Martin Morlock, Christoph Schwindt, Norbert Trautmann, Jürgen Zimmermann (Eds.)

Perspectives on Operations Research

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Essays in Honor of Klaus Neumann

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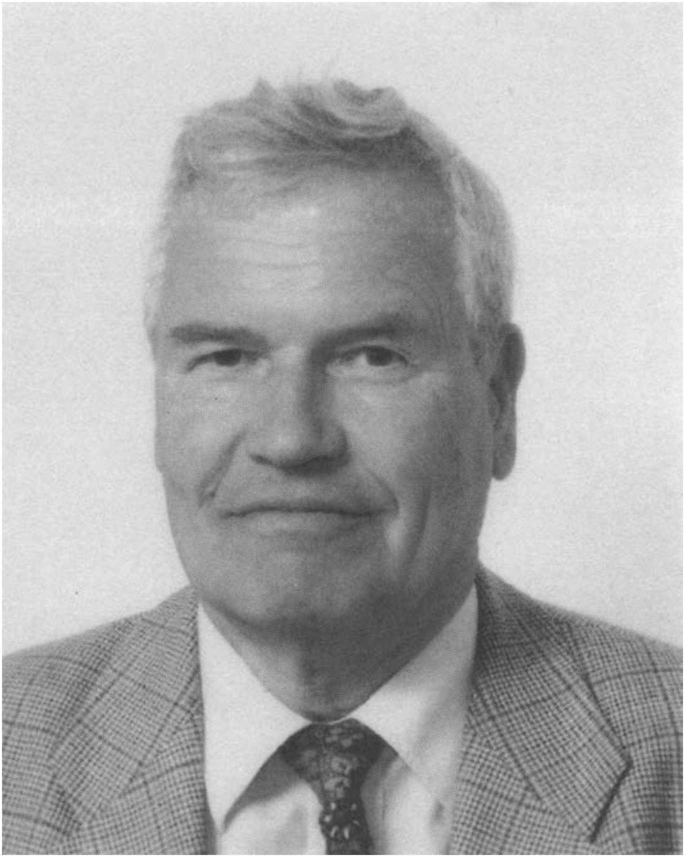

Preface

This collection of essays is dedicated to Professor Klaus Neumann, Head and Chair of the Institute for Economic Theory and Operations Research WiOR at the University of Karlsruhe. On the occasion of his emeritation, disciples, colleagues, scientific companions, and friends coming from different fields have contributed their perspectives on Operations Research to form a broad view on the discipline. The papers are organized in four parts on optimization, OR in production and service management, OR in logistics, and interdisciplinary approaches. We thank all the authors for their participation in publishing this volume. Mrs. Ute Wrasmann from Deutscher Universitäts-Verlag deserves credit for her interest and assistance on this project. Finally, we would like to express our gratitude to PTV Planung Transport Verkehr AG in Karlsruhe and to numerous former WiOR colleagues for their financial support.

Klaus Neumann was born in Liegnitz (Silesia) in 1937. From 1955 to 1961 he studied mathematics at the Technical Universities of Dresden and Munich. His first paper on analog computers and dynamic programming was published less than two years later. In 1964 he obtained a Ph.D. in mathematics under the supervision of Josef Heinhold in Munich. After a two-year stay in industry, he returned to his alma mater, working on the fields of dynamic optimization and control theory. In 1968 he was conferred the venia legendi for mathematics from the Technical University of Munich with a habilitation thesis on optimization subject to nonholonomous constraints. The same year he moved to the University of Karlsruhe, where he took up the head of the computer center. Since 1970 he is full professor of Operations Research at the School of Economics and Business Engineering in Karlsruhe.

Klaus Neumann has strongly influenced the development of Operations Research in Germany over more than four decades. For generations of German-speaking students his seminal trilogy *Operations-Research-Verfahren* has been the OR textbook of choice. His books on Operations Research and Production and Operations Management published in the 1990s remain a major reference in the field. Scientific monographs on dynamic programming (1969), control theory (1969), stochastic project networks (1979 and 1990), and project scheduling (2003) are evidences of his fruitful research, which has repeatedly been supported by the German Research Foundation DFG and by industry. The main achievements of this research are outlined in the first chapter of this book. From 1970 to date Klaus Neumann has supervised more than 30 doctoral and habilitation candidates. He held visiting professorships at the Universities of California at Berkeley and Riverside, Stanford, Florida, Waikato at Hamilton, Kunming, and Beijing Institute of Technology. Since 1972 he has been editor of several scientific series and journals like *Mathematical Systems in Economics*, *Methods of Operations Research*, and *Mathematical Methods of Operations Research*. In addition, he has been chairman and (and still is) member of the program committee of numerous scientific conferences such as EURO WG PMS, IEPM, IKM, or MISTA.

