Proceedings of the 2018 Winter Simulation Conference
M. Rabe, A.A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, eds.

A MULTI-LEVEL MODELING APPROACH FOR SIMULATION-BASED CAPACITY PLANNING AND SCHEDULING OF AIRCRAFT MAINTENANCE PROJECTS

Christian Fabig

Institute of Material Handling and
Industrial Engineering
Technische Universität Dresden
Dresden, 01062, GERMANY

Elias Winter

Saxony Media Solutions GmbH
Bärensteiner Str. 27/29
Dresden, 01277, GERMANY

ABSTRACT

The aim of this contribution is to provide a modeling approach for multi-project manufacturing. Existing approaches for capacity planning and detailed scheduling in those complex environments are using separate models that are linked by instruction and feedback slopes. In contrast, we include multiple levels hierarchically into one simulation model. Thus, the possibilities to propagate restrictions such as precedence dependencies and starting times from gross to detailed levels in a consistent manner are established. The approach is implemented in Java, extending the modeling capabilities of a simulation-based optimization framework. A real-life application to project-oriented aircraft maintenance is presented to highlight the practicality and efficiency of the integrated model for simulation-based capacity planning using work packages as well as detailed scheduling using activities of work plans.

1 INTRODUCTION

In multi-project manufacturing, each product can be seen as an individual project. Industry examples are production and maintenance of heavy special machinery, ships, and aircrafts. Those complex production systems typically contain a few resource groups with some hundreds of individual resources that are shared by all projects, i.e., projects are executed contemporaneous. Each project consists of a unique compilation of work packages, sub-work packages, and work plan activities. Between those elements, precedence dependencies and hierarchical assignments are present. Planning data arise in different planning horizons and detail since project contents are commonly not known in advance. E.g., work orders that have to be fulfilled are subject to considerable uncertainties or completely unknown at the point of time where a project due date has to be quoted. Thus, tools for production planning and control (PPC) have to facilitate a refinement of the planning model.

The analysis of the performance of PPC procedures via simulation is a well-known issue in science. Also, simulation environments can be used for capacity planning and scheduling in daily operation of a manufacturing system. Instead of using mathematical modeling and solving techniques such as linear programming, a simulation-based scheduling and optimization framework can be used for creating schedules that satisfy specific constraints while optimizing a target function (Frantzén et al. 2011; Mourtzis et al. 2014).

Simulation modeling is a crucial issue since each field of application contains special characteristics. Thus, several authors have proposed models for capacity planning and scheduling for real-world planning problems (Angelidis et al. 2011; Carvalho et al. 2015). However, separate models for the aforementioned planning levels are used, leading to a re-modeling effort since several restrictions that have to be fulfilled on an upper planning level also must hold for lower planning levels. In particular, a simulation model for project environments has to facilitate a propagation of those restrictions and upper-level decisions in a consistent manner.

978-1-5386-6572-5/18/$31.00 ©2018 IEEE

The remainder of the paper is as follows. In the next section, we describe the problem of multi-project manufacturing and review existing approaches. In Section 3, we present our mathematical description for capacity planning and scheduling and the multi-level modeling approach for solving the planning problems by a simulation-based optimization framework. Section 4 will present an application of the approach to aircraft heavy maintenance. Conclusions and suggestions for future research are given in Section 5.

2 LITERATURE REVIEW

2.1 Problem Description

Real-world planning problems for multi-project manufacturing can appropriately be modeled and solved using hierarchical approaches. Instead of creating a "total model" for simultaneous planning, the planning problem is divided into hierarchical levels, providing a more detailed model in subordinated levels (Schneeweiss 2003; Carvalho et al. 2015). A hierarchical model is also appropriate due to practical limitations, since there is an increasing effort and limited possibility for gathering all the necessary planning data in advance. For example, as will be shown later, aircraft maintenance projects are subject to considerable uncertainties. Thus, the need arises for maintenance managers to estimate capacity requirements far in advance of project start and schedule necessary work plan activities during the project execution while meeting deadlines that were quoted based on those estimates.

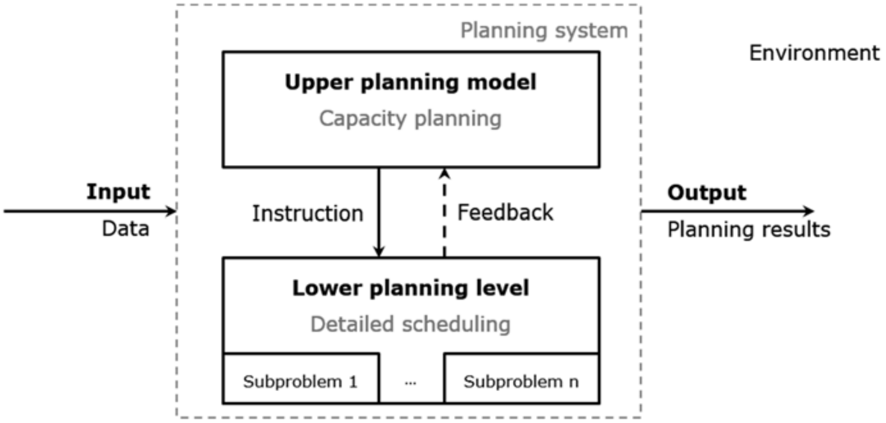


Figure 1: Basic structure of a hierarchical planning system (adapted from Schneeweiss 2003).

