainty, $q_h = P \cdot D_h$. Note that D_h is equal for all products. The length of the longest path for the three products is respectively:

Product	Length of longest path as function of batch size q_h
1	200 + 97·q_h minutes
2	200 + 98·q_h minutes
3	200 + 104·q_h minutes

Other parameters for the progressive search heuristic are :

AfwVol		0	(i.e., constant demand of 5 items per order)
Volume		75	orders per T=7200 minutes
	D_h	375	items per 7200 minutes (Volume·AfwVol=75·5)
Holding costs	HC_h	6·12/25	per item that remains T=7200 minutes in the system
Set-up costs	SC_{hi}	0.1	per minute set-up time
Transfer costs	TC_{hi}	0.1·25/12	per transfer batch ($TC'_{hi} = TC''_{hi}$)
MaxNrSub	nb^{max}_{hi}	4	(maximum number of transfer batches per period)
Machines	m_{hi}	1	(no identical machine available for operations)

§ 7.1.1 Results of progressive search heuristic without correction factor (MI = 1)

The progressive search heuristic calculates two lowerbounds on the length of P. Appendix G discusses the corrections necessary in these lowerbound calculations in order to accomplish for differences in modelling assumptions between the simulation model and the heuristic. It concludes that a correction factor MI < 1 should be used in both lowerbound calculations. However, it does not provide a suitable value for MI. Therefore, we have first analysed the outcomes of the progressive search heuristic for a MI factor = 1. This will give us an indication of the required size of the correction factor.

For MI=1, the load oriented lowerbound in the progressive search heuristic gives us:
minimum period length = 0.1286·T, almost two days.

This load oriented minimum is caused by machine 3, which has a long set-up time, but is not on the longest path. A shorter period length would cause a utilization of this machine > 100%. Higher volumes (e.g. Volume=90) or a fluctuating demand (AfwVol > 0) would result in a higher minimum period length.

Note that machine 3 does not remain bottleneck over the whole range of period lengths. Longer period lengths result in a diminishing set-up time effect at machine 3 and a faster increasing total processing time at machines with longer processing times per operation. This makes machine 13 bottleneck for longer period lengths than the load oriented minimum P.

The progressive search starts the search for a PBC configuration at the minimum period length with one subbatch per operation. The outcomes of the progressive search heuristic are:

P = 0.3767 · T
N = 1

machine	1	2	6	7	8	9	10	11	12	13	14	15
nb(product 1)	2	2	2	2	1	1	4	2	2	4	4	1
nb(product 2)	1	2	2	2	1	1	4	2	2	4	4	1
nb(product 3)	2	2	2	2	2	1	4	2	2	4	4	1

The exhaustive search gives us the same value for P and N, but a different subbatch strategy that reduces costs. The proposed subbatch strategy of the exhausted search heuristic is:

machine	1	2	6	7	8	9	10	11	12	13	14	15
nb(product 1)	2	2	2	2	2	2	2	2	2	3	2	1
nb(product 2)	2	2	2	2	2	2	2	2	2	3	2	1
nb(product 3)	2	2	2	2	2	2	3	2	2	3	3	1

The subbatch strategy of the exhausted search heuristic almost reflects an equal number of subbatches strategy with nb_h=2. The bottleneck operation at machine 13 has a longer processing time and the heuristic chooses for each product a higher number of transfer batches at this operation. Product 3 has the highest expected throughput time, which is reduced with an increased number of transfer batches in order to avoid overtime work. The high loaded machines 10 and 14 use therefore one more transfer batch.

The heuristic advises not to use a total manufacturing throughput time of T=7200 minutes, but to reduce this to P·N=0.3767 · 7200 = 2712 minutes, i.e. five and a half days. Within this throughput time, no further stages should be distinguished. Instead, at least two transfer batches per operation should be used. Relevant subbatch strategies are therefore nb=2, or 3. If only one transfer batch would have been used, the throughput time of product 3 would have become at least 200+104·P·375=14891 minutes (more than 31 days) at the proposed period length.