All over the years, students and colleagues at WiOR have not only benefited from Klaus Neumann's comprehensive scientific knowledge and expertise. We all have been influenced by his cultivated personality and generosity. Memorable excursions, wine tastings, and exquisite dinner receptions at his home in Conweiler have set very high cultural standards at our institute. We wish Klaus all the best for the future.

Gießen, Clausthal-Zellerfeld, Bern
November 2005

Martin Morlock
Christoph Schwindt
Norbert Trautmann
Jürgen Zimmermann

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Martin Morlock

Department of Economics
University of Gießen

Christoph Schwindt and Jürgen Zimmermann

Institute for Management and Economics
Clausthal University of Technology

Norbert Trautmann

Departement für Betriebswirtschaftslehre
University of Bern

1 Introduction

In this paper we give a short overview of the research conducted, initiated, and supervised by Klaus Neumann from the early sixties up to present. Of course, we do not claim exhaustiveness of our review. The major themes of research can be clustered into the three main areas sketched in Sections 2 to 4:

- Control Theory and Dynamic Programming (1960s and 1970s)
- GERT Networks (1970s to 1990s)
- Resource-Constrained Project Scheduling (since 1990s)

In any of those fields, Klaus Neumann has significantly influenced the development of OR in Germany and beyond. From the very beginning, his research has combined solid mathematical foundation and applicability of theoretical results. The relevance of his achievements to the treatment of real-world problems has been reflected in many applied research and development projects. A selection of the projects that have been carried out in cooperation with different industrial partners is sketched in Section 5.

2 Control Theory and Dynamic Programming

Among the various approaches existing at the beginning of the 1970's in quantitative economic science, only linear programming has been successful on a broad front. For this simply structured class of static optimization problems, a commonly accepted and transparent model as well as efficient solution algorithms could be developed and applied due to the enormous advances in computer technology.

However, a multitude of practical problems in management and economics is not static in nature, but concern the analysis and optimal solution of time-dependent (decision) processes. Such problems are well-known as control problems (particularly in technology). To find an optimal solution to such problems, mainly two different approaches have been investigated: *control theory* and *dynamic programming.*

Control theory in continuous time is based substantially on an analytic approach referring to the *Pontrjagin maximum principle* and *transversality conditions.* Fundamental to dynamic programming is the so-called *Bellman optimality principle*, which was developed in the 1950's by the American mathematician Richard Bellman (cf. Neumann 1969a). In particular Neumann contributed several publications to the spreading of those two optimization techniques and to their application. Together with Bauer (1969), he was one of the first who explained in a very lucid way these two fundamental approaches and their relationship. For the acceptance and successful use of dynamic models, both their theoretical foundation and the development of numerical methods were essential. Major contributions to the latter topic, as well as descriptions of relevant applications, can be found for example in Neumann (1969a) and (1975a).

Initial considerations were concerned with the question whether analog or digital computers should be used for the numerical solution of dynamic optimization problems, especially for dynamic optimization problems in continuous time (cf. Neumann and Neumann 1963). Rapid progress in the digital computer technology soon decided in favor of the digital computers. In the following, research in the areas of control theory and dynamic programming concentrated on the development of solution procedures for different problems with a great diversity of applications and on their theoretical foundations (cf. e.g., Neumann 1965a, 1965b, 1968, 1969b, 1969c, 1970a, and 1971a). In addition, for applying the dynamic optimization principle, which represents a universally applicable instrument, large numerical problems had to be tackled. Dynamic programming mainly suffers from the curse of dimensionality. This means that the search process exploiting Bellman's optimality principle in higher-dimensional state and control spaces results in exponentially growing computational requirements. Some efficient procedures reducing the costs of computation by using approximating approaches and appropriately adapted gradient methods are, for example, presented in Neumann (1970b, 1975b).

A substantial strength of the Bellman optimality principle and its successful use appears if the problem decomposes into many similar and interdependent sub-problems. These sub-problems are exposed to coincidental influences and the solution of the total problem can be built up from optimal solutions of the sub-problems. This is for instance the case for *Markov decision problems.* These problems belong to the field of stochastic dynamic programming and cover economic questions for which stochastic influences are relevant. The aspect of risk, connected with economic acting, plays a more and more important role in decision making (cf. Neumann and Morlock 2002).

