

# Keep on rolling – understanding the migration dynamics of a large railway improvement project

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## **Abstract**

*This paper describes the application of system dynamics to planning a major upgrade for an underground railway system. The upgrade involves new train and signals introduction along with other engineering works. A working system needs to be maintained during the upgrade process, necessitating a carefully planned migration process. The operators receive financial payments based on service performance against incremental targets. A system dynamics model was developed that represented progress on train introductions and engineering work, its impact on system performance, and the corresponding financial implications. The model allows analysis of different options for work scheduling and activities under conditions of restricted access to the line in order to understand the performance and financial impacts throughout the migration period.*

## **Introduction**

Planning and undertaking a large engineering project is difficult. It generally involves the coordination of a large number of organisations, people and materials. Inter-dependence between tasks means that slippage of one task can have knock-on effects on others with the potential to have major impacts on cost and time. Add the complication of working underground, with restricted access for people and machinery. Then try to keep your system operating all the while that you are undertaking the engineering project. These are just some of the challenges faced when upgrading an underground railway system.

The underground system consists of a number of lines, divided up between a number of operating companies. The operating companies receive revenues (including bonuses and penalties) for running the line and associated infrastructure with payment based on meeting or exceeding performance targets. Part of the responsibility of the operating companies is to undertake system upgrades that will improve performance and correspondingly result in increased payments.

The study reported in this paper has taken place in a number of stages to help in the planning of the upgrade for a particular underground line. It was developed initially to help understand the system performance and financial implications of a number upgrade issues, and has subsequently been refined to further help the planning for implementation of the selected option.

The study problem was recognised as having the following features:

- An understanding of the interrelationship between a number of upgrade, engineering and business activities was required.
- Activities share scarce resources, with resource allocation required and resource shortfall likely. Timing of activities is important, with significant risks of knock-on delays.
- The impact of work on system performance needed to be captured, with performance-based payment being calculated on the basis of complex metrics. Progress on each activity acts as an enabler or limit on various performance metrics, with performance often being dependent on several activities. Appropriate sequencing of activities can produce benefit from earlier performance improvements
- The system needed to migrate from its current capability to the improved capability without undue disruption to its operations, so that an understanding of system state during migration (rather than snapshots of before and after) was required;
- The contract allows for three levels of performance targets – initial, interim and final. Adoption of a new target provides improved standard payments but greater risk of penalties. The timing of target adoption can have a major impact on revenue.

System dynamics was selected as an appropriate methodology because:

- It provided a systemic view of a number of disaggregated planning activities and business functions;
- It allowed explicit representation of decision making and performance over time;
- It formed a common basis for understanding and discussing the system and issues of interest.

### **Drivers of Performance Behaviour**

The key components of interest in the system and measures of performance are summarised in Figure 1.