§ 7.1.2 Evaluation of proposed configuration in simulation model

We have tested this configuration in our simulation model. Parameters as Policy, Idd, and AfwVol have been fixed at their initial values Policy=FiFo, Idd=0, AfwVol=0 in all simulation experiments. The next values have been used for the other relevant parameters:

P	0.3767 · 7200 minutes
N	1
NrSub	either 2 or 3
Volume	0.3767 · 75 orders per P·N minutes = 28 orders
MI correction factor	1

The outcomes of the simulation for NrSub=3 are presented in Figure 7.1. If we simulate with NrSub=2 a similar pattern is obtained with somewhat more overtime work. The figure shows clearly that a considerable amount of overtime work results if we apply the PBC configuration that was proposed by the progressive search heuristic.

If we examine Figure 7.1 in more detail, we see that product 1 first enters the system and starts at time 0. This product is finished around 2630 minutes, i.e., within the period length P=2712 minutes. The other products encounter a considerable start delay, which cannot be recovered during the period. This results in significant amounts of overtime work.

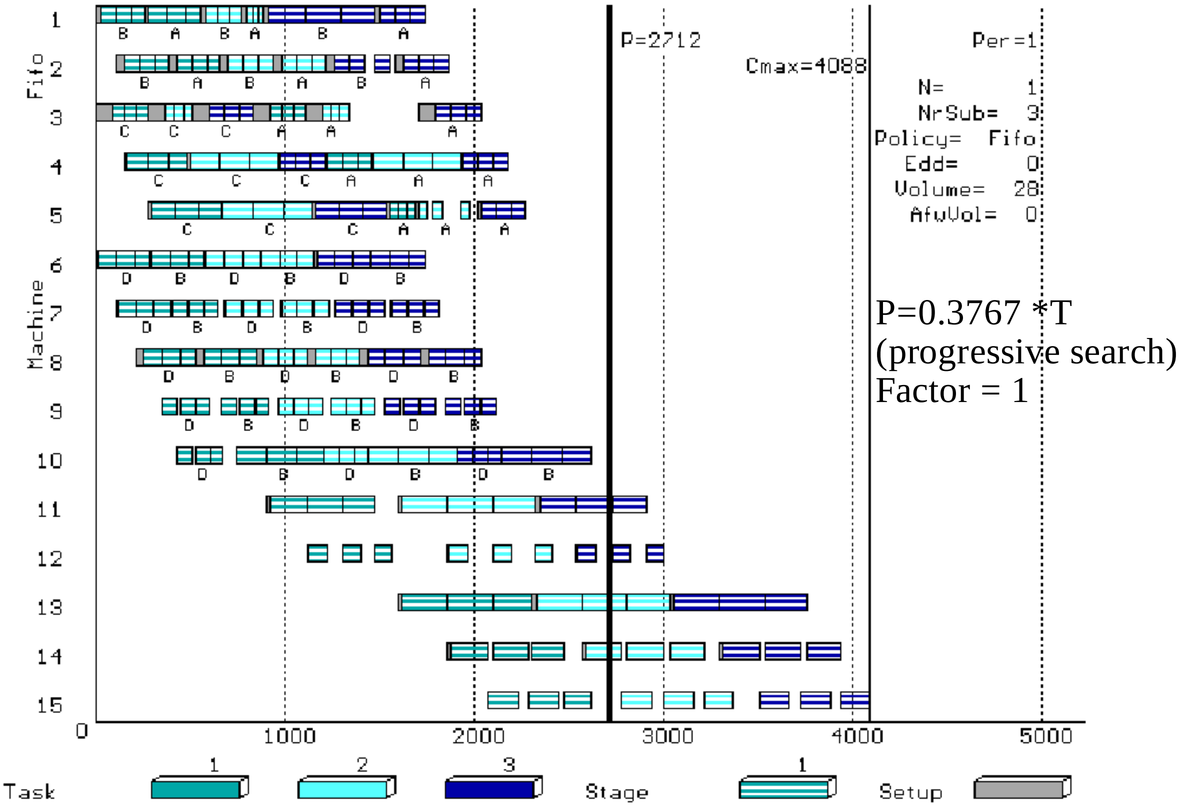

Figure 7.1 Gantt chart for PBC design with N=1, P=0.3767·T, NB=3

In a flow shop structure as tested here, we expect this pattern of start/finish delays to occur. However, the progressive search heuristic that determines the PBC configuration does not presume this (extreme) production structure. It assumes that operations that require capacity at the same resource will not delay each other’s progress, i.e. it ignores interactions between operations that do not belong to the same product routing. The simulation results show that the interaction between capacity usage and the timing of the operations has a strong effect on make span performance. This makes it necessary to correct the path oriented lowerbound with a correction factor MI < 1. Note that we also encounter delays on the longest path (family B) due to the performance of activities that are on a non-critical path (family D at machine 6).

The simulation model does determine the relevant cost factors for the proposed configuration. We can compare these cost factors with the costs of similar configurations with N·P=T=7200. There are two similar configurations possible with T=7200. One with the same N and subbatch strategy as proposed, but a different P: P=7200/N. The other configuration with a different number of stages N such that the resulting period length is nearest to the one proposed. The number of subbatches remains the same as proposed. Table 7.1 compares the results of the proposed configuration and the two similar configurations with T=7200 minutes.

Costs per 7200 minutes	Proposed configuration N=1, P=0.3767·T, NrSub=3	Similar configuration *N=1*, P=1 · T, NrSub=3	Similar configuration N=3, *P=0.3333·T*, NrSub=3
Holding costs	399	1092	822
Set-up+Transfer costs	297	112	337
Overtime costs	750	474	46