Finally, a class of problems which are relevant to practice and for which stochastic dynamic programming proved suitable are known as *decision activity networks.* This is a very clear planning instrument for the representation and handling of stochastic network project control and scheduling problems, which, since the middle of the 1970's, are studied in numerous publications (cf. Neumann 1977a). In the following section, those networks are treated in more detail.

3 GERT Networks

Project planning, scheduling, and control are widely used in practice to accomplish outcomes under critical time constraints and given limited resources. Classical network techniques like CPM, MPM, or PERT are used for projects whose evolution in time can be uniquely specified in advance (cf. Neumann and Morlock 2002). Unfortunately, in practice this condition is frequently not fulfilled. Consider for instance an inspection that takes place during a production process and which reveals that a product does not conform to a set of given specifications. Thus it must be repaired or replaced, i.e., we have to return to a preceding stage of the production process. Since only a certain percentage of tested products does not comply with the specifications, this feedback loop occurs with a probability of less than one. To deal with these more general projects, whose evolution in time cannot be anticipated precisely (stochastic evolution structure of the project) and where feedback is permitted, so-called GERT networks with an activity-on-arc representation have been introduced (cf. Neumann 1971b, 1976, and 1977b).

The essential features of **GERT networks** as compared to CPM or PERT networks are more general arc weights, cycles to represent feedback, and six different types of nodes. These node types arise from combining three different *node entrances* corresponding to the logical operations "and", "inclusive-or", and "exclusive-or" as well as two possible *node exits*, which determine whether exactly one ("stochastic exit") or all ("deterministic exit") emanating activities must be performed if the corresponding node is activated. For each arc (activity) there is a conditional execution probability given that the corresponding initial event has occurred and a conditional distribution function for the duration of that activity given that the activity is carried out. For an in-depth treatment of the theory of GERT networks, we refer to Neumann and Steinhard (1979a) and Neumann (1989, 1990).

In CPM, MPM, or PERT network techniques, the **temporal analysis** of the project includes the determination of the earliest and latest start times of the project activities, the earliest and latest occurrence times of certain project events, as well as the computation of the project duration or its distribution. For GERT networks these concepts have been discussed by Neumann (1979a) and Neumann and Steinhard (1979a). However, in the case of GERT networks the meaning of those concepts is quite different because project events may occur several times and their computation is much more complicated. Therefore, the temporal analysis of GERT networks usually only considers quantities that are associated with the terminal events of the project such as the probability that certain terminal events will occur (a GERT network generally has more than one sink) and the respective (conditional) distribution function (cf. Neumann 1979b, 1990). For general GERT networks the temporal analysis is usually very time consuming because it requires the evaluation of multiple integrals (cf. Neumann 1984b). For special GERT networks such as so-called *EOR networks*[1] or *reducible GERT networks*[2] results from Markov renewal processes can be exploited for the temporal evaluation of the network, which simplifies the determination of the activation distributions (cf. Fix and Neumann 1979, Neumann and Steinhard 1979b, and Neumann 1985).

Besides the temporal analysis of stochastic projects, the **cost minimization** of such projects is of great interest. In the case of GERT networks different types of costs are incurred by the execution of activities and the occurrence of events. For EOR networks the cost minimization problem again leads to a Markov renewal decision process and can thus be modeled and solved as stochastic dynamic programming problem (see Neumann 1981, 1984a and Foulds and Neumann 1989). A different approach to solving the cost minimization problem, which leads to an optimal control problem, has been proposed by Delivorias et al. (1984).

If scarce resources (e.g., machines) are required for performing the proj-

[1] EOR networks are GERT networks whose nodes have an "exclusive-or" entrance.

[2] A GERT network is called reducible, if all nodes with "and" or "inclusive-or" entrances are part of special subnetworks which can be reduced to structures containing only "exclusive-or" nodes with a stochastic exit.

ect activities, so-called **GERT scheduling problems** have to be solved, whose type depends on the structure of the underlying production processes (cf. Neumann 1999). In particular single machine, parallel machine, flow shop, and job shop scheduling problems with GERT network precedence constraints arise in practical applications involving product variants. For single machine scheduling problems with stochastic precedence constraints a dynamic programming approach can be found in Neumann (1990). Polynomial algorithms for single machine scheduling problems with precedence constraints given by an EOR network are developed by Bücker et al. (1994). Heuristic procedures for parallel machine problems with GERT precedence constraints are discussed in Foulds et al. (1991) and Neumann and Zimmermann (1998). Neumann and Schneider (1999) deal with minimizing the expected makespan of flow shop and job shop scheduling problems with EOR network precedence constraints. A comprehensive summary on scheduling problems with GERT precedence constraints is given by Neumann (1990, 1999).

