

Essays on
Integrated Maintenance and Production Scheduling with
Stochastic Failures and Non-Resumable Jobs

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Preface

I studied logistics on the deterministic field with a specialisation on production planning. With Prof. Dr. Gudrun P. Kiesmüller a world of stochastics in logistics was opened to me. Although our research backgrounds have been quite different, I was most grateful that she gave me the trust and incorporated me in her team. I learned a lot during my PhD studies, and I can say that it was a steadily increasing learning effect. And I would like to give my most profound thanks to Prof. Dr. Gudrun P. Kiesmüller for this opportunity she offered to me, for her helpful and improving advice and the supervision of my thesis even from the chair in Magdeburg.

As the new chairholder at Christian-Albrechts-University of Kiel I also want to expose a special thank to Prof. Dr. Frank Meisel for the adaption and the friendly collaboration, for good advice and of course for co-refereeing this thesis. Prof. Dr. Birgit Friedl I would like to thank for chairing my oral defense.

Through all these years my colleague Sarah was at my side and I want to give big hugs and special thanks for her content-related and moral support and for a friendship I never want to miss again. I also want to thank Florian for his words of advice, for patience and friendship. I wish you all the best.

Of course, I would also like to thank my husband Johannes for not letting me going crazy, for his proof readings and his time when I needed to discuss or practice presentations.

Additionally, I want to say thanks to Stefan Wende and Ethel Fritz as well as all our "Hiwis" for support and warmth, teamwork and stomachaches from laughing and of course for never complaining about my singing.

And of course I want to thank all of my friends and family, for trusting in me, for proofreading again and again, for motivating me and reminding me, that this is not the most important thing in life.

Life has just begun!

Wiebke von Hoyningen-Huene

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Synopsis

1 Introduction

This dissertation is about the integration of the subject areas production scheduling and maintenance planning with a special focus on the existence of production tasks which are not allowed to be interrupted, because otherwise the product in process would be destroyed. In some industries, like for example in the chemical industry or in industrial bakeries, several components are processed at a specific temperature, which is essential for a successful production. An unexpected machine breakdown would lead to a loss of the component for this kind of production tasks, which are called non-resumable jobs, and the whole job would have to be started from the beginning. Therefore, for non-resumable jobs special attention should be turned to maintenance decisions on the considered machines. Not only because preventive maintenance (PM) activities could avert machine failures, but also for the reason that this PM activities have to be planned between the production tasks since even an expected disruption of a non-resumable job is not convenient. Since the jobs do not necessarily need to have the same production length, additionally the sequence of those jobs between PM activities is of crucial relevance, caused by the fact that a machine failure during the production of a time-consuming job could also imply long repeating times.

In the production planning at operative level decisions are made regarding which jobs should be assigned to which machine, and in which sequence should the jobs be produced to achieve a predetermined aim. An aim can for example be to finish the production of all jobs as fast as possible to be prepared for following jobs, but also to ensure an efficient production flow. The modelling and solving of assignment and sequence problems are widespread in literature regarding a deterministic scheduling environment. An overview of this research field is given in Pinedo (1995). Also in the field of maintenance decisions isolated from production scheduling there are numerous articles considering the determination of optimal maintenance intervals (see for example a survey in Wang (2002)). When both problem fields are considered concurrent,

it is often assumed that a machine stop is given beforehand and fixed in time, see for example Lee (1996), Sanlaville and Schmidt (1998), Schmidt (2000) and Ma et al. (2010). Unexpected machine failures together with the scheduling of PM activities in dependence on the sequence of jobs is a problem field which came into focus only recently. The most important articles are Cassady and Kutanoglu (2003) and Cassady and Kutanoglu (2005). The authors created models to represent the described problem assuming different objective functions and provided initial solution methods. Despite the problem underlying this dissertation they assumed the considered jobs to be resumable and therewith to be able to be continued after a machine failure. Since the provided solution algorithms are only practicable for a small number of jobs and the assumption of non-resumable jobs afford more comprehensive challenges, the following research questions accrued which are the basis of this dissertation:

- Are there established priority rules which suit to solve the described problem, and is it possible to anticipate optimal preventive maintenance intervals for those job sequences?
- How does a generally valid mathematical model look like to describe the problem, and is it possible to identify the optimal schedule composed of non-resumable jobs and PM activities with this model in reasonable time?
- How can the problem be solved satisfactorily by heuristics, and which speciality should be provided by a solution algorithm?

