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FASTEST

Fast-track hybrid testing platform for the development of battery systems

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Resource scheduling concept

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Project Abstract

Current methods to evaluate Li-ion batteries safety, performance, reliability and lifetime represent a remarkable resource consumption for the overall battery R&D process. The time or number of tests required, the expensive equipment and a generalised trial-error approach are determining factors, together with a lack of understanding of the complex multiscale and multi-physics phenomena in the battery system. Besides, testing facilities are operated locally, meaning that data management is handled directly in the facility, and that experimentation is done on one test bench.

The FASTEST project aims develop and validate a fast-track testing platform able to deliver a strategy based on Design of Experiments (DoE) and robust testing results, combining multi-scale and multi-physics virtual and physical testing. This will enable an accelerated battery system R&D and more reliable, safer, and long-lasting battery system designs. The project's prototype of a fast-track hybrid testing platform aims for a new holistic and interconnected approach. From a global test facility perspective, additional services like smart DoE algorithms, virtualised benches, and DT data are incorporated into the daily facility operation to reach a new level of efficiency.

During the project, FASTEST consortium aims to develop up to TRL 6 the platform and its components: the optimal DoE strategies according to three different use cases (automotive, stationary, and off-road); two different cell chemistries, 3b and 4 solid-state (oxide polymer electrolyte); the development of a complete set of physic-based and data-driven models able to substitute physical characterisation experiments; and the overarching Digital Twin architecture managing the information flows, and the TRL6 proven and integrated prototype of the hybrid testing platform.

LIST OF ABBREVIATIONS, ACRONYMS AND DEFINITIONS

Acronym	Name
B&B	Branch & Bound
DUT	Device under Testing
FF	First-fit algorithm
FFD	First-fit decreasing algorithm
IP	Integer Programming
ILFD	Iterated-Lowest-Fit-Decreasing Algorithm
LP	Linear Programming
MIP	Mixed Integer Programming
PMX	Partially-Mapped Crossover Operator
PTAS	Polynomial-Time Approximation Scheme
FPTAS	Fully-Polynomial-Time Approximation Scheme

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1. EXECUTIVE SUMMARY

This work package, WP6.1, is focused on investigating the daily activities involved in scheduling test resources within a test center, aiming to optimize the utilization of available hardware, resources, test requirements, and various constraints. The objectives include collecting representative task descriptions, test data, and real-life scenarios, as well as performing a literature survey on existing scheduling algorithms for potential solution approaches.

In the current testing facility landscape, operations are often managed locally, with data management and storage handled directly within the facility. The Laboratory Inventory Management System (LIMS) is introduced as a central component of the FASTEST project to streamline the management of testing facilities. The efficient use of available resources is highlighted as crucial for overall efficiency improvement.

The description of work in WP6.1 focuses on systematically assessing the requirements within the battery testing domain. The planning challenge is characterized as a problem involving identically parallel machines with precedents and additional resources. The assessment includes an analysis of theoretical foundations, the planning scenario within a battery test field, and concludes with the selection of the Branch & Bound algorithm as the most promising solution approach for the FASTEST project.

The conclusion emphasizes the machine allocation planning of a battery test field as a novel planning problem with new requirements. The goal of WP6.1 is to develop an approach for automating machine allocation planning, laying the theoretical foundation. WP6.2 will subsequently focus on implementation. The chosen solution approach involves modeling the planning problem as a mixed-integer program, with flexible components for future extension. The final development of the LIMS will be addressed in WP6.2.

2. OBJECTIVES

Main purpose of this work package WP6.1 is to investigate, which daily activities are executed today to perform the scheduling of test resources in a test centre to optimally utilize available hardware, resources, test requirements, boundary conditions and other constraints. Representative task descriptions, test data and real-life scenarios are collected. The impact of respective shortness and approaches for optimization are generally described. Literature survey on existing scheduling algorithms must be performed and compared for candidates of potential solution approaches.

3. INTRODUCTION

Nowadays, the operation of test facilities is typically performed under a local approach. Here, "local" is interpreted in two fashions. First, data management and storage are handled directly related to the facility. Often, manual data management based on Excel or home-brewed software solutions is established. In some cases, the movement towards so-called Laboratory Inventory Management Systems (LIMS) is ongoing to optimise the management of testing facilities.

As a central component of the FASTEST project, the Laboratory Inventory Management System (LIMS) handles all local tasks, resources, configuration, and data. The efficient usage of available resources (physical benches and equipment, specialist personal, virtualized benches, simulation and calculation resources, etc.) is key to the overall efficiency increase of the test centre.

4. DESCRIPTION OF WORK

This work exclusively addresses the deliverables of W6.1. Hence, the emphasis lies on systematically assessment of the requirements within the battery testing domain. The planning challenge is characterized as a problem involving identically parallel machines with precedents and additional resources. Evaluating various approaches from the literature. The analysis encompasses the theoretical foundations, the planning scenario within a battery test field, and concludes with an assessment of the chosen solution approach.

5. Theoretical foundations

5.1 Machine assignment planning

In this section, machine utilization planning is placed in the framework of production planning and basic terms are introduced.

Machine utilization planning is part of production planning. First, the term production is explained and then the term planning is defined.

Production involves the bringing forth of goods. A distinction is made between three types of goods: the material goods such as household objects, services such as the translation of a text, and purely ideal goods such as ideas. All three types are the subject of production planning [1].

Planning is the systematic evaluation of alternative actions with the aim of making decisions that optimize target variables. Production planning is divided into several steps. Machine capacity planning is preceded by capacity scheduling and followed by order execution control.

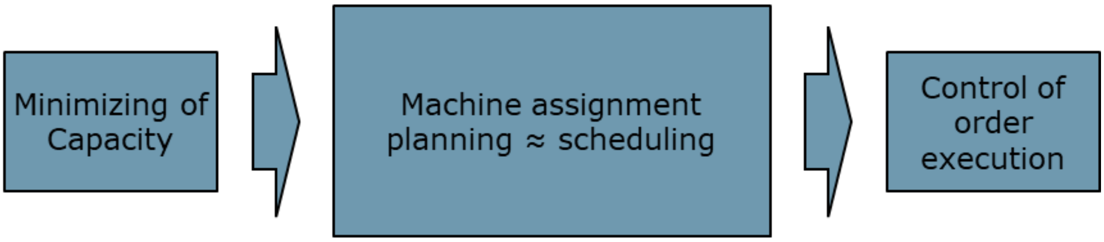

Figure 1 Machine assignment planning in production [2]

Machine allocation planning deals with the allocation of orders to resources in a temporal and spatial perspective. In technical literature, the term machine is more often used instead of the term resource [1]. The term machine is to be understood abstractly. Depending on the trade, the term machine can stand for the workbench in the locksmith's store, for the co-worker in the company, for a lathe or for a test bench at the eDLP. In this chapter, in order to remain true to the theory, we will continue to speak of machines. Chapter 6 deals with the planning situation at a battery test facility, the term test bench will be used. Both terms are to be understood as synonyms in the following.

