Available online at www.sciencedirect.com
ScienceDirect
European Journal of Operational Research 193 (2009) 805–819
EUROPEAN JOURNAL OF OPERATIONAL RESEARCH
www.elsevier.com/locate/ejor

# Scheduling tests in automotive R&D projects

J.-H. Bartels *, J. Zimmermann

*Clausthal University of Technology, Institute of Management and Economics, Julius-Albert-Strasse 2, D-38678 Clausthal-Zellerfeld, Germany*

Available online 7 November 2007

**Abstract**

In automotive R&D projects a major part of development cost is caused by tests which utilize expensive experimental vehicles. In this paper, we introduce an approach for scheduling the individual tests such that the number of required experimental vehicles is minimized. The proposed approach is based on a new type of multi-mode resource-constrained project scheduling model with minimum and maximum time lags as well as renewable and cumulative resources. We propose a MILP formulation, which is solvable for small problem instances, as well as several variants of a priority-rule based method that serve to solve large problem instances. The developed solution methods are examined in a comprehensive computational study. For a real-world problem instance it is shown that the introduced approach may enhance the current methods applied in practice.


*Keywords:* Project scheduling; Renewable and cumulative resources; Multiple execution modes; Experimental vehicles

## 1. Motivation

During the last decades the automotive industry has been confronted with a shortening product life cycle, as its market changed from a seller's to a buyer's market (cf. e.g. Henseler, 2003). Consequently, the time-to-market has been reduced in order to support the integration of current needs from customers in the development of new car models. Furthermore, the number of cars produced throughout the life-span of a model cycle has decreased, which has led to an increase in the portion of indirect costs. While production divisions were able to counteract this trend, for instance by enlarging the utilization of non-variable parts among different car models (cf. Stake, 2001), it is still a challenge to significantly reduce development costs in interaction with a decreasing time-to-market (cf. Gembrys, 1998; Risse, 2002).

The product development process in the automotive industry generally consists of two alternating stages. First, new components are constructed using computer aided engineering techniques. Subsequently, these components are tested with the help of *experimental vehicles* that have to be built up by the prototype section. Testing is necessary to reveal further demand for engineering in order to reach the level of quality customers expect. Additional tests verifying certain product attributes are prescribed by law. While engineering costs have decreased throughout the last few years due to the successful implementation of platform strategies, testing costs have risen because of increasing product complexity and variety (cf. Risse, 2002). Since the construction of one experimental vehicle costs up to one million Euros, the majority of testing costs is caused by the prototype section. All tests that have to be carried out are specified in advance such that the demand for experimental vehicles depends only on the schedule of these tests. Thus, we consider a scheduling problem where we have to determine a start time for each test such that the number of required experimental vehicles is minimized and several constraints are met.

It seems that there currently exists no quantitative procedure for scheduling tests in automotive R&D projects. Neither our industrial partner nor an extensive literature research provided any information on an appropriate method. The only

* Corresponding author. Tel.: +49 5323 727600; fax: +49 5323 727699.
*E-mail addresses:* jan-hendrik.bartels@tu-clausthal.de (J.-H. Bartels), juergen.zimmermann@tu-clausthal.de (J. Zimmermann).

0377-2217/$ - see front matter 
doi:10.1016/j.ejor.2007.11.010

publication that deals with a related problem is given by Chelst et al. (2001). Due to the fact that each test imposes several requirements regarding the equipment of the used vehicle, Chelst et al. (2001) focus on minimizing the number of differently equipped prototypes by solving a set covering problem. For this problem, it was sufficient to consider only due dates for the individual tests and to neglect further important constraints that are relevant in our context.

In particular, we will present the problem of scheduling tests as a multi-mode resource-constrained project scheduling problem, where we will introduce two new concepts. On the one hand, so-called partially ordered destructive relations are considered. Such a relation describes that some project activities cannot make use of the same resources if they are carried out in a certain sequence. On the other hand, we have to take into account that the key resources need to be created by certain project activities prior to their first use by other activities, where in advance the number of required resources is unknown.