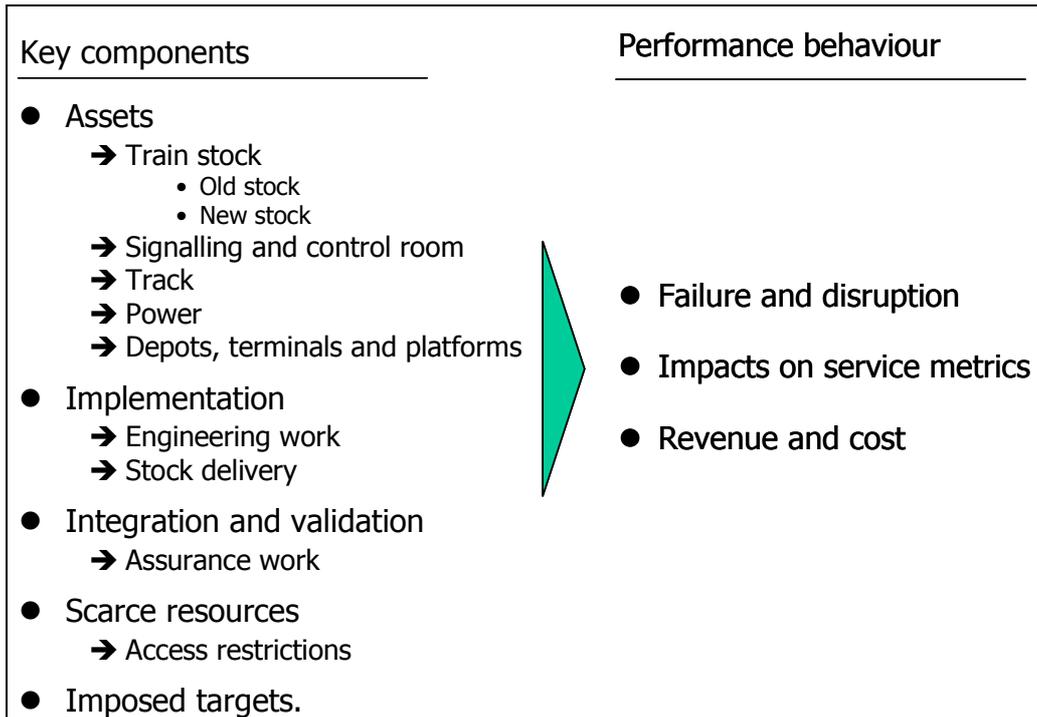


Figure 1: Drivers on Performance Behaviour

Assets are key resources in the system that provide the foundation for system performance. The assets have characteristics that contribute to the system performance in terms of service metrics (such as run speeds and wait times) and risks of service failure.

Implementation is the mechanism that allows asset build up in terms of delivery and commission of new stock and replacement or improvement of infrastructure. Access to the line limits the number of tasks that can be undertaken in parallel and rate at which work can be undertaken due to time constraints. Integration and validation is required for safety and performance reasons before equipment can be commissioned for use with passengers. Choices exist to increase the amount of access time available in order to speed up work but at the expense of penalties due to disruption of service.

Revenue is driven by base payments that are determined by the target levels that have been adopted, and bonuses for exceeding target levels. Costs are incurred through train acquisition, asset development, leasing costs, penalties for failing to meet targets, failures and disruption.

Figure 2 shows an illustrative (and simplified) high-level influence diagram showing some of the drivers and how policy decisions can be used to trade-off between Access time availability (with associated disruption penalties) and progress of activities (with corresponding revenue or service penalty implications).