In literature, several frameworks for hierarchical planning and control have been proposed. E.g., Herroelen (2005) introduces a framework especially for project environments containing three hierarchical levels to address different planning horizons (strategic, tactical, and operational). The framework proposed by Drexl et al. (1993) define a general hierarchical planning structure, where a master production scheduling on the strategic level is refined on the tactical and operational level using specific planning approaches for different production types. The framework by Drexl et al. is stating the fundamentals of Production Planning and Control (PPC) modules of Enterprise Resource Planning (ERP) systems. However, traditional ERP systems incorporate well-known deficiencies with regard to planning (Stadtler 2015):

- inadequate modeling of the planning task (e.g., lead time scheduling without resource limitations),
- subsequent execution of planning tasks without allowing for revisions to upper-level decisions, and
- using lead times as a fixed planning input even though it is common knowledge that lead times are the result of planning.

Advanced Planning and Scheduling (APS) systems are intended to remedy the defects of ERP systems. Besides a closer integration of modules and the use of more advanced scheduling algorithms, a hierarchical planning concept is one building block of those systems. However, APS do not replace but supplement existing ERP systems. Planning tasks are taken over by the APS while an ERP is still required for, e.g., defining planning data such as project networks and work orders as well as plan execution (Stadtler 2015). Capabilities of actual APS systems have been extensively studied by Stadtler et al. They conclude that improving modeling capabilities is a main topic of further developments that must be addressed. Especially, there is a need for "... enhanced modeling capabilities and more robust solution procedures solving large problem instances" (Stadtler et al. 2015, p. 503). This is especially true for multi-project environments. Since each project consists of a unique compilation of work packages, sub-work packages, and work plan activities that are arising in different planning stages, there are complex precedence dependencies that have to be gathered. Furthermore, planning results and restrictions have to be propagated from gross to detailed levels consistently.

2.2 Fundamentals of Capacity Planning and Scheduling in Multi-Project Manufacturing

Project scheduling is well known in operations research and management and has been the subject of extensive research. The Resource-Constrained Project Scheduling Problem (RCPSP) is the classical project scheduling problem. Practical applications range from strategic planning of capacities (e.g., determination of resource requirements in development projects) to detailed scheduling of work plan activities on a production floor (Herroelen 2005; Beşikci et al. 2015). In order to incorporate further aspects of real-world problems, a broad variety of extensions of the RCPSP have been proposed in literature (Hartmann and Briskorn 2010). The RCPSP is generalized primarily in two ways, leading to the four general classifications shown in Figure 2. First, there may be execution alternatives for activities and, second, multiple projects have to be scheduled simultaneously while sharing resources (Wauters et al. 2016).

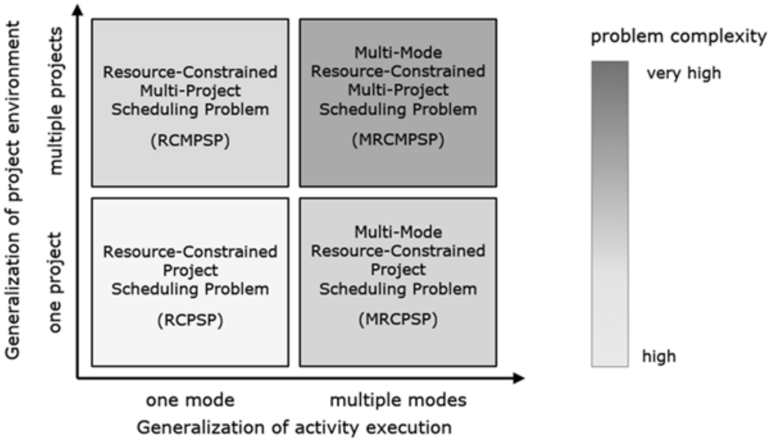


Figure 2: General classification of project scheduling problems.

In practice, a typical planning process for multi-project manufacturing is as follows. Far in advance to project start, an effort estimation based on pre-defined work packages is done. A capacity planning is carried out, using the relatively gross work package model and the limited amount of available resources per group and time period. This is especially important, since project due dates have to be quoted while resources are not dedicated to a specific project. While work package efforts are estimates of the sum of working hours of (yet unknown) associated work plan activities, there usually is the possibility to compress or stretch each work package duration. The shorter the duration, the higher is the amount of required resources and vice versa. This problem is defined as Multi-Mode Resource-Constrained Multi-Project Scheduling Problem (MRCMPSP). Shortly before and during project realization, work plan activities are defined and released to the shop floor. Those activities possess associations to a specific work package, i.e., restrictions such as precedence dependencies and planning decisions such as starting and finishing times of that work package have to be propagated to activities. Activities may also contain further precedence restrictions among each other. However, usually no possibilities to compress or stretch an activity are considered, since a detailed work planning is done. Work planners define, e.g., required resource amount, skills, duration, and sequence of activities of a work order. The arising problem of detailed scheduling of activities is defined as Resource-Constrained Multi-Project Scheduling Problem (RCMPSP).

Figure 3 provides mode examples of a work package with estimated work effort during capacity planning. The amount of time necessary to complete a work package depends on the amount of resources assigned to it. Possible extensions of the mode concept may also consider qualifications for restricting whether a specific resource, e.g., a named worker, is eligible for execution (Angelidis et al. 2011; Heimerl and Kolisch 2010).