In the context of production planning, a distinction is made between machine allocation planning and sequence planning. In contrast to machine allocation planning, sequence planning in the broader sense also deals with operational and tactical planning as well as with interdependencies in the organizational structure [2]. This understanding is not adopted. Instead, sequence planning is understood in the narrower sense and equated with machine allocation planning. Both terms are defined as the planning of production processes in spatial and temporal terms. The machine allocation problem can be summarized in the following sentence:

> The goal of machine assignment planning is the spatial and temporal assignment of orders to machines, considering all boundary conditions and the optimization of target variables.

5.1.1 Simultaneous and Sequential Planning

After the general terminology of production and machine allocation planning has been explained, the following section will present categorizations that can be used to classify planning problems.

Machine allocation problems are characterized by a high number of variables and influencing variables that must be taken into account in the planning. In order to arrive at a permissible planning, available machine locations, mobile resources, such as required tools and individual parts, or energy resources must be taken into account, among other things. If all variables and influencing variables are considered in the planning at the same time, this is called simultaneous planning. If the planning is solved step by step and independently of each other in partial plans, it is called sequential planning or successive planning [3]. By breaking down the planning into partial plans, even complex planning situations become manageable. However, if these sub-plans are not coordinated with each other, as is the case in sequential planning, it is not guaranteed that an optimal overall plan will be achieved. Only with the consideration of all mutual interdependencies of the variables and influencing factors, an optimal solution can be guaranteed. In the sense of the enterprise goal a simultaneous planning is to be aimed at. In reality, lack of knowledge about functional relationships, information asymmetries and uncertainties in data limit the extent to which simultaneous planning can be carried out.

5.2 Classification of machine occupancy problems

The machine allocation problem, or scheduling problem, which was defined as an optimization problem in chapter 5.1, is characterized by constraints and assumptions. The following section presents these systematically.

The following basic assumptions are made for scheduling problems in the literature [4] and adopted in this work:

- Each job can be assigned to only one machine at a time.
- A machine can process only one job at a time.
- There is no consumption of resources. This means that a machine is fully available again after a completed job.

It is already clear from the previous explanations that a scheduling problem can be equipped with a wide variety of job characteristics and machine properties.

For a systematic description, the three-field notation α | β | γ is used in the following.

The notation divides the scheduling problem into the 3-field notation machine characteristics (α), job characteristics (β), and the target criteria (γ).

5.2.1 Machine characteristics

The α-field, the machine characteristics, is composed of the machine environment and the number of machines [5]. The machine environment defines the type of machines and how they are related to each other. Common characteristics that the α value can take are listed and explained below.

Table 1 Machine environment α

P_m	The case of identical-parallel machines: There are m identical machines that can be used in parallel. Machines are considered identical if all orders on the machines have the same processing time. An order is completed after machining on one machine.
UP_m	The case of parallel machines of different speeds: There are m machines that can be used in parallel and differ in their processing time. The machining time depends on the machine.
F_m	The flow store: There are m machines that are not necessarily identical. Each order must be processed exactly once on each machine. The sequence is predefined and the same for all orders. The flow store corresponds to flow production.
J_m	The Job Shop: The job store represents a generalization of the flow store. There are m machines. For each job, a sequence of machines is given on which the job must be processed. The sequence is not necessarily the same for all jobs and machines can be omitted or used more than once. The job store corresponds to shop floor production.

The job store J_m can be extended to include more flexibility and operations. Such a problem is called Flexible-Job-Shop FJ_m. The flow store F_m can also be adapted to specific problems. A distinction can be made between the permutation flow store PF_m and the flexible flow store FF_m. [6]. These extensions are not considered further in this thesis. In addition to the machine environment, the index *m* can be used to define the number of machines. If no number is defined, it is assumed to be arbitrary. A flow store with seven machines would have the characteristic $\alpha = F_7$.

5.2.2 Order characteristics

The β-field, the machine characteristics, is composed of the machine environment and the number of machines [5]. The machine environment defines the type of machines and how they are related to each other. Common characteristics that the ɑ value can take are listed and explained below.

Table 2 Order characteristics β

$p_j = p$	All jobs have the same processing time. p_j is the processing time of job *j*.
$d_j = d$	All orders have the same delivery date. d_j is the delivery date of order *j*.
r_j	Arrival times must be taken into account. Job *j* cannot be started before its arrival time r_j .
pmtn	If the *pmtn* (preemption) entry is set, a job can be interrupted and continued as desired. If the entry is not set, a job cannot be interrupted.
prec	The *prec* (precedence constraints) entry is set if precedence relationships exist between jobs. If this is the case, job j can only be started after its predecessors have been processed
s_{jk}	The value s_{jk} specifies sequence-dependent setup times. If it is set, the setup times between two machines depend on the order of the jobs
res	The entry *res* indicates that further limited resources are needed to execute jobs.

If all parameters are given and known, the model is deterministic. If one parameter is given as a random number, the model is stochastic [5]. If, for example, the arrival time arrival time, for example, was not known but was normally distributed around a planned delivery date, it would be a stochastic model.

5.2.3 Target criteria

The γ-field, the target criteria, determines the parameters according to which the scheduling problem is optimized [5]. In the following, a non-exhaustive list of possible target criteria is presented.

Table 3 Target criteria γ

C_{max}	Minimize the total duration (makespan) of a schedule. C_j is the completion time of job *j*.
T_{max}	Minimization of the maximum delay. T_j is the delay of order j.
U_j	Minimizes the number of delays (missed deadlines). U_j indicates whether order *j* is delayed or not.
KA	Maximizing capacity utilization.
L	Minimization of idle times over the total duration on all machines. The value L denotes the idle times.
$w\ T_{jj}$	Minimize weighted schedule overruns. $w\ T_{jj}$ is the weighted schedule overrun of job *j*.

5.3 Solution approaches

In chapter 5.1the terminology of production planning was explained and in chapter 5.2 the theory for the categorization of the planning problem was presented. Based on this knowledge, the following section will deal with the theoretical principles for solving scheduling problems. The aim of this chapter is to explain general solution approaches and to classify sequence planning within the framework of complexity theory.

5.3.1 Off-line and on-line approaches

In this section, the distinction between off-line and on-line approaches to scheduling is presented.

Previously, it was determined in chapter 5.2.2 that the considered models are deterministic. This means that orders and information about resources and constraints are given and known. If all information is planned simultaneously and is available for the complete planning horizon at the time of planning, this is called off-line planning. On-line planning, on the other hand, is understood as step-by-step planning [7]. In on-line planning, orders are scheduled at the moment of the decision-making situation and not in advance. As a result, the sequence planning changes constantly. On-line planning takes into account the fact that at the time of planning, information about later points in time is either not available at all or only partially available. This makes on-line planning more dynamic. This means that disruptions and new information can be better integrated into existing planning. Simple rules for order selection are often used to implement on-line planning [7]. This reduces the optimality of the solution.

5.3.2 Complexity classes

In this section, the complexity theory will be briefly and simplified introduced, the relevance for sequence planning is highlighted and a rough categorization is made. Sequencing problems are difficult to solve [8]. To quantify this difficulty complexity theory will be used as an aid. Among other things, complexity theory deals with complexity classes, which make it possible to measure complexity and to cluster different orders of magnitude of complexity [9]. If it is proven that a problem lies in a complexity class, all statements of the complexity class also apply to the problem. One way to measure the complexity of a problem is via the resource cost depending on the size of the problem n. The resource cost or complexity of a problem is given by $O(f(n))$ according to the Landau notation, where $f(n)$ describes the order of magnitude of the resource cost [8].