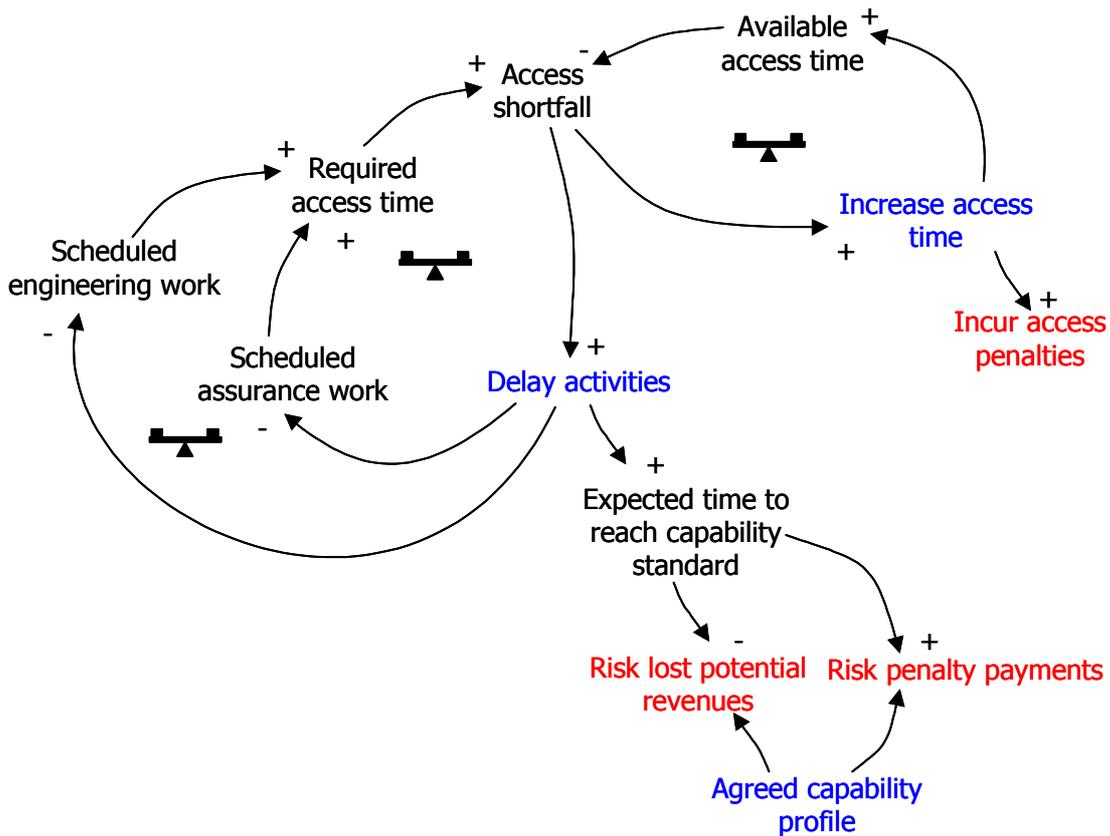


Figure 2: Illustration of Trade-offs with Impacts on Revenue

### Overview of the Model Structure

The model was built up as a series of prototypes by a project team involving HVR consultants and a cross-functional team from the operating company. Additional advice was sought where matters of detail arose. The starting point was high-level stock-flow diagrams that concentrated on key resources and measures of performance. A number of stages of development, review and refinement took place. Small prototypes of part of the simulation model were developed to help illustrate points and help discussion, and then the underlying code was developed for the whole model. The simulation model was further reviewed, tested and refined, including a major update to support implementation planning after the selection of the assets solution.

A key resource was the spreadsheet model that represented an implementation of the contract for payments in relation to achieved performance measures. This was used for development and testing of the model to ensure that it had captured all relevant parts of the payment and penalty scheme.

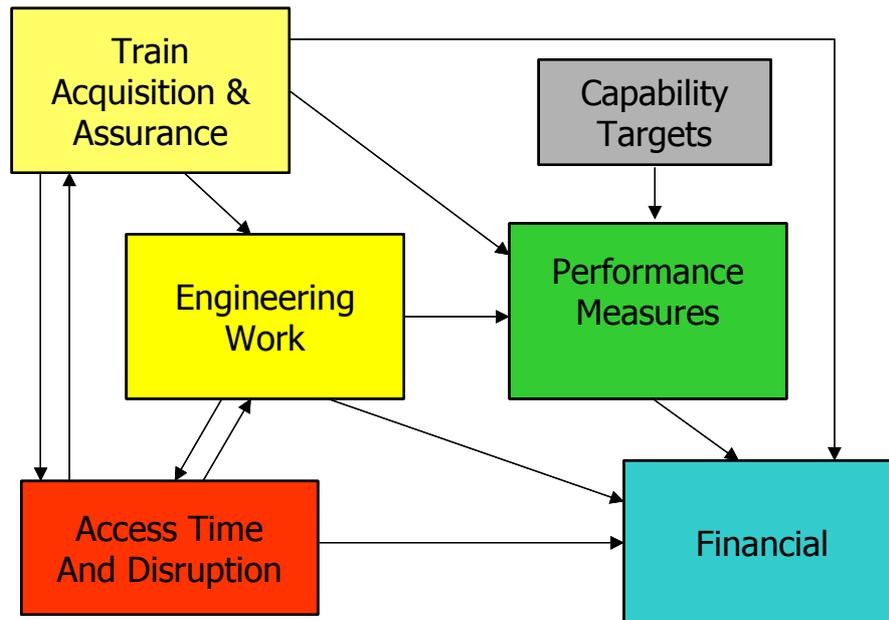


Figure 3: Model Sectors

Figure 3 shows the key sectors and their broad relationships within the model. Each of the sectors is described in turn.