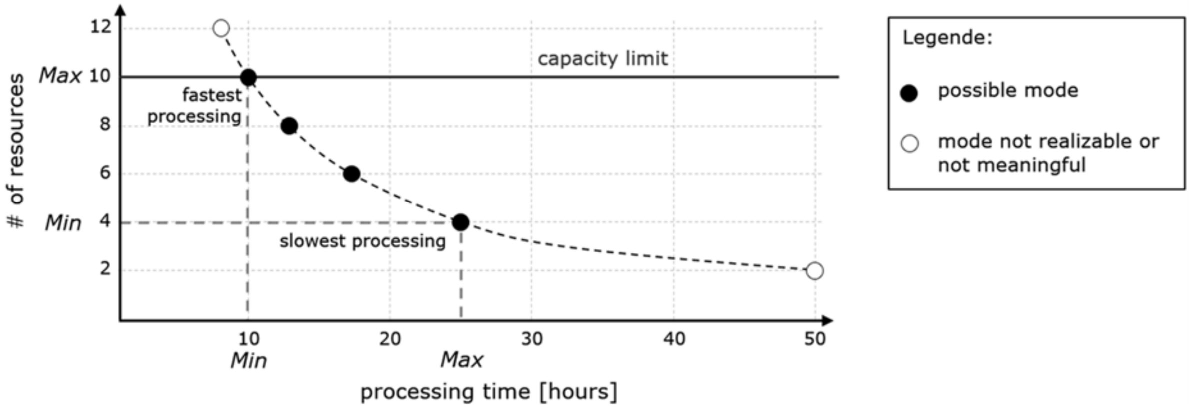


Figure 3: Mode examples for executing a 100 hours work effort.

Problems of capacity planning and detailed scheduling are commonly solved using separate models that are linked by instruction and feedback slopes (Zhang and Wang 2013; Carvalho et al. 2015). With those separate models, severe coordination problems will arise in practice (Stadtler et al. 2015). E.g., when a manufacturing system is in short supply of a specific resource, planning instructions from an upper level cannot be fulfilled by a lower level (Schneeweiss 2003; Zhu et al. 2005). As in multi-project manufacturing, the MRCMPSP of capacity planning is a generalized problem of the RCMPSP of detailed scheduling, the problem may also be considered as an integrated model.

3 MULTI-LEVEL MODELING APPROCH

3.1 Basic Idea

In project management, work packages are hierarchically structured in a Work Breakdown Structure (WBS). Based on that pre-defined structure, the effort is estimated and precedence dependencies are added between work packages in order to create a project network. For large-scale projects, e.g., in construction industry, different stakeholders and levels of detail can be addressed by a hierarchy of project networks as shown in Figure 4 (Harrison and Lock 2016).

The proposed multi-level modeling approach includes a hierarchy of project networks and the multi-mode concept in order to create an integrated capacity planning and scheduling model. Elements of the project network obtain a level attribute and are typed as work packages or work plan activities. Work plan activities can be associated with every work package. Due to the existing knowledge they can be assigned to a more detailed work package (e.g., removal of a specific component) or to a more aggregated work package (e.g., removal works). When an activity is assigned to a work package, precedence dependencies are inherited.

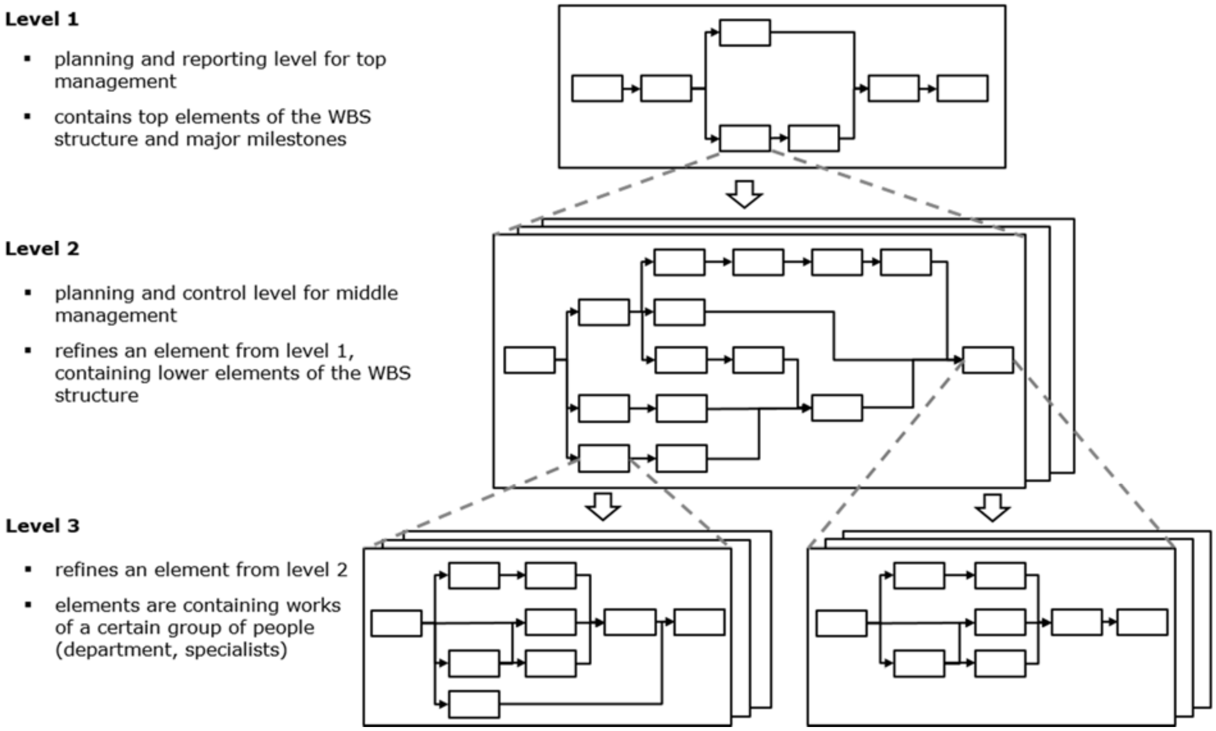


Figure 4: Example of a 3-level project network hierarchy (adapted from Harrison and Lock 2016, p. 133).

