Second Year Report on Case Study 4: Improvements in Modelling, Analysis, and Solving the Value Chain Optimization Problem

Sebastian Panek, Olaf Stursberg, Sebastian Engell

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1 Introduction

This report summarizes the progress made in modeling, analyzing, and optimizing the value chain case study in year two. We first summarize the problem statement as provided by AXXOM AG, and outline the objectives for the report period. Section 2 describes the advances with respect to systematically transforming the informal specification into formal representations, Sec. 3 reports on the synthesis of feasible schedules and the schedule analysis by probabilistic techniques, and Sec. 4 sketches the results of solving the scheduling problem by mixed-integer programming. Section 5 summarizes the results and outlines the plans for the upcoming year.

1.1 Problem Statement

The value chain optimization task provided by AXXOM AG constitutes a prototype job-shop scheduling problem, intended as a challenging benchmark for the methods developed in the project. The underlying system is a batch production system (pipeless plant) in which three different lacquers are produced according to the following production sequence: The materials required to produce a specific lacquer are first prepared in a pre-dispersion and dispersion unit, and are subsequently filled into mobile mixing vessels. After completing the filling procedure through a set of dose spinners, the mixing is carried out for a product-dependent duration. A quality check then determines if the product meets given quality requirements. If the result is positive, the mixing vessels are emptied into filling stations and the product is shipped to customers – otherwise the quality is improved by returning the lacquers to the dosing operation. The original problem formulation contains a set of 29 jobs, each of which is specified by the release and due date of an order, the type of lacquer, and the required amount of product. With six to eight operations per job, a total number of 202 operations has to be considered. The scheduling task consists of assigning these operations to overall 14 resources, where some of the operations can be carried out on alternative resources which differ in their capacities. In addition to capacity constraints, a number of different restriction are formulated for the production process, mainly falling into the following two categories: (a) product-dependent constraint (e.g., for a given lacquer some operations must be run on specific resources), (b) time requirements for the operations. The latter include the start-to-start, end-to-start, and end-to-end restrictions for subsequent operations in order to specify, e.g., that the dose spinners must be allocated a certain time period after the dispersion step has been started. The scheduling task of determining a suitable operation-resource assignment is subject to an objective function that combines terms for the delayed finishing of jobs, operational costs per amount of product, and the storage costs (i.e. early termination of jobs is penalized). When minimizing this cost function, it has to be considered that the three different lacquers incur different production cost.

In this form, the scheduling task represents a mid-size value chain planning problem as it typically occurs in industrial manufacturing plants.

1.2 Status at the End of Year One and Objectives for Year Two

As documented in the first year report, the initial investigations aimed at identifying suitable problem representations (namely by timed automata and as Mixed-Integer Linear Programs (MILP)), and to obtain first results on the solvability of the scheduling task. It was identified at that stage, however, that the approaches had the following shortcomings: (i) The partly informal specifications of the scheduling problem as provided by AXXOM AG did not translate uniquely into the formalisms used by the academic partners in their approaches. (ii) The initial attempts to solve the scheduling problem were lacking a desired efficiency with respect to computation time and memory consumption. (iii) For the schedules obtained from the various solution techniques, it was unclear to which extent a schedule is robust with respect to a typically existing uncertainty about the availability of resources. As a consequence, the consortium agreed on focussing the work in year

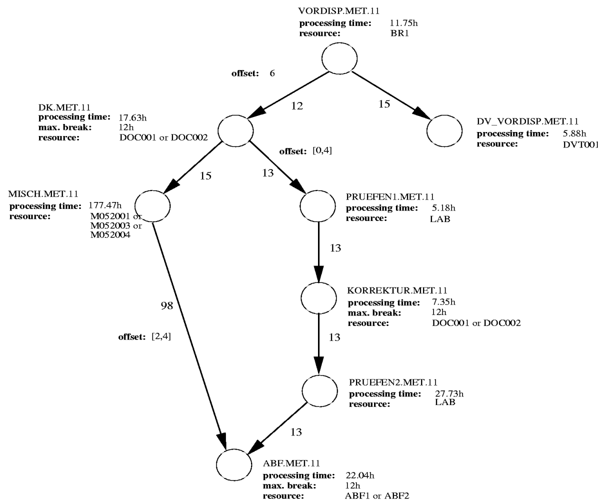

Figure 1: Example of a product flow diagram.

