Provision of Model Parameters for Capacity Planning of Aircraft Maintenance Projects: A Workload Estimation Method based on Enterprise Resource Planning Data

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***Abstract*—Capacity planning is a major issue in aircraft Maintenance, Repair and Overhaul (MRO) companies, given that significant parts of the workload are stochastic in nature. Vast amounts of data are gathered within Enterprise Resource Planning (ERP) systems. Despite their availability, data still has to be utilized to assist the capacity planning process. Besides a quantitative characterization of the capacity planning problem in aircraft MRO, this paper proposes a method for the classification, analysis and estimation of maintenance workloads. This enables to provide model input parameters for a discrete-event simulation on a daily basis. The proposed method comprises the selection of comparable historical projects for analysis, the transformation and mapping of operation data by means of rule-based data wrangling and the characterization of maintenance workloads broken down into network activities and skills.**

***Keywords*— aircraft maintenance; workload estimation; project scheduling; simulation-based capacity planning.**

I. INTRODUCTION

Maintenance is defined as the ”combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” [6]. Examples of items to be maintained include physical assets (e.g., machines, plants, buildings, ships, and aircraft). Maintenance, Repair and Overhaul (MRO) companies produce maintenance services. Thus, maintenance can be regarded as a production process that needs to be planned [16]. Far in advance to a maintenance project, an overall effort estimation is done resulting in a rough estimate of the *total project workload*. In order to carry out a capacity planning, this estimate has to be broken down into required resources and workloads of (predefined) work packages, serving as model input for specialized planning software. Performing the effort breakdown manually is cumbersome, especially when a rescheduling is needed to take production confirmations and more detailed information into account, and is prone to produce model inconsistencies. Thus, the workload estimation process ought to be supported by the Enterprise Resource Planning (ERP) system.

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. From a theoretical point of view, the problem of capacity planning in aircraft MRO corresponds to a Multi-Mode Resource-Constrained Project Scheduling Problem (MRCMPSP; see [9]). In order to provide model input, ERP systems data are found to have shortcomings. For example, there may be an ambiguous classification of maintenance events, non-use of industry standards (e.g., aircraft zoning [17]) and outdated or duplicated work centers resulting from past organizational changes. These issues severely hamper data consistency and may prove them invaluable for capacity planning purposes [7]. Therefore, the objectives of this paper are as follows. Based on data from a German third-party MRO provider, (1) we quantitatively analyze the capacity planning problem in terms of routine and non-routine workloads of different types of maintenance projects and (2) propose an ERP-based method to classify maintenance operations of previously performed aircraft maintenance projects in order to estimate the workload for an integrated capacity planning process of prospective maintenance projects.

The remainder of the paper is as follows. Section II presents related work on the practical application of capacity planning models and fundamentals of aircraft maintenance. A quantitative analysis of aircraft maintenance workloads is given in Section III concerning maintenance project types, aircraft types and aircraft ages. In Section IV, we present the proposed method to classify maintenance operations based on ERP data of previously completed maintenance projects. Furthermore, we show how the evaluation can be used for estimating workloads per project network activity and skill of future projects. Section V presents an example of a maintenance workload estimation for an Airbus A380 cabin modification event that can be transferred into a simulation-based capacity planning software. Finally, in Section VI we draw conclusions on the presented method and future research opportunities.

II. RELATED WORK

1) Practical application of capacity planning models: Significant research on allocating limited resources to competing activities has been carried out using mathematical solution techniques (see, e.g., [5][12][18]). Since large-scale problems can hardly be handled using mathematical modeling and solving techniques, simulation-based scheduling and optimization is

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proposed by several authors for real-life applications [11]. Concerning the field of Production Planning and Control (PPC), Carl [3] proposes a simulation model for planning and optimization of assembly lines and Pinha and Ahluwalia [15] address the short-term resource management in a ship yard using a discrete-event simulation software. In order to incorporate further aspects of real-world problems, a broad variety of model extensions of the basic Resource-Constrained Project Scheduling Problem (RCPSP) have been proposed in literature (see [9][14]). The MRCMPSP model comprises, briefly described, the following aspects (see [2][20]):

