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SIMULATION AIDED DEVELOPMENT OF ALTERNATIVES FOR IMPROVED MAINTENANCE NETWORK

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ABSTRACT

The success of organizations operating in complex environments depends on how well their value chain can adapt to disruptions caused by unanticipated events. Building this resilience requires the capability to identify uncertainties and modelling their impact on operations. To effectively achieve this is very difficult. Thus, increasing resilience in maintenance and repair networks calls for an adequate approach to address uncertainties. It is necessary to consider the maintenance activities within and outside the company and those affecting all supplier partners of equipment. This paper presents a comprehensive analysis, a potential approach to model their impact and alternatives to increase the flexibility of the network to ensure profitability and continuity.

KEYWORDS

Simulation, Maintenance, Network

1. INTRODUCTION

Organizations involved in the business field Maintenance, Repair and Overhaul (MRO) are more strongly affected by unsteady incoming work orders from scheduled and voluntary maintenance than product manufactures.

The complexity of MRO activities is indicated by highly fluctuating work volumes between the maintenance orders, different disassembly and assembly depths, unplanned express orders as well as differentiated qualification levels of the workers. The differences in the conditions of operating products and existing of several workshops in a maintenance and repair network for an MRO organization further exacerbates the situation.

Therefore, to guarantee on-time delivery and short turnaround times, despite of the capacitive, logistical and order specific conditions, a reasonable sequencing in the context of maintenance planning and control is needed.

For the realization of the sequencing suitable scheduling and priority rules are required. There are a wide variety of tools to support the analysis of complex systems such as those involving maintenance from simple static spread sheet based tools to those incorporating more sophisticated simulation technology.

In order to solve sequencing problems Nyhuis and Hartmann (2010) recommend the use of tool modelling and simulation for the validation of a suitable rule. Models emphasise main features of a system to clarify interrelationships and ensure transparency (VDI 2893, 2006). Simulation tools are widely used for manufacturing systems as well as services, defence, healthcare and public services (Jahangirian, 2010).

It is defined as experimentation with a simplified imitation of an operating system as it progresses throughput time, for the purpose of better understanding and/or improving the whole system (Robinson, 2004). Simulation techniques have the capability to analyse the performance of any operating system without affecting the real system.

This paper is based on an industrial case study in a cleaning and waste management service company for vehicular maintenance. The services provided by the company range from the punctual emptying of refuse bins to ecological waste utilisation and disposal in its own plants as well as street cleaning and winter road maintenance.

2. MAINTENANCE NETWORK

In the past decade, various maintenance strategies have been proposed for complex systems. In summary, the European Federation of National Maintenance Societies defines maintenance as the "combination of technical, administrative and managerial actions during the lifecycle of a product intended to retain or restore it to a state in which it can perform its required function" (Klemme-Wolff, 2009).

The main features of complex systems include business processes, their organisation, the resources used, and the outcomes. Seliger (2007) introduces the factors of value creation networks as product, processes, equipment, organisation and people.

Vehicles present the products in the considered maintenance and repair network. Business processes cover all MRO activities, whether preventive, predictive, proactive or corrective. Resources and materials are used as equipment in the workshops. Replacement materials are obtained on demand from a centralised warehouse. The organisation, planning and control in and between the workshops entail progressive detailing and the performance of respective MRO processes. The qualification level, number of employees, their knowledge and working habits, relationships, and absenteeism considerably influence the performance of the MRO network.

Based on the performance requirements of the network, more specific maintenance planning can be carried out. A comprehensive maintenance and repair network addresses all aspects of MRO, from preventive to corrective maintenance.

The performance of such a complex system with operating and maintenance activities is determined by the reliability and availability of the system components depending on time and costs.

Time is one of the key performance indicators here including operating time, daily overhaul time, periodic maintenance time, condition based maintenance and additional run to failure time of vehicles (Rajpal, 2006).

The operating time is generally recorded as cumulative working time of the product since the last overhaul and gains profit for the service provider company.

The daily overhaul time consists of services and inspections conducted daily before the first operation of the vehicle and after the completion of daily assignments. These routine works include small inspections and cleaning before causing a failure and should not entail any expense (Wireman, 1990).

Periodic maintenance is a preventive method with predetermined plans and schedules for MRO activities to keep a product in stated working condition through the process of checking and reconditioning (Sharma, 2011).

Condition based maintenance is a predictive approach. It implements modern measurement tools and signal processing methods proactively to diagnose the condition of the vehicle during the operation time and optimise the maintenance intervals.