two on the following issues: (a) developing a modeling methodology for a systematic transformation of the various production constraints into formulations required for the developed scheduling approaches, (b) introducing problem-specific improvements for the solution algorithms in order to reduce the effort to compute feasible and optimal production schedules, and (c) providing an assessment scheme to evaluate the generated schedules with respect to uncertain specifications of the resource availability.

The partners decided to invest a relatively high percentage of effort into accomplishing these goals in year two, since the ability to solve this case study satisfactory at the end of year one was lagging behind the results for the case studies provided by Terma and Cybernetics.

2 Advances in Modeling and Requirement Specification

It was an important observation in year one, that the academic partners interpreted the various constraints and cost contributions contained in the problem formulation not identically, and thus dealt with slightly different problem versions. It was deemed necessary to produce a representation scheme that formulates the requirements in an intuitive yet precise and unique manner. A systematic modeling scheme comprising the following steps was developed [5]: (a) create a dictionary to explain the domain-specific vocabulary used by the industrial problem providers, (b) resolve semantic ambiguities in the specification of the production sequence and constraints, (c) define adequate levels of abstraction with an explicit representation of the design decisions, (d) supplement the so-called *product flow diagrams* (provided by AXXOM AG) with recipe-like representations, and (e) systematically transform the latter representations into timed automata.

With respect to step (d), the product flow diagrams provided by AXXOM, which represent the production steps in a graphical arrow-node representation, were first enriched by the processing and offset times for the operations and by the information on the resources on which an operation can be carried out. (The latter data were originally provided in separate tables.) An example for such an extended product flow diagram is shown in Fig. 1 – a drawback of these diagrams is, however, that parallel and alternative operations cannot be distinguished in all cases, and that some timing restrictions have different meanings in different situations. It has thus been proposed in [5] to supplement the product flow diagrams by the recipe-based representation shown exemplarily in Fig. 2. This representation illustrates in which sequence the different types of resources have to be

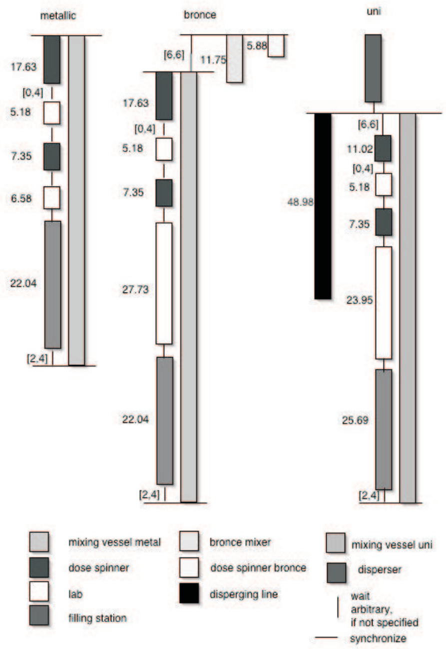

Figure 2: Recipe-based representation of the production sequence.

allocated for a specific lacquer, and which time requirements are relevant.

Based on these representations, the systematic transformation into Timed Automata is achieved relatively easy by: (1) translating each production step from the recipe representation into an automaton fragment (i.e. a sequence of states and transitions), (2) composing the fragments, (3) converting the timing constraints (e.g., the processing times) into corresponding guard and invariant conditions, and (4) modeling the resources by variables.