- Projects are divided into activities, which require multiple renewable (worker force, machines, tools, etc.) or non-renewable (standard parts, components, etc.) resources to be performed.
- Activities have to respect certain precedence constraints that can be modeled by means of relationships in a project network.
- Resource groups are available with limited amounts and may have certain skills and/or organizational affiliation, thus being applicable to perform a certain proportion of the activities' workload.
- Resources are not dedicated to a specific project. Thus, activities of multiple projects compete for the same set of limited resources.

However, despite considerable research effort, there exist gaps between the model capabilities and its practical application. In particular, model inputs have to be updated with ERP data (e.g., production confirmations, resource availabilities) and hand over to a planning system in order to facilitate a (daily) PPC procedure. Alfieri and Urgo [2] provide an application of project scheduling and a model formulation based on network activity workloads to one-of-a-kind production systems. Dinis and Barbosa-Póvoa [7] propose a set of generic requirements for aircraft maintenance data treatment in order to improve the MROs risk management and planning process.

One important set of parameters in MRCMPSP model formulations describes the (estimated) activity workload for a given project network. The workload of renewable *resource* k incurred by *activity* i is given as W_{ik}. Activity i can be performed in each discrete combination of processing time p_i and resource request r_{ik} that allows to reach the workload, i.e.,

$$W_{ik} \leq p_i * r_{ik}. \tag{1}$$

A mathematical formulation of the MRCMPSP is given in [20]. In Section IV, we will focus on our method for estimating W_{ik} in aircraft MRO based on ERP data.

2) Fundamentals of aircraft MRO: Concerning aircraft MRO, the following maintenance actions can be distinguished (see Figure 1):

- *Preventive maintenance* is carried out intended to assess and/or to mitigate degradation and reduce the probability of failure of an item during flight operation. Therefore, a comprehensive set of work orders is carried out at prescribed intervals of time or number of flight hours. This may require a complete or partial dismantling of the item (i.e., a 'overhaul').
- *Corrective maintenance* has to be carried out after fault recognition. It is intended to restore an item into a state in which it can perform a required function. In case of a safety-critical item corrective actions are mandatory in order to assure airworthiness before the aircraft is allowed to return to flight operation.
- *Modification & Improvement* actions are intended to change the functions of an item or to improve existing functions. This also includes available modifications that are judged by the manufacturer to be a matter of safety rather than simply product improvement.

During the planning process, actions for preventive maintenance and modification & improvement are referred to as *routine* or scheduled maintenance, defined as work orders "carried out in accordance with a specified time schedule or specified number of units of use" [6]. Corrective maintenance is referred to as *non-routine* or unscheduled maintenance, resulting from Discrepancy Reports (DR) that are detected during routine activities and thus are not completely known before inspection tasks are finished. In case of a third-party MRO provider, the customer might also inquire further services while the aircraft is already undergoing its routine maintenance. Since those Additional Service Requests (ASR) are not part of the previously assigned routine work orders, it is also regarded as non-routine. Due to the uncertainty caused by non-routine workload, proper planning 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 process [19]. Low and predictable costs as well as guaranteed turnaround times are the main production targets [16]. Hence, there is a need for accurate estimations of the future maintenance workloads.

III. Quantitative Analysis of Maintenance Workloads

The project samples originate from 201 maintenance projects conducted at a German third-party MRO provider between January 2013 and March 2020 on a total of 147 different aircraft from five different Airbus aircraft families. Projects are classified within that mentioned company into 'Event Types', reflecting the main objective of a maintenance project. Concerning the necessity of accurate workload estimations, so called Heavy Maintenance Checks (HMC) are of particular interest as they are complex due high intensity of workload and scope. HMC projects are labor-intensive and often subcontracted to a third-party service providers. HMC comprise the 'C-check' and the 'D-check' that have to be performed every two year and every six years, respectively [19]. We will further elaborate on the event types in Section IV.