Preventive and predictive maintenance incur costs based on replacement materials, lost operations, workforce and material like rags and lubricants for MRO activities (Salonen, 2011).

Corrective maintenance comprises immediate, unplanned and unscheduled activities to run to failure or deficiencies and return the product to a defined operating state. These are caused by components with random failure distribution and lack measurable deterioration or in cases of infeasible or poorly performed preventive measures. Additional costs occur in breakdown times related to scrap, rework or overtime for recovery.

3. DESCRIPTION OF THE AS-IS STATE

The business of collecting waste and cleaning the streets throughout the year requires an effective fleet with different kinds of vehicles operating in a predefined area.

The vehicle's condition is affected by several factors such as type, number, age, and arrangement of components in the vehicle. The operating and environmental conditions including operating personnel, working habits, and safety measures also impact the wear (Ebling, 1997).

The steps in running the MRO activities depend on the conditions of the vehicle and vary in duration, required workforce and equipment. To prevent unexpected large failures, some maintenance activities and services are collected preventively in scheduled overhaul sets and run regularly on the vehicles.

The MRO activities are processed in workshops with different repair stations. This aspect of the maintenance and repair presents a hybrid flow sequencing problems with a pre assignment of vehicles to repair stations.

The objective of the study is to balance the volume of orders utilising the capacity of the network in order to minimize the throughput time of maintenance orders. To solve it, different simulation alternatives have been applied.

3.1. PROCESS FLOW OF MRO ACTIVITIES

The vehicle fleet contains more than 1,600 vehicles enabling the cleaning activities and waste management. There are 34 types such as garbage truck, rinsing vehicle, collection vehicles, road sweepers and etc.

The main target of the vehicles is to fulfil their tasks to clean and dispose in their predefined area. Each vehicle of the fleet is assigned to a location in the network according to its operation area. That means an operating vehicle starts its daily tour from a specific station und returns to the same location and parks when its work shift is over.

Some small breakdowns lead to temporary interruption of the daily tour, e.g. flat tire. These are repaired either by the driver himself or by a mobile MRO workshop promptly without the need to make a maintenance order.

After the assignment is finished, some small overhaul activities are completed which mature as part of the daily business and do not require a maintenance order.

A new preventive maintenance order is placed after the daily tour in the event of a scheduled maintenance check. In this case, the vehicle is checked for further damages which do not interrupt the daily assignment, but can be repaired during the MRO activities.

Damages or breakdowns of the vehicle reported by the driver and his team or found during the daily overhaul lead to a corrective maintenance order, if the vehicle is not available for the next shift.

In this case, the vehicle will be moved from the parking area to the MRO area which is also called a maintenance and repair workshop, hereinafter referred to as workshop. Around 24 operating and parking areas are assigned to 14 workshops which are the first point to receive vehicles with MRO requirements.

So the municipal maintenance and network developed in 1951 consists of two main workshops (MW) and 12 small workshops (W) distributed across the state.

The small workshops are able to handle simple repairing activities specifically for their certain types of vehicles. The main workshops differ from small workshops by offering a large spectrum of preventive maintenance services (scheduled) and corrective repair activities (voluntary). If preventive maintenance or more severe corrective maintenance is required, the vehicles are moved from a small workshop to one of the main workshops and return after the completion of the MRO activities to its home workshop and hereafter to its home area.

A workshop is full when all of its repair stations are occupied and their staffs work on vehicles. This means the next incoming vehicle will occupy an already occupied repair station or will be moved from the parking places to wait in designated buffer. The capacity of these buffers is also limited and if they are also full, the vehicles must wait in the parking area of the operating area.

Waiting in any parking area to be maintained or repaired results in an overall increase in non-operating time for one of these vehicles. Such waiting times are to be minimized for better performance of the service business. Therefore an optimal utilization of the network is needed. The current network works without any predefined priorities. But workshop staff and management self-adjust based on the repair portfolio of other workshops and their personnel relations to colleagues from other workshops to encourage the establishment of some time-critical orders.

3.2. DATA ANALYSIS

The general procedure of modelling and simulation has been used as a based in performing this study. A workflow for the case study is shown in Figure 1 starting from defining the problem and objective until interpretation of the results. As the problem and objective have been defined the next and the most important step is data mining and system analysis.