4 Resource-Constrained Project Scheduling

In this section we consider the planning of projects for which the evolution structure, activity durations, and resource data can be estimated in advance with sufficient accuracy. In this case we may consider the predictive data as being deterministic and take uncertainty into account by constructing robust plans or dynamically reacting on disruptions during the implementation. Project scheduling as part of project planning is concerned with computing time intervals for the execution of project activities in such a way that the precedence relationships between activities are satisfied and an objective function formulating the planning goal is minimized or maximized. In resource-constrained project scheduling, the latter problem amounts to allocating scarce resources over time to the execution of the activities. Different types of resources have been considered in the literature. The availability of *renewable resources* like personnel, machines, or equipment at a given time solely depends on the activities being in progress. Examples of *cumulative resources*, whose availability depends on the complete project history, are funds, materials, or storage space.

For what follows, we suppose that the execution modes defining the resource requirements of each activity have been fixed and that the activities must not be interrupted during their execution. A solution to such a single-mode scheduling problem is usually represented as a vector of activity start times, which is called a schedule. Furthermore, we assume that the precedence relationships between activities are given as *minimum and* *maximum time lags* between the start times of activities. The activities and time lags can be modeled as an MPM network, possibly containing cycles. Minimum and maximum time lags allow to formulate many constraints arising in practical applications of project scheduling like release dates, deadlines, quarantine and shelf life times, or overlapping activities (see Franck et al. 1997 and Neumann and Schwindt 1997, 1998 for applications of project scheduling models in production planning). Minimum and maximum time lags greatly add to the complexity of resource-constrained scheduling problems since in difference to the case of ordinary precedence constraints, the problem of finding a feasible schedule is already NP-hard even if the project only contains renewable resources.

An **overview** of models and methods for project scheduling is given by Brucker et al. (1999), which also provides a three-field classification scheme for project scheduling problems. Many of the results on project scheduling in MPM networks mentioned in this section are presented in more detail in a review by Neumann et al. (2002b) and the monograph by Neumann et al. (2003a).

Exact and heuristic algorithms for project scheduling are based on the exploration of finite sets containing efficient points of the feasible region. The type of schedules to be investigated depends on the objective function under consideration. Based on a **structural analysis** of the feasible region, Neumann et al. (2000) have proposed a classification of objective functions and corresponding efficient points. The analysis shows that basically, efficient points can be enumerated in two alternative ways. If the temporal scheduling problem arising from deleting the resource constraints can be solved efficiently, the classical approach consists in using some relaxation-based generation scheme branching over alternatives to resolve resource conflicts. Examples of objective functions for which temporal scheduling can be done efficiently are the makespan (project duration) and the sum of discounted cash flows associated with the project activities (net present value of the project). If already the temporal scheduling problem is NP-hard, an optimal schedule can be computed with a constructive generation scheme, which iteratively establishes binding temporal or precedence constraints. Resource leveling problems, where the objective is to smooth the resource utilization over time, belong to this second class of problems.

For solving the **project duration problem** with renewable resources, both the constructive and the relaxation-based approache have been used. Priority-rule based methods exploiting the cyclic structure of the MPM project network have first been presented by Neumann and Zhan (1995) and Brinkmann and Neumann (1996). In Franck et al. (2001), the performance of different priority-rule based methods, local search procedures, and truncated branch-and-bound algorithms based on resource relaxation have been compared with respect to accuracy and computation time. A branch-and-bound algorithm for the project duration problem with cumulative resources can be found in Neumann and Schwindt (2002).

Schedule-construction algorithms for the **net present value problem** have been devised by Neumann and Zimmermann (2000). A relaxation-based branch-and-bound algorithm for this problem has been developed by Neumann and Zimmermann (2002). In this algorithm, the temporal scheduling problems are solved by efficient primal and dual vertex-following algorithms.

Brinkmann and Neumann (1996) and Neumann and Zimmermann (1999, 2000) have treated several variants of the **resource leveling problem**. Depending on whether the maximum resource usage or the variability in resource utilization shall be minimized, different sets of tentative activity start times are investigated. According to the principle of the constructive schedule-generation scheme, the sets are chosen in way ensuring that in each iteration some temporal or precedence constraint becomes binding. Order-based neighborhoods for project scheduling problems with general nonregular objective functions like the net present value of resource leveling functions can be found in Neumann et al. (2003b).