For capacity planning, work packages and precedence dependencies are filtered based on a given hierarchy level (e.g., filtering level 2 will extract only work packages on Level 1 and Level 2). Lower-leveled work packages are removed from the generated simulation model. If work plan activities are already known partially (e.g., when the multi-project capacity planning is updated on a rolling horizon), they will be removed from the simulation model. However, they are used for model validation and adjustment: if the sum of working hours of associated work plan activities is higher than the (previously) estimated work package effort, those efforts will be set higher. After this, possible modes are generated for each work package and resource type. Possible modes respect practical limitation, i.e., generated modes may not fall below a user-defined minimal work package duration, exceed the total amount of resources of the manufacturing system, or fall below a minimal amount of resources (either specified by the user or limited to 1 by default). Thus, a MRCMPSP model is generated.

For detailed scheduling, work plan activities are filtered independently from the work package they are associated with. Precedence dependencies that may be defined between two activities directly or through dependencies of work packages are taken over or transformed into direct precedence dependencies in the generated simulation model, respectively. One single execution mode is given for each activity by the work planning. Planned start times of work packages, i.e., the planning results of the capacity planning, are set as earliest start time restrictions for the associated work plan activities. Thus, a RCMPSP model is generated with a pre-limited solution space in order to respect and refine capacity planning results.

3.2 Mathematical Model

In the following, we will present the proposed mathematical problem description for resource-constrained capacity planning and scheduling in a multi-project manufacturing environment. Model definitions are given in Table 1.

Table 1: Model definitions.

Value	**Description**
Indices and sets:	
P	*Set of projects,* $p \in P$
I	*Set of activities of project* p, $i, j \in I_p$
M	*Set of modes of activity* i *of project* p, $m, m' \in M_{p,i}$
T	*Set of time periods,* $t \in T$
K	*Set of resource types,* $k \in K$
Parameters:	
EST_p	*Earliest start time of project* p
$EST_{p,i}$	*Earliest start time of activity* i *of project* p
LFT_p	*Latest finish time of project* p
$LFT_{p,i}$	*Latest finish time of activity* i *of project* p
$W_{p,i}$	*Total work content of activity* i *of project* p
$\overline{r_{p,i,k,t}}$	*Upper limit of resource amount of resource type* k *used by activity* i *of project* p
$r_{p,i,k,t}$	*Lower limit of resource amount of resource type* k *used by activity* i *of project* p
$R^G_{k,t}$	*Resource amount of resource type* k *available at time* t
Decision variables:	
$x_{p,i,m,t}$	*Binary decision variable.* *Contains 1, if activity* i *of project* p *is executed in mode* m *at time* t*, otherwise 0.*
$r_{p,i,k,t}$	*Resource amount of resource type* k *used by activity* i *of project* p *at time* t
$s_{p,i}$	*Starting time of activity* i *of project* p
$f_{p,j}$	*Finishing time of activity* j *of project* p

Minimize

$$f(S) \tag{1}$$

Subject to

$$\sum_{t=EST_{p,i}}^{f_{p,i}} \sum_{m=1}^{M_{p,i}} w_{p,i,m} \cdot x_{p,i,m,t} = W_{p,i} \qquad \forall p \in P;\ \forall i \in I_p;\ \forall m \in M_{p,i};\ \forall t \in T \tag{2}$$

$$\sum_{m=1}^{M_{p,i}} x_{p,i,m,t} \leq 1 \qquad \forall p \in P;\ \forall i \in I_p;\ \forall m \in M_{p,i};\ \forall t \in T \tag{3}$$

$$x_{p,i,m,t} + x_{p,i,m',t} \leq 1 \qquad \forall p \in P;\ \forall i \in I_p;\ \forall m \neq m';\ \forall t \in T \tag{4}$$

$$f_{p,j} \leq s_{p,i} \qquad \forall p \in P;\ \forall (i,j) \in I_p \tag{5}$$

$$\sum_{p=1}^{P} \sum_{i=1}^{I_p} r_{p,i,k,t} \leq R^G_{k,t} \qquad \forall p \in P;\ \forall i \in I_p;\ \forall k \in K;\ \forall t \in T \tag{6}$$

$$\underline{r_{p,i,k}} \leq r_{p,i,k,t} \leq \overline{r_{p,i,k}} \qquad \forall p \in P;\ \forall i \in I_p;\ \forall k \in K;\ \forall t \in T \tag{7}$$

$$\underline{d_{p,i}} \leq d_{p,i} \qquad \forall p \in P;\ \forall i \in I_p \tag{8}$$

$$EST_p \leq f_{p,i} \qquad \forall p \in P;\ \forall i \in I_p \tag{9}$$

$$EST_{p,i} \leq f_{p,i} \qquad \forall p \in P;\ \forall i \in I_p \tag{10}$$

The MRCMPSP problem is optimized in Equation (1) with respect to a still anonymous objective function $f(S)$. Constraint (2) requires that the work content is completely scheduled for each activity. According to constraint (3), activities may never be carried out in more than one mode at a time, whereby a mode change is allowed by constraint (4) after an interruption, e.g., a shift end or break, and working on the activity is resumed until the activity is finished (i.e., preempt-resume, see Afshar-Nadjafi 2016). Constraint (5) reflects the precedence dependencies among the activities of all projects. Compliance with the maximum available resources per resource type is required in constraint (6). Unlike in an explicit mode definition, modes are defined implicitly: the amount of resources that can be used to perform an activity is limited by a minimum and maximum limit per resource type in constraint (7). The same applies to the minimum duration of an activity, which is constrained through (8). Finally, constraints (9) and (10) ensure that earliest start times of the projects and activities will be respected, respectively.