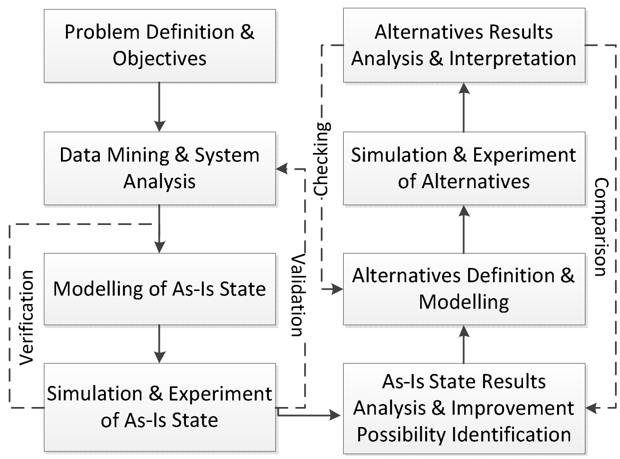

Figure 1 – A workflow for the case study

For the analysis of the network and process flow and the case study, the data of the MRO network from 2009 is taken. The volume of orders is analysed in detail for the current maintenance and repair network. In order to simplify the complexity of the case study, a survey of some system features is helpful.

This can be done with the value creation factors introduced in chapter 2 using the question method: where (workshop), what (vehicle, and maintenance order), how (MRO activities), when (date), and who (employees).

Within one year, approximately 39,000 maintenance orders are received and serve as input data for the simulation case study. An illustrated input data as an excerpt is shown in Table 1.

Table 1: Example of used inputs for data analysis

Location	Maintenance order number	Maintenance order type	Vehicle type	Order item	Service description	Date	Working time (dd.hh.mm.ss)
MW1	52840765	Preventive	Garbage truck (Type 19)	001	Full inspection	12.01.2009	01:11:33:44
				002	Replacements	12.01.2009	00:08:26:01
W8	52846969	Corrective	Collection vehicle (Type 1)	001	Installation auxiliary heating	12.01.2009	00:02:37:43
MW2	52840773	Corrective	Road sweeper (Type 18)	001	Small inspection	13.01.2009	00:05:51:18
				002	Replacement break light	13.01.2009	00:02:37:43
				003	Replacement gear system	14.01.2009	00:13:23:58
				004	Deletion of failure memory	14.01.2009	00:00:09:32
				...	...	...	...
MW1	52841420	Preventive	Collection Vehicle (Type 1)	001	Replacement break system	12.01.2009	01:07:16:23
W3	52847738	Corrective	Garbage truck (Type 19)	001	Replacement of lubricants	13.01.2009	00:02:12:35
				002	Filter cleaning	13.01.2009	00:01:53:51
				003	Replacement alternator	14.01.2009	00:03:06:26
				004	Replacement Wipers	14.01.2009	00:01:17:34
MW1	52842108	Corrective	Rinsing vehicle (Type 5)	001	Replacement of lubricants	13.01.2009	00:02:33:44

"Location" shows the workshop in which MRO activities proceed. The "maintenance order number" is the ordinal number of failure. "Maintenance order type" differentiates between corrective or preventive maintenance and "vehicle type" classifies the vehicle handled during the order.

One maintenance order consists of many "order items" followed by the description of the performed service ("service description"). In some orders, corrective or preventive items are listed together if some unscheduled activities caused by damages are completed in the same order.

"Date" defines the exact time (year, month, and day) of failure and an order item is completed. The duration of a maintenance order is defined as the interval between the earliest and latest date of its order items.

"Working time" is the value adding real working time of the workshop staff to fulfil the required service. The fifth entity row in Table 1 is explained here in detail for a better understanding of the process flow: An error of garbage truck was reported in January 2009 and this vehicle of vehicle type 19 was not able to operate in the next day.

The corrective maintenance order 52847738 was received on the January 13th in the small workshop W3. Four order items were identified by the staff of W3 and ranked in the feasibility of the small workshop W3. Its staff spent 2 hours 12 minutes to replace the lubricants and 1 hour 53 minutes to clean the filters on the same day. All four items were completed in two work days and the real working time of the workshop staff on the vehicle has taken only 8 hours 28 minutes.

3.2.1. Performance Figures

The order frequency indicates the number of MRO orders as recorded breakdowns per year.