5 Selected Applications

In what follows, we briefly discuss some selected applications of the research that has been described in the preceding sections. Together with further applications, they all are the result of applied research projects carried out in cooperation with partners from different industries.

A six-year research and development project building on the achievements in the field of resource-constrained project scheduling was concerned with **short-term production planning in the process industries**. In those industries, final products arise from several successive chemical or physical transformations of bulk goods, liquids, or gases processed on *processing units* such as reactors, heaters, or filters. Each transformation process may consume several input products and may produce several output products, whose amounts may be chosen within prescribed bounds. Perishable products must be consumed within a given shelf life time, which may be equal to zero. In addition, the storable intermediate products must be stocked in dedicated *storage facilities* like tanks or silos. Further peculiarities encountered in the process industries are cyclic product structures and sequence-dependent cleaning times on processing units.

For the case of batch production, Neumann et al. (2002a) present a new solution approach, which can solve much larger practical problems than the methods known at this time. The new approach decomposes short-term planning for batch production into *batching* and *batch scheduling*. Batching converts the primary requirements for products into individual batches, where the objective is to minimize the resulting workload. The batching problem is formulated as a mixed-integer nonlinear program. The latter problem is transformed into a mixed-binary linear program of moderate size, which can be solved by standard MILP software. A solution to the batch scheduling problem allocates the batches to scarce resources such as processing units, workers, and intermediate storage facilities, where some regular objective function like the makespan is to be minimized. The batch scheduling problem is modeled as a resource-constrained project scheduling problem, which can be solved by new efficient truncated branch-and-bound or priority-rule based methods. The performance of the new solution procedures for batching and batch scheduling is demonstrated by solving several instances of a case study from process industries. Recently, the truncated branch-and-bound algorithm for the batch scheduling problem has been generalized to the case of continuous material flows (cf. Neumann et al. 2005).

Schwindt und Trautmann (2003) study a real-world scheduling problem arising in aluminium industry. They consider the production of *rolling ingots*, i.e., ingots of a certain aluminium alloy in rectangular form. These ingots are the starting material for the rolling of sheet, strip, and foil. It is shown how to model this scheduling problem as a resource-constrained project scheduling problem using minimum and maximum time lags between operations, different kinds of resources, and sequence-dependent changeovers. A solution procedure of type branch-and-bound is presented.

Now we turn to a project scheduling application from the area of **service operations management**. Car manufacturers increasingly organize visit programs for the customers that pick up their new cars at the factory. Such a program consists of a broad range of *event-marketing activities* and is designed to establish an emotional relationship between the customer and the brand. Mellentien et al. (2004) study the problem of scheduling all program activities of one day in such a way that the sum of the customers' *waiting times* during their visit is minimized. In service operations management, short customer waiting times are considered to be a key performance indicator of customer satisfaction.

Eventually, resource-constrained project scheduling has been applied to the problem of managing **research and development projects** in the pharmaceutical industries. Kolisch et al. (2003) study the problem of scheduling research activities in *drug development*. A particularity of this problem is that the manpower requirements of the activities may vary over time, the requirement profiles being subject to decision.

In a current research project, quantitative methods for decision support in the **service industries** are developed. Schön-Peterson (2003) has developed various models and solution methods for the pricing of telecommunication services.

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Part I
Optimization

Matrices in Shop Scheduling Problems

Heidemarie Bräsel

Faculty of Mathematics
Otto-von-Guericke University Magdeburg

Es ist für mich eine ehrenvolle Aufgabe, einen Beitrag für dieses Buch einzubringen. Gleichzeitig ist es ein herzliches Dankeschön für Herrn Prof. Klaus Neumann für seine wissenschaftlichen Arbeiten, deren Ergebnisse ich sehr gern nutze, und für seine Unterstützung und sein stetes Interesse an der Entwicklung unserer Forschungsgruppe. Ich verbinde dies mit allen guten Wünschen für einen gesunden Ruhestand der Familie Neumann, der - dessen bin ich mir sicher - öfter auch in einen Unruhestand ausarten wird.

1 Introduction

In this paper shop scheduling problems are modeled by matrices. Initially we assume that each job is processed at most once on each machine. It is shown how the model can be extended to shop problems with more than one operation on each machine and to the case that preemption is allowed.

Modelling shop problems by matrices is a very natural approach of modelling such scheduling problems. At first it was presented by BRÄSEL [1]. The model is easy comprehensible and can be applied to simplify the description of algorithms in this field, for instance the block-approach idea for job shop problems and algorithms in the case of unit processing times.