2 Research Contributions

From my time at the chair ‘Supply Chain Management’ at Christian-Albrechts-University of Kiel the three articles summarised in Table 1 arose under the supervision of Prof. Dr. Gudrun P. Kiesmüller. Each of these articles addresses the problem described in the introduction. In the following, I will briefly give the motivation for each article and describe the content.

Table 1: Overview of research papers.

A	Maintenance and Production Scheduling on a Single Machine with Stochastic Failures	W. von Hoyningen-Huene, G.P. Kiesmüller
B	Evaluation of the Expected Makespan of a Set of Non-Resumable Jobs on Parallel Machines with Stochastic Failures	W. von Hoyningen-Huene, G.P. Kiesmüller Published in: <i>European Journal of Operational Research</i> , 2015, vol. 240, issue 2, pages 439-446
C	Heuristics for an Integrated Maintenance and Production Scheduling Problem on Parallel Machines with Stochastic Failures and Non-Resumable Jobs	W. von Hoyningen-Huene Submitted to: <i>International Journal of Production Research</i>

2.1 Maintenance and Production Scheduling on a Single Machine

The intention of the first article was to find a preferable simple way of solving the integrated problem for practical relevance and therefore for a huge number of jobs. Additionally it served as an overview for the problem with regard to the sensibility of the output to the input data. The aim was to find a schedule of non-resumable jobs and PM activities for a single machine, which minimises the objective function. The objective function was composed of cost aspects like it is classically done in maintenance literature. Established priority rules were chosen which serve as optimal sequences of jobs for similar problems in the production scheduling environment. The related optimal PM intervals were determined by a simulation study. Furthermore, we used PM intervals which are suggested in maintenance literature isolated from production scheduling and adjusted them to the underlying problem. This was done in order to evaluate if these established solution methods are still applicable, to unveil the challenges evolving when solving the new problem, and to find out if the optimal PM interval could be identified independent of the job sequence.

We found out that one priority rule based on the First Fit Decreasing algorithm introduced by Coffman et al. (1997) outperforms the other rules when using the optimal PM interval. An equal determination of the best interval regarding all priority rules was not possible. But during

the estimation of the PM interval we showed that the best result was detected by adapting the problem assumptions to the calculation of the PM interval instead of using other existing methods, since the optimal cost are very sensitive to the estimation of the PM interval if jobs are non-resumable.

2.2 Evaluation of the Expected Makespan on Parallel Machines

On the basis of the insights resulting from our first paper we spare the determination of PM intervals and constructed a generally valid mathematical model instead, in order to make it possible to find optimal production and maintenance schedules in a simultaneous manner. Therewith we defined a new problem class $Pm|nr - pm|E(Cmax)$ according to the classification scheme for scheduling problems created by Pinedo (1995). It denotes the use of parallel identical machines (Pm) with non-resumable jobs and the insertion of multiple variable PM activities ($nr - pm$) underlying an objective function which minimises the expected makespan ($E(Cmax)$). Although the model was made for multiple machines it is also applicable for problems addressing a single machine. The objective function is defined as the expected completion time of the latest scheduled job with respect to all machines and is influenced by the schedule as well as the stochastic machine failures. In this article we defined the composition of the expected makespan and presented its complexity. Since this complexity is quite high we further determined approximations for this objective function to receive evaluations of solutions in adequate computation time. The correlation of those approximations to the exact objective function was calculated through the evaluation of randomly chosen schedules for different input data.

The correlation of both approximations was very high and the quality of the solutions was very close to the exact values, especially for the optimal solution or those near the optimal schedule. Since the approximated expected makespan can be computed much faster, our formulae have a very valuable contribution when the optimal integrated production and maintenance schedules have to be determined.