According to VDI 2893 "Mean Time To Repair" (MTTR) stands for the average breakdown time per repair. It shows the ratio of the total amount of breakdown time ($t_{failure}$) divided by the number of recorded breakdowns ($x_{failures}$) per year:

$$MTTR_{Vehicle} = \frac{\sum t_{failure}}{x_{failures}} \qquad (1)$$

"Mean Time Between Repair" (MTBR) is the average time between repairs. It consists of the total operating time ($t_{operating}$) divided by the number of recorded breakdowns per year:

$$MTBR_{Vehicle} = \frac{\sum t_{operating}}{x_{failures}} \qquad (2)$$

"Mean Time Between Failures" (MTBF) is the average running time of the MRO network between breakdowns:

$$MTBF_{Vehicle} = \frac{MTTR_{Vehicle} + MTBR_{Vehicle}}{x_{failures}} \qquad (3)$$

3.2.2. Classification of maintenance orders

Due to large differences between the reported working times it is not suitable to use the mean of working times for the modelling of the considered MRO activities.

Thus, to get a realistic output from the modelling, working times for each vehicle type are separated into corrective and preventive orders and analysed to provide occurrence probabilities. Therefore five time classes are defined for each vehicle type. The lower limit *l* for the first class is the minimum duration of the reported working times:

$$x^{l}_{j,k,1} = \min\left\{ t_{repair,j,k} \right\} \qquad (4)$$

Hereby *j* is considered as vehicle type, *t* stands for the specific working time and *k* indicates whether the reported time is for corrective or preventive orders. Index 1 stands for the first time class. The upper limit *h* for the fifth class is the highest duration of the observed working times within the considered vehicle group:

$$x^{h}_{j,k,5} = \max\left\{ t_{repair,j,k} \right\} \qquad (5)$$

The width of the specific time classes of each vehicle group and their appropriate lower and upper levels are calculated as the following:

$$\Delta x_{j,k} = 1/5 * \left\{ x^{h}_{j,k,5} - x^{l}_{j,k,1} \right\} \qquad (6)$$

The reported working times for each vehicle type are sorted in a descending order and assigned to the time classes as defined in formula (4)-(6). A working time is assigned to a class if it is smaller than the upper level, but higher as the lower level of a time class. Afterwards the number of observations in each time class are counted and set into relation to the total amount of observations for each vehicle type to obtain their relative share. This relative share, which is now considered as the occurrence probability of the average mean of each time class, is an appropriate dimension to get a realistic output from the modelling.

4. MODELLING AND SIMULATION

Despite the importance of the model design phase in the simulation process, it is very often overlooked. In this phase, the project participants are to be identified, the project goals are to be clearly delineated, and the basic project plan is to be developed. If these activities are not conducted effectively, the model developed could be too detailed or generic. While incorporation of detail may increase the credibility, excessive levels of detail may render a model hard to build, debug, understand, and deploy. The determination of the detail level is a primary goal of the design stage.

The preliminary work of the conceptual model design is followed by the development of the model. This involves choosing the modelling approach, building the model, and doing verification and validation of the model. The choice of approach can make a large difference in the subsequent model building and model execution times.

In this project, the sequencing problem for maintenance and repair network has been modelled using discrete event simulation with top-down approach (Figure 2). A top-down approach is essentially the breaking down of a system (maintenance and repair network) to gain insight into its compositional subsystems (workshops and repair stations).

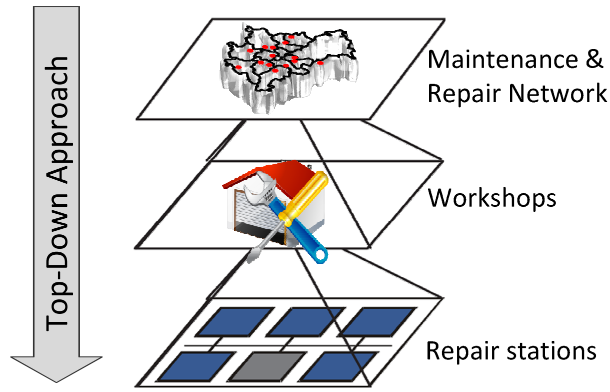

Figure 2 - The project view from Top-down Approach

In a top-down approach an overview of the system is formulated, specifying but not detailing any first-level subsystems. Each subsystem is then refined in yet greater detail, sometimes in many additional subsystem levels, until the entire specification is reduced to base elements.

After determining the modelling approach, the next step is to build the model with appropriate system elements. Three levels of systems and subsystems have been defined and modelled with the discrete-event simulation software from Siemens AG., Tecnomatix Plant Simulation. There are maintenance and repair network levels, workshop levels and repair stations levels. At maintenance and repair network level, twelve small workshops and two main workshops are modelled based on their locations in the state (Figure 2). A buffer is placed in front of each workshop to represent a parking place for waiting vehicles which are to be maintained or repaired in this workshop.