Moreover, this model gives rise to new theoretical results. We give a brief review on such papers. The complexity question of some open shop problems with unit processing times was solved, see for instance BRÄSEL ET AL. [7], [8] and [9], TAUTENHAHN [16] and [17]. The insertion technique (cf. [1]) was developed for enumeration algorithms and beam search strategies, see for instance BRÄSEL ET AL. [10], WERNER AND WINKLER [18] and SOTSKOW ET AL. [15]. Theoretical results were obtained for counting problems, see BRÄSEL AND KLEINAU [5], HARBORTH [14] and BRÄSEL ET AL. [2] and [3]. Moreover, the model was applied for structural investigations of sequences and schedules: Shop scheduling spaces were characterizised algebraically by DHAMALA [12]. The irreducibility theory was developed, introduced by BRÄSEL AND KLEINAU [6]. Here especially the papers of BRÄSEL ET AL. [2], [3] and WILLENIUS [19] has to be mentioned. Furthermore, the software package LiSA works with this model succesfully.

However, there is no article in English to explain the basic model in detail. This paper closes this gap. It is organized like an introductory lecture on shop problems. We start with basic notations, give an overview on the used graphs and their description by matrices and present simple algorithms concerning the defined matrices. The insertion technique for construction of sequences is introduced and some properties of sequences are charakterized. We next show how the model can be modified for other classes of shop problems. Finally, the software package LiSA - A Library of Scheduling Algorithms is presented which contains the introduced matrices and their visualization as graphs and Gantt charts.

2 Basic Notations

In a *shop scheduling problem* a set of n *jobs* A_i, $i \in I = \{1, \ldots, n\}$, has to be processed on a set of m *machines* M_j, $j \in J = \{1, \ldots, m\}$, in a certain machine environment α under certain additional constraints β such that an objective function γ is optimized. Such a problem is called deterministic if all parameters are fixed and given in advance. Various optimization problems concerning allocation of restricted resources can be modeled as scheduling problems. We use the standard $\alpha \mid \beta \mid \gamma$ classification of deterministic scheduling problems developed by GRAHAM ET AL. [13].

At first we consider so-called *classical* shop problems, i.e., each job is processed on each machine at most once.

Processing of job A_i on machine M_j is called an *operation* (ij). PT denotes the matrix of processing times: $PT = [p_{ij}]$. The set of all operations SIJ is given by $SIJ = \{(ij) \mid p_{ij} > 0\}$. We assume that each job is processed on at most one machine at a time and each machine processes at most one job at a time. For certain shop problems, a *release time* $r_i \geq 0$, a *due date* $d_i \geq 0$ or a weight $w_i > 0$ for job A_i, $i \in I$, are requested. Let u_i and v_j be the number of operations for job A_i and on machine M_j, respectively. Then we define:

The *machine order of the job* A_i is the order of machines on which this job has to be processed: $M_{j_1} \to M_{j_2} \to \ldots \to M_{j_{u_i}}$.

The *job order on machine* M_j is the order of the jobs which this machine processes: $A_{i_1} \to A_{i_2} \to \ldots \to A_{i_{v_j}}$.

In a *job shop problem* $(\alpha = J)$ the machine order of each job is given in advance. In a *flow shop problem* $(\alpha = F)$ the machine orders of each job are the same , w.l.o.g. in the case of $SIJ = I \times J$: $M_1 \to M_2 \to \ldots \to M_n$. In an *open shop problem* $(\alpha = O)$ both machine orders and job orders can be chosen arbitrarily. Other precedence constraints on the operations can be easily integrated into the model.

In a shop problem a combination of machine orders and job orders is to determine such that a time table of processing (schedule) can be constructed, which satisfies the additional constraints and minimizes the given objective function.

Let C_i be the completion time of job A_i. An objective function $\gamma = F(C_1, \ldots, C_n)$ is called *regular* if it has the following property:
If for two schedules S and S^* the inequality $C_i^* \geq C_i$ holds for all $i \in I$ then $F(C_1^*, \ldots, C_n^*) \geq F(C_1, \ldots, C_n)$ is satisfied.

The makespan C_{max}, the weighted sum of completion times $\sum w_i C_i$, the maximum lateness L_{max}, the weighted tardiness $\sum w_i T_i$ and the weighted number of late jobs $\sum w_i U_i$ are regular, where:
$C_{max} = \max\limits_{i \in I}\{C_i\}$, $L_{max} = \max\limits_{i \in I}\{d_i - C_i\}$, $\sum w_i T_i = \sum\limits_{i \in I} w_i \max\{0, d_i - C_i\}$

and $U_i = \begin{cases} 1, & \text{if } C_i > d_i \\ 0, & \text{otherwise} \end{cases}$ for all $i \in I$. Often $w_i = 1$ for all $i \in I$ holds.

