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A CASE STUDY ON SIMULATION OF RAILWAY FLEET MAINTENANCE

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ABSTRACT

This paper presents a joint simulation project in the area of railway fleet maintenance management. A simulation model was developed to understand and visualize the complex interaction in a railway system comprising rolling stock, depots, and maintenance guidelines. In many cases, requirements on such a system come from different sides, such as fleet operation (timetables and availability), maintenance engineering (maintenance regime), and depot management (depot restrictions). The paper describes the domain-specific challenge, the model, the implemented scheduling algorithm, and resulting insights. It, furthermore, describes how the model can be used for a variety of different use cases all along a railway project: from sizing to forecast and performance analysis and from initial tender theory check to operational risk analysis. Two real-world use cases are presented: West Coast Main Line and TransPennine Express, both in the United Kingdom.

1 INTRODUCTION

According to the Office of Rail Regulation (2011), more than one third of the lifecycle costs of rolling stock is spent on maintenance. Maintenance quality, cost, and fleet availability are complementary goals that have to be carefully balanced, keeping in mind national regulations that have to be fulfilled. Modern railway systems pose a great challenge for the fleet maintenance management, as the traditional maintenance schemes with fixed cycles (mileage- or time-based) reach their limits on flexibly managed rail systems. Innovative approaches with data-driven predictive maintenance are being developed, but are still far from being an industrial standard in an industry that tends to stick with well-proven traditional technology (Schwilling et al. 2016).

One way to evaluate system behaviour and performance is discrete-event simulation (DES), which is already widely deployed in manufacturing and logistics processes. DES provides an alternative to analytic methods (such as Value Stream Mapping or Process Mining) and mathematical optimisation methods (such as linear optimisation or metaheuristics) for evaluating system behaviour and performance. Simulation has already been applied in the field of railway, however, compared to other business areas, the number of DES applications is still rather low. Jahangirian et al. (2010) list only one (!) single railway-related paper in their survey on 281 papers on DES applications in manufacturing and business, which shows that simulation is underrepresented in railway applications. However, simulation has been used for rescheduling in train networks as the survey of Fang et al. (2015) and case studies such as Sajedinejad et al. (2011) illustrate. Some railway operating companies make extensive use of simulation, as the example of the Dutch railways shows (Middelkop et al. 2012). The latter also covers maintenance operations of tracks, but not the combination of rolling stock operation and its maintenance as in this paper. Moreover, the case presented in this paper demonstrates a simulation application during planning of railway operations and during fleet operation, thereby covering two out of the three life-cycle phases: planning, implementation, and operations, which are discussed in several publications on simulation (Klingstam and Olson 2000; Kosturiak and Gregor 1999; VDI 2014).

The origin of the developed solution lies in the Optimised project, a joint research project funded by the European Commission's Horizon 2020 program. The project was started in 2015 and it will be finished in October 2018. Optimised comprised ten partners from several industries and research institutions. The project's main goal is to develop and demonstrate an Operational Planning Tool Interfacing Manufacturing Integrated Simulations with Empirical Data. In other words, the project aims to develop novel methods and tools for deployment of highly optimised and reactive planning systems that incorporate extensive factory modelling and simulation based on empirical data, captured using smart embedded sensors and pro-active human-machine interfaces (European Union 2015). Three demonstrators are determined among the industrial partners to showcase the developed solutions. Among them is the challenge faced by Alstom, which proved to be a special case, as it does not quite focus on the manufacturing aspect as the other demonstrators. The specific challenge in the Optimised project is the evaluation of a major modification of an existing maintenance system on the West Coast Main Line (WCML) in the United Kingdom. Alstom is responsible for maintaining a fleet of high-speed Pendolino trainsets operated by Virgin Trains on a network that extends from London to Edinburgh and Glasgow. One of this fleet's trainsets is shown in Figure 1. Not only the length of the maintenance cycles distances and the extent of the exams are to be changed, but also the maintenance capacity should be newly distributed among the maintenance depots. As a consequence, maintenance intensity, offered capacities, and the fragile interaction with the diagrams are to be put to the touch. The simulation model can be deployed to highlight bottlenecks and thus mitigate risks for both operation and maintenance before actually implementing any of the changes. The development on this demonstrator was carried out between 2015 and 2017.