In the following, the complexity classes P and NP are presented.

- A problem is in class P if it can be solved deterministically with polynomial runtime. This means that the required resources do not increase with the size of the problem more than with a polynomial function.
- A problem is in the class NP, if it is not deterministic with polynomial run-time is solvable. For problems of class NP, the resource cost can increase exponentially. The class P is a subset of the class NP ($P \subseteq NP$).

Problems in P are called "efficiently" solvable [10]. Problems in NP are called "hard" or "difficult" to solve [8]. It is known that the machine occupancy problem with more than one machine is in NP [4]. This means that no solution algorithm be-

is known, which can solve this problem in the worst case in polynomial runtime. It does not mean that this is always the case. Some machine occupancy problems can be solved in acceptable running time [11]. However, it should be noted that there are large differences even between algorithms with polynomial running time. An algorithm of complexity O(n3) solves the problem n = 10 in the worst case in 1000 time units, an algorithm of complexity O(n18) needs a trillion time units.

5.3.3 Exact solution methods

There are two basic approaches for solving machine scheduling: exact solution methods and heuristic solution methods. Exact solution methods find the optimal solution and prove it as such [8]. They are characterized by the fact that they consider the complete solution space. However, in methods such as the branch-and-bound method, not every solution is evaluated individually. By setting lower and upper bounds, the solution space is cleverly restricted. Nevertheless, exact solution methods are often associated with higher computational effort [8].

5.3.4 Heuristic solution methods

Heuristic solution methods, on the other hand, cannot guarantee an optimal solution, but are often characterized by much shorter computation times [8]. Heuristic approaches can be divided into the following categories.

1. Opening procedures are used to determine the first permissible solutions. Priority rule methods also belong to them. These are used to determine sequences. This is done by priority values, which are assigned to each solution element. The definition of the priority values has a decisive influence on the solution.
2. Local search or improvement methods start with an admissible solution and try to successively improve the target value based on this solution. For this purpose, the method scans the solution space in the immediate vicinity of the given solution. Therefore, the method is strongly dependent on the given solution and the chosen scanning method.
3. Incomplete exact methods are exact methods that are terminated before the optimal solution is found. Termination criteria can be defined based on the running time of the algorithm, the number of iterations or other variables.
4. Combinations of 1) - 3).

Local search methods are distinguished from improvement methods by the fact that they allow for degradations. Local search methods include tabu search, simulated annealing, and evolutionary algorithms. All three methods are meta-strategies. Meta-strategies are basic schemes that can be applied to a variety of problems [12].

6. Planning situation at a battery test field

The following chapter presents the planning situation of a battery test center. As reference the eDLP will be used. To start with, chapter 6.1 introduces the subject-specific nomenclature of battery testing and correlations. Subsequently, chapter 6.2 introduces the subdivision of test stands into three different areas. For this purpose, the characteristics of the different test bench areas are discussed. Chapter 6.3 then derives the requirements for sequence planning from the planning situation at the eDLP. A distinction is made between the general requirements and the planning requirements. The planning requirements form the basis on which the planning is abstracted in a model in chapter 5. Finally, chapter 6.4 places the planning situation in the planning theory from chapter 5.2.

6.1 Basic terms of battery testing

It is known from chapter 5.1 that orders are assigned to machines within the framework of machine allocation planning, taking into account the applicable boundary conditions and the optimization of the target variables. The constraints of the eDLP are presented in chapter 6.2. Before that, the terms machine and orders are transferred from theory to the situation at the eDLP in this section.

At eDLP, the theoretical term machine represents a test stand. A test bench is neither a climatic chamber, temperature chamber, test device or chamber of special requirements. Test devices are e.g., a crusher or a stone impact device. Chambers of special requirements can be, among others, chambers for dust or saltwater splash tests. The respective characteristics of the test stands must be considered individually in the planning. A classification of the test benches according to their properties is given in the next section. The test specimens are tested on the test stands. In the context of battery testing, a DUT is an inverter, an electric motor or a battery. Batteries for motor vehicles are divided into three segments. The smallest unit of a battery is the cell. In addition, there is the test object module, which is composed of the composite of several cells. Several modules constitute the largest unit, a battery pack. The eDLP is mainly used for testing modules and battery packs. In the context of a test drive, the test object is often called DUT, Device under Testing.

In the context of the sequence planning of a battery test field, an order is understood to be the execution of a test. This is also called a test run. The assignment by a customer in the form of an order from sales is not the same as the order from planning.

In the following, the term "customer order" refers to the order by the customer, which may include several orders from the planning point of view. The nomenclature "order" thus represents the execution of a specific test (with one or more test objects). A sequence planning order starts at the point in time at which a test item is used on a test stand and ends with the removal, cleaning and refitting of the test item from the test stand. The customer order, on the other hand, may include additional steps that do not have to be performed in the test stand, such as preparation, reporting, shipping or disposal of the test item. These steps are not considered in the sequence planning and are not included in the order definition. In the following, this work will exclusively refer to the order of the sequence planning. If a DUT runs through several tests on different test benches, each test causes an order in the planning. Basically, each test run causes an order in the sequence planning.

6.2 Presentation of the test capacities

Depending on the test methods, the test capacities at the eDLP can be divided into three different areas. These areas are defined by test rigs of different types, different order characteristics and different boundary conditions. These differences will be shown in the following.

6.2.1 Endurance range

The endurance range includes, among other things, long-term tests, tropicalization tests and cooling tests. During long-term tests, the batteries are subjected to typical load scenarios of up to one year and longer. During this time, the test specimen undergoes charge and discharge cycles. At the same time, temperature and humidity profiles can be run depending on the chamber. These environmental influences are generated in test chambers.

The endurance test area consists of temperature and climatic chambers. Temperature chambers enable the testing of test specimens under consideration of specified temperature profiles. Climatic chambers also allow the humidity to be regulated. The chambers additionally differ in size, maximum and minimum temperature and humidity, temperature and humidity gradients, maximum permissible weight and electrical performance data, hereinafter collectively referred to as test rig characteristics. The electrical performance data are determined by the connected energy system. A power system can consist of several channels. The electrical channels can be used individually, connected in series or in parallel. Depending on the energy system wired to the chamber, various combinations of electrical channels are possible. The assignment of energy systems and chambers is fixed within the framework of the sequence planning and cannot be changed.

Orders differ according to the test method to be performed, the specific characteristics of the test and the properties of the test specimen. Each property related to the order is assigned to the order properties in the following. Job properties can be project information (project number, customer), time information (start, end, duration, hardware availability) and technical information (energy consumption, temperature, humidity, cooling). The runtimes of orders in the continuous operation area are many times higher than in the environment and misuse areas. In addition, they require longer preparation phases, especially in the case of long-term tests. However, these preparation phases are independent of the test bench and the order of the jobs. Cooling units are used to cool the DUT during runtime. Although these can not only cool but also heat, they will continue to be called cooling units in the following to remain true to the common designation. Batteries have a cooling system inside. The cooling units are used to pump a coolant through the cooling system of the battery units. A cooling unit has two cooling channels with which several DUTs can potentially be cooled. The cooling units are mobile and can be moved between chambers with little effort.