### Train Acquisition and Assurance

The model contains original trains and new trains. New trains are acquired according to a timetable. Before a new train can be commissioned it must undergo safety assurance testing. The first new trains to be acquired require more assurance testing time than later trains. Original trains can be retired after a period of overlap with the train to replace it (although there is an option to keep more trains available for a period of time to cover higher maintenance requirements).

Trains have characteristics such as run speed, headway (gap between trains), ambience (a customer rating on train interior), and reliability. Run speed and headway for new trains can also be different depending on whether or not the new signals system has been commissioned. When a mixed fleet of original and new trains is being run, the run speed and headway of any train can only be that of the worst performing train, since the underground system is a closed system. The model can determine whether a mixed fleet is required or whether a fleet of only new trains can be used.

New trains can have higher failure rates during their bedding in period. Bedding in faults will be resolved over time (using an exponential delay).

### Engineering Work

A number of different types of engineering work are represented in the model. Each type has a number of engineering hours that are required to complete the work. A schedule can be specified for each type for the number of hours to be undertaken each month. A comparison of work required versus work completed is used to determine the percentage of the task that has been completed.

The types of engineering work are as follows:

- Track Infrastructure;
- Control Room Upgrade;
- Signalling;
- Terminal Infrastructure;
- Platform Infrastructure;
- System Power;
- Depot Infrastructure.

Each type of engineering work has one or more performance metrics associated with it. The metrics are determined using a lookup table that specifies the percentage of the work completed against the performance measure. Note that performance can improve over time as the percentage of work completed increases or it may get worse for a period (representing that performance may be limited while work is in progress). Figure 4 has an example of a lookup table for run times given progress on three types of engineering work.

	Percentage of engineering work complete										
	0	10	20	30	40	50	60	70	80	90	100
<b>Minimum run-time</b>	<i>(minutes)</i>										
Track infrastructure	6.8	6.8	7	7	7.1	7	6.8	6.5	6.4	6.2	5.9
Signal upgrade	7	7	7	7	7	6.9	6.8	6.8	6.6	6.5	6
Power upgrade	5	5	5	5	5	5	5	5	5	5	5

Figure 4: Lookup Table for Run-time (Illustrative Data)

Signalling requires assurance before it can be commissioned, requiring additional engineering hours. Additionally there may also be a train/signal assurance (known as system assurance) requirement that must be performed before new trains can benefit from performance advantages of the upgraded signalling system.