Figure 1: Pendolino trainset on the WCML, first use case for the simulation model (Hair 2011).

2 BACKGROUND ON RAILWAY SYSTEMS

A railway maintenance system comprises fleet, maintenance depots, maintenance regime, and train timetables, which are called diagrams in the railway industry. The train operator provides the diagrams. Table 1 shows an example of such a diagram. It covers a daytrip of a trainset via seven stops (PO, GLC, EUS, MAN, EUS, MAN, LG) starting at 8:47 and ending at 23:28 with a total mileage of 956 miles. Usually, two types of those diagrams exist: a long-term version and minor updates each week. A trainset will be assigned to each of the diagrams for each day. Assignments are sometimes switched on short notice due to operational reasons such as weather conditions, disruptions, or defects.

A fleet traditionally has a fixed maintenance scheme that follows contractual commitments to the fleet operator and regulatory obligations to state legislation. Maintenance operations are usually executed in one or several maintenance depots along the route. Maintenance operations can be categorized into two types: preventive maintenance and corrective maintenance. A traditional preventive maintenance regime features a cycle of a fixed usage and follows a fixed pattern of operations. Usage measurement points can be either mileage- or time-based, such as days or hours in service. Maintenance can be carried out overnight, when no train service is offered anyway. However, multi-day exams or extensive corrective maintenance bring the need to keep a trainset in a depot over one or several entire days. A trainset that is out of service for one day is called 'stabled' and is assigned to a 'stabled' diagram that shows no routes. The number of stabled diagrams or trainsets can be derived from the diagrams or is contractually defined between operator and maintainer.

Table 1: Example train diagram.

Headcode	*Route*	*Time*	*Distance*
5M10	PO - GLC	08:47 – 08:57	2 miles
1M10	GLC - EUS	09:40 – 14:10	401 miles
1H33	EUS - MAN	15:20 -17:28	183 miles
1A61	MAN - EUS	17:56 – 20:08	183 miles
1H75	EUS - MAN	20:40 – 22: 48	183 miles
5H75	MAN - LG	23:17 – 23:28	1 mile

Each depot features specific capabilities, capacities, and constraints on the maintenance operations it can offer. Operations of a maintenance depot need certain resources, which can be tracks, special work places, equipment, or personnel. To simplify this complex intra-depot scheduling, slots are used. A slot for a certain depot features a date or weekday, a time, and an operation type offered. It already implies the availability of required resources without otherwise explicitly scheduling them.

3 THE CHALLENGE

The challenge is to fit the aforementioned components together. Let us assume that a trainset has a maintenance operation due in several days. This is defined by the cyclic maintenance regime and the current usage measurement (mileage or time) of the trainset. Also known is the current overnight location of the trainset. The network consists of the end locations (depots) and the connections defined by the diagrams. The trainset should now be assigned to diagrams that allow for travelling through this network to the depot where the needed maintenance operation is offered. It should ideally arrive there at exactly the due limit, as to not over-maintain the trainset. The diagrams to and the slot inside the depot have to be reserved exclusively for this trainset to ensure the timely execution of this maintenance. The described procedure has to be applied to all trainsets of the fleet.

The system performance depends on three factors: the components' capacity, the stress put on the system, and the scheduler's performance. The capacity of the system depends on the diagrams and the depot capacity. The diagrams influence the capacity in several ways: If the overnight locations of diagrams overlap, more possibilities for the combination of diagrams of subsequent days are available and, thus, more flexibility for finding paths through the network to a certain location and time exists. The stabled diagrams are important as well. Without an available stabled diagram during the exam date, a maintenance during daytime cannot be executed, as the trainset is expected to be in normal service. Finally, missing depot capacity can be a bottleneck as well.

The other influencing factor is the stress put on the system by the maintenance regime and the fleet size. The more trainsets and the shorter the maintenance intervals, the more maintenance operations need to take place and thus need reservations for diagrams to cross the network, diagrams to reach the depot, slots, and stabled diagrams. Additionally, maintenance regimes with unevenly distributed exams or unevenly distributed usage of the fleet can lead to a bunching of demand that cannot be met even if the average performance offered would be sufficient. The uniformity of the distribution of usage among the fleet can be influenced by a cyclic assignment of diagrams, in order to level the varying asset usage among diagrams. Last but not least, the quality of the solution found by the scheduling algorithm decides how close to the maximum capacity the system can be exploited.