2.3 Heuristics for an Integrated Maintenance and Production Scheduling Problem on Parallel Machines

With the second paper we set the course for the detection of suitable solution approaches along with their evaluation in reasonable computation time. Together with the insights resulted through the first paper, I created solution algorithms which regard the properties of the new problem and anticipate near optimal results. Four heuristics were constructed and implemented in Matlab where the focus was set to a heuristic based on the Ant Colony System (ACS) approach published by Dorigo and Gambardella (1997) which belongs to the class of meta-heuristics and appeared to be suitable for this kind of problems. The other heuristics are construction heuristics.

The first (*List&tau*) is a composition of two existing approaches, one taken from scheduling literature and the other from maintenance optimisation. The two remaining algorithms (*MatchingBatches* and *Batchfit*) are completely self-constructed and regard the characteristics of the problem in a more adequate way. These two heuristics also serve as starting approaches for the ACS meta-heuristic. The ACS algorithm uses the advantage of iterative improvement and is inspired by the behaviour of ants while they are searching for food. Ants orientate themselves by the pheromone value earlier ants deposited on their tracks, thus using the pheromone as information where to get food. The artificial ants of the algorithm are searching for schedules with small expected makespan. The most successful ant deposits pheromone on the used tracks by raising the probability of these schedule parts to be chosen by the next ant colony. Sooner or later more ants are using the shorter trails and therewith components of the best found solution so far. Thus, good schedules are developed by joining individually and collectively made decisions. In the article, among others, the tracks as well as the problem-adapted heuristical information where to find good solution components were defined. One of the approximations, introduced by the second paper, was used to evaluate intermediate solutions in a fast manner.

The comparison of the four heuristics was determined by a numerical study. By the use of a Lower Bound all solutions were referred to the same basis, making a comparison pos-

sible for problem instances which were not solvable exactly in reasonable computation time. Through the use of the heuristics I solved problems with up to 60 jobs and 8 machines. The computational results state the advantage of using the meta-heuristic. Besides that, the sequential approach *List&tau* performed weak, compared to those heuristics that solve the production and maintenance scheduling problem jointly. With increasing instance size, the ACS_{BF} benefited from its starting solution *Batchfit*. Thus, if technical conditions allow no fast running of the *ACS*, a recommendation is to prefer the use of the construction heuristic *Batchfit*, which performed well and fast. In all other cases, the ACS_{BF} is the best choice.

3 Manifestations on Co-Authorships

Two of the three papers have been developed in co-authorship, where the order of authors reflects the contribution to the paper.

4 Relevant Literature

- Cassady, C. R. and Kutanoglu, E. (2003). Minimizing Job Tardiness Using Integrated Preventive Maintenance Planning and Production Scheduling. *IIE Transactions*, (35):503–513.
- Cassady, C. R. and Kutanoglu, E. (2005). Integrating Preventive Maintenance Planning and Production Scheduling for a Single Machine. *IEEE Transactions on Reliability*, (54(2)):304–309.
- Coffman, E. G., Garey, M. R., and Johnson, D. S. (1997). Approximation Algorithms for Bin Packing: A Survey. *D.S. Hochbaum (Ed.), Approximation Algorithms for NP-hard Problems, PWS Publishing Company, Boston*, pages 46–93.
- Dorigo, M. and Gambardella, L. M. (1997). Ant Colony System: A Cooperative Learning Approach to the Traveling Salesman Problem. *IEEE Transactions on Evolutionary Computation*, (1(1)):53–66.
- Lee, C. Y. (1996). Machine Scheduling with an Availability Constraint. *Journal of Global Optimization*, (9):395–416.
- Ma, Y., Chu, C., and Zuo, C. (2010). A Survey of Scheduling with Deterministic Machine Availability Constraints. *Computers & Industrial Engineering*, (58):199–211.
- Pinedo, M. (1995). *Scheduling: Theory, Algorithms, and Systems*. Prentice-Hall, NJ.
- Sanlaville, E. and Schmidt, G. (1998). Machine Scheduling with Availability Constraints. *ACTA Informatica*, (35):795–811.
- Schmidt, G. (2000). Scheduling with Limited Machine Availability. *European Journal of Operational Research*, (121):1–15.
- Wang, H. (2002). A Survey of Maintenance Policies of Deteriorating Systems. *European Journal of Operational Research*, (139):469–489.

A Maintenance and Production Scheduling on a Single Machine with Stochastic Failures

W. von Hoyningen-Huene, G.P. Kiesmüller

Published as working paper at Arbeitspapiere des Instituts für Betriebswirtschaftslehre der Christian-Albrechts-Universität zu Kiel, available at: <http://hdl.handle.net/10419/106608>

Abstract In this paper we study the problem of determining a production schedule for an order of n jobs on a single machine which is subject to stochastic machine failures. To avoid long downtime of the machine caused by unexpected failures, preventive maintenance should be planned as well. If a failure cannot be averted, a corrective maintenance activity is performed. Both maintenance activities are assumed to restore the machine to become ‘as good as new’. Furthermore it is assumed that jobs, interrupted by a machine failure, have to get restarted after the corrective maintenance is finished (non-resumable case). The aim is to minimise the average cost, composed of cost through order tardiness, when exceeding a due date, and cost for preventive as well as corrective maintenance activities. In order to regard practical relevance we compare simple production and maintenance scheduling rules for a huge number of jobs. In the course of a simulation study we first illustrate that in general an adjusted First Fit Decreasing algorithm generates the best results compared to other common used scheduling rules. We secondly show that the optimal length of the preventive maintenance interval can be estimated by using an extended decomposition approach which regards the non-resumable case, even if the processing times of the jobs are very long.

Keywords: Maintenance, Scheduling, Stochastic Failures, Non-Resumable, Simulation Study

B Evaluation of the Expected Makespan of a Set of Non-Resumable Jobs on Parallel Machines with Stochastic Failures

W. von Hoyningen-Huene, G.P. Kiesmüller

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Abstract In this paper we consider a production process at operative level on m identical parallel machines, which are subject to stochastic machine failures. To avoid long downtime of the machines, caused by unexpected failures, preventive maintenance activities are planned and conducted, but if a failure could not be averted a corrective maintenance has to be performed. Both maintenance activities are assumed to restore the machine to be “as good as new”. The maintenance activities, the number of jobs and their allocation to machines as well as their sequence have a large impact on the performance of the production process and the delivery dates. We study an order of n jobs, scheduled for a frozen period on the machines. It is assumed that jobs, interrupted by machine failure, have to get repeated right after the corrective maintenance is finished (non-resumable case). We first derive an exact formula for the expected makespan. Since the exact evaluation of a schedule is highly complex, we propose two approximations for the expected makespan. The excellent performance of the approximations is illustrated in a numerical study.

Keywords: Maintenance, Scheduling, Stochastic Failures, Non-Resumable, Approximation

C Heuristics for an Integrated Maintenance and Production Scheduling Problem on Parallel Machines with Stochastic Failures and Non-Resumable Jobs

W. von Hoyningen-Huene

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Abstract Maintenance activities can have a large impact on the performance of a production process and promised delivery dates. Therefore, maintenance and production planning should be handled as an integrated problem. In this paper, the problem of scheduling n jobs on m identical parallel machines is solved such that the expected makespan is minimised. The machines are affected by stochastic machine failures which are assumed to result in long production stops. To avoid this, preventive maintenance activities are planned beforehand. If a failure cannot be averted, a corrective maintenance has to be performed. Furthermore, it is assumed that jobs, interrupted by machine failure, have to be repeated (non-resumable case). In this paper, three construction heuristics and an Ant Colony System (ACS) algorithm are developed for solving this integrated problem. The excellent performance of the ACS as well as the benefit solving the problem in an integrated manner instead of sequentially, is shown in a numerical study.

Keywords: Parallel Machine Scheduling, Maintenance, Stochastic Failures, Non-Resumable Jobs, Ant Colony System

Curriculum Vitae

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