Table I shows the comparison of event types with regard to median workloads in man-hours (MH) of work performed. As can be seen, the project workload diverges greatly from a

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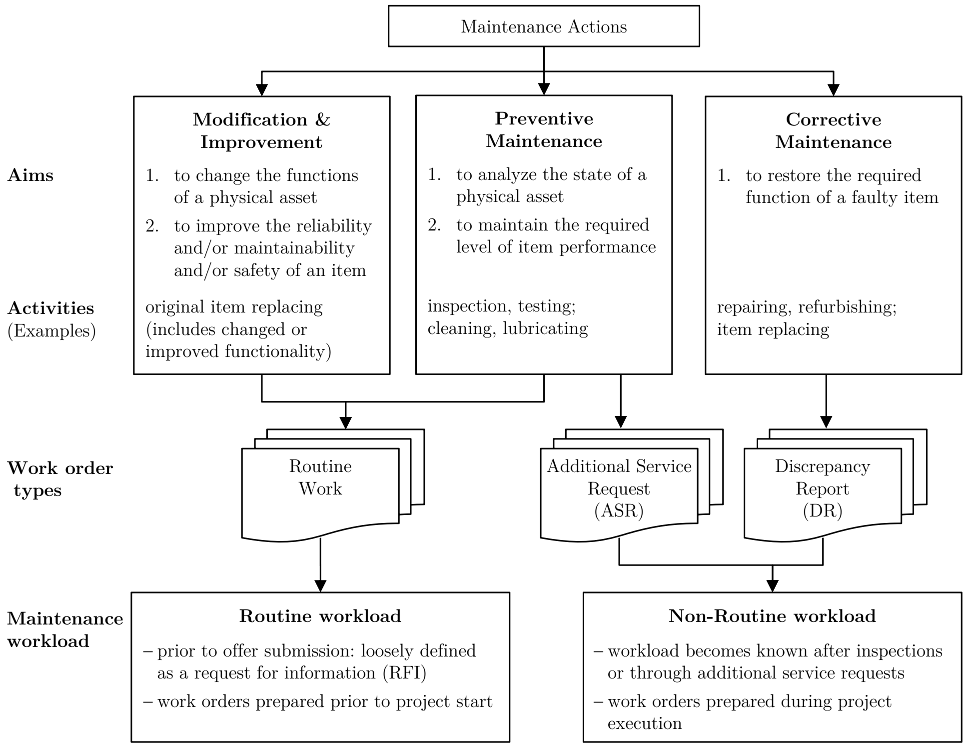

Figure 1. Maintenance actions and origin of workloads in aircraft maintenance projects

TABLE I
WORKLOAD CHARACTERISTICS OF MAINTENANCE EVENT TYPES

Event Type	# of projects [-]	Project workload [MH, median]	Routine [% of project workload]	Non-Routine [% of project workload]
COMPONENTCHANGE--ENGINES	4	464	56%	44%
COMPONENTCHANGE--GEARS	29	659	75%	25%
MODIFICATION--AVIONICS	4	718	67%	33%
CHECK--A	5	1.103	64%	36%
REPAIR--STRUCTURE	13	1.512	47%	53%
CHECK--B	23	6.659	56%	44%
CHECK--C	54	8.159	44%	56%
MODIFICATION--CABIN	28	13.010	65%	35%
CHECK--D	20	16.612	54%	46%
MODIFICATION--STRUCTURE	17	23.450	86%	14%
MODIFICATION--PTOF	4	55.210	64%	36%
Overall (median)	**201**	**6.641**	**62%**	**38%**