Note that Equations (3) and (4) are defining multiple execution modes while through Equation (7) possible modes are defined indirectly through a lower and an upper limit of resource usage. Since multi-mode execution is a generalization of the single-mode case (see Figure 2), our mathematical problem description is applicable for capacity planning (MRCMPSP) as well as detailed scheduling (RCMPSP).

3.3 Model Implementation

The multi-level modeling approach is implemented in Java, extending the modeling capabilities of the simulation-based optimization framework SaxMS.APS (Schönherr et al. 2012). The implementation is based on the following model classes:

- *Work packages:* A work package represents a group of work plan activities within a project. While work plan activities are yet unknown in an early stage of the project, the group of work plan activities is represented by means of effort estimates. I.e., a work package contains estimated working hours for one or more resource types.
- *Work plan activities:* Work orders that are created and released to manufacturing within the ERP system contain work plan activities. Thus, they represent concrete task execution. Required resources, workplaces, execution duration, work area, and other restrictions are defined in detail by the work planning department. Work plan activities are relevant for detailed scheduling.
- *Workflows:* In order to establish a hierarchical structure of work packages as well as work plan activities, the workflows are a central element of our model definition and implementation. They act as containers, having exactly one work package, may contain further workflows on a lower level, and may also contain work plan activities.
- *Milestones:* One start and one end milestone are modeled for each workflow. Those milestones act as the well-known dummy-start/end milestones when projects are artificially bound together into a single project in scheduling theory (Hans et al. 2007). In our modeling context, those milestones are connection points for all the elements within a workflow (work package, workflow, and work plan activities). Figure 5 provides a modeling example.

Simulation models for capacity planning, i.e., planning work package execution, and detailed scheduling, i.e., scheduling of work plan activities, are generated. Following, we provide details for generating those simulation models.

- *Capacity planning model:* Within the model, upper and lower limits of resource usage per work package and resource type are defined. Additionally, the model contains available amounts of those resource types. Thus, resource upper limits and availabilities (R_{max}), respectively, enable to calculate a minimal duration (D_{min}) for each work package. If, as another option, D_{min} was restricted by the user, R_{max} will be further restricted. Moreover, a minimum resource usage (R_{min}) may be defined by the user to calculate a maximum duration (D_{max}). A linear parameter from 0 (use R_{min}) to 1 (use R_{max}) is given from outside the simulation model. The optimizer can vary that parameter in pre-defined steps per each work package, i.e., different modes as shown in Figure 3, to obtain different simulation models. The second phase is the simulation of the model with chosen modes per activity, where priority rules decide the order of work package execution.

- *Detailed scheduling model:* The simulation model will be reduced at first for a detailed scheduling. Work packages are removed by deleting the project model node and directly connecting the predecessor and successor of that node. Finally the model reduction performs an edge reduction to optimize the simulation performance. Hierarchical workflows still know about their planning results from capacity planning (start and end times). Thus, start and end times of associated work plan activities are further restricted. After that, SaxMS.APS is carrying out detailed simulation and optimization procedures as described in Schönherr et al. 2012.