4 THE SOLUTION

In order to capture the interaction between diagramming, maintenance demand, and depots, a physical representation of trainsets and depots, as well as non-physical aspects such as the scheduler and the diagrams are part of the implemented simulation model.

The core of the solution is a heuristic scheduling algorithm that is emulating a fleet planner. All trainsets' upcoming maintenance exams are collected in a list and sorted by the order of their due value. The scheduling algorithm then covers those exams one after another. For a given exam on a trainset, slots that fulfill the requirements are collected. Using the trainsets' current overnight location as the starting point and the potential slots as end points, the full tree of possible diagram combinations between start and end is explored and saved in a list. Figure 2 shows conceptually how the tree of solutions is built up from two sides, using a meet-in-the-middle approach. Each dot represents a location connected by diagrams (depicted in Figure 2 as arrows). On the left side, the tree starts at the current overnight location of the train, here marked with a trainset. On the right side, the trees start at depot locations (A, B, C) that offer maintenance. In this example, depot A and depot C offer the required maintenance exam and, therefore, are starting points, whereas depot B does not feature the required maintenance. Since each diagram comprises one day, the resolution of the tree is one day. The final tree of solutions is built by matching the separate trees from both sides together to form continuous paths.

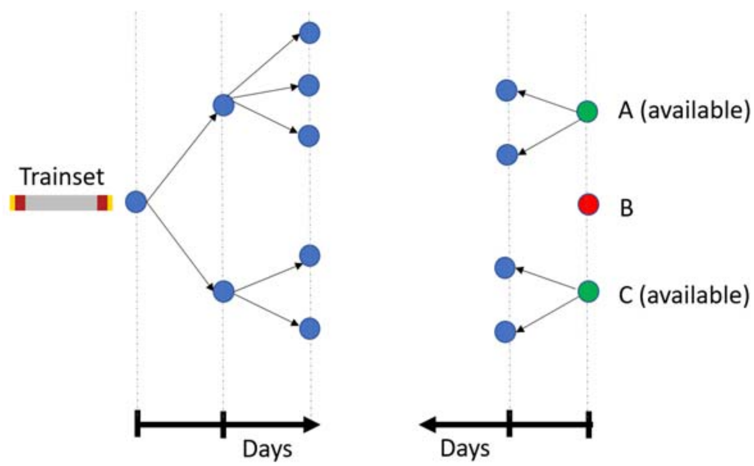

Figure 2: Creating a tree of solutions, from start location (left) to available maintenance depots A, C (right).

One of the solutions combining a path (itself consisting of one or several diagrams) and a slot are selected based on certain criteria. Criteria may be the minimization of over-maintenance, shortest found path, or others. The solution is assigned to that trainset while the corresponding slot and diagrams are blocked from other reservation or use to prevent a double assignment. This search and assignment is done in sequence of due priority for each maintenance exam. Since the scheduler is scheduling the upcoming maintenance items one at a time according to certain criteria, it is not a global optimization, but only a heuristic approach. Alternatively, a schedule provided by an external optimization solution can be imported into the simulation at start up and used instead of the built-in scheduler.

The physical system is modelled on a rather high level. For movement of trainsets along the network, the trainsets move with an average speed linearly from one destination to the next, according to the given diagram data. Signalling, train protection systems, or even collision detection are out of scope for the simulation in this application. The modelling of the movement of *Trainset* agents between the *Depot* agents serves as a logical and visual check that the scheduler's solution works according to the given constraints. If, for example, the scheduler would ignore one of the diagrams, the trainset positions would not meet the next day's diagram starting points and the simulation would throw an error to inform the user about the mismatch. Position and movement of the trainsets between the locations are estimated for animation reasons on an interactive map, as depicted in Figure 3. Although the physical representation would not necessarily be needed, it helps in validation of input data and system behaviour.