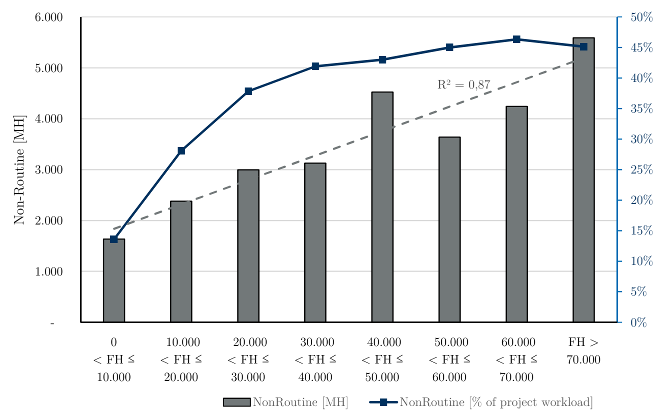

Figure 2. Median of non-routine workload by age of aircraft

’component change’ with less than 1,000 MH to a ’passenger-to-freighter conversion’ (PtoF) with more than 55,000 MH. The share of non-routine workload for ’modification’ event types is rather low (14 - 35% of total project workload) while it is comparably high for HMC (46 - 56% of total project workload). Further analyzing the non-routine workload, Figure 2 shows the median of non-routine workload by age of aircraft measured in flight hours (FH). According to the linear regression trendline, in this regard an increase occurs throughout the service life of an aircraft. However, compared to the total project workload one can see that maintenance events performed on aging aircraft (40,000 FH or more) comprise of approximately 45% non-routine workload.

IV. WORKLOAD ESTIMATION METHOD

The proposed workload estimation method consists of a set of data mining procedures based on aircraft maintenance data stored in an ERP system and of a procedure to classify and analyze the data. Two motivations have let to the development: (1) to characterize the maintenance workloads accurately despite uncertain and scare information during the offer submission process; and (2) to provide means for a simulation-based capacity planning software that allow for scheduling and

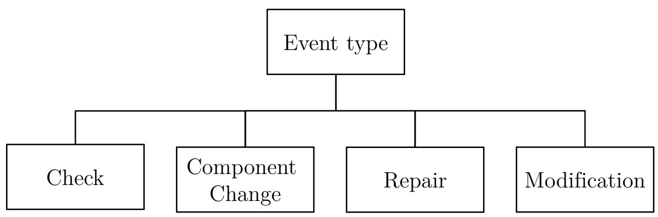

Figure 3. Event types of aircraft maintenance projects

progress control of aircraft maintenance projects. The main steps of the method are presented next.

A. Select completed projects for analysis

The starting point for estimating workloads of future maintenance projects is to select similar completed projects. In aviation, a maintenance project is called 'event'. Separately from an aircraft model, the '*Event Type*' has been established in order to gather the main purpose of an event (Figure 3). The aforementioned *checks* refer to periodic execution of scheduled inspection tasks that have to be done on all commercial and civil aircraft after a certain amount of time or usage, ranging from minor extent (A- and B-check) to major overhauls (C- and D-check). The second category is *component change* (e.g., engine change and landing gear change). Changes might occur as a separate event since the item is subject to wear and tear or, expiring lease contracts (e.g, aircraft engines and the aircraft often have separate lease contracts) and other reasons. *Repair* refers to any maintenance service with the main purpose of corrective actions. Those events include repairs such as lightning strikes, bird strikes, skin panel replacements and fuel tank resealing. The fourth category *modification* includes maintenance services with the main purpose of changing the functions of an item or to improve existing functions. Subcategories are reconfiguration of the passenger cabin, sharklet modification, avionic modification, and others. A PtoF-modification is a way to extend the economic life of an aircraft by converting it into a freighter when it reaches its useful operational service as a passenger jetliner and is one of the most extensive modifications.

An event often includes parts from two categories. E.g., a customer may want to perform a C-check including an engine change or a PtoF-modification with an accompanying A-check. In those cases the event is classified due to its main purpose, i.e., the part with the most extensive workload. When choosing similar projects out of the ERP database, the event type serves as a pre-selector. It is up to the user to either reference only one project or multiple projects of an event type for further data classification and analysis.