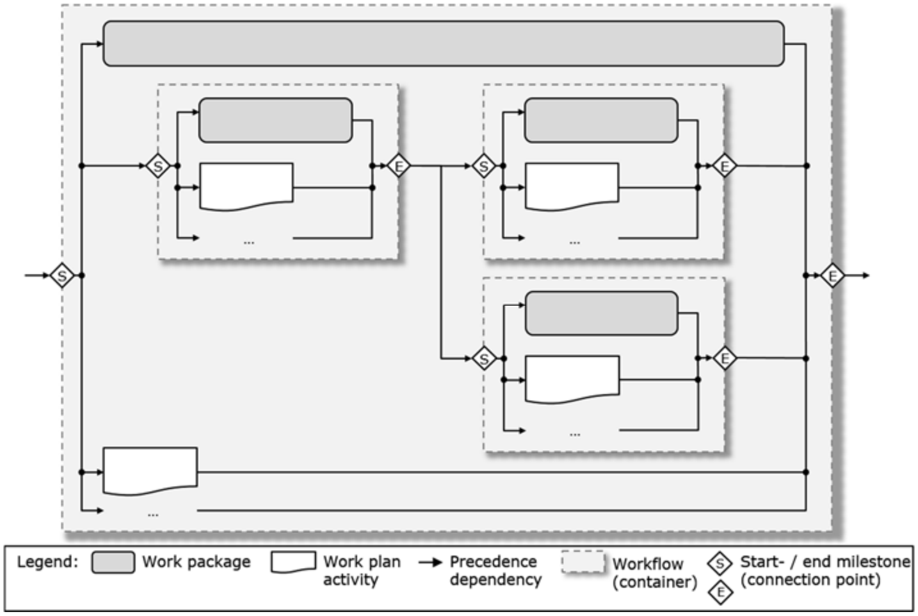


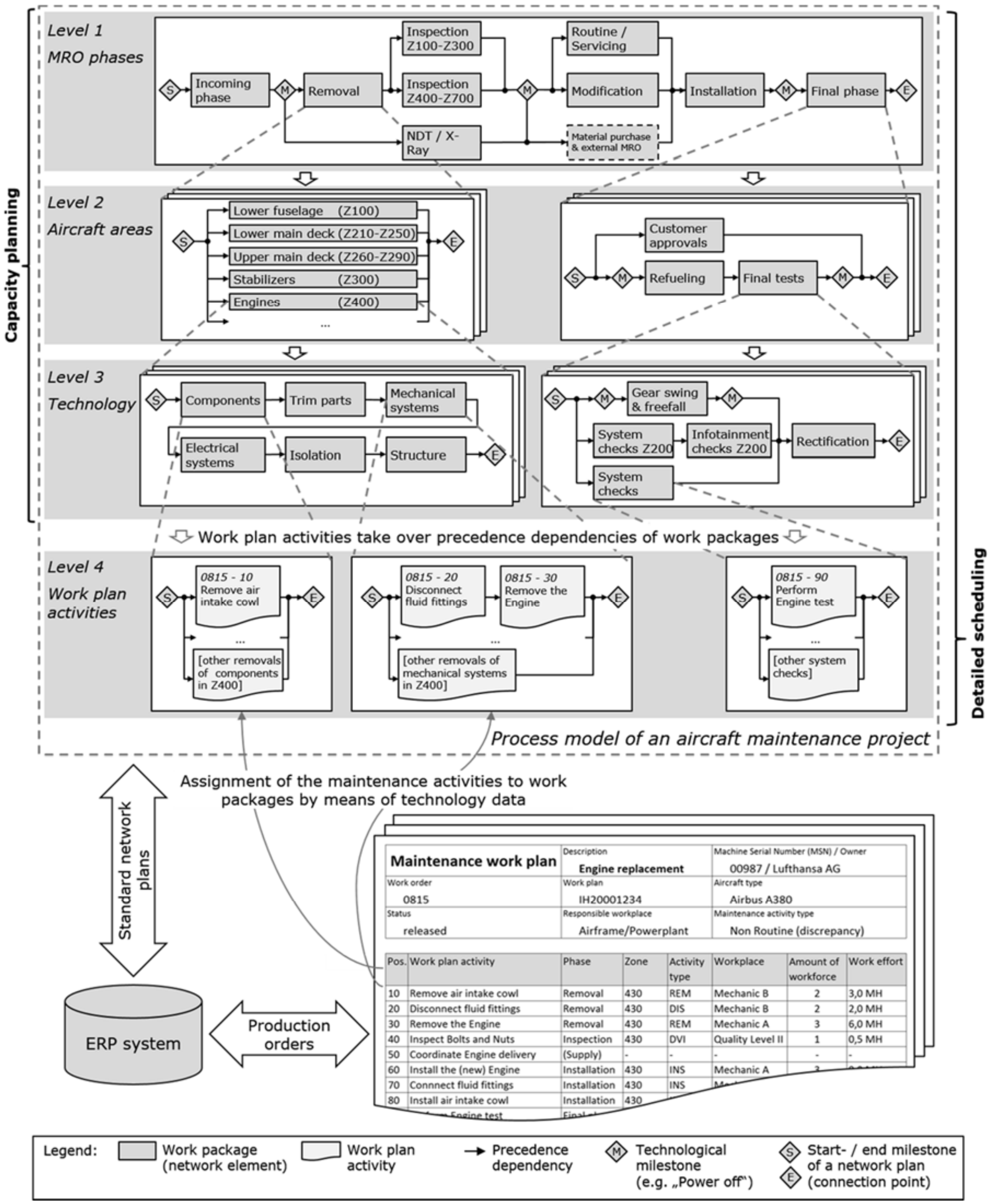
Figure 5: Example of a workflow containing a work package, 3 sub-workflows and work plan activities.

4 REAL-LIFE APPLICATION

A case study from aircraft maintenance industry is presented to highlight the practicality and efficiency of the integrated model for simulation-based capacity planning and detailed scheduling.

4.1 Aircraft Maintenance, Repair, and Overhaul (MRO)

Proper production planning and control is of key importance in aircraft maintenance. Multiple examples and research papers show that cost savings can be gained through a fitted, robust capacity planning and scheduling (Van den Bergh et al. 2013). So called “C-“ and “D-checks” are the most difficult types of maintenance. Capacity planning and scheduling are subject to considerable uncertainties, originating from unknown conditions of the aircraft components. The projects´ workload always consists of work orders that are known prior to the project (i.e., “routine” work) as well as unforeseen work orders needed to repair or replace components (i.e., “non-routine” work; Van den Bergh et al. 2013). According to case studies, those non-routine efforts cause 25-60% of the total workload (Fabig et al. 2016; Kulkarni et al. 2017). Thus, in order to quote short but also reliable due dates far in advance of project start, an effort estimation based on pre-defined work packages is done. All MRO projects have to be combined into one multi-project simulation model for capacity planning and scheduling.



Maintenance work plan	Description Engine replacement	Machine Serial Number (MSN) / Owner 00987 / Lufthansa AG
Work order 0815	Work plan IH20001234	Aircraft type Airbus A380
Status released	Responsible workplace Airframe/Powerplant	Maintenance activity type Non Routine (discrepancy)

Pos.	Work plan activity	Phase	Zone	Activity type	Workplace	Amount of workforce	Work effort
10	Remove air intake cowl	Removal	430	REM	Mechanic B	2	3,0 MH
20	Disconnect fluid fittings	Removal	430	DIS	Mechanic B	2	2,0 MH
30	Remove the Engine	Removal	430	REM	Mechanic A	3	6,0 MH
40	Inspect Bolts and Nuts	Inspection	430	DVI	Quality Level II	1	0,5 MH
50	Coordinate Engine delivery	(Supply)	-	-	-	-	-
60	Install the (new) Engine	Installation	430	INS	Mechanic A		
70	Connnect fluid fittings	Installation	430	INS			
80	Install air intake cowl	Installation	430				

Figure 6: Scheme of a hierarchical maintenance process model and data.