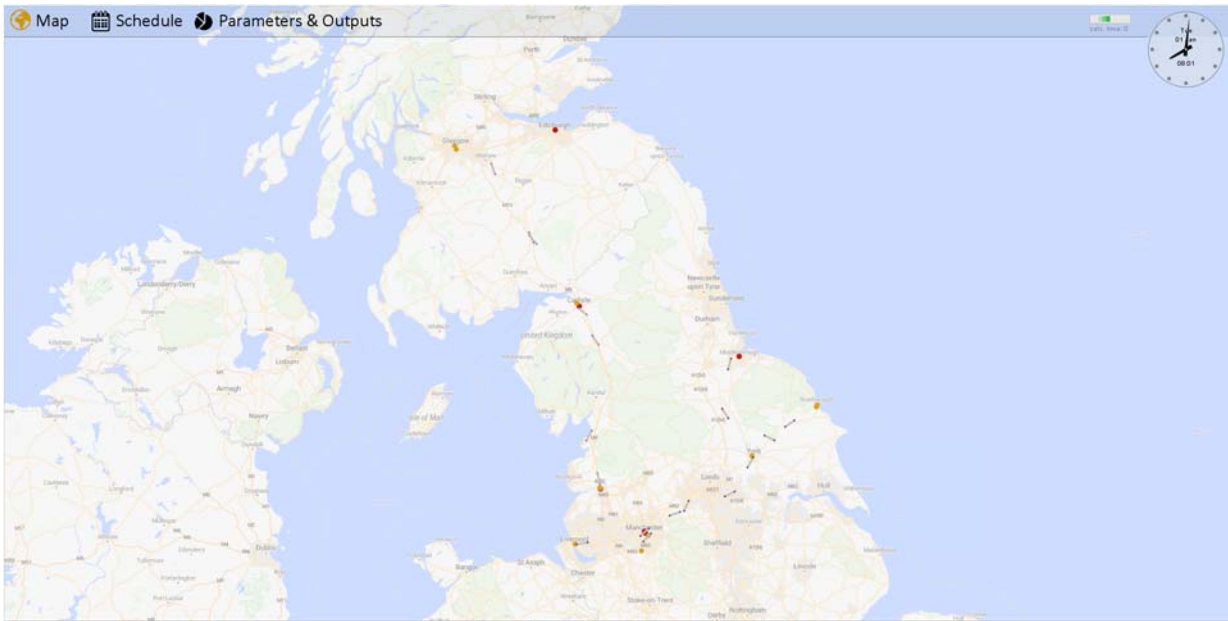

Figure 3: GUI of simulation model, GIS view.

An object-oriented structure was used to represent the system. The structure and its main components, *Trainsets* and *Depots* are depicted in Figure 4. *Trainsets* can have a *Diagram* attached and optionally *Maintenance Items* that are upcoming for execution. *Depots* feature the counterparts for the *Maintenance Items*, the *Maintenance Slots*, meaning maintenance exams that they have the capability to offer in the upcoming days. These *Maintenance Slots* also contain information about the constraints that apply on their usage. A *Path* comprises one or several *Diagrams* and gets assembled and assigned by a scheduling algorithm. *Maintenance Regimes* that are attached to each trainset are regularly evaluated and *Maintenance Items* created whenever an exam defined in the regime comes within a threshold of the trainset usage measurement. Trainset usage measurement and regime definitions can be defined as mileage, days in service, or hours run. *Depot* agents feature a list of the maintenance exams that they offer on the upcoming days (maintenance) and the corresponding constraints for each of the exams. Upon arrival at a *Depot, Trainsets* can request a maintenance exam and the depot will allow or deny this request depending on the available maintenance exams.

As a framework for the implementation of the simulation, the multi-method modelling software AnyLogic was selected. The crucial factor for the choice was the high customizability with Java code and libraries, support for agent-based modelling (ABM) as well as conventional discrete event simulation (DES) and the rich geographic information system (GIS) module. Processes like maintenance execution and the movement of trainsets among the network are modelled with DES. *Trainsets* are modelled as agents, having their individual maintenance requirements and interacting with the *Depots*. The two approaches complement each other, for example when *Trainsets* are treated in process flowcharts of a *Depot*.