6.2.2 Environmental

As part of the environmental section, the test specimens are exposed to a number of different environmental influences. Among other things, dust, splash water, dip tank and salt spray tests are carried out. Due to the different test methods, the test rig characteristics are very inhomogeneous. The environmental area consists on the one hand of test rigs on which test devices are installed for carrying out environmental tests and on the other hand of chambers which are intended for the preconditioning of test specimens. In the context of preconditioning, DUTs are first preconditioned in a separate cam- ber before they are subsequently tested on a test fixture. For both test runs, a test order is created and executed in the sequence planning. The execution of an environmental test does not require cooling and accordingly no cooling units need to be scheduled. A special feature of the environmental area is the shaker test stand. This represents a separate area: mechanical testing. In the first clustering, it was assigned to the environmental area, and this is used as a basis for this work. Among other things, vibration and shock tests are carried out on the shaker. The technical design of the shaker sets it apart from the competition, and as a result it is highly booked and utilized.

6.2.3 Area of abuse

In the abuse area, test specimens are subjected to mechanical loads. These test scenarios simulate accident situations or situations of severe shock or stress. For some test methods, there is a risk of thermal propagation, which is why any test devices are located in so-called bunkers. Thermal propagation includes the thermal propagation associated with fire within battery cells. For safety reasons, only one test can be performed per bunker at any one time. Therefore, a bunker represents a test stand for sequence planning purposes. The bunkers are supplemented by a fire hall designed for fire tests.

The following table summarizes the test field capacities and provides a qualitative overview of the differences between the three test bench areas

Table 4 Overview of the capacities in a test field

	Areas of the test bench field		
	Endurance run	Environment	Abuse
Maturities	Long	Short	Short
Test Benches	Temperature and climate chambers	Chambers and test devices	Fire hall and bunker
Resources	Technical devices	Test specific	Test specific
Test Methods	Long-term tests and further	Immersion, splash, dust tests and others	Fire, short circuit tests and other
Precedence	No	Yes	No
Cooling units	Yes	No	No

6.3 Planning requirements

In the context of sequence planning, the first step is to compare the test bench properties with the order properties for each order. This defines a set of test stands for each order that are technically capable of executing the order. This step represents the preselection. The set of test benches that can be considered for a test bench defines the order pool. The order pool can be different for each order. Once the order pool has been defined for each order, the actual sequence planning takes place in the second step. In this step, the various orders are assigned to the test stands on the basis of defined targets and technical and time constraints. This is the actual planning and optimization problem. This procedure is shown graphically in Figure 2.

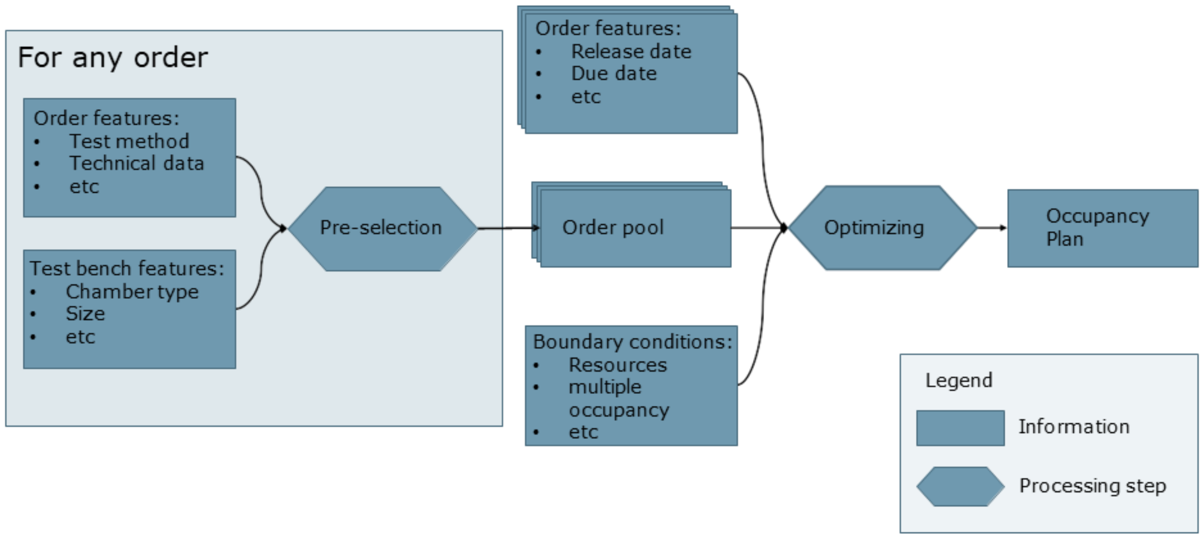

Figure 2 Schematic sequence of machine assignment

On the one hand, attention must be paid to compliance with planning requirements, also referred to as boundary conditions in the following, and on the other hand, the planning and solution must meet general requirements, which are explained in the next section. The general requirements are explained first in Chapter 0, followed by a description of the planning requirements in Chapter 6.3.1. Table 5 summarizes the requirements considered in the following.

Table 5 Requirements for planning a battery test

General Requirements	Planning requirements	
- Extensibility	1) Basic requirements	7) Prioritizing test benches
- Scalability	2) Time requirements	8) Prioritizing orders
- Real-time capability	3) Delimitation of the test benches	9) Resources
- Optimality	4) Priority relationships	10) Personnel capacities
	5) Deadlines	11) Multiple occupancy
	6) Maximization of capacity utilization	12) Energy restriction
		13) Cooling units

General requirements

The general requirements of the sequence planning of a battery test field include the achievability, scalability, real-time capability, and optimality. The general requirements result from the demands on the planning and the context of the sequence planning. They were derived from the expectations on the planning and are based on practically relevant variables.

Extensibility is understood as the possibility that the planning model can also be extended and modified at a later point in time with acceptable effort. Changes in guidelines for test methods could result in further resources must be taken into account as part of the process planning. It should also be possible to realign the target criteria later with a proportionate amount of effort.

In the context of battery testing, scalability includes the requirement that the model can be extended by test stands, orders and resources without the model becoming unsolvable in terms of time. Basically, it must be ensured that during the transfer of the model from small numbers of cases to larger planning scenarios, the solvability of the model is maintained. In addition, it should be noted that a well-scalable model allows more subproblems to be solved simultaneously. This increases the degree of simultaneous planning and in the course of this also, as known from chapter 5.1.1, the optimality of the solution.

The real-time capability of a system is defined according to DIN 44300 as an operation in which programs are constantly ready for operation in such a way that processing results are available within a specified period of time. Data can occur at defined times or randomly [13]. In the context of battery testing, this means that scheduling must meet the time requirements of planning and be able to deal with unforeseen events in an acceptable time. An example of this is the delay of orders and the failure of machines. These events require rescheduling, which must be resolved in an acceptable amount of time. Failure to do so can result in opportunity costs or contractual delay costs.

In the context of business management, optimality describes the state that optimally solves the set goal using all available resources [14]. In this context, solving optimally means maximizing or minimizing the target value. Optimality is thus a higher-level requirement. Any characteristic that improves the value of the target variable is to be preferred.