3 Graphs and Matrices for Shop Problems

This chapter starts with a model of shop problems where preemption of the operations is not allowed.

3.1 Partial Orders and Schedules

We define the following digraphs where in each case the set of vertices is the set SIJ of operations:

- The digraph of machine orders $G(MO) = (SIJ, A_{mo})$ contains all arcs which describe the direct precedence constraints in all machine orders.
$$((ij), (kl)) \in A_{MO} \Longleftrightarrow \begin{cases} i = k \ \wedge \text{ after the processing of job } A_i \text{ on} \\ M_j \text{ job } A_i \text{ is processed on machine } M_l \end{cases}$$
- The digraph of job orders $G(JO) = (SIJ, A_{JO})$ contains all arcs which describe the direct precedence constraints in all job orders.
$$((ij), (kl)) \in A_{JO} \Longleftrightarrow \begin{cases} j = l \ \wedge \text{ after the processing of job } A_i \text{ on} \\ \text{machine } M_j \text{ machine } M_j \text{ processes } A_k. \end{cases}$$
- The digraph $G(MO, JO) = (SIJ, A)$ contains all arcs of $A = A_{MO} \cup A_{JO}$.

A combination (MO, JO) of machine orders and job orders is called *feasible*, if the corresponding digraph $G(MO, JO)$ does not contain a cycle. In this case $G(MO, JO)$ is called a *sequence graph.* The described acyclic graphs are partial orders on the set of all operations.

Example 1 *Assume that three jobs have to be processed on four machines. The matrix* PT *of processing times is given by*

$$PT = \begin{bmatrix} 2 & 1 & 0 & 1 \\ 2 & 3 & 4 & 3 \\ 1 & 5 & 1 & 2 \end{bmatrix}, \textit{ therefore } SIJ = I \times J \backslash \{(13)\} \textit{ holds.}$$

We consider the following machine orders and job orders:

$$\begin{array}{llll} A_1: & M_1 \to M_2 \to M_4 & M_1: & A_1 \to A_2 \to A_3 \\ A_2: & M_2 \to M_4 \to M_1 \to M_3 & M_2: & A_2 \to A_3 \to A_1 \\ A_3: & M_4 \to M_1 \to M_2 \to M_3 & M_3: & A_3 \to A_2 \\ & & M_4: & A_3 \to A_1 \to A_2 \end{array}$$

The corresponding digraph $G(MO, JO)$*, see Figure 1, contains* vertical *arcs, which represent job orders on the machines and* horizontal *arcs representing machine orders of the jobs.*

The combination of machine orders and job orders is not feasible because $G(MO, JO)$ *contains the cycle* $(12) \to (14) \to (24) \to (21) \to (31) \to (32) \to (12)$. *Since we have a cycle, there can not exist any schedule of processing.*

If we choose the natural order of the machines in each machine order and of the jobs in each job order, the digraph $G(MO, JO)$ *cannot contain any cycle, because all arcs are directed to the left or downwards. In this case a corresponding schedule can easily be constructed.*

Now we assign the weight p_{ij} to each vertex (ij) of the sequence graph $G(MO, JO)$. Then a schedule can be constructed. Usually schedules are described by the start times or the completion times of all operations. There exist the following classes of schedules:
A schedule is called a *non-delay* schedule, if no machine is kept idle when there exists a job available for processing.
A schedule is called *active*, if no operation can be completed earlier by changing the job orders without delaying any other operation.
A schedule is called *semiactive*, if no operation can be completed earlier without changing the job order on any of the machines.

Note, that each non-delay schedule is also active and each active schedule is also semiactive, but not vice versa.