The remainder of this paper is organized as follows. Section 2 gives an introduction to the problem of scheduling tests in automotive R&D projects and presents an appropriate project scheduling model. In Section 3, properties of the feasible region as well as candidates for optimal solutions of the problem are characterized. Section 4 introduces two different solution procedures. We present a MILP formulation of the underlying scheduling problem, which is solvable for small problem instances by means of a standard solver like CPLEX 10.0. The second approach is a priority-rule based heuristic that can be applied with different schedule generation schemes. In Section 5, a comprehensive computational study shows that the proposed methods may enhance the manual scheduling procedure that is currently applied in practice. Finally, Section 6 is devoted to concluding remarks and directions for further research.

## 2. Problem description

In cooperation with an industrial partner we have formulated the problem of scheduling tests as a multi-mode resource-constrained multi-project scheduling problem with minimum and maximum time lags as well as renewable and cumulative resources. Moreover, the respective problem formulation has been validated by another automotive manufacturer who is also interested in the implementation of the proposed scheduling approach.

Automotive R&D projects consist of $m$ *development stages*, each containing an engineering stage and a corresponding *test series*. The $m$ stages differ by the development status of the automobile under construction such that each test series makes use of a different type of experimental vehicle. At first, vehicles of the preceding car model with incorporated components of the currently developed automobile are used. In a later stage, the first prototype vehicle, which is almost totally hand-made and which contains all new components, is available for testing. Finally, vehicles that were built under conditions of the serial production process are tested. Most kinds of tests are executed in every stage. As there are no dependencies between any tests of different test series, each of the $m$ series can be treated independently. In what follows, we restrict our considerations to a single test series which, for simplicity, will be called a *project*. Note that the processing times of the tests are specified a priori. After a test has been executed for a constant duration, it is decided whether the test was successful or needs to be repeated. The repetition of the test is usually done in the subsequent test series, after the engineering sections were able to alter the failing components. Thus, uncertainty usually does not influence a single project significantly and an independent near-term planning of the individual test series that can make use of up-to-date data is possible.

A test series consists of a set $V^t := \{1, \ldots, n^t\}$ of $n^t$ tests, each of which has to be executed on an experimental vehicle. Before an experimental vehicle can be used for testing, it must be built up. The process of building up a vehicle is represented by a so-called *building up activity*. Set $V^b := \{1, \ldots, n^b\}$, with $n^b$ being an appropriate upper bound for the number of required vehicles, contains all the latter activities. All activities $i \in V^t \cup V^b$ have to be scheduled such that the number of used vehicles is minimized. Executing an activity $i \in V^t \cup V^b$ requires *processing time* and some *scarce resources*. Moreover, the following constraints must be observed:

- *temporal constraints*: there are precedence relations between tests, release and due dates for some tests and a prescribed duration for each test series,
- *variant and mode feasibility*: each test has to be carried out on a suitable variant of experimental vehicle,
- *destructive tests*: several tests destroy the used vehicle, which therefore cannot be used for further tests afterwards,
- *partially ordered destructive relations*: some test $i$ disables the used vehicle to perform some other test $j$ afterwards,
- *prototyping feasibility*: an experimental vehicle cannot be used to perform a test before it has been built up by the prototype section.

*Temporal constraints* between the start times of the activities can be described by an activity-on-node network (cf. e.g. Roy, 1964). Such a network contains a set $V := \{0, 1, \ldots, n, n+1\}$ of nodes, each of which represents an activity, where $n := n^t + n^b$ is the total number of real activities and 0 as well as $n+1$ are fictitious activities with processing time zero that specify the start and the end of the project, respectively. For each minimum time lag, claiming that activity $j$ has to start at least $d_{ij}^{\min}$ time units after the start of activity $i$, the project network contains an arc $\langle i, j \rangle$ with weight