6.3.1 Planning requirements

The planning requirements for occupancy planning represent the constraints that must be considered when solving the sequence planning. These can be resource restrictions or constraints of various kinds. The boundary conditions relevant for battery testing are presented in the following.

(1) Basic requirements

The basic requirements include the condition that an order can only be scheduled on a test bench that is technically capable of executing it. It must apply that an order is only processed on one test bench from the order pool defined for it. Furthermore, an order can only be processed on one test bench at a time. This means that an order cannot be divided into partial orders and thus be processed on several test stands at the same time. It is also not possible to execute several orders simultaneously on one test bench at one point in time. However, the last condition is relativized in requirement (11) Multiple occupancy of test stands.

(2) Time requirements

The following time restrictions apply to orders: An order may only be scheduled from its release time. The release time is the earliest possible time from which an order can be scheduled. In the context of classic production planning, orders are released by the order release [2]. In the context of battery testing, a separate order release is not necessary. In some cases, for example, the arrival time of the DUT represents the release time. In all other cases, it is set manually in the information management system. In addition, the trivial condition that the start time of a subsequent order must be after the completion time of the previous order applies to the assignment if the orders are scheduled on the same test bench.

(3) Limitation of the possible test benches

Within the framework of sequence planning, it can make sense to manually limit the number of test stands that can be considered for an order. One reason for this can be situational influences that could not be taken into account in the planning model, or a contractual agreement with the customer. Such an agreement could be that an order must be run on a certain type of test bench. A special case is the restriction of an order to only one test bench. In principle, it must be possible for the planner to influence which test stands are considered for an order.

(4) Priority relationships

Within the scope of the environmental area, orders are driven in so-called lanes. A lane is a series of test runs through which a test item passes. Each test of the lane triggers an order in the sequence planning. The order in which the tests are run is not arbitrary, but predetermined. This results in priority relationships, also precedents. If an order is part of a track, the subsequent order can only start with the completion of the previous order of the same track. The preconditioning steps mentioned in chapter 6.2.2 represent such a part of the track.

(5) Meet deadlines

Deadlines apply to every order. If an order is not processed by a deadline, a missed deadline occurs. This can cause contractually regulated delay costs and damage customer relationships. Therefore, it is important to meet deadlines. Within the framework of process planning, deadlines can be implemented either via restrictions or in the form of a target criterion to be minimized.

(6) Target: Maximize utilization

The utilization of the test bay indicates how many test stations are occupied at any one time. Test stands that are not occupied do not generate any sales, with the exception of special cases. Therefore, the maximum utilization of the test bay should be aimed for in relation to the corporate objective. A measure of capacity utilization is the number of occupied test stands for a period of time. A non-occupied test stand represents a vacancy. About the number of vacancies, a second measure of utilization can be defined: The number of vacancies. The number of vacancies must be minimized. Two further statements can be made on the basis of vacancy rates. The negative assessment of vacancies increases with the proximity to the actual time, since it is difficult to react to underutilization in the short term. For vacancies that occur in the medium or long term, on the other hand, acquisition can become active. In addition, it is true that vacancies that are short in time, with the same amount of vacancies, are evaluated more negatively than a contiguous vacancy over a longer period of time. This is due to the fact that connected vacancies can be occupied much more easily by a new project than many short vacancies.

(7) Prioritize test benches

From a planning perspective, it can make sense to prioritize test stands. One example of this is the Shaker test stand. As this is in high demand from customers, it is important to fully utilize the capacities of this test stand. It should therefore be possible to prioritize test benches positively and negatively.

(8) Prioritize jobs

An order may have a higher urgency regardless of its deadline. To cover this case, it is possible to prioritize orders. In systems with prioritization, misuse can occur when setting priorities by prioritizing a large part of all orders. However, approaches on how to prevent such behavior are not dealt with in the context of this work.

(9) Resources

Resources are required to perform some test methods. The basic rule for resources is that they are available in discrete numbers and are renewable. This means that the resources are not used up and are completely available again after the execution of a job. There is only a limited number of each resource, so the number of available units per resource type must be considered over time.

(10) Personnel capacities

Another resource is personnel capacity. In order to carry out a test drive, different levels of personnel effort are required at different points in time. Each group of employees represents a separate personnel resource that can be requested. It must be taken into account that the scheduling of an employee for an order does not equal the complete workload for this employee.

(11) Multiple occupancy of test stands

Another special case must be considered in the context of the endurance test area. If several DUTs of a customer are run with the same temperature and humidity profiles, they can either be tested bundled in one chamber or individually in different chambers. The first case occupies one large chamber, whereas in the second case several but smaller chambers are occupied. If the utilization of the small chambers is low and the utilization of the large chambers is high, the occupancy of the small chambers could be more advantageous. In the opposite case, the occupancy of the large chamber could be more advantageous, as this could lead to an increase in turnover. These combination possibilities are to be covered by the sequence planning.

(12) Energetic restrictions

A limited amount of electrical power is available to the complete battery test field Disposition. Via charge and discharge cycles of various tests, electrical power is demanded. The sum of all power demands of the test field at one point in time may not exceed a safety limit. To guarantee this, the complete electrical power over all test stands at any time be limited.

(13) Cooling units

Cooling units represent another resource of the continuous run area. However, cooling units cannot be assigned to a job in the same way as other resources. This is because the number of cooling channels available at a chamber depends on the location of the cooling units and the wiring of the cooling channels. A cooling channel is a volumetric flow circuit for cooling the test specimens. Each cooling unit has two cooling channels.

The temperature and the flow rate can be controlled independently for the two cooling channels. The coolant, on the other hand, must be the same for both cooling channels. The coolant to be used is determined by the application properties and thus often by the customer. Depending on where the cooling units are located, they can serve different test specimens in different chambers with cooling channels, provided the test specimens use the same coolant. Thus, it is necessary to find an optimal position for the cooling units so that all cooling channels are used while complying with the order requirements. This defines, besides the assignment of orders to test stands, another assignment problem. As a result, the position and allocation of the channels from cooling unit to chamber must also be planned.

6.4 Classification in the planning theory

The three-field notation $\alpha \mid \beta \mid \gamma$ introduced in Section 2.2 is applied to the battery testing planning problem in the following.

6.4.1 Determination of the machine characteristics α

The entire battery test field is composed of a wide range of different test benches. For the classification of the machine characteristics, however, reference is made to the quantity of test stands that come into question for a test stand. These are the orders from the respective order pool. Within the order pool, all test benches can be operated simultaneously, and an order is completed with the execution on a single test bench, thus it is a *parallel machine* type problem. Furthermore, the processing time does not depend on the choice of the test bench but is solely determined by the job characteristics. Thus, the further restriction to a problem of the type of *identically parallel machines* can be made. The number of machines *m* corresponds to the number of test benches of the test field. Thus, α takes the expression $\alpha = J_m$.

6.4.2 Determination of the order characteristics β

The β-field indicates the order characteristics. The job characteristics are defined by the planning requirements defined in chapter 6.3.1. The requirements of a battery test field are more specific than those of the theory. Therefore, this section will focus on the general characteristics that are consistent with theory. The more specific requirements are dealt with in Chapter 5.

