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### Shop floor design

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## Summary

The topics addressed in the six papers of this thesis fall within the broad field of Operations Management (OM), and particularly relate to the process design activity. The thesis covers issues within three specific design activities addressed in the design of processes: (1) Layout, (2) Process technology, and (3) Job design. Since their focus is on the shop floor level, we call these three design activities “shop floor design activities”. The issues we deal with in this thesis are:

- The choice of a basic layout
- Investment appraisal
- Cross-training
- Labor allocation

The layout shop floor design activity includes the choice of a process structure as a first design decision, the choice of a basic layout as a second design decision, and the filling-in of a detailed design of the layout as a third design decision. In the paper “Decision support framework for the selection of a manufacturing layout”, we focus on the choice of a basic layout (the second design decision). This is one of the most important design decisions in a firm and many times, the choice is not obvious. Previous research has compared alternative layouts (e.g. cell layouts versus process layouts), but it often focuses on a small set of factors, without explicitly assisting practitioners in making a choice between the alternative layouts in their specific situation. Our contribution presents a general decision support framework for the selection of a manufacturing layout, including a hierarchical decomposition of the decision problem. This decomposition simplifies the decision problem and enables an efficient and effective employee participation. In the decision which layout to choose, strengths and weaknesses of each layout alternative are related to the performance objectives of the firm. For this, answers are needed for the following three sets of questions: (1) What are the relative scores of the various alternative layouts on the aspects mentioned in the decision framework? (2) What is the relative importance of the various aspects for the performance objectives? and (3) What is the relative importance of the various performance objectives for the firm? The performance objectives included in the framework are: price, quality, speed, flexibility (product/service, mix, and volume/demand), dependability, and quality of labor. The approach is integral, since it considers a broad set of performance objectives, including qualitative as well as quantitative aspects, and it shows how a decision can be made incorporating all these aspects. We use the AHP (Analytic Hierarchy Process) approach, since this approach is useful in multi-criteria situations where intuitive, qualitative and quantitative aspects play a role. The proposed method is illustrated by means of a practical instance. The framework is applied in several practical situations and, in our opinion, the decision hierarchy presented in the paper and the use of the Analytic Hierarchy Process (AHP) form a robust framework for the selection of a layout in many situations.

With respect to process technology as shop floor design activity, we focus on materials-processing technologies and specifically on conventional machine technology and Computer Numerically Controlled (CNC) technology. The paper “An integrated model for part-operation allocation and investments in CNC technology” addresses the issue of investment appraisal of CNC machines in conjunction with optimal allocation of parts and operations as the investments take place. The part-operation allocation decision is the decision to allocate the parts and operations either to the conventional machines or to the new CNC machines. Unlike the FMS part type selection, which is a short-term FMS production planning problem, the part-operation allocation problem which is considered together with investment decisions, can be seen to be a medium- or long-term problem. In (re)designing processes, an important consideration is what process technology to apply in the transformation of inputs to outputs. Each alternative process technology or alternative variant of the same technology has different characteristics and will contribute differently to the production system’s effectiveness. Essentially, CNC machines contribute to an increase in the three main performance criteria of efficiency, flexibility and quality. The most distinct characteristics of CNC machines are that they are computer controlled, they integrate several operations and they may also have automatic part handling and transportation facilities. Investing in new machines (either replacement or expansion investments) implies that the effectiveness of the production system changes and the extent of the improvement is influenced by the part-operation allocation decision. We present a mixed integer programming model to determine (i) which part types to manufacture (fully or partially), on new and/or current machines, and in what quantities each period, (ii) what new CNC machine(s) to invest in and when, and (iii), which of the current machines to dispose of, and when. The optimality criterion is based on a maximization of net present value (NPV) over a specified planning horizon. The application of the model is illustrated using a numerical example. The main contribution of the paper is that it makes clear that part allocation is an important consideration in the assessment of profitability from investments in CNC technology. In our opinion and in line with our model, the investment decision should be based upon an integral view on the effect of part allocation on the effectiveness of the production system. Furthermore, CNC machine tools are often employed as multi-machine systems, and each CNC machine typically serves to replace more than one traditional machine. Using a phased implementation approach, the time horizon of the investment procedure (which not only decides what new machines to invest in, but also what current machines to dispose of) should be several years and numerous alternative investment options may be considered.

With respect to job design as shop floor design activity, we focus on two issues: (1) cross-training, and (2) labor allocation. We devote two papers to each issue, presented in Chapter 3, and Chapter 4, respectively. For the issue of cross-training, the main research question is who should be trained for which machine? Of course, in a Dual Resource Constrained (DRC) system, where the number of operators is smaller than the number of machines, at least some of the operators need to be trained for more than one machine. The question is how much cross-training is needed and who should be cross-trained. In previous research, it has been shown repeatedly that increases in the number of cross-trainings positively affect system performance. Furthermore, research shows that most of the positive effects are achieved without going to the extreme of full flexibility. However, even with a fixed number of cross-trainings in a system, there are many possible distributions of skills to workers. In our research, we develop models to support in making cross-training decisions. An important basic assumption in our models is that the distribution of cross-training

should enable an equal workload division among the workers, to encourage “chaining”. Previous research has shown that chaining is an effective policy. To obtain a chain, flexibility should be added in such a way that a path is created that connects every worker directly or indirectly with every machine. Furthermore, we want the resulting cross-training configuration to be able to effectively deal with fluctuations. These may be fluctuations in the demand for jobs, or in the supply of labor. The latter can be caused by absenteeism, for instance.

In the paper “Cross-training in a cellular manufacturing environment”, we address the question “Who should be cross-trained for which machine?” in a cellular manufacturing environment with variations in the demand mix and fluctuations in the labor supply. We have developed an integer programming (IP) model that can be used to select workers to be cross-trained for particular machines so that absenteeism becomes manageable, fluctuations in demand can be dealt with, and the available skills can be applied as efficiently as possible. We take into account the training costs as well as the efficiency-levels workers can ultimately achieve on machines. Further, constraints concerning a maximum and/or a minimum amount of multifunctionality and redundancy are formulated. The basic assumption in our approach is that training should lead to a situation in which all workers can be equally loaded in various circumstances. This creates the possibility of chaining. The model is helpful when making a trade-off between training costs and the workload balance among workers in a manufacturing cell. The workload balance indicates the usefulness of labor flexibility in a particular situation. A numerical example is presented to illustrate various elements and features of the model.

The paper “Development and evaluation of cross-training policies for manufacturing teams” is devoted to the question “What is an effective cross-training policy?” A cross-training policy can be regarded as a set of rules to determine the distribution of workers’ skills. In this paper, we discuss which aspects are important in developing a cross-training policy, develop several alternative cross-training policies, and evaluate the policies by means of a simulation study. The concept of chaining is incorporated in all cross-training policies developed. The policies are based on different choices that are made with respect to the aspects of multifunctionality, machine coverage, and collective responsibility. Multifunctionality refers to the number of machines that can be operated by a worker, machine coverage is defined as the number of workers who are able to operate a machine, and collective responsibility measures the sum of all overlapping workloads of machines to which workers can be assigned. For the Integer Goal Programming model, choices have to be made with respect to the desired number of additional cross-trainings, the minimal levels of multifunctionality and machine coverage, whether equal multifunctionality and machine coverage is strived for or not, and whether collective responsibility should be minimized or maximized. For the evaluation by means of simulation, we use mean flow time from an operations management viewpoint, and the standard deviation of the distribution of workload among workers from a human resource management viewpoint. Further, three routing structures are examined: a parallel routing structure, a serial routing structure, and a job shop routing structure. With the parallel structure, part-types must visit only one machine out of a set of non-identical machines with different processing times. Each machine has its own queue of part-types, independent of other machines. In the serial structure, part-types must visit all machines in a fixed order, representing an asynchronous flow line. In the job shop structure, the number of machines that a part-type must visit and the order in which they must be visited will differ across part-types. The simulation models incorporate absenteeism to evaluate the performance with fluctuations in the supply of

applying different who-rules in simulation studies modeling limited labor flexibility and worker differences. Factors likely to affect the extent of the effect of the who-rule are included as experimental factors as well. As for worker differences, we consider single-level flexibility (each worker has the same level of multifunctionality) versus multi-level flexibility (workers are trained for different numbers of work centers) in the first experiment. Furthermore, we consider homogeneous labor with respect to task proficiencies in the first experiment (no differences in the level of proficiency of workers) versus heterogeneous labor with respect to task proficiencies in the second experiment. Finally, we consider six levels of differences in the loads of work centers in which workers can operate in both experiments. The first experiment models DRC systems with homogeneous labor with respect to task proficiencies, single or multilevel flexibility, and six levels of disparity of work center loads, under three levels of average labor utilization. The three who-rules considered in this experiment are (1) the “Longest Idle Time” (LIT) who-rule, (2) the “Random” (RND) who-rule, and (3) the “Priority” (PRIO) who-rule. The LIT who-rule assigns the worker who has been waiting for the longest period of time. The random who-rule chooses a worker randomly, and the PRIO who-rule is specifically designed for the shop we modeled and always gives priority to one of the two workers. The second experiment models a DRC system with heterogeneous labor with respect to task proficiencies, single-level flexibility and six levels of disparity of work center loads, with 60% labor utilization. Here, the who-rules considered are: (1) the RND who-rule, and (2) the “Most Efficient” (MEF) who-rule, which assigns the worker who is the most efficient at performing the task. The results of the study show that DRC shop characteristics influence the impact of the who-rule. The impact of the who-rule is larger under lower levels of labor utilization than under higher levels of labor utilization. Furthermore, the first experiment shows that under lower levels of labor utilization, the effect of the who-rule is relatively larger with multilevel flexibility, and with distributions of work centre loads which create larger worker differences in terms of unique workloads of workers. The second experiment modeling heterogeneous labor with respect to task proficiencies shows larger effects of the who-rule than the first experiment. The higher the load of the shared work center, the more the who-rule is applied and the more often the most efficient worker is assigned. Furthermore, we show that the team-based assignment approach outperforms the individual-based assignment approach that is used in the current literature.

The paper “Labour allocation rules in Dual Resource Constrained (DRC) manufacturing systems with worker differences” examines the flow time effects of the “when-rule”, the “where-rule”, and the “who-rule” in systems with limited labor flexibility with respect to the number of machines workers can operate. We argue that skills of workers should be regarded as an individual human factor, and therefore we model workers who differ in their task proficiency and/or in the number of skills they possess. Different configurations of a DRC system with 5 workers, 10 machines, and 30 skills are simulated in three experiments. The first experiment focuses on the where-rule and the who-rule in three configurations with increasing differences in task proficiency of workers. The results show that where-rules and who-rules that base their choice on task proficiency differences result in better flow times than a simple First In System First Served (FISFS) where-rule and a random (RND) who-rule in case there are task proficiency differences. The second experiment focuses on the who-rule in three configurations with increasing differences in the number of skills workers possess. The results show that with relatively large differences in the number of skills per worker, a who-rule that assigns the worker with the fewest number of skills (FNS) results in better flow time performance than a RND who-rule. The third

labor. With respect to fluctuations in the demand of jobs, each machine has a different, but constant average utilization. Here, capacity balancing thus becomes an objective of cross-training. Jobs arrive according to a Poisson distribution, and the differences in utilization are modeled by specifying a different average processing time for each machine. The processing times of machines are distributed according to a 2-erlang distribution. In other words, the average demand per machine does not change, but at any specific moment, there can be large differences in the number of jobs in queue and in the processing times of jobs. In such a system, variability buffering becomes an important objective of cross-training as well. The results show that within the parallel and job shop structure, equal multifunctionality and equal machine coverage are important for achieving an optimal mean flow time. Within the serial structure, more attention should be paid to the bottleneck machines by combining unequal machine coverage and maximum collective responsibility. Within all routing structures presented, equal multifunctionality combined with maximum collective responsibility seems to enable a fair distribution of workload among workers. This measure relates to the social dimension of a manufacturing team.

Designing labor allocation rules is another job design activity. The two papers in Chapter four of this thesis deal with this issue, addressing the question which rules should be designed to allocate workers to tasks in order to perform well. Labor allocation rules are required in production environments where workers need to sequentially work on more than one machine. In labor limited systems, it may happen that there is sufficient machine capacity at a certain workplace, but jobs have to wait because there is not sufficient worker capacity. This can be caused by the fact that workers are busy at other workplaces or because they do not have the right skills to work at the specific workplace. Labor allocation rules are able to redirect a worker at a specified moment from his/her current activity to another activity that is given a higher priority. Designing rules that transfer labor at the right moment and to the right place improve system performance compared to less sophisticated labor allocation rules. Previous studies on labor allocation mostly study the “when-rule” and the “where-rule”, which decide when a worker is eligible for transfer, and where he/she should be transferred to, respectively. Furthermore, most studies consider a homogeneous workforce, or workers who have the same characteristics. Our studies include another labor allocation rule (the “who-rule”) and investigate systems with worker differences. The who-rule decides who should be transferred if more than one worker is available.

The paper “On the who-rule in Dual Resource Constrained (DRC) manufacturing systems” focuses on the “who-rule”. It starts out with a practical instance that serves as the empirical driver of the experimental factors chosen in the simulation study, and motivates the problem addressed in this paper. Although the who-rule seems to play a role in the daily practice of worker assignment, it is not systematically dealt with in simulation studies presented in the current literature. Previous studies either have not mentioned the who-rule or have treated it as a fixed factor. This forms the starting point for a descriptive study on the role of the who-rule in simulation studies. The who-rule may be applied in simulation when a job arrives at an empty work centre, or when a worker becomes available for transfer. The paper describes this in detail. Furthermore, an individual-based assignment approach and a team-based assignment approach are distinguished. In an individual-based assignment approach, reallocation to a specific machine is only considered for the worker who just left that machine. In contrast, a team-based assignment approach also checks whether other qualified workers are available for the machine. Based upon the descriptive study, two simulation experiments are conducted to indicate the possible impact of

experiment focuses on the when-rule, the where-rule, and the who-rule in a configuration with a large difference in task proficiency and a large difference in the number of skills workers possess. The results show that a centralized when-rule performs considerably better than a decentralized when-rule. Furthermore, the where-rule and who-rule that base their choice on task proficiency perform better than a FISFS where-rule and a FNS and RND who-rule, respectively. Finally, the effect of the where-rule and the who-rule seems to be larger in case of a centralized when-rule.

In this thesis, various issues have been dealt with: the choice of a basic layout, investment appraisal, cross-training, and labor allocation. These issues are -at a high level- related by their process design focus within the field of Operations Management. Furthermore, the papers deal with decisions that have to be made by companies with respect to the design of the shop floor. These decisions are at least tactical decisions, and some may even have impact on the strategic level. Another similarity in most of the papers is the attention to the human factor and the integrated approach. Even though these issues have been treated more or less independently in different papers, there is a link between the issues dealt with in the papers and it may be fruitful to integrally study some or all of these issues. The four papers dealing with cross-training and labor allocation show most coherence. Cross-training and labor allocation are two job design activities that can be related to labor flexibility. The extent and distribution of cross-training impacts the flexibility of the workforce, as well as do the allocation rules chosen to allocate workers to machines. An interesting direction for further research is to integrally study the shop floor design issues of cross-training and labor allocation. An integral study of layout and investments, or layout and cross-training may also be fruitful. Studying the relations between these issues may enrich the research on shop floor design.