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Replacement and Repair of Common Components in Systems Subject to Operations Planning

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1 Motivation

While a system operates its components deteriorate and in order for the system to stay operational, the components have to be maintained regularly in relation to their usage in the system. When planning the maintenance for the system, the decisions to be made concern when each of its components should be maintained (i.e., repaired or serviced) and what kind of maintenance should then be performed, with respect to the operational schedule of the system. So-called preventive maintenance (PM) can often be planned well in advance, while corrective maintenance (CM) is done after a failure has occurred, which may come on very short notice. On the other hand, an unexpected but necessary CM action may provide an opportunity for PM actions to be be rescheduled, starting from the system's current state. While both PM and CM are aimed at restoring the components in order to put the system back in an operational state, CM is often much more costly than PM, due to a longer system down-time and also due to possible damages to other components caused by the failure. In this research, we consider PM scheduling, while CM is implicitly included by an additional cost which increases with the time between PM occasions. The increasing cost reflects the increased risk of having to perform CM.

We consider a setting with one *system operator* and one *maintenance workshop*, which are typically two separate stakeholders, and a *contract* governing their joint activities. Components that are to be maintained are sent to a maintenance workshop, which needs to schedule and perform all maintenance activities while satisfying the contract, which may define conditions on delivery dates for and/or requirements on the availability of components for the system operator.

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The workshop's ability to fulfill the contract is dependent on its capacity, in terms of the number of parallel repair lines; the investment costs for additional repair lines should thus be weighed against the cost of not being able to fulfill the contract at hand.

The original goal of this research was to investigate how different contracting forms between the stakeholders affect the efficiency of maintenance activities, the flow of components through the system–of–systems, as well as the availability of the systems over time. The first contract we modeled resembles the type of contract currently employed by our case industry, i.e., a component repair turn-around time based contract. Since the resulting mathematical model [1] appeared to be computationally intractable we chose to challenge and compare this contract with a contract aimed at regulating the availability of repaired components. The corresponding mathematical model appeared to be substantially more tractable, and also the solutions—in terms of resulting numbers of repaired components on the stock—seem to be more robust in terms of ability to keep the systems running.

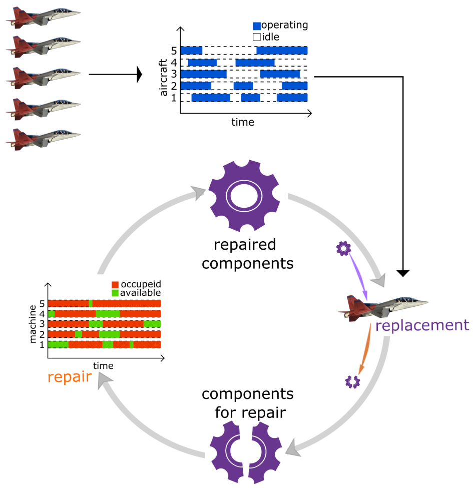

Figure 1: Illustration of the problem for an application with a system of aircraft.

2 Problem description

A number of systems are operating to fulfill a common production demand; their operating schedules are assumed to be predefined, resulting in certain time-windows during which maintenance of the systems' components may be performed. While the systems operate their components degrade, which lead to a requirement for maintenance (i.e., service, replacement, or repair of the components of the systems). At a maintenance occasion, one or several components are taken out of the system, sent to the maintenance workshop for repair, and returned back to the stock of repaired components, ready to be used again (by any of the systems). The components that are sent for repair are instantly replaced by components that are currently on the the stock of repaired components. Hence, there is a circulating flow of individual components, being used and degraded, replaced, repaired or serviced, and then put back in a system to be used again. This structure of the system–of–systems is illustrated in Figure 1.

We make a formal definition of the generalized PMSPIC—which models the replacement scheduling for the components of the systems considered—along with a mixed-binary linear optimization (MBLP) formulation. Then, the scheduling of the maintenance workshop is modeled using mixed-integer linear optimization (MILP). These systems are then integrated through the dynamics of the stocks of components waiting to be maintained and those that have finished maintenance and are available to be used again by the systems. We analyze an availability contracting form between the system operator and the repair workshop by studying and comparing the Pareto fronts resulting from different parameter settings, regarding minimum allowed stock levels as well as investments in the repair capacity of the workshop.

3 Summary of Results

Figure 2 shows the computed points on the Pareto front in the bi-objective optimization problem for the workshop capacities $L = 10$ and $L = 3$. The lower limit on the availability is in the interval $[5, 10]$ while the total maintenance cost is in the interval $[5542, 5828]$ for $L = 10$ and in the interval $[5631, 5856]$ for $L = 3$. We observe that for every increase by one in the availability, the increase in the maintenance cost becomes higher. That leads to longer maintenance interval lengths which increases the risk of component/system failure. To receive a high lower limit on components available, there has to be a loss on the system operator's side, which could be, for example, that maintenance intervals are longer which leads to higher maintenance costs. Another observation is that the difference between maintenance costs for $L = 3$ and $L = 10$ decreases as the availability of repaired components increases; this means that it is costly to obtain a higher availability, regardless of the capacity in the maintenance workshop.

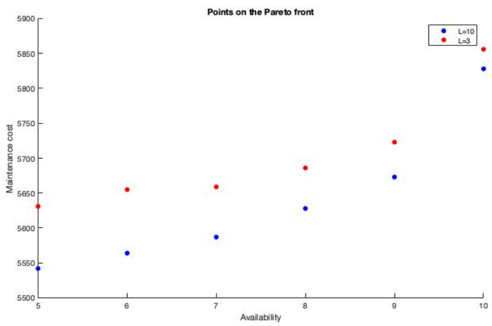

Figure 2: Availability vs. Maintenance cost. The computed points on the Pareto front for $(I, J_i, K, T, \underline{b}^i) = (5, 15, 10, 40, 1)$, $\epsilon = 1$, $L \in \{3, 10\}$.

Figure 3 shows the load of the maintenance workshop over time, for capacities $L \in \{3, 5, 10\}$. We observe that for $L = 10$, the number of active repair lines does not exceed 7, which implies that $L \geq 7$ does not constrain the number of repair lines used at any time in an optimal solution. However, when reducing the capacity to $L = 5$, there are many time steps at which the workshop is working at full capacity, and that is even more expressed when L is reduced to 3. If some unexpected failures occur, or if some components have longer processing times, a planned utilisation of the full capacity of the workshop at multiple consecutive time steps might lead to later/postponed deliveries. A consequence of later deliveries is lower levels on the stock of repaired components, which may not satisfy the

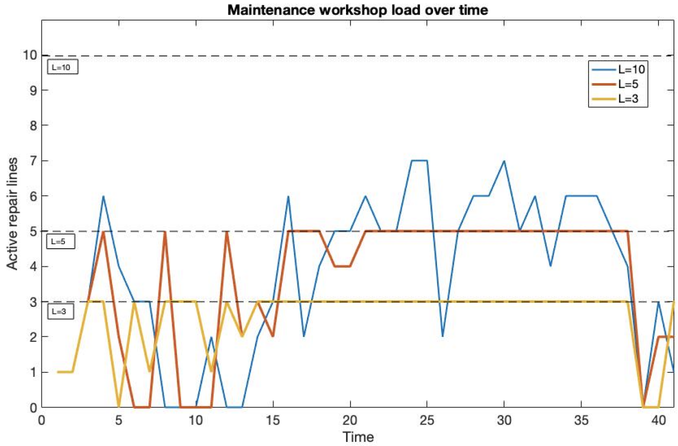

Figure 3: Load of the maintenance workshop over time for $(I, J_i, K, T, \underline{b}^i) = (5, 15, 10, 40, 1)$. For $L = 10/5/3$, the point on the Pareto front is given by: Availability=5 and Maintenance cost=5542/5546/5631.

lower limit on availability. This may lead to maintenance intervals having to be extended. Therefore, the loading of the parallel repair machines should not be at the level of its upper limit for too many time steps.

4 Conclusions

We present a brief overview of an integrated model of a system–of–systems composed by the maintenance scheduling for components, the maintenance workshop, the stock dynamics, and an availability contract governing joint activities of the two respective stakeholders. The solutions resulting from our modelling can be used to find a lower limit on an optimal joint performance of a collaboration between stakeholders governing a common system–of–systems regulated by an availability contract.

References

[1] G. Obradović (2021). *Mathematical Modeling, Optimization and Scheduling of Aircraft's Components Maintenance and of the Maintenance Workshop.* Chalmers University of Technology, Sweden. https://research.chalmers.se/en/publication/524023