The First-In-First-Out (FIFO) strategy is used at the buffer so that the first vehicle entering the buffer will be the first sent to the available repair station. The capacity of these buffers is fixed and varies depending on workshop size. Due to that condition, overload of maintenance orders in buffers are possible. To overcome that problem, a dummy overall buffer is modelled.

The workshops are then refined at the workshops level (Figure 3). The number of repair stations and workers for each workshop are modelled here.

In the next level each repair station is refined considering capacity and specification of the repair station, availability of resources and productivity of workers at the repair station.

The discrete-event simulation is entity-based; it deals with entity flows rather than with single entities. In discrete-event simulation the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system.

In this model, entities are representing maintenance orders. There are two types of maintenance orders; preventive maintenance order and corrective maintenance order. The preventive maintenance orders are generated based on the preventive maintenance list from 2009. Information such as date of maintenance, vehicle type and planned workshop for the maintenance are listed in a similar data sheet as Table 1. Each maintenance order will be created at the specific date by a generator. This maintenance order will be sent to the planned workshop buffer and will wait until a repair station is available.

The corrective maintenance orders are created by random generators based on MTBF. It is calculated for each vehicle type separately as shown in chapter 3.3.1. One random generator for each vehicle type has been modelled. There are 34 random generators representing each type of vehicle which create the corrective maintenance order independently.

For the implementation of unplanned maintenance orders, there are following rules (Figure 4): When a corrective maintenance order is created, the location of the vehicle and the responsible workshop are identified. Availability of responsible workshop is checked.