3 Synthesis of Schedules and Stochastic Assessment

The automaton model obtained from the procedure described above was the basis for synthesizing production schedules with the tools Uppaal (Aalborg) and IF (Verimag). To obtain schedules with Uppaal in acceptable time, a set of heuristics has been developed to efficiently prune the search space. These heuristics include: sorting product orders by deadlines, implementing non-overtaking strategies, restrict the maximal number of orders active at a time, greedy strategies (i.e., resources are taken as soon as they are available), and non-laziness concepts. For the original problem formulation with 29 orders of lacquers, feasible schedules could be obtained within 30 second (on a Pentium PC with 1 GHz) with the combination of the heuristics *sorting by deadlines*, *maximal number of active orders*, and *non-laziness*. In a problem variant that additionally considered performance and availability factors, the combination of the heuristics *sorting by deadlines*, *maximal number of active orders*, *non-overtaking*, and the *greedy strategy* was found to be most efficient, however.

In order to synthesize schedules with the tool IF, Verimag has further developed the approach of encoding the benchmark problem by the specific type of timed automata used in IF (in which each order of lacquer is modeled as an acyclic timed automata and available resources are represented by shared variables, see [2]). A focus of these activities was to generalize and systematize the modeling step, in order to be able to translate a part of the problem formulation automatically into the IF-format. For an efficient solution of the scheduling task, problem specific heuristics have

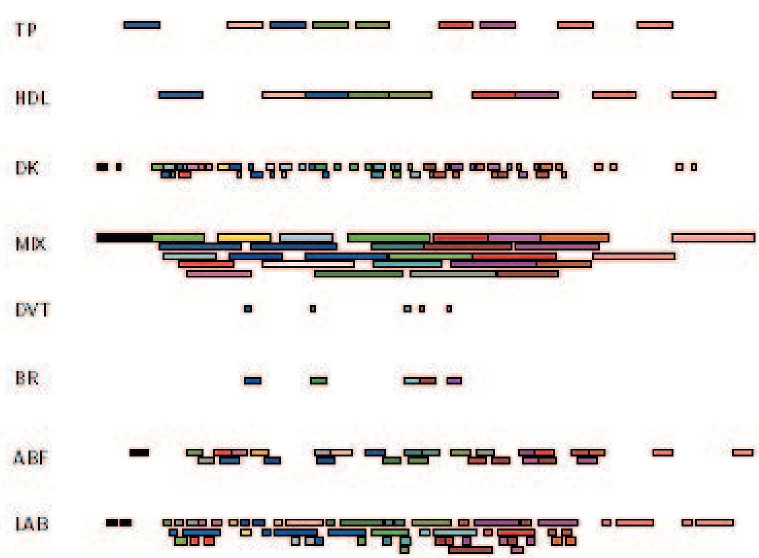

Figure 3: Example schedule.

been identified, most notably the *non-overtaking* rule for instances of the same product and the exclusion of *lazy runs* (i.e. useless waiting is removed). With these rules, schedules without delay could be produced within 15 seconds, as the example shown in Fig. 3.

For the generated feasible schedules, the objective was to investigate the robustness with respect to breakdown of the resources, and to rank alternative schedules accordingly. The problem formulation provided by AXXOM AG contains performance factors (formulating the fraction of time in which a resource is not operational) and availability factors (as the fraction of time at which a resource can be used because operators are available). AXXOM AG proposed to extend the durations of operations by considering these factors. In order to check whether this modification is advantageous and to accomplish the schedule assessment, the following approach was taken [1]: The scheduling task was modeled in the language *MoDeST*, which combines modeling features from stochastic process algebra and from timed and probabilistic automata with light-weight notations such as exception handling. It is supported by the *Motor* tool, which facilitates the execution and evaluation of *MoDeST* specifications by means of the discrete event simulation engine of the *Moebius* tool. The performance and availability were modeled in detail by considering the mean time between failures (MTBF), the mean time to repair (MTTR), and a pace as the frequency of failure occurrence.