In the context of requirement (2), the time constraints, the entry r_j is set, which means that jobs cannot be started before their arrival time r_j. The entry pmtn, on the other hand, is not set since arbitrary interruption and continuation of jobs is not possible in the context of battery tests. However, precedence relationships must be respected in the context of the environmental domain, β = prec. Setup times and transport times are not considered. The entry res is set because with requirement (9) technical resources, with requirement (10) personnel resources and by requirement (13) cooling units must be considered in the planning.

6.4.3 Determination of the target criteria γ

In the context of a battery test field, the capacity utilization is to be maximized according to requirement (6). Thus, γ = KA is valid, whereas a concrete mathematical formulation of the capacity or vacancies will follow in chapter 5. In addition, schedule overruns must be minimized in terms of requirement (5). Thus, this is an optimization with multiple objective variables and the planning problem can be classified as a multiobjective optimization problem.

This concludes the description of the planning situation. The test field capacities and requirements for planning have been systematically defined. In the following chapter 7, based on this definition of the planning problem, approaches to solutions from theory are presented.

7. Solution approach for the sequence planning of a battery test center

According to chapter 6.4, the scheduling problem of the battery test field is a problem of identically parallel machines Pm with resource constraints, precedents, and deadlines. In this chapter, based on this problem definition, solution approaches from the literature are first presented in chapter 7.1, then evaluated in chapter 6.27.2 based on the requirements from chapter 6.3.

7.1 Presentation of the solutions

In chapter 5.3.3, the basic distinction between exact and heuristic solution approaches was presented. Within these two categories, three basic approaches to solving the Pm payoff problem are selected, presented and evaluated. In the context of exact solution methods, the Branch & Bound algorithm is selected. This is widely used in the literature because it can be easily applied to a variety of different combinatorial problems [15]. In the context of heuristic approaches, approximation algorithms and, in the context of metaheuristics, evolutionary algorithms are presented. All three methods represent approaches that are commonly used in the literature to solve Pm scheduling problems [16].

7.1.1 Branch & Bound Algorithm

The Branch & Bound (B&B) algorithm is a decision tree method. In the form of an incomplete enumeration, the problem to be solved is decomposed into disjoint subproblems and admissible solutions are generated step by step. The B&B algorithm is often applied to planning problems that can be modelled well in the form of a linear program. Therefore, the term "linear program" is introduced in the following. A Linear Program (LP) is the mathematical description of a planning problem via exclusively linear constraints and linear objective functions. The related term Linear Programming, on the other hand, refers to the research area of Linear Optimization. In the context of linear programs, an additional distinction is made between integer programs (IP from Integer Programming) and mixed integer programs (MIP from Mixed Integer Programming). An integer program consists exclusively of integer variables. In a mixed integer program, only some variables are integers. In the literature, the B&B algorithm has become widely accepted for solving MIP problems. The procedure of the B&B algorithm can be described with the help of a solution tree, as shown in Figure 3. The solution tree is composed of nodes and branches. A node represents a subproblem and the branches represent relationships. The first node, also called the root, represents the initial problem. Starting from the root, subproblems are generated. For each subproblem, admissible solutions are calculated. The solution space can be cleverly restricted with the help of lower and upper bounds, so that subproblems do not have to be branched further. Using the current best admissible solution, a lower bound can be defined for each subproblem in the context of a maximization problem. An upper bound is determined by the relaxation of a problem - the simplification of the problem by omitting constraints [8]. Thereupon, only branches that lie within the given bounds are pursued further. The efficiency of the algorithm depends on the strategy chosen for finding new branches and the procedure for determining lower and upper bounds. In addition, a trade-off must be made between the computational effort used to search for new branches and the computational effort used to determine new bounds. The computational effort or time required cannot be predicted. And in most cases, large-scale computer-aided computations are required to determine the quality of a concrete implementation [12]. To shorten computation times, the B&B algorithm can be started with an initial solution. An initial solution is an admissible solution to the planning problem. This initial solution can be generated by a heuristic or come from a previous run of the B&B algorithm.

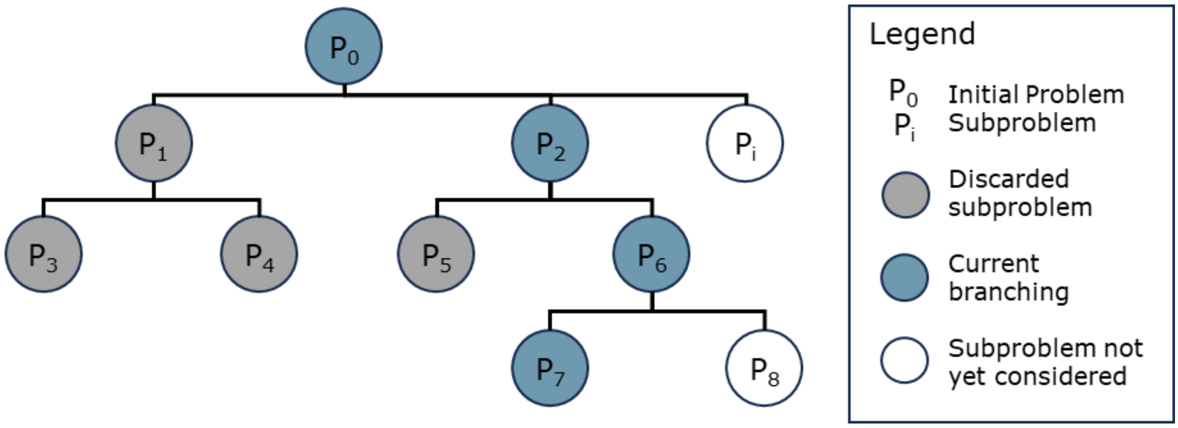

Figure 3 Visualization of the solution

To make the B&B algorithm more efficient, many efforts in the literature focus on developing better bounds, approximations, and heuristics to support the B&B algorithm [15]. One of these approaches is the *Cutting Plane*

Method for determining valid solutions of mixed integer programs. In the context of the cutting plane method, the relaxed program is extended by additionally generated restrictions to limit the solution space. If the solution of the adjusted program corresponds to the integer variables of the original program, then the solution [15]. This means that subproblems that are far removed from the optimal solution are no longer considered by the algorithm. An additional extension of the B&B algorithm is the *column generation* method. In the course of this method, a constrained program is solved by setting some of the variables to zero. If all omitted variables have so-called non-negative reduced costs, an optimal solution to the actual problem has been found. If this is not the case, the limited program is extended by the variables with the negative reduced costs [15]. Reduced costs are the costs by which the objective function value changes if the variables are taken into account in the program. Variables with negative reduced costs have a positive effect on the optimal value of the objective function. This method is particularly suitable for solving programs with many variables in acceptable time. [17] implements a B&B algorithm in combination with the column generation method to solve a machine occupancy scheduling with resource constraints in the context of Amsterdam Schiphol Airport. It is shown that the B&B algorithm in combination with the Column Generation Method can be successfully applied to Identically Parallel Machines problems to reduce running times [17]. He applies the same approach to a machine occupancy problem with resource constraints and shows that in the context of time-indexed variables, time can be reduced to determine lower bounds. His model formulation encompasses precedents as well as multiple types of resources. He then successfully applies the solution approach to the airport allocation problem. Here, the model is able to solve assignments of flights to gates at scales of up to 128 gates and nearly 700 flights in acceptable time [17]. [18] applies in the context of a factory for the production of electrical components adopts a similar approach. Based on a linear program, they solve the weekly assignment of orders to injection molding machines [18]. With their model formulation, they are able to map several types of resources and assign orders to only a subset of all available machines. The production area to be planned comprises 36 machines and, as part of the planning process, they 374 different molding tools used to produce over 1000 different plastic parts Produce. Edis & Ozkarahan note that an implementation based solely on a linear program is unable to meet the timing requirements of the planning. Therefore, they extend the linear program by the approach of *constraint programming*. In the context of constraint programming, admissible solutions are generated with the help of restrictions. In contrast to the B&B algorithm, this approach does not optimize a target variable. Their results show that this can reduce runtimes in various test scenarios. Only with a high number of available resources is the performance of the pure linear program superior