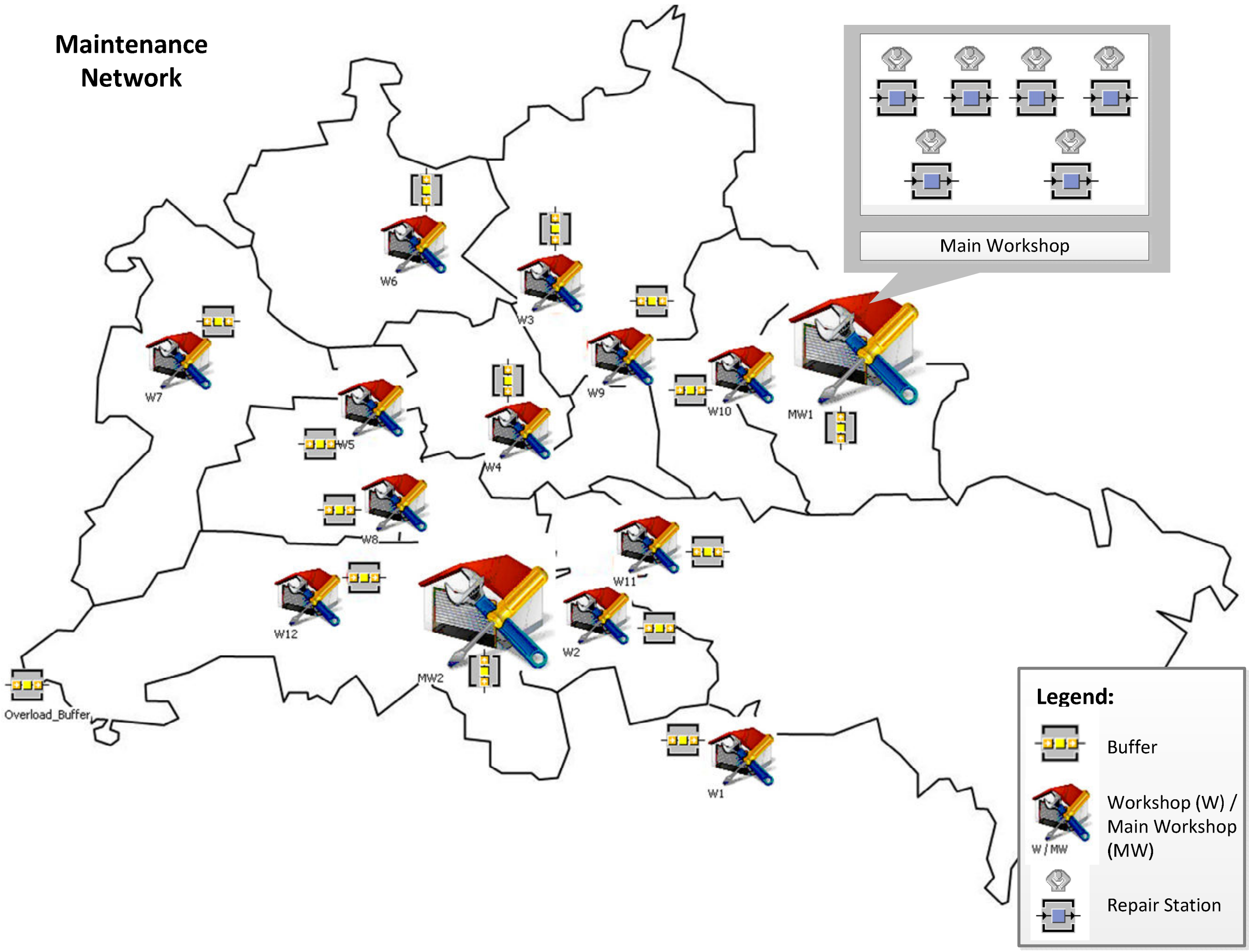

Figure 3 – Maintenance and repair network models

If the workshop is able to receive the maintenance order and there are available repair stations or places at the buffer, the workshop will accept it. The vehicle will be sent to the buffer before reaching the repair station for maintenance activities. Then the maintenance order will be completed according to its order items and closed.

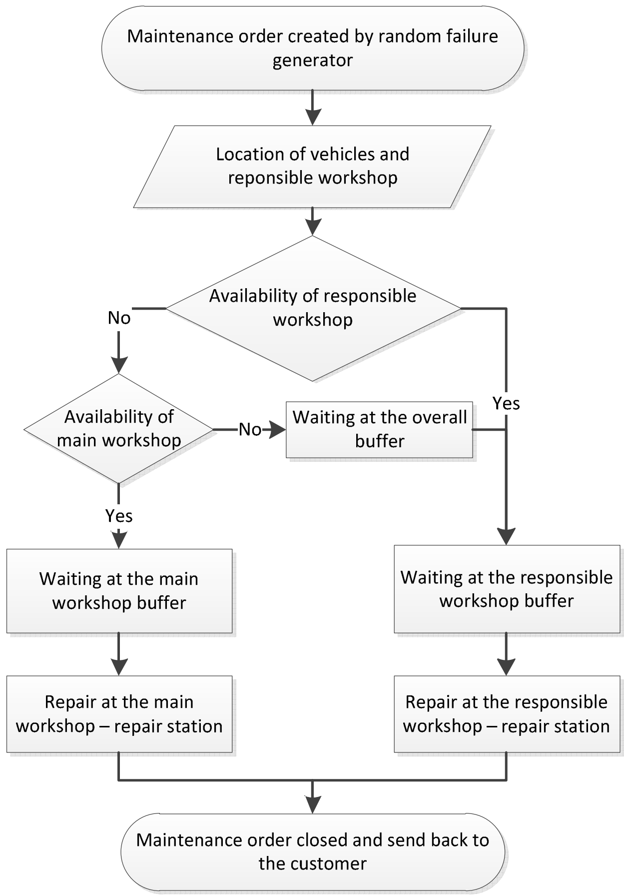

Figure 4 – Procedure for corrective maintenance order implemented in simulation model

If the responsible workshop cannot accept the maintenance order, the availability of main workshops is checked. One of the main workshops will accept the order if it has enough capacity. The maintenance activities will then take place at the main workshop. In case both main workshops cannot accept the order, it will be sent to the overall buffer. At the overall buffer, the maintenance order will wait until the buffer of the responsible workshop is able to receive it.

Corrective and preventive maintenance orders are classified during their transfer from the generator to workshop. Each order will be assigned to a class with its maintenance time randomly based on the occurrence probability of their classes as introduced in chapter 3.3.2.

In modelling for a simulation, the level of abstraction always comes into question. A high level of abstraction will lead the model to be closely to the real system and low level of abstraction will not adequately represent the real system. The optimum level of abstraction is hard to define. In many cases data availability and duration of the study will be the determinant for modelling abstraction level.

Due to these factors, some assumptions have to be made and implemented in the model. Assumptions made and implemented for this case study are:

i. Every workplace is able to receive every type of vehicle (resource independent).
ii. Every worker is able to repair all kinds of maintenance (capabilities independent).
iii. Each maintenance order involves only one worker at a particular time. There are no parallel activities in one maintenance order.
iv. Seasonal effect has not been considered and there are no priority applied for seasonal vehicles.

By implementing these assumptions into the model and simulation, certain factual aspects were not considered. To ensure that the model still represents the real system and is enough to achieve the objective of the study, verification and validation was conducted.