B. Transform and map data of completed work orders

In order to analyze the 'raw' data from the ERP system it is necessary to transform and map data into another format or into a standardized classification. Data wrangling and preparation

TABLE II
RULE TYPES FOR DATA WRANGLING

Rule type	Description
Translate Value (TV)	Translation of the field content based on the field name and content to a defined value.
Translate RegEx (TR)	Translation of the field content using a Regular Expression to a defined value.
Translate Unit (TU)	Translation of a unit field and offsetting of the associated data fields.
Replace Part (RP)	Replacement of character part of field content based on start / end position with a defined value.
Replace Content (RC)	Replacement of a field with a certain field content by the field content of an external table.
Replace Field (RF)	Replacement of a field content with field contents of an alternative field.

is applied using a rule-based approach. Table II shows the rule types implemented to translate a field content or to replace it by alternatively using content from another storage location. A rule might be used for an arbitrary field of an ERP data table (e.g., work center, duration, date). Also, a combination of rules might be used whereby the order of the rules corresponds to their processing.

The Aircraft Maintenance Manual (AMM) and other manuals are available from the aircraft manufacturer Airbus SE, defining work content and workflow, required personnel skills and equipment for routine tasks. The aforementioned rules are applied to perform a data preparation and classification (1) to provide an adequate level of detail for the purpose of capacity planning and (2) to align the companies' ERP data with the AMM standards. Next, we present the classifications.

1) Aircraft locations: Among other location systems, a three-digit *'zone'* numbering system applies to every aircraft and is used within the AMM maintenance task specification [1]. Locations are refined from major zone (e.g., 200 - passenger deck), to major subzone (e.g., 210 - cockpit), to unit zone (e.g., 211 - cockpit, left hand side). However, workload estimation and capacity planning based on unit zones and even major subzones is hard to master. By grouping zones one can, obviously, characterize the workload spatially throughout the aircraft. The adequate level of detail can be controlled by the user through wrangling rules. Maintenance planning managers have defined the major zones 100 - 700 complemented with five selected major subzones (e.g., cockpit, main aviation compartment) and

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TABLE III
MAJOR ZONES OF AN AIRCRAFT (EXTRACT)

Major zone	Major subzone	Description
100	-	LOWER THIRD OF FUSELAGE
	110	RADOME - NOSE CONE TO FR0
	120	MAIN AVIONICS COMPARTMENT
	130	LOWER DECK FORWARD CARGO COMP.
	140	CENTER WING BOX
	150	LOWER DECK AFT CARGO COMP.
	160	LOWER DECK BULK CARGO COMP.
	170	AFT CABIN UNDERFLOOR COMP.
	190	BELLY FAIRING, AIR CONDITION COMP.
200	-	UPPER TWO THIRDS OF FUSELAGE
300	-	REAR FUSELAGE SECTION
400	-	POWER PLANT NACELLES & PYLONS
500	-	LEFT WING
600	-	RIGHT WING
700	-	LANDING GEARS & GEAR DOORS
800	-	DOORS

four selected backshops (e.g., Non-Destructive Testing (NDT), saddler shop) as an appropriate level of detail for capacity planning purposes, resulting in a total of 16 locations.

2) Skills: Skills can be broadly defined as the ability to perform certain tasks [5]. In aircraft maintenance, a skill can be further defined as to possess a license to perform particular maintenance tasks on a specific aircraft model. A skill certificate can be held by a technician and is issued by a national aviation authority [4]. One way to model skills for tasks in an ERP system is to define a specific work center for each of them [10]. In analyzed data of the German third-party MRO provider, more than 150 work centers are currently in use and another 550 work centers are outdated or duplicated resulting from past organizational changes. Thus, in order to estimate workloads by analyzing previously performed aircraft maintenance projects the work centers have to be grouped through wrangling rules. Table IV presents the skills that maintenance planning managers have identified as an appropriate level of detail for capacity planning.

3) Network activities: Maintenance events are typically conducted in several phases. In the 'Reception' phase (I), the aircraft undergoes initial tests and preparations, e.g. docking. After that, in the 'Disassembly' phase (II), access panels, doors and aircraft components are removed in order to accomplish the maintenance actions. In the 'Inspection' phase (III) airframe, systems and components are inspected for wear and tear and other discrepancies such as dents or corrosion. Discrepancies are then corrected to ensure the items functions and airworthiness in a 'Repair & Overhaul' phase (IV). After completion of all non-routine works, the removed aircraft components, doors and panels will be reinstalled in the 'Installation' phase

TABLE IV
CONSIDERED MAINTENANCE SKILLS

Skill code	Description
A/P	Airframe & powerplant systems
AIM	Aircraft interior maintenance
E	Engineering
ERI	Electric & avionic systems
FRL	Outsourced services
KM	Painting & Composites
NDT	Non-destructive testing
QS	Quality inspection (general)
STR	Structural mechanics
TP	Work preparation

(V) before operational and functional tests of aircraft systems and components are performed in a final 'Redelivery' phase (VI). Although the above sequence of phases is technologically given, concerning the maintenance event as a whole those phase may overlap with each other since work in one location can (largely) be executed independently from that of other locations [8]. Sequence dependencies are modeled by means of a project network, as shown in Figure 4. The project network for MRO events has been defined in collaboration with maintenance managers and technicians. It includes the aforementioned MRO phases further detailed into the aircraft locations, if appropriate, and consists of a total of 56 network activities.

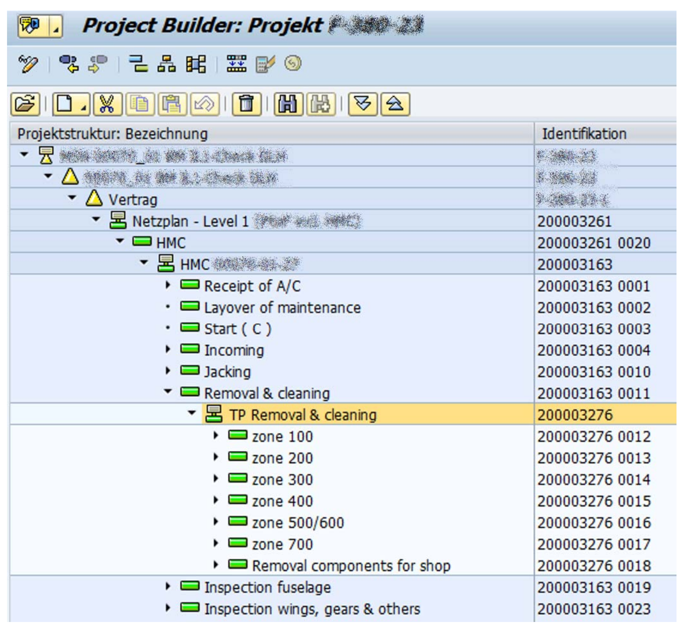


Figure 4. Network activities of a maintenance event (extract)

C. Classify and assign operations to network activities

An algorithm has been developed to assign operations listed in work orders of completed projects to the most appropriate network activities one by one. The order in which the assignment of an operations to the most appropriate network activity is checked has a decisive influence on the correct and complete classification of the operations. In general, the possible assignment of an operation to a network activity with the most specific classification (e.g., NDT inspection work in zone 140) should be checked first while its assignment to a network activity with a more general classification (e.g., inspection work in zone 100) is evaluated afterwards since the former is a subclass of the latter.

The classification and assignment process is implemented within the ERP system by extending each network activity with its classification after data wrangling in terms of aircraft location, skill, work order type, AMM reference and other attributes in an additional data table. The algorithm thus starts with checking for the matching of an operation to the network activity with the highest amount of attributes (field), i.e., the most specific classification, and subsequently those network activities with a lower amount of attributes until a matching is found. In case no matching could be found, the operation is assigned to the 'project' as the root element. Multiple values (field contents) of the same attribute are linked via a logical OR-concatenation while different attributes are linked via a logical AND-concatenation when checking the amount of attributes. A first draft version had been designed by [13]. The algorithm has been implemented in ERP system "SAP ERP 6.0", using its Advanced Business Application Programming (ABAP) language, and further improved together with maintenance planning managers.

D. Evaluate workload distribution

The analysis of the completed projects is consolidated using a *workload distribution matrix* shown in Figure 5.

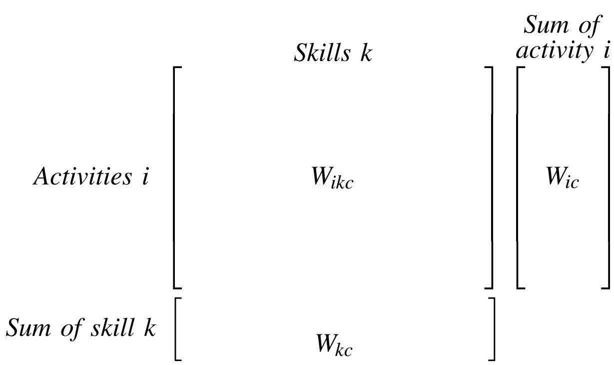


Figure 5. Structure of the workload distribution matrix

Where:

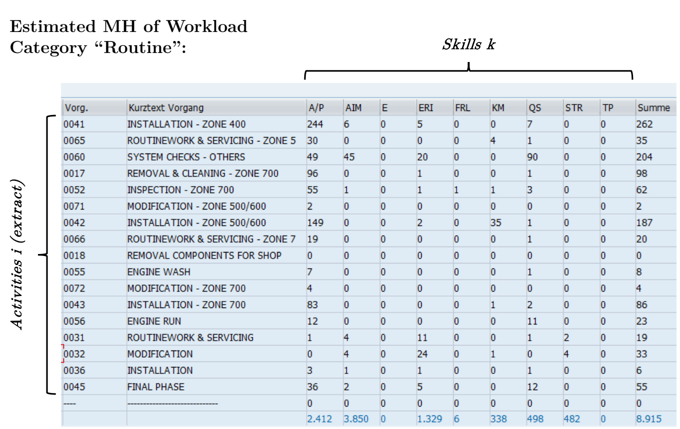
- W_{ikc} - median workload in network activity i for skill k of workload category c, in [MH],
- W_{ic} - median workload in network activity i of workload category c, in [MH],
- W_{kc} - median workload for skill k of the workload category c, in [MH].

Typically, there are several work order types that have to be mapped into a workload category c by means of the rule-based data wrangling procedure in order to differentiate '*routine*' and '*non-routine*', respectively. To quantitatively assess the workload of a prospective maintenance event for each category, the work performed through operations o from historical ERP data of completed projects p is sorted using the classifications defined in Subsection IV-B. Each matrix element is calculated as the median value of the analyzed historical projects and provides model input parameters for the left-hand side given in equation (1).

V. Case Example

Figure 6 presents an example of a maintenance workload estimation for an Airbus A380 cabin modification event. The workload distribution matrix for routine and non-routine workloads has been obtained analyzing five historical maintenance events that were classified as event type "MODIFICATION-CABIN" and assessed to be comparable to the prospective event by maintenance managers. These events contain 2,700 2,900 2,400 3,100 and 3,400 order operations, respectively. In the data wrangling procedure, the 'raw' order operation data has been transformed and mapped into the standardized classifications given in Section IV-B. Among other things, the roughly 700 work centers defined in the ERP system were mapped to the skills shown in Table IV using wrangling rules. Note that in this case example skill "NDT" is not present in the workload distribution matrix as there were no order operations having structural testing works (as could be expected for cabin modifications). On top of that, operations have been assigned to the network activities of the maintenance event (see Figure 4) and classified into workload categories. The total "routine" workload is estimated at 8,915 MH (64 %) and the total "non-routine" workload is estimated at 4,960 MH (36 %), which roughly corresponds to the workload characteristics given in Table I.

The aim is to use these results as model input for a multi-project capacity planning. An interface to a simulation-based



Vorg.	Kurztext Vorgang	A/P	AIM	E	ERI	FRL	KM	QS	STR	TP	Summe
0041	INSTALLATION - ZONE 400	244	6	0	5	0	0	7	0	0	262
0065	ROUTINEWORK & SERVICING - ZONE 5	30	0	0	0	0	4	1	0	0	35
0060	SYSTEM CHECKS - OTHERS	49	45	0	20	0	0	90	0	0	204
0017	REMOVAL & CLEANING - ZONE 700	96	0	0	1	0	0	1	0	0	98
0052	INSPECTION - ZONE 700	55	1	0	1	1	1	3	0	0	62
0071	MODIFICATION - ZONE 500/600	2	0	0	0	0	0	0	0	0	2
0042	INSTALLATION - ZONE 500/600	149	0	0	2	0	35	1	0	0	187
0066	ROUTINEWORK & SERVICING - ZONE 7	19	0	0	0	0	0	1	0	0	20
0018	REMOVAL COMPONENTS FOR SHOP	0	0	0	0	0	0	0	0	0	0
0055	ENGINE WASH	7	0	0	0	0	0	1	0	0	8
0072	MODIFICATION - ZONE 700	4	0	0	0	0	0	0	0	0	4
0043	INSTALLATION - ZONE 700	83	0	0	0	0	1	2	0	0	86
0056	ENGINE RUN	12	0	0	0	0	0	11	0	0	23
0031	ROUTINEWORK & SERVICING	1	4	0	11	0	0	1	2	0	19
0032	MODIFICATION	0	4	0	24	0	1	0	4	0	33
0036	INSTALLATION	3	1	0	1	0	0	1	0	0	6
0045	FINAL PHASE	36	2	0	5	0	0	12	0	0	55
----	----------------------------	0	0	0	0	0	0	0	0	0	0
		2.412	3.850	0	1.329	6	338	498	482	0	8.915

Figure 6. Example of a workload estimation matrix of a cabin modification

capacity planning software has been implemented, allowing to export the workload distribution matrix as well as project networks, skills, resources, and resource availabilities (see [8]).

VI. CONCLUSION

The objectives of this paper were twofold: (1) to quantitatively analyze the capacity planning problem in terms of routine and non-routine workloads of different types of maintenance projects and (2) to propose an ERP-based method to classify maintenance operations of previously performed aircraft maintenance projects in order to estimate the workload for an integrated capacity planning process of prospective maintenance projects.

Regarding the first objective, results show that the workload of a maintenance project diverges greatly depending on the event type carried out. Non-routine workload has been found to be comparably high for HMC checks with 46 - 56% of total project workload. Furthermore, aging aircraft turned out to have a non-routine workload share of 45% independently from the type of maintenance event. Those amounts of uncertainty imply a serious threat to MROs capacity planning, particularly when multiple aircraft are maintained contemporaneous. As for the second objective, an ERP-integrated method for selecting comparable projects for analysis, transforming and mapping of operation data by means of rule-based data wrangling is proposed. Each operation is then assigned to one network activity of the prospective project in order to estimate routine and non-routine workloads. The workloads are further broken down into network activities and skills. This allows to characterize the maintenance workloads accurately despite uncertain and scare information as early as during the offer submission process.

Furthermore, gathered within a workload distribution matrix, the method can provide model input parameters for simulation-based capacity planning software that allow for capacity planning, scheduling and progress control of aircraft maintenance projects. This constitutes research opportunities to further enhance the multi-project planning and scheduling methods for aircraft maintenance companies, thus providing them a decisive competitive advantage.

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