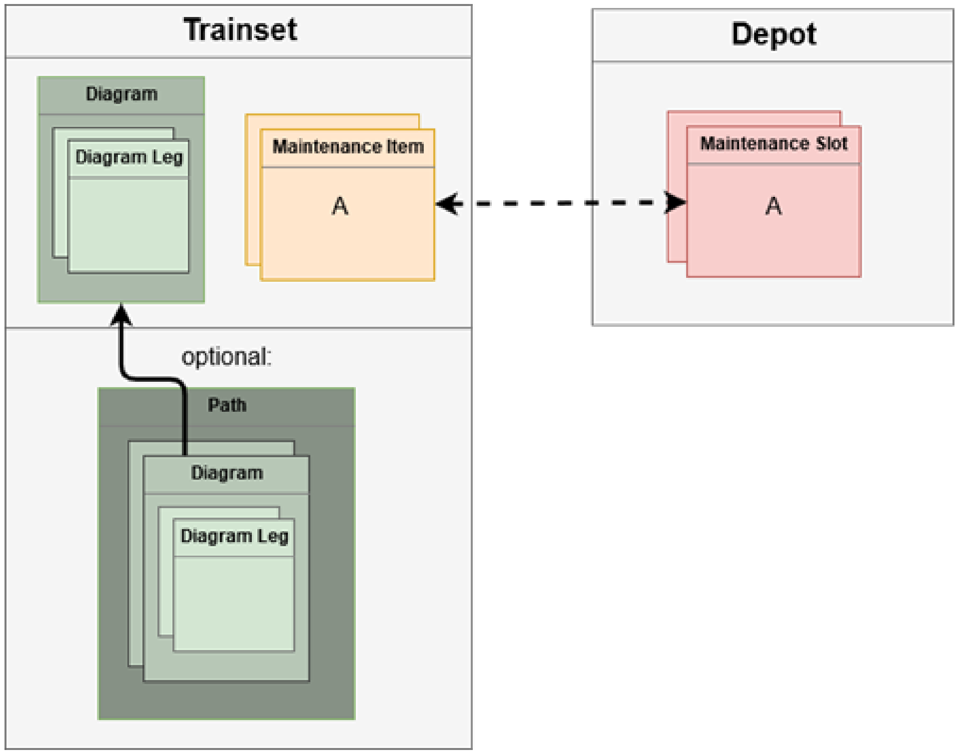

Figure 4: Object-oriented class structure.

The model can be parameterized to represent different railway systems. Base data, such as trainset definitions, are stored in a central Excel sheet that is filled in at simulation start-up. Diagrams get loaded from a csv-file that directly gets parsed in the simulation at start-up as well. Additional model settings, such as the scheduling horizon, can be set by the user at the start-up screen and are maintained in a separate configuration file. Different approaches are possible for the evaluation of the system: The interactive GUI lets the user explore the system during simulation and look 'inside' each depot and trainset. As two examples, Figure 5 (left) shows a part of the trainset view. The second diagram from below shows if a backlog in corrective maintenance is building up. Figure 5 (right) shows a part of the fleet dashboard, which gives a live overview of the system's KPI, such as missed maintenance and over-maintenance that occurred. The scheduler's work is made visible in a schedule overview where assignments and reservations of slots and diagrams for each trainset are listed. After the simulation run, a range of log files is created that can be used for external evaluation of system behaviour and performance.

5 RESULTS

The most interesting questions to answer are the following: Can the defined system cope with the maintenance demand? How efficiently can it do this? Is there oversupply of maintenance capacity, or do bottlenecks in parts of the system cause over-maintenance?

In the case of the 56-trainset fleet of Pendolinos on WCML, the analysis showed a high risk of missing a certain type of maintenance when the trainset counter values do not happen to be uniformly distributed ('bunching'). This specific maintenance exam had a long-cycle distance and could only be executed in slots that were infrequently available, thus having trouble to deal with a sudden peak demand. A more flexible slot usage and a switch from mileage-based to day-based counters was advised. For mileage counters a rotational assignment would balance the mileage counters among the trainsets. Such an assignment strategy is not implemented yet, but when switching to day counters, the only source of bunching can come from premature or late (inside tolerance) maintenance. Over-maintenance level was seen to be low and acceptable.

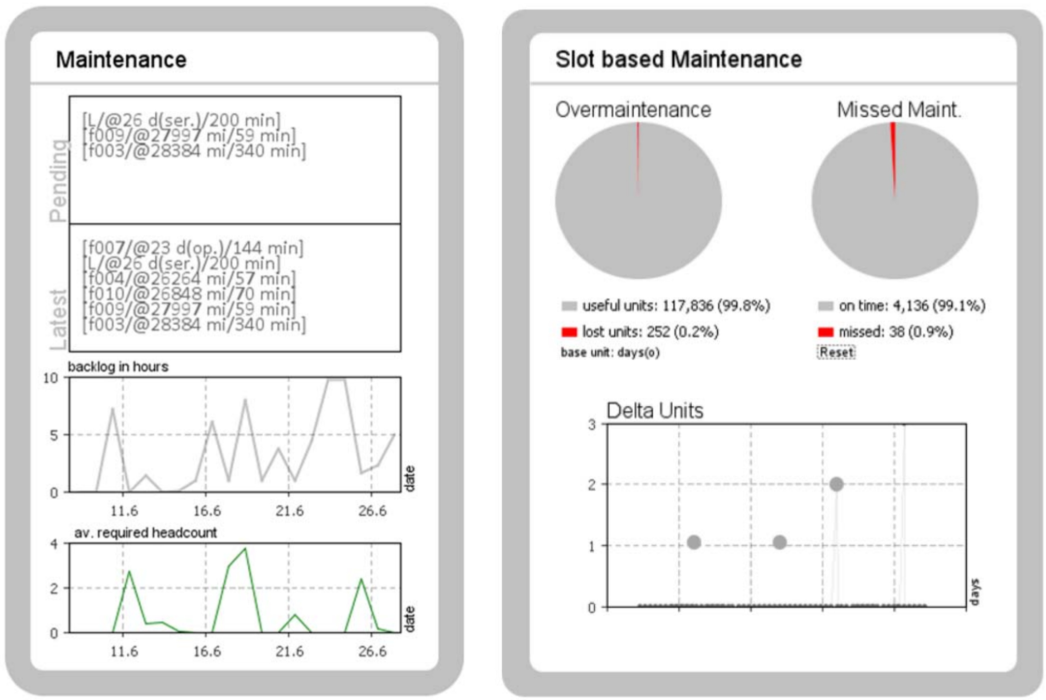

Figure 5: Screenshots of the simulation model GUI, trainset maintenance (left) and scheduling performance (right).

In another use case for this tool, TransPennine Express (TPE), simulation showed an insufficient maintenance execution rate. The bottleneck could be traced back to a) scarcely available slots at almost exactly the needed capacity, b) inflexible slots, and c) diagramming issues, not giving trainsets the possibility to reach and arrive at a needed maintenance slot. Possible identified solutions were to increase the offered slot capacity to gain some room for fluctuation and scheduling, while at the same time making the available slots more flexible. An example for increasing flexibility of slots is instead of offering slot A and slot B on two subsequent days, to have a slot each of the days that can be either used for operation A or B, based on the scheduler's needs. The diagramming issues will be reviewed together with the fleet operator, who naturally plans the diagrams primarily according to customer demand and not according to maintenance engineering preferences. Since the system was working at its limit, using all possible tolerances, almost no over-maintenance could be detected.

For the use cases stated in section 6, the simulation gave Alstom the possibility to take data driven decisions in the negotiations between fleet maintenance and fleet operations, two stakeholders which often have conflicting goals. If the model fits the situation, simulation is both a design (TPE) and an operational (WCML) tool.

6 USE CASES FOR ALSTOM

Alstom historically acts as an asset manufacturer and then, during operation, as an asset maintainer using technical knowledge, advanced maintenance engineering, and maintenance operational skills as market differentiators on railway projects. Fleet simulation is delivering value during many different project stages.

First of all, at tender stage, project teams are using simulation to refine project sizing. Indeed, diagrams provided by the customers contain a lot of information about where the depot should be located, what its capacity should be, and how the maintenance regime would react to network configuration. Submitting a sizing scenario to the simulation engine gives in return a fair assessment of the impact on assets availability and depot capacity. Through this process, a maintainer would propose the most suitable sizing to the asset operator minimizing risks while optimizing proposal figures. On TPE, for instance, we revised depot organisation iteratively to see how fleet scheduling is impacted. We reduced the missed maintenance indicator (showing scheduling risks) by 80% proposing additional slots for maintenance to the scheduler at Manchester depot.