Verification is a determination of whether the computer implementation of the conceptual model is correct. It was conducted by following the principle of structured programming, usage of interactive run controller or debugger and monitoring the model animation.

Validation on the other hand is a determination of whether the conceptual model can be substituted in the real system for the purposes of experimentation. Validation of this model has been done through consistency checks, input-output transformation and historical input data comparison.

The model was simulated for one year. The outcomes; utilisation of workshops, utilisation of workshops' buffer and throughput time for maintenance orders are recorded. The result from the simulation is presented and explained in the next chapter.

5. ANALYSIS OF THE OUTCOME

The simulation was run several times and the average outcomes recorded. Figure 5 shows the utilisation of workshops in the maintenance network.

The value in the graph represents the mean utilisation of all repair stations at the workshop based on working, waiting and pausing percentages. Working means the repair station has a vehicle to be repaired and a worker to repair it. The repair station is empty in the waiting mode and the pausing mode demonstrates breaks in the working shift.

From the graph three workshops with high utilisation are identified. Workshop 3 (W3), workshop 2 (W2) and workshop 8 (W8) have an average utilisation of more than 70% in a year. With an average utilisation between 50-60%, imbalance in utilisation occurs in the remaining workshops. Two determining factors for this imbalance have been identified.

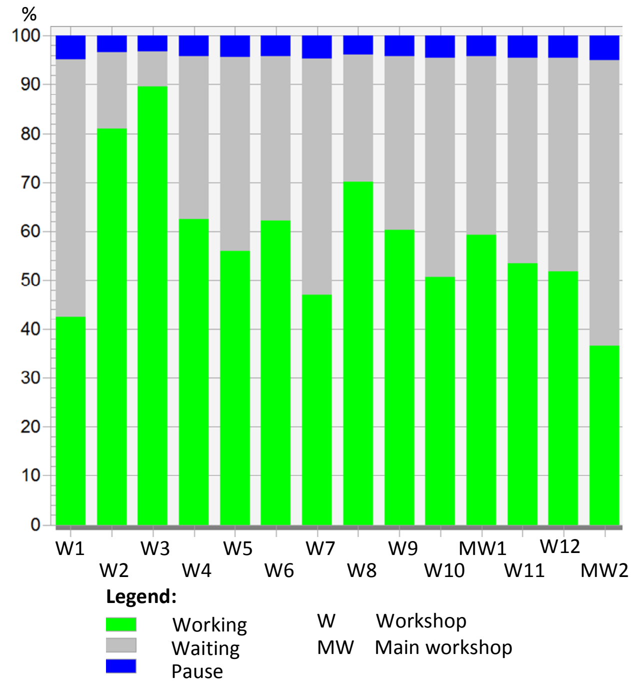

Figure 5 – Utilisation of Workshops from simulation of AS-IS state model

The first is a high ratio in preventive maintenance orders over available repair stations at certain workshops. Preventive maintenance orders created through a scheduled list implemented in 2009, have to be repaired at the planned workshop and cannot be transferred. Huge numbers of preventive maintenance orders have therefore been scheduled for a particular workshop without considering the fact that their capacity will lead to high utilisation of the workshop.

The second factor for the imbalance comes from the corrective maintenance order rules and arrangement. For corrective maintenance, the operation area of vehicle determines the responsible workshop. Some vehicle types appear to be high in corrective maintenance, with higher maintenance throughput time than others.

Figure 6 shows the simulated annual number of maintenance orders and average maintenance throughput times according to vehicle types. The assignment of responsible workshop added to the corrective maintenance orders for certain vehicle type increases the workshop utilisation.

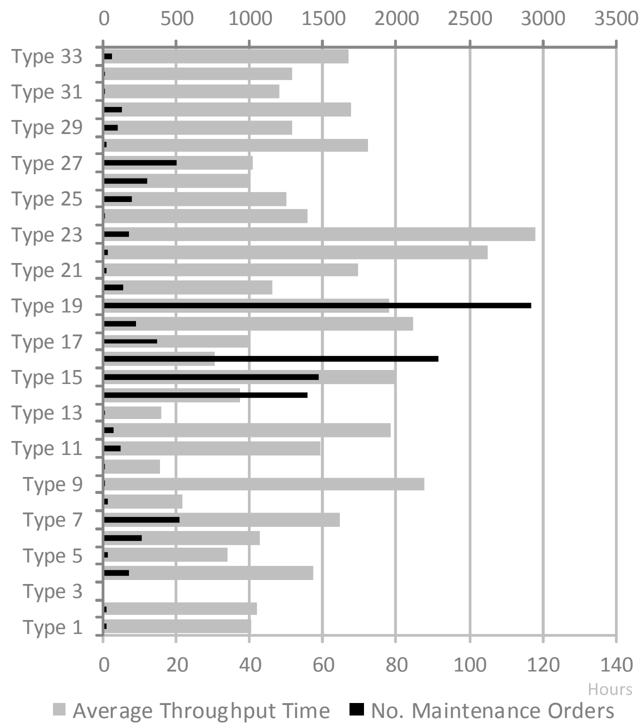

Figure 6 – Average maintenance throughput time and numbers of maintenance order according to vehicle types