Total costs	1447	1678	1205

Table 7.1 Comparison of the costs of proposed and original configurations with T=7200

The total costs of the proposed configuration consist for more than 50% of overtime costs. These costs were not counted for in the heuristic. Without these overtime costs, total cost would have been almost 697 for this configuration[1]. The total amount of overtime work is considerably higher than for similar configurations with a manufacturing throughput time of T=7200 minutes. The cost of overtime work per 7200 minutes is for the new configuration 750 compared with 474 of the similar configuration with a much higher period length and identical number of stages and with 46 for the similar configuration with almost identical period length and higher number of stages. The total costs for the proposed PBC configuration are significantly smaller than for the T=7200 configuration with equal number of stages (1678-1447=231), but the T=7200 configuration with equal period length results in a significantly lower total cost (1447-1205=242).

The progressive search heuristic reduces the total manufacturing throughput time to almost 1/3 the original throughput time of T=7200 minutes. This leads to a similar reduction of the work in progress and holding cost, and a corresponding increase in the set-up+transfer batch costs with a factor of nearly 3 (exactly 1/0.3767).

If we use NrSub=2, the configurations have higher total costs. The proposed configuration shows a cost of 1736, the similar configuration with P almost identical 1292 and with N identical 2021.

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[1] Note that the costs that we report are obtained from the simulation model and reflect the average costs over 7200 minutes. This explains the difference between the holding costs and set-up+transfer batch cost for the proposed configuration. The solution that the progressive search heuristic finds generally has both cost types equally sized.

§ 7.1.3 Results of progressive search heuristic with correction factor MI < 1

The main reason for the high costs for the proposed configuration is that we have underestimated the amount of overtime work. The flow shop structure in the data of production situation I is not recognized in our throughput time determination approach in the mathematical model behind the progressive search heuristic. It is possible to improve the estimation of the throughput time in the heuristic using some flow shop scheduling lowerbounds (e.g., adding the minimal remaining processing time at one of the machines to the calculated throughput time, see Riezebos, Gaalman & Gupta, 1995). However, we should recognize that a flow shop structure where each product visits the operations exactly in the same order is rather extreme, even in a cellular manufacturing situation. Therefore, we prefer a more flexible approach and apply a quick correction on the calculated throughput time estimation using MI < 1.