During project mobilization, both operators and maintainers receive additional constraints that may differ from the initial tender hypothesis. For instance, diagrams foreseen are not the ones finally defined between operator and the infrastructure owners. When that happens, simulation provides a good picture of what would be the impact of these input changes on the assets' availability and depot capacity. Thus, risk registers can be updated and a mitigation plan can be built to manage the new situation. Obviously, any moves on diagrams are impacting the balance between train situation and depot capacity. Practically, on European networks, diagrams are changing twice a year. By that time, running a 6-month simulation on the West Coast Main Line fleet allows fleet planners for highlighting to customers over-capacity situations at depots, especially at the edge of the network in Glasgow.

As soon as the assets are running on the network, operational constraints are leading to daily plan rework and decision-making on allocation. What would be the impacts of these changes on the mid- and long-term horizon? A matching short-term program may generate issues on the mid- and long-term horizon as preventive maintenance is generating natural bottlenecks when assets are reaching overhauls and heavy maintenance steps. Simulation is acting as a spyglass for checking if each asset is still able to reach its overhaul maintenance while respecting availability objectives of the operators. If availability is impacted, there is still time to rework the short-term plan to adapt asset usage distribution ensuring smooth access to overhaul and heavy maintenance without coping with too much over-maintenance. The Manchester Longsight depot capacity to deal with overhaul exams without excessive over-maintenance is a key indicator that fleet planners are looking at. Simulation is now part of their toolkit anticipating bunching of trains in front of that bottleneck.

If the fleet has been used for many years, the knowledge about the asset reliability has also improved a lot. Therefore, maintainers and operators are reshuffling the cards and can jointly propose new operation and maintenance plans and layouts taking into account the benefits of reliability-centered maintenance and increased availability rates. A new maintenance plan can be a new maintenance regime with different exam content, frequencies or requirements. A new maintenance layout means different capacity distribution across the network. This is the right point of time for simulation to secure the decision process, playing the foreseen scenario, and giving figures ensuring that the diagramming process does not generate any issues on availability and depot capacity. Even in later project stages, the model can be of value: a fleet renewal process might be started, where operators are switching their old assets to new ones. When would the old assets reach their renewal trigger points? Simulation foresees the answer, asset per asset, using true diagrams and not only an average usage rate, so that assets can be used in an optimised way until decommissioning. All these additional topics can be explored in further use cases.

7 PERSPECTIVE

Simulation is still on the way to deliver its full power. Many developments will enrich the provided model. In an operation and maintenance project, there is a need for implementing operation knowledge in the simulation engine. During operation, many events occur that disturb the asset allocation plan. We can imagine implementing scenarios in the simulation engine where assets are not being operated as planned. Playing these scenarios on the allocation we decided on will give us a confidence level for an allocation plan, a level of robustness. Robustness transforms an optimised plan into a reliable plan.

Meanwhile, preventative activities are completed by corrective works arising on assets being used. Using existing data about typical degradation rates of asset components as an input, the simulation could virtually raise corrective works at depots in addition to preventive exams. Analysing corrective work arising would give a more accurate sizing analysis, comparing total workload (corrective + preventative) to depot capacity.

No assets should be left behind. Infrastructure assets such as rail, catenary, power stations, or railway station equipment could follow the same trend. Exploiting rolling stock assets means exploiting infrastructure as well. This opens the door to network simulation, simulating wear and usage of any asset of the railway system. Maintenance plans are including these assets as well and therefore Alstom's field team maintenance capacity can be compared to the simulated workload.

Getting the knowledge recorded in the simulation models demonstrates capacity to properly size, operate, and maintain a railway system. When more data gets available, the better model accuracy will deliver even more valuable insights.

Beside the classical planning approach, the simulation can also be used as an evaluation tool of historical operations. Based on recorded data, the operations of the past days and weeks can be visualised and analysed with the focus on optimising the rules of decision making in selecting trains for maintenance and the depot as well as assigning maintenance slots.

Furthermore, this simulation method can be applied to other types of public transportation systems such as bus or tramway networks. Street-bound systems naturally feature higher variations in driving times, leading to higher uncertainty in keeping the timetable. For this reason, the focus of the simulation can be extended to the evaluation of the impact of distributed driving times to the adherence to the timetable and potentially to the maintenance management strategy.

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