4.2 Model for Simulation-based Capacity Planning and Scheduling of Aircraft MRO

The concept proposed in Section 3 has been applied to aircraft MRO as shown in Figure 6. The model comprises 4 levels, each providing further details of a work package on a higher level. The relevant project structure (MRO phases, aircraft areas, assembly technology) and the effort estimation are gathered within the ERP system as separate "standard networks" that have been hierarchically referenced with each other.

The SaxMS.APS system is taking over the project networks as well as work plan activities (if available) in order to generate a multi-level model for simulation-based capacity planning and scheduling.

4.3 Results

The modeling approach has been verified using a case study containing 3 parallel D-checks for an Airbus A380. Typically one of those maintenance projects takes about 2 months and causes maintenance cost of about 3 Mio. € (without material cost). For capacity planning, an example result is shown in Figure 7. Each project consists of three hierarchical levels as illustrated in Figure 6 with a total of 84 work packages and 5 possible modes for each work package. Further verification and calculation will be done in the near future in collaboration with Elbe Flugzeugwerke GmbH, a maintenance service provider for Airbus aircrafts headquartered in Dresden, Germany.

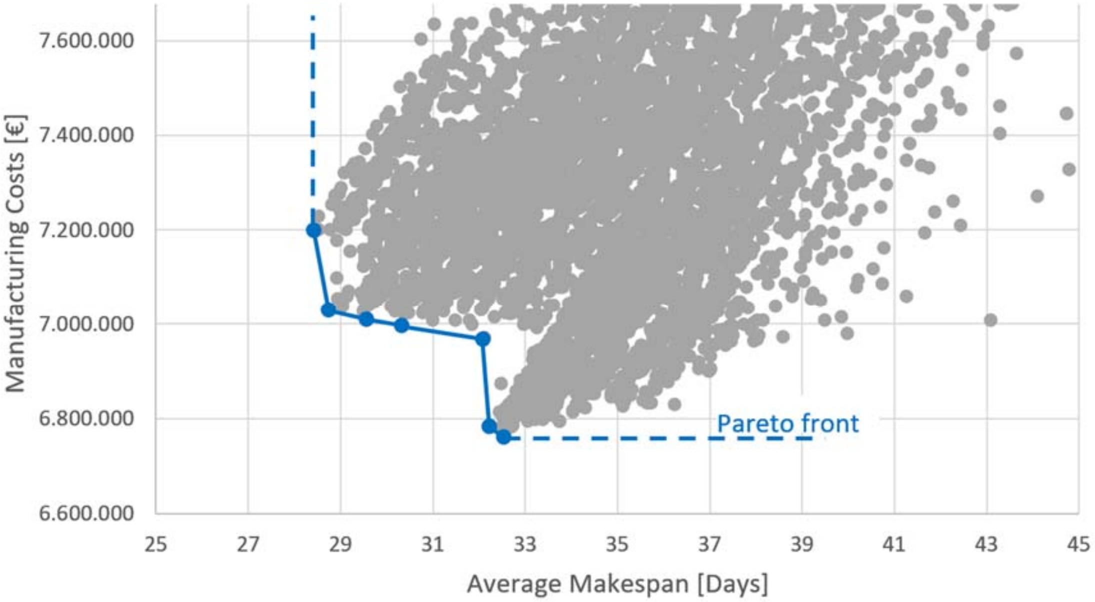


Figure 7: Optimization example for capacity planning using work packages of 3 parallel Airbus A380 D-checks, obtained with the Pareto-Optimization module of SaxMS.APS.

5 CONCLUSION

In multi-project manufacturing, each project consists of a unique compilation of work packages, sub-work packages, and work plan activities. Among those elements, precedence dependencies and hierarchical assignments are present. However, at the time where a project´s due date has to be quoted to the customer not all of those elements and efforts are known. Separate models are, therefore, most often utilized in practice: a rather gross capacity planning model is created early for due date quotation. Later on, a detailed scheduling model is created for scheduling work plan activities. Besides higher modeling efforts and the need for distinct software, severe coordination problems between those models may arise in practice.

The aim of this contribution was to provide a modeling approach for multi-project manufacturing. A mathematical description applicable for capacity planning (MRCMPSP) as well as detailed scheduling (RCMPSP) have been presented. Furthermore, we showed how those calculations can be implemented as an integrated simulation model. Our modeling approach enables to include multiple levels of detail hierarchically into one simulation model by using encapsulation and inheritance principles. Hence, the possibilities to propagate restrictions such as precedence dependencies as well as starting and finishing times from gross to detailed levels in a consistent manner are established.

A real-life application to project-oriented aircraft maintenance was presented. Capacity planning and scheduling are subject to considerable uncertainties, originating from unknown conditions of the aircraft components. Effort estimations based on pre-defined work packages and general precedence restrictions between them are forming the basis for a due date quotation. Next, each work package is detailed on a lower level with associated work plan activities, taking over all the time constraints and precedence restrictions defined on the hierarchically next higher level.

In further research, the presented modeling approach will be used in conjunction with robust optimization principles in order to perform capacity planning and scheduling in daily operation of a project-oriented aircraft maintenance organization.

REFERENCES

Afshar-Nadjafi B. 2016. “A Solution Procedure for Preemptive Multi-Mode Project Scheduling Problem with Mode Changeability to Resumption”. *Applied Computing and Informatics*, in Press.

Angelidis E., F. S. Pappert, and O. Rose. 2011. “A Prototype Simulation Tool for a Framework for Simulation-based Optimization of Assembly Lines”. In *Proceedings of the 2011 Winter Simulation Conference*, edited by S. Jain, 2378–2389. Piscataway, New Jersey: IEEE.

Beşikci U., Ü. Bilge, and G. Ulusoy. 2015. “Multi-Mode Resource Constrained Multi-Project Scheduling and Resource Portfolio Problem”. *European Journal of Operational Research* 240(1):22–31.

Carvalho A. N., F. Oliveira, and L. F. Scavarda. 2015. “Tactical Capacity Planning in a Real-World ETO Industry Case: An Action Research”. *International Journal of Production Economics* 167:187–203.

Drexl A., B. Fleischmann , H.-O. Günther, H. Stadtler, and H. Tempelmeier. 1993. *Konzeptionelle Grundlagen kapazitätsorientierter PPS-Systeme*. Working Paper, Universität Kiel.

Fabig C., A. Kern, and M. Völker. 2016. “Herausforderungen einer robusten Ressourcenplanung der Flugzeugumrüstung und -wartung”. In *Tagungsband zum Forum Technische Logistik und Arbeitssysteme 2016,* edited by T. Schmidt et al., 55–68. Dresden: Selbstverlag der Technischen Universität Dresden.

Frantzén M., A. H. C. Ng, and P. Moore. 2011. “A Simulation-based Scheduling System for Real-time Optimization and Decision Making Support”. *Robotics and Computer-Integrated Manufacturing* 27(4):696–705.

Hans E. W., W. Herroelen, R. Leus, and G. Wullink. 2007. “A Hierarchical Approach to Multi-project Planning under Uncertainty”. *Omega* 35(5):563–577.

Harrison F. L., and D. Lock. 2016. “*Advanced Project Management: A Structured Approach*”, 4th ed. Aldershot: Gower Publishing.

Hartmann S., and D. Briskorn. 2010. “A Survey of Variants and Extensions of the Resource-Constrained Project Scheduling Problem”. *European Journal of Operational Research* 207(1):1–14.

Heimerl C., and R. Kolisch. 2010. “Scheduling and Staffing Multiple Projects with a Multi-Skilled Workforce”. *OR Spectrum* 32(2):343–368.

Herroelen W. 2005. “Project Scheduling – Theory and Practice”. *Production and Operations Management* 14(4):413–432.

Kulkarni A., D. K. Yadav, and H. Nikraz. 2017. “Aircraft Maintenance Checks using Critical Chain Project Path”. *Aircraft Eng & Aerospace Tech* 89(6):879–892.

Mourtzis D., M. Doukas, and D. Bernidaki. 2014. “Simulation in Manufacturing: Review and Challenges”. *Procedia CIRP* 25:213–229.

Schneeweiss C. 2003. “Distributed Decision Making – a unified Approach”. *European Journal of Operational Research* 150(2):237–252.

Schönherr O., J. H. Moss, M. Rehm, and O. Rose. 2012. “A Free Simulator for Modeling Production Systems with SysML”. In *Proceedings of the 2012 Winter Simulation Conference,* edited by C. Laroque et al. Piscataway, New Jersey: IEEE.

Stadtler H. 2015. "Supply Chain Management: An Overview". In *Supply Chain Management and Advanced Planning: Concepts, Models, Software, and Case Studies*, edited by H. Stadtler et al., 3-28. Berlin: Springer.

Stadtler H., C. Kilger, and H. Meyr. 2015. "Conclusions and Outlook". In *Supply Chain Management and Advanced Planning: Concepts, Models, Software, and Case Studies*, edited by H. Stadtler et al., 501-511. Berlin: Springer.

Van den Bergh J., J. Beliën , P. De Bruecker, and J. Peeters. 2013. "*Aircraft Maintenance Operations: State of the Art*". Research Paper, Leuven: Katholieke Universiteit Leuven.

Wauters T., J. Kinable, P. Smet, W. Vancroonenburg, G. Vanden Berghe, and J. Verstichel. 2016. "The Multi-mode Resource-constrained Multi-project Scheduling Problem". *Journal of Scheduling* 19(3):271–283.

Zhang Z., and Y. Wang. 2013. "A Bi-level Model for Resource-constrained Multiple Project Scheduling Problems". In *Proceedings of the 2013 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM),* edited by T. Laosirihongthong et al., 83–87. Piscataway, New Jersey: IEEE.

Zhu G., J. F. Bard, and G. Yu. 2005. "Disruption Management for Resource-constrained Project Scheduling". *Journal of the Operational Research Society* 56(4):365–381.

AUTHOR BIOGRAPHIES

CHRISTIAN FABIG is a member of the Institute of Material Handling and Industrial Engineering at the Technische Universität Dresden. He is also working as a consultant for production management and ERP systems. His research interests include applications of robust scheduling strategies and discrete-event simulation in order to optimize real-life production systems. In particular, he is working in the field of multi-project manufacturing environments such as aircraft maintenance. His email address is christian.fabig@tu-dresden.de.

ELIAS WINTER is one of the two founders and the technical head of Saxony Media Solutions GmbH (SaxMS) in Dresden. Together with his team, he developed a framework for simulation-based optimization, the core of the SaxMS.APS that is used in many projects of various domains in production and logistics. His interests in current research are due to the complexity and scope of the projects he works on, like aircraft maintenance or supply chain networks. His email address is elias.winter@saxms.de.