From Figure 7.1 we see that the final make span exceeds the estimated make span with more than 50% (2630 versus 4088). We need however not use a correction factor of 50%, as we also consider the correction on the lowerbound with respect to the load of the machines. We will start with correction factors of 5% and 10% and see what will be the effect on the required amount of over time work.

If we apply correction values for the lowerbounds of MI=0.95 and MI=0.9, we obtain the configurations presented in the left column of Table 7.2. These configurations have been simulated. We present both the total costs and the overtime costs of the various configurations. The costs of the proposed configuration are in the columns labelled ‘proposed’, while the costs of the similar configurations with T=7200 are in the next two columns. First, we present the results of a configuration with equal number of stages and a different period length, and next a similar value for the period length and a different number of stages. The value for the similar period length is presented in a separate column in the table. Figure 6.13 showed for all configurations with different N and NrSub that were considered. Note that all these configurations resulted in a throughput time T=7200 minutes.

PBC Configuration						Total cost per T=7200			Overtime costs per T=7200		
MI	T	N	P	NrSub	Similar P value	Proposed	N equal	P equal to similar P	Proposed	N equal	P equal to similar P
1	2712	1	0.3767	3	0.3333	1447	1678	1205	750	474	46
1	2712	1	0.3767	2	0.3333	1736	2021	1292	1086	853	184
0.95	3826	2	0.2657	4	0.25	1060	1379	1365	0	0	7
0.95	***3826***	***2***	***0.2657***	***3***	0.25	***1023***	1369	1328	23	23	30
0.95	3826	2	0.2657	2	0.25	1075	1431	1303	134	121	68
0.9	4806	3	0.2225	4	0.2	1135	1207	1610	19	0	32
0.9	4806	3	0.2225	3	0.2	1108	1205	1554	60	46	51

Table 7.2 Cost comparison for different values of lowerbound correction factor MI

The results in Table 7.2 show that minimal total costs are obtained for MI=0.95 and a PBC configuration with P=0.2657·7200 minutes, N=2, and 3 transfer batches per period. Figure 7.2 shows the Gantt chart for this configuration. The total manufacturing throughput time is N·P=0.5314 · 7200 minutes = 3826 minutes (8 days instead of 15 days). For this configuration, the minimal total cost per 7200 minutes is 1023. This is considerably lower than the minimal cost if a total manufacturing throughput time of 7200 minutes is used. Figure 6.13 shows that the minimum is then obtained at N=3, NrSub=3 with a cost of 1205. That makes a difference of 182 per 7200 minutes.

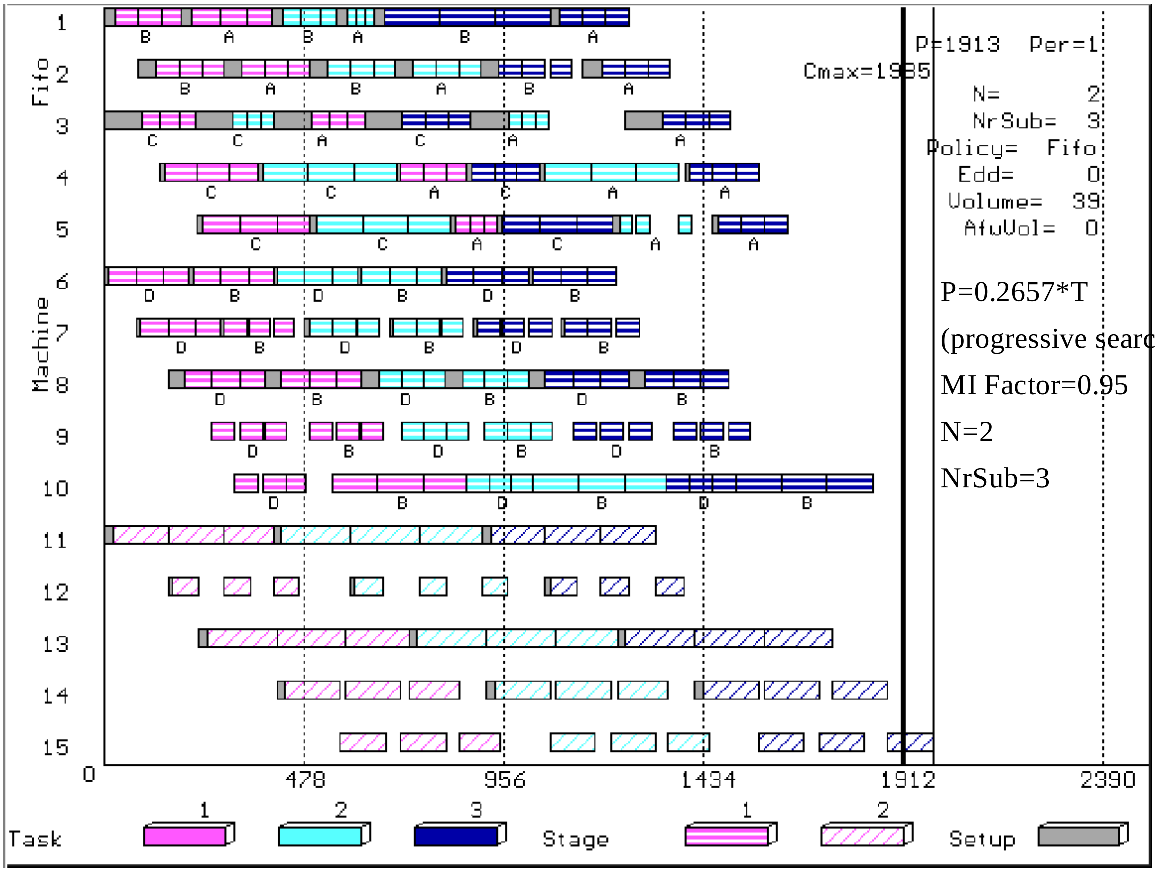

Figure 7.2 Gantt chart for minimal cost configuration of PBC: N=2, P=0.2657·T, NB=3

This cost difference can be studied in more detail if we further look at Figure 6.13. The configuration that results in minimum total costs if T=7200 has a holding cost of 822 (more than 68% of the total costs of 1205), the set-up and transfer batch costs are 337 (almost 28%), while the overtime costs are very low (46=4%). The proposed configuration that we obtained for MI=0.95 has a minimum total cost of 1023, consisting of 56% holding costs (579), 41% set-up and transfer batch costs (422) and a very small amount of overtime costs (2%, 23). This configuration shows a better balance between holding costs and set-up + transfer batch costs.

Finally, we can see from Table 7.2 that the percentage of overtime costs in the total costs strongly decreases as the correction factor (1/MI) increases. One reason is that the total manufacturing throughput time N·P increases as well, which results in higher holding costs. The other reason is that the correction of the lowerbounds results in a better estimation of the required throughput time. This results in almost no overtime work in the system. As the costs increase for MI=0.9, we need not examine larger correction factors as well. However, we cannot easily predict at what value of MI the minimum cost will occur. This depends amongst other factors on the specific product structure.

From this analysis, we conclude that the PBC configuration resulting from the progressive search heuristic can be used to determine a suitable value for the period length P and number of stages N in a PBC system for production situation I. This configuration results in lower cost solutions than found with trial and error search procedures with T fixed at 7200 minutes. The proposed configuration determines a throughput time that is much lower than T=7200. For this configuration, we find a better balance between holding costs and set-up and transfer costs.

In order to be effective, the progressive search heuristic needs to include a correction factor MI < 1 in the lowerbounds for the expected throughput time calculation. This reduces the amount of overtime work that will otherwise occur in the system.