7.1.2 Approximation algorithms

While the B&B algorithm guarantees an optimal solution, approximation algorithms do not provide such a guarantee. Instead, approximation algorithms approach the optimal solution only successively. The simplest form of approximation algorithms are selection rules. They assign orders to machines iteratively according to simple rules. For problems of identically parallel machines with resource constraints, there are three extensively discussed selection rules in the literature:

- First fit (FF): Each job is assigned to the next possible time slot in such a way that no resource restriction is violated.
- First fit decreasing (FFD): The job with the highest resource requirement is scheduled next so that resource constraints are not violated.
- Iterated lowest fit decreasing (ILFD): Represents an extension of the FDD algorithm with lower estimates, resulting in better performance.

Approximation algorithms are evaluated on the basis of the performance guarantee R, among other things. In most cases, however, the performance guarantee cannot be determined unambiguously, but only worst- and best-case estimates can be made [16]. With the help of selection rules, test areas of identically parallel machines with several resources can be mapped. Selection rules that enclose more complex constraints are not addressed by the literature. One way to address this shortcoming is to use algorithms independently by adding further conditions. Statements about the performance Ga and thus about the runtime behavior of the algorithm would then have to be mathematically can be derived. Another category of approximation algorithms are so-called polynomial-time approximation scheme (PTAS) algorithms. PTAS algorithms guarantee a solution that is at most a factor of $1 + \varepsilon$ far away from the optimal solution for a minimization problem. The running time is determined by the chosen ε. However, for very small ε, exponential running times may occur. A PTAS algorithm is called a fully polynomial-time approximation scheme (FPTAS) if it has a polynomial running time even for small ε. A large part of the literature on PTAS algorithms deals with the theoretical derivation of better approximations. Furthermore, the problem definition used in the literature is mostly limited to only one resource. Additional constraints are usually not considered in the literature. In addition, almost all algorithms are designed to minimize the maximum lead time and do not allow for any other target variables [16].

7.1.3 Evolutionary algorithms

Evolutionary algorithms are meta-heuristics because they can be applied to a variety of different problems. The procedure of evolutionary algorithms is based on the theory of evolution. In the context of evolutionary algorithms, an individual is a possible solution to the problem, and thus in the context of scheduling, an admissible allocation plan. Several individuals form the population. The population is iteratively modified. Each iteration step represents a generation. A generation consists of individuals from the previous generation, called survivors, and newly generated individuals, called offspring. The transition from one generation to the next is accomplished with the help of three operators. These operations are:

- Selection comprises the process that determines whether an individual will pass into the next generation or not. This decision is made using a fitness function that evaluates the quality of the individual. The goal is to ensure that only solutions with high quality pass on to the next generation.
- In recombination, individuals are randomly grouped in pairs. Using various recombination methods, a third individual, an offspring, is created from two individuals with a certain probability. Care is taken to ensure that the fitness value of the offspring is not too far from that of the parents and that the characteristics of the offspring match those of the parents.
- In the context of mutation, individuals are randomly selected and the characteristics of the individual are changed according to different procedures. With the help of the mutation operator, diversity of individuals can be ensured within the population even over several generations.

The solution of an evolutionary algorithm depends, among other things, on the choice of the procedure for selection, the recombination procedure, the concrete fitness function, the chosen mutation steps, and the given probabilities. Due to the wide variety of approaches that can be chosen, there is abundant literature on Evolutionary Algorithms in the context of machine occupancy scheduling [12]. In [19]an evolutionary algorithm is applied to an identically parallel machine allocation field with up to forty machines and one additional resource. Deviating from the problem definition of the battery test field, only one machine is ever considered for an order. In addition, only ten orders are scheduled per machine. However, the results show that the turnaround times do not exceed 15 seconds even for problems with up to 40 machines. Furthermore, in no case does the optimality of the solutions deviate from the optimal solution by more than ten percent [19]. In order to map the complex requirements and configuration possibilities of Evolutionary Algorithms, [20] presents a framework for classifying different approaches. It is emphasized that the biggest challenge for the research field of Evolutionary Algorithms is to develop efficient and scalable approaches that can deal with the often much more complex planning situations in reality. Furthermore, it is pointed out that multiple target criteria can lead to difficulties in the application of an Evolutionary Algorithm [20]. In the context of a master thesis, an Evolutionary Algorithm was developed in [21] for the planning of the test stand field. For this purpose, the planning situation was categorized, whereupon an Evolutionary Algorithm was selected as an approach, fully designed and tested. The selected implementation includes a selector to determine all suitable resources and test beds of an order, a scheduler over which admissible occupancy plans are generated, a plan evaluator to evaluate individuals and a generator to generate the next generation. Three operators for performing mutation, a PMX operator for recombination, and three weighted objective functions were selected to implement the algorithm. The application of the approach to a section of the original test field was successful, insofar as a very good solution could be obtained within acceptable time. The transfer of the approach to the entire test field, however, led to unacceptably long runtimes of the algorithm. As the number of test benches increased, so did the number of possible combinations of test benches and resources, so that the complexity of the algorithm became too great [21]. Since this was a completely independently programmed algorithm, the algorithm was not optimized in terms of processing time. [21] was able to show that a complex planning problem can be mapped using an evolutionary algorithm.

7.2 Evaluation of the solutions

In this subchapter, the solution approaches presented in the previous subchapter will be evaluated for their suitability for solving the sequence and process problems on the basis of the requirements defined in chapter 6.3. planning of a battery test field. The general requirements extensibility, scalability, real-time capability and optimality and the twelve planning requirements are addressed. The focus is on highlighting the strengths and weaknesses of the approaches. The first step is the classification of the approaches and the next step is the evaluation in Table 6. The evaluation is based on the discrete evaluation scheme according to [22]. The visualization is done with the help of Harvey Balls. This results in an evaluation scale with gradations as shown in Figure 4.