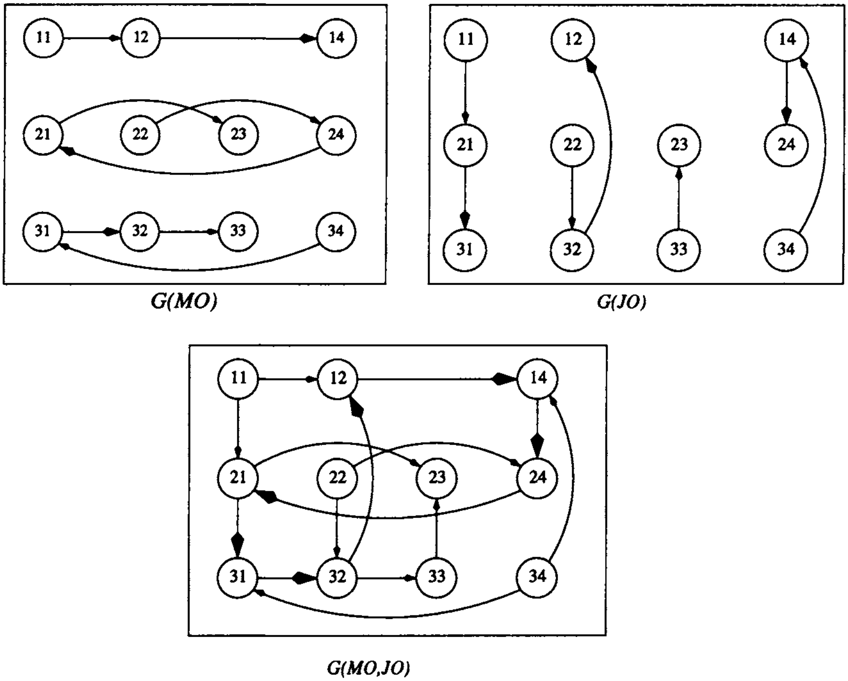

Figure 1: $G(MO)$, $G(JO)$ und $G(MO, JO)$ for Example 1

In the case of regular objective functions there always exists an optimal semiactive schedule and the computing of a longest path in $G(MO, JO)$ yields the makespan. We use the notation *longest path* with respect to the sum of the weights of the vertices contained in the path. Schedules are visualized by *Gantt charts*, which can be *machine oriented* or *job oriented.* In Figure 2 a job-oriented Gantt chart of a schedule with minimal makespan is given (see Example 1). There cannot be any better schedule because the longest job A_2 has no idle time within its processing.

In general, the set of schedules is infinite, but the set of sequences is finite. The binary relation R in the set of schedules:
"schedule 1 R schedule 2 if and only if both schedules have the same machine orders and job orders" is an equivalence relation. We can choose all semiactive schedules with unit processing times as representativs of the equivalence classes, whose number is finite.

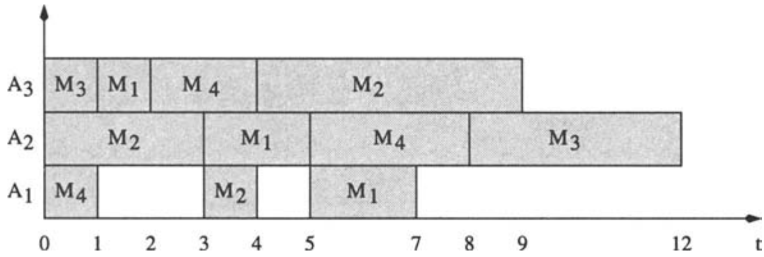

Figure 2: Job-oriented Gantt chart

3.2 Matrices in Shop Problems

In the literature the most commonly used model for shop problems is the well-known disjunctive graph model, see for instance BRUCKER [11]. We obtain the model used here by the following modifications:
- Cut the inserted source and sink and the corresponding incident arcs.
- Determine an acyclic orientation of the disjunctive graph.

We obtain the sequence graph (cf. Section 3.1) by deleting all transitive arcs which are not direct precedence constraints in the machine orders and in the job orders.

Now we define a set of matrices, where in each matrix an information of the operation (ij) on position (ij) is contained, this is the real advantage of the model. The digraphs $G(MO), G(JO)$ and $G(MO, JO)$ and in particular, the structure of the contained paths are visible by the matrices without drawing the digraphs. The number of vertices on a longest path with respect to unit weights of all vertices from a source to the vertex v is called *rank* of v: $rk(v)$. Now we define the following matrices:

- the *machine order matrix* $MO = [mo_{ij}]$: mo_{ij} is the rank of the operation $(ij) \in SIJ$ in the digraph $G(MO)$.
- the *job order matrix* $JO = [jo_{ij}]$: jo_{ij} is the rank of the operation $(ij) \in SIJ$ in the digraph $G(MO)$.
- the *sequence (matrix)* $PO = [po_{ij}]$: po_{ij} is the rank of the operation $(ij) \in SIJ$ in the sequence graph $G(MO, JO)$.

These matrices describe structural properties of a solution of a shop problem.

We extend this set by matrices with properties of the weighted sequence graph, i.e. the corresponding schedule (see Figure 3):