The performance analysis with *Moebius* included 80 experiments overall, where 20 different feasible schedules were investigated for two different paces and two different deadline policies (1: give up a job once it is sure it misses its deadline, 2: proces all jobs to the end). One half of the schedules included the modeling of availability and performance, while the other half did not. Each experiment was executed 20,000 times and took around 4 to 5 hours. Figure 4 summarizes the results from this investigation (left part: availability and performance not considered; right part: both factors are considered). It can be concluded that: (a) a higher pace is advantageous to successfully complete a job in time, (b) the success rate of the investigated schedules does not differ significantly, and (c) it is not advantageous to simply extend the duration of operations by the availability and performance factors since jobs are started later as necessary if an equipment malfunction does not occur. Hence, the availability and performance factors should be used only for sequencing and the prediction of delivery dates but not for the timing of operations.

The investigation does furthermore allow to quantify the success rate for each individual job. The obtained rates confirm the expectation that jobs which are scheduled to start late finish less likely on time and that two jobs which are roughly started at the same time have a lower probability to be finished timely.

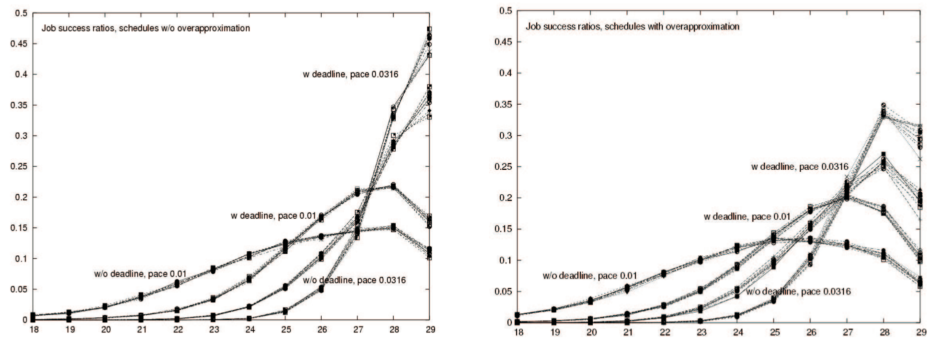

Figure 4: Assessment of schedules.

4 Solution by Mixed-Integer Programming

The first-year report [3] described how the case study can be formulated in a completely algebraic from such that optimal schedules can be generated by mixed integer linear programming (MILP). The main idea was to derive a mixed integer formulation containing: (a) binary variables which describe precedence relations between operations being executed on same machines, (b) real variables which represent starting and finishing dates of operations, and (c) an objective function defined as a weighted sum of makespan, accumulated tardiness, and earliness terms. Based on this formulation, a set of heuristic rules was developed in order to allow an efficient solution by MIP. Among these rules were: (i) pre-ordering by earliest due date (EDD), (ii) non-overtaking of operations belonging to jobs of the same type, and (iii) non-overtaking of operations whose start and finishing dates do not overlap. These heuristics were combined in a two-step-procedure as follows: First, the heuristics (i) and (iii) are applied by fixing some binary precedence variables, and the problem is solved. In the second step, the variables fixed before are relaxed, and the heuristics (ii) and (iii) are applied by fixing the corresponding binary variables. This problem is then solved by using the result of step one as initialization. This procedure was combined with a rolling-horizon solution procedure which decomposes the problem into a series of smaller sub-problems. These are first solved separately, and the solution of the complete problem is finally composed of the solutions of the sub-problems.

This strategy was the starting point for the work in the second year. The first part in this phase was focussed on testing the solution performance. It was found in numerous numerical experiments for scaled problem instances that valid schedules could be computed successfully within a few minutes. For instances up to 20 jobs, also optimal or near-to-optimal schedules were obtained within this period. Larger instances turned out to be difficult and schedules computed with limited computation times can be far away from the optimum. Qualitatively good results could be computed using the rolling-horizon strategy referenced above, as documented in detail in [4]. These observations motivated the developments in the second part of the report period, which aimed at improving the solution performance by modifying the mixed-integer formulation and the search heuristics.

An initial improvement, which is not method-related, has been obtained by switching to newer versions of the software used for solving the MILP (i.e. GAMS 21.3 and CPLEX 9.0). While the best solution found within a fixed period of time could be improved for small problem instances with the new version, the performance was not improved, however, for most of the larger instances. In order to investigate the reason, extensive studies have been carried out to find appropriate parameter settings that can be used within CPLEX to steer the optimization. In particular, it has been determined by which setting for the following parameters the best performance was obtained: (a) the type of the pricing algorithm for the primal and dual simplex method, (b) the strategy for choosing priorities in ordering variables during the MILP solution, (c) the choice of nodes for branching in the search tree, and (d) the choice of variables that are selected first in each node for branching. It has been found that especially choosing standard dual pricing is a strongly preferably option for (b). Details on the effect of the other parameters are described in [4].

A second investigation aimed at determining modifications of the algebraic problem representation in order to reduce complexity. This part predominantly aimed at identifying non-critical resources (as, e.g., the quality checks in the laboratory), and to eliminate the corresponding parts from the model. This reduces the number of operations, and thus the computation time considerably.

Furthermore, modifications of the objective function have been investigated. While previous optimizations had minimized the tardiness of jobs, a modified version introduces cost penalties only for the lateness of each job. This change improves the efficiency drastically such that in most problem instances the optimal solution could be found in a few iterations.

The improvements in solving the case study by MILP can be summarized as follows:

- Using both tardiness and earliness penalties, delay-free schedules could be computed in less than 60 minutes for all examples.
- An objective function which penalizes only the tardiness leads to problems which are much easier to solve, and delay-free schedules are computed within 12 minutes.
- The combination of an improved MILP model with less operations and an objective function which penalizes only the tardiness allows computing delay-free schedules in less than 700 seconds.
- The second step of the solution procedure leads to efficiency improvements which can be attributed to the new version of CPLEX and an appropriate choice of the solver parameters.

5 Conclusions

5.1 Achievements in the second year

In summary, the goals listed in Sec. 1.2 have been largely accomplished:

- A concept for systematically transferring the informal specifications of the value chain problem into semantically correct formal models (specifically timed automata) has been developed.
- Major progress has been made in efficiently solving the original formulation of the case study. For the case of 29 orders, the techniques based on timed automata as well as the MILP-based approaches generate feasible schedules as a matter of minutes. The improvements are mainly due to the development of effective search heuristics and a model reduction with respect to details that are not relevant for finding feasible or optimal schedules.
- By extending the investigation to stochastic timed automata, the notion of robustness of schedules with respect to a reduced availability of resources has been introduced. This allows to determine the probability by which a job is finished in time.

5.2 Perspectives for the third year

In order to keep this case study a challenging test-bed also for the upcoming year, AXXOM AG has produced an extended version of the problem formulation. The extensions, that make the problem even more realistic with respect to the actual industrial lacquer production, include the increase of the number of jobs to 70 and the introduction of additional, qualitatively different constraints. Furthermore, the objective function is extended by cost contributions for the setup and cleaning of vessels, the storage of materials, the raw materials, and the transport of the mixing vessels. The objective is to further improve the scheduling methods and tools in year three such that this problem instance can be solved at the end of the next report period. In particular, it is planned to:

- use C-Uppaal for schedule synthesis. (This version of Uppaal allows to not only generate feasible schedules by model-checking, but to consider rather general optimality criteria for schedules.)
- extend the schedule analysis with *Moebius* to costs.
- apply the approach which combines reachability analysis for timed automata with linear programming (as currently developed in Dortmund) to the case study.

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