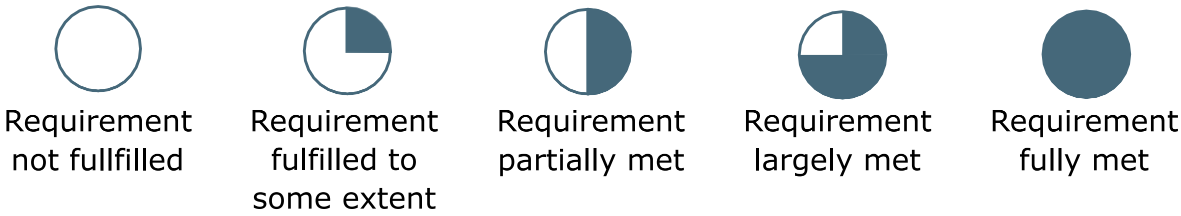

Figure 4 Gradations of the rating scale

7.2.1 Evaluation of the B&B algorithm

The basic strength of the B&B algorithm is that it can be applied to a large set of scheduling problems using a linear program and can solve them optimally. However, it is problematic that the runtimes become too large in complex planning situations. Therefore, an implementation of the B&B algorithm is only realistic in connection with further methods to reduce the complexity. Therefore, in the following, the implementation of runtime planning using the B&B algorithm in combination with further methods, such as the cutting plane method, is evaluated and not the B&B algorithm alone. Via the model formulation of a linear program, the B&B algorithm can be applied to any planning problem that can be formulated in linear inequalities.

In case an additional restriction is to be added to the model, the linear program is simply extended by the necessary variables and inequalities. The conversion of the model in the program code happens on the basis of the mathematical formulations and is thus simply accomplished. Even additional target values are available via additional variables and corresponding weightings can be added easily. It should be noted, however, that the addition of further variables and restrictions changes the runtime behavior of the algorithm. However, it is not possible to predict what effects a concrete change will have on the runtime behavior. In general, the solution space increases with each added variable and thus the possible combinations that have to be considered. However, variables are often accompanied by further restrictions. Restrictions limit the solution space and can have a positive effect on the number of combinations that must be considered. Both effects are opposing. Which effect predominates depends on the concrete planning scenario and the chosen implementation. Basically, it is not guaranteed that a planning problem can be solved with a B&B algorithm in an acceptable time if the number of variables is significantly increased. However, with the help of methods such as the cutting plane method or the column generation method, approaches exist that have successfully solved complex scheduling problems of identically parallel machines in acceptable time, as [17] has shown. Another advantage of the B&B algorithm is its handling of unforeseen events. For delays of orders and failures of test benches, the B&B algorithm does not have to solve the complete scheduling problem again. Instead, it can fall back on a previous solution to the planning scenario. This solution is given to the algorithm as an initial solution. Based on this initial solution, the new planning scenario can then be solved.

7.2.2 Evaluation of approximation algorithms

Selection rules are simple and quick-to-implement methods to solve straightforward planning problems. They do not solve the problem optimally and only consider a limited number of constraints. Therefore, they are not suitable for more complex planning problems and are not able to solve the planning problem of identically parallel ma- chines with additional constraints. PTAS guarantee a minimum degree of optimality via the parameter ε and thus allow to influence the solution result and the runtime. However, PTAS algorithms, like selection rules, are difficult to transfer to more complex planning situations. It is unrealistic to develop a PTAS algorithm specifically for the scheduling of a battery test field that covers all technical requirements. Moreover, any statements about the runtime and optimality of the algorithm would become invalid with the addition of further restrictions and target variables.

7.2.3 Evaluation of Evolutionary Algorithms

Evolutionary algorithms are in principle capable of solving scheduling problems of identically parallel machines, as shown by [19] and [21]. As a metaheuristic, an Evolutionary Algorithm can be applied to a variety of different scheduling problems and constraints. Unlike the B&B algorithm, there are no frameworks for implementing an approach for Evolutionary Algorithms. Therefore, all components have to be developed by the user. On the one hand, this offers the possibility to choose individual implementations, but it can also lead to inefficient implementations. Since concrete implementations can differ strongly, a general statement about the extensibility of evolutionary algorithms cannot be made. As a heuristic approach, the Evolutionary Algorithm does not solve the planning problem optimally. A statement about the degree of optimality can be made by comparing it with real planning solutions or by comparing it with solutions of a B&B algorithm. Since an evolutionary algorithm uses random variables, solutions can differ in several test runs despite the same parameters. Thus, the optimality can also be different for multiple runs. Similarly, to the B&B algorithm, a Evolutionary algorithm launched based on an initial solution. This offers the possibility to intercept delays and failures and thus to meet the requirement of real-time capability. In the context of the planning problem at the eDLP, several objective functions have to be considered. This is possible in the context of Evolutionary Algorithms but can have negative effects on the runtime of the algorithm. Especially the test results of [21] show that long runtimes can occur even for Evolutionary Algorithms in planning situations with many combinatorial possibilities.

Table 6 Final rating of the different algorithms

	Branch and bound	Approximation algorithm	Evolutionary algorithm
Extensibility	●	◔	◕
Scalability	◑	◕	◕
Realtime capability	◕	●	◕
Optimality	●	◑	◔
Planning requirement	●	◔	◑

7.3 Selection of a solution approach

Approximation algorithms do not meet the requirements of the planning of a battery test field, since they can neither solve the problem in an optimal way, nor in its complete scope. Thus the further consideration refers to the comparison of the B&B algorithm and evolutionary algorithms. Due to the model formulation as a linear program, B&B algorithms can be extended better than evolutionary algorithms. Both approaches offer the possibility to start with an initial solution. Thus, delays or failures can be absorbed appropriately. In contrast to evolutionary algorithms, the B&B algorithm solves the planning problem optimally and can, in case of a termination before the optimal solution has been found, output the maximum difference to the optimal solution. For many of the technical requirements from chapter 6.3.1, model formulations exist for linear programs. In the context of evolutionary algorithms, it is possible to develop individual mathematical formulations. Standardized and proven procedures, however, do not exist to the same extent. Both approaches can be applied to small planning scenarios as well as to large ones. For both approaches, however, the runtime increases with the size of the planning scenario. The B&B algorithm can be used with larger numbers of scenarios of orders and test benches, but the results is generally worse than an evolutionary algorithm. However, the actual run times strongly depend on the concrete planning scenario, so that a general statement is not possible. The general challenge of planning a battery test field is the high number of variables. These lead to a high number of combinatorial possibilities, which neither the B&B algorithm nor an evolutionary algorithm can handle efficiently. The successful implementation of an automated scheduling system must be able to handle the combinatorial complexity. The B&B algorithm in combination with further methods like the cutting plane and column generation method offers this potential. With the help of additional methods, the combinatorial complexity could be reduced to the point where a solution to the problem is possible. Since the B&B algorithm can describe the planning problem completely in the form of a linear program, can be easily extended by restrictions, solves the planning problem optimally and can be extended by further methods to reduce the complexity, the B&B algorithm is selected for implementation.

8. CONCLUSION

The machine allocation planning of a battery test field, such as the one at the eDLP, represents a planning problem with new requirements. The objective of WP6.1 & WP6.2 is to develop an approach that automates the machine allocation planning considering the practical requirements. WP6.1 creates the theoretical foundation and WP6.2 will subsequently deal with the implementation.

The documentation till this chapter concentrates only about the deliverables of W6.1. Hence the requirements of the battery testing field were systematically defined, and the planning problem could be categorized as a problem of identically parallel machines with precedents and further resources. Based on this problem definition, approaches from the literature were evaluated and the concept of the Branch & Bound algorithm was selected as most promising for the purpose of the FASTEST project. Subsequently, the planning problem must be modelled in the form of a mixed-integer program. This must be most likely structured into components to allow flexible extension of the modelling at a later stage. The development of the final LIMS will be done in WP6.2.

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