The progressive search heuristic does not determine a suitable allocation of operations to the number of stages N that it proposes. It assumes a multi-phased PBC system, where an operation can start processing a subbatch after the preceding operation has completed it. In our simulation analysis we used the stage allocation of Chapter Six and tested the performance of the proposed configuration for this specific allocation. However, in general, we need to obtain a suitable stage allocation for proposed configurations with N>1.

§ 7.2 PBC system design and the value of a search heuristic

We have shown that a search heuristic can be used in determining a configuration for a PBC system, as long as we correct for overtime and modify the heuristic such that it fits with the product structure. The question now rises how we can use a search heuristic in the design of a PBC system.

In order to answer this question, we consider the characteristics of the design approach that we proposed for the integral design of a production and planning system. In Figure 4.2 we presented such an approach. Figure 7.3 amplifies upon this approach, using the knowledge that we gained in the Chapters Four to Seven on PBC system design factors.

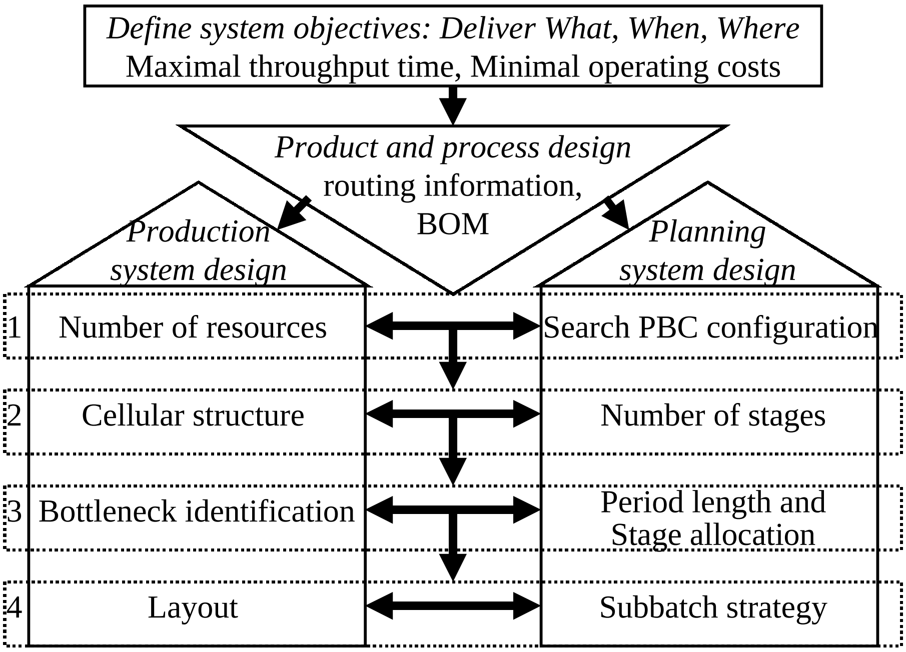

Figure 7.3 PBC system design approach

We start with determining relevant system objectives, such as minimal costs, and an acceptable range of throughput times. This enables us to determine the products and production activities that have to be considered in the system design. Therefore, we identify product structures (Bills Of Materials (Figure 6.9)) and routing information. This information is used as input for designing the production and the planning system.

The design of production and planning system shows a constant interaction, but can be divided into four main steps. The first step (1) consists of determining the elements of the production system (number of resources) and the characteristics of the planning system (initial values of N, P, identification of longest paths, and subbatch strategies). We use the search heuristic to identify these initial values. This procedure does not require information on the allocation of operations to stages, cellular structure of the production system, or layout of the facilities. It only uses cost data, product and process data, and information on the number of resources in the production system. The output of the search heuristic can be used to reconsider the allocation of resources to the production system.

Next, the basic structure of both systems can be designed in step (2). Decomposing the production system into cells and defining the number of stages are parallel activities that influence each other, as discussed in Chapter Four. The number of stages N that is proposed by the search heuristic should be considered as a lowerbound on N. The cellular structure may make it necessary to use more stages. Furthermore, the impact of a single-phase PBC system is not taken into account in the proposed number of stages[2]. Therefore, the single phase loading of this system may lead to a higher number of stages than proposed.

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[2] The heuristic assumes a multi-phased PBC system, even if it proposes to use several stages.

After designing the basic structure of both systems, decisions have to be taken in step (3) about the period length and hence about the throughput time of the products. These decisions have to be taken together with the definition of the stage contents, e.g., the determination of work orders per stage or allocation of operations to the stages. A trade-off has to be made between the length of the longest path (throughput time) and the load balance (bottleneck). We can use the framework for stage definition and the mathematical model that supports the decisions on stage allocation of Chapter Four. For this decision, we need information on the occurrence of bottlenecks in the production system.

The period length and total throughput time that resulted from the search heuristic should be reconsidered as well, especially if the number of stages has increased. We can use our simulation model to evaluate several alternatives. These alternatives can be generated using the insights from Chapter Four on specific period lengths that help to improve the learning capability of the production system or reduce the operating costs. The co-ordination requirements within and between the cells can be a significant factor in determining N and P.

The final step (4) is to determine an adequate layout within and between the cells. This decision influences the efficiency of the material flow system, which is very important in order to realise a specific subbatch strategy. Facilities of different cells that have to cooperate for performing operations on several longest paths need to be positioned such that the transfer of work can be performed without problem. The proposed subbatch strategy needs to be revised, as it has not taken into account either stage or cell boundaries. We possibly will prefer a lower number of subbatches at operations just before the boundary.

Concluding, we see the value of a search heuristic in providing a starting point for finding a configuration of a PBC system. It gives an indication for the minimal total throughput time, the number of stages, the length of the period, a suitable subbatch strategy for operations on the longest path, as well as the total costs in the system. Additionally, it provides a load oriented lowerbound on the period length P that assures that all operations do have enough remaining capacity available in order to perform their work. Literature on PBC system design omits such a starting point, as discussed in Section § 4.2.

However, the configuration that is proposed by a search heuristic should not be considered as a blueprint for PBC system design. The characteristics of the production system deserve a more important role in the final design of the planning system. Our design approach pays attention to this interaction.

The contribution of our design approach is that it considers the relationship between production system design and planning system design. The possibility of achieving system objectives with respect to throughput time, dependability, and costs, depends both on characteristics of the production system and the planning system. The value of the initial configuration produced by a search heuristic is that detailed knowledge on the product and process routings is included at an early phase in the design process.

§ 7.3 Conclusion

The PBC configuration for production situation I as proposed by the progressive search heuristic has been tested in the simulation model of Chapter Six. We had to modify several elements of the heuristic in order to make it possible to determine a configuration for the more complex input data structure of production situation I.

The tests with the proposed configuration without correction factor for the calculated lowerbounds showed a strong underestimation of the required amount of overtime work. A small correction factor (MI=95%) resulted in a more realistic configuration that showed a strong decrease in costs compared with configurations obtained with trial and error search procedures. We found a decrease in costs of at least 15% compared to the best solution found in the simulation study of Chapter Six.

The search heuristic can provide us with valuable information on an initial configuration of the PBC system. It gives an indication for the essential characteristics of the planning system, such as minimal total throughput time, number of stages, period length, longest path, and total costs. We would not like to consider the proposed configuration as a blueprint for PBC system design. The characteristics of the production system should play a far more important role in the final design of the planning system. Therefore, we propose four main steps in the integral design of production and planning system:

1. determining number of resources and initial configuration
2. determining basic structure of both systems
3. determining work orders, period length, throughput time using information on bottlenecks
4. determining lay-out, material flow, and subbatch strategy

In the next chapter, we will further explore characteristics of the production system that should be taken into account in the design process. We will discuss the effect of PBC system design choices on the logistical co-ordination in a cellular decomposed production system that still has to be performed when PBC is used for the overall goods flow planning.