The next outcome from the simulation is maintenance throughput times for each vehicle type. The times are recorded from the opening of a maintenance order until its completion. With different maintenance order classes, random maintenance times and uncertain waiting times, the maintenance throughput time for every vehicle type varies. There are four to six vehicle types with longer throughput times. In order to minimize the throughput time of maintenance in the whole network, these types of vehicles need to be invigilated during scheduling and arrangement of responsible workshops.

One element of maintenance throughput time is waiting time. Most of the waiting time for a maintenance order occurs at the workshop's buffer. To investigate workshop influence in throughput time, the utilisation of the workshop's buffer is recorded through their ratio of full and empty capacity through the simulation year. In other words the utilisation of workshop's buffer can be seen as a bottleneck of the maintenance network.

The recorded outcome is shown in Figure 7. Compared with the workshop utilisation, a similar trend can be found.

Workshop 3 (W3) and workshop 2 (W2) are the two workshops with high buffer utilisation. Both workshops' buffers are full during nearly the whole simulation running time. This will lead to longer waiting times for the maintenance orders scheduled and assigned to these workshops.

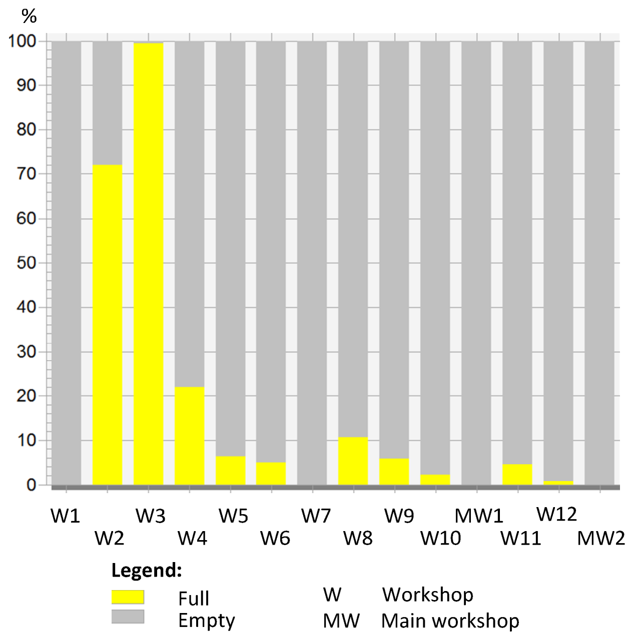

Figure 7 – Utilisation of Workshops Buffer from simulation of AS-IS state model

6. CONCLUSION AND FUTURE WORK

This paper has presented a case study of the current state of the MRO network and improvement potentials. The objective of this study is to balance the volume of maintenance orders by utilising the capacity of the network. A discrete event simulation technology has been used in order to understand the system, analyse the possible cause for imbalanced maintenance network and to experiment the network by different maintenance strategies, rules and scenarios.

In the scope of this paper, a part of the study is presented; definition of problem and objective, data mining, system analysis, modelling of the AS-IS state, simulation, and analysis of the simulation outcomes. Data analysis provided the input for modelling and simulation steps. Outcomes from the simulation of AS-IS state shows that imbalances of utilisation appeared in the current maintenance and repair network. The types of vehicles with longer throughput time and bottleneck of the MRO network which lead for the imbalances have been identified.

As the main outcome of this paper, the analysis of the AS-IS state presented will be used for developing the alternative network models in the future work. Several alternatives of the maintenance network models with different maintenance strategies are going to develop and simulate. The outcomes from these alternatives will then be analysed and compared technically and economically with the AS-IS state and between alternatives. The best alternative will be chosen. Its outcomes and strategies will be interpreted. As a conclusion of the case study, the best strategy for the maintenance network is going to be proposed to the industry partner for a possible improvement.

7. ACKNOWLEDGMENTS

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