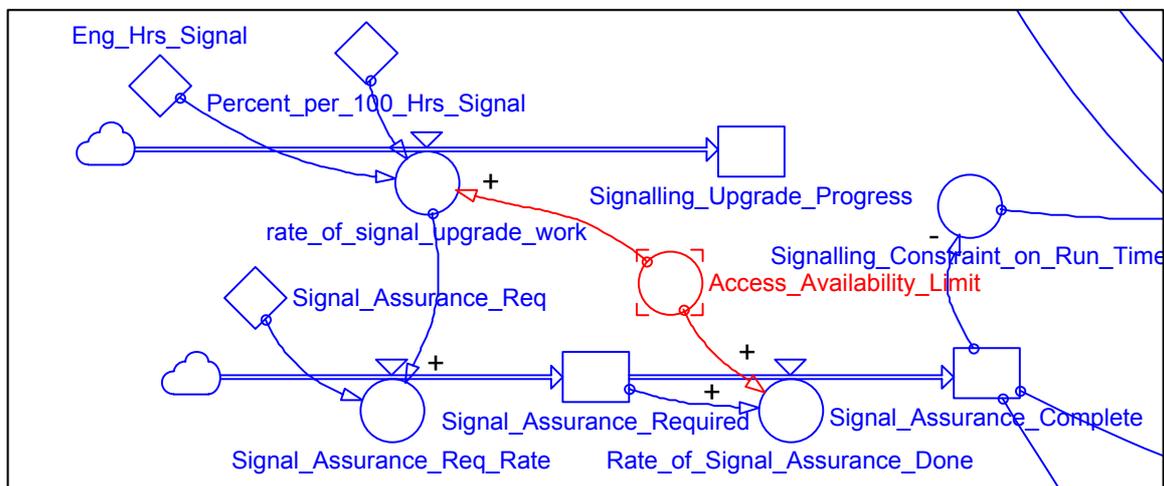


Figure 5: Model Extract Representing Signal Engineering Work

Figure 5 shows a stock-flow extract from the model. The rate of signalling work done is specified in a schedule but may be limited by access restrictions to the line. The progress on work is captured in a level. For signalling, the engineering work also generates a requirement for assurance work. The amount of signal assurance complete (measured as a percentage of the total assurance work required to complete the signalling task) is used with a look-up to determine the signalling constraint on train run times.

## Access Time and Disruption

Engineering and assurance work requires access to the line and can generally only be undertaken when the line is closed to passengers. An amount of time is available each week when the line is normally closed. Some of the available time will be lost at the start and end of a session to allow for ingress and egress of work teams and engineering trains. There may also be some non-engineering activities that take up access time (these can be specified on a monthly basis).

Some types of engineering work require exclusive access to the line, while others allow other work to be done in parallel. Factors are used to indicate the extent to which work can be done in parallel.

A cap on the amount of access time that is allowed can be specified for each month. A lookup table is used to associate access time with a penalty for disruption (this is measured in 'Notionally Accumulated Customer Hours' or NACHs). A certain number of hours are available without penalty since the line is closed anyway, however as hours increase the rate that NACHs are incurred changes as closure eats into peak travel time.

The impact of the access cap is that it limits the amount of engineering work and assurance work that can take place each week. If the required access hours for scheduled work exceed the access hours available then engineering work time will be limited (delaying the schedule and therefore progress).

The model contains a switch to disable the access hours cap. This allows the engineering work to run to schedule but will incur penalties if excess access hours are required. The switch allows a quick comparison of constrained and unconstrained situations.

## Performance Measures

The model has a number of performance measures that are impacted by train fleet mix, progress on engineering work, and policies. As noted above, trains have characteristics for the performance that they can achieve, and engineering progress is used to determine performance using lookup tables.

<b>Contributor</b>	<b>Run Time (mins)</b>
Original Trains (5 in operation)	5.9
New Trains (12 in operation)	6.7
Track Infrastructure (60% Complete)	6.8
Signal Upgrade (90% Complete)	6.5
Power Upgrade (50% Complete)	5
Target	5.9
<b>Actual Performance Measure</b>	<b>6.8</b>

Figure 6: Example of Contributors to a Performance Measure

In most cases the actual level of performance applied for a measure will be the worst case of any of the individual performance measures for the contributory factors. Figure 6 shows an example for the run-time performance measures. At a particular point in time in the simulation, the performance measure is calculated for each of the contributors. The performance used is the worst case of all of the contributors (Track Infrastructure in the example).

Some measures such as ambience and reliability use a weighted average of train scores depending on the fleet mix for original and new trains.

As well as applying train characteristics and engineering progress for calculating performance metrics, the policies for the service offered differ depending on whether it is peak or off-peak times. The model uses arraying to represent these periods.

The contractual arrangements for bonus and penalties use a headline measure that is an amalgamation of separate performance measures which brings together run-time, headway, ambience and reliability (amongst other things). This is calculated in the model as a key performance measure and to apply to the financial sector of the model.

### Capability Targets

Capability targets are specified for the operating company and become the benchmark against which performance is measured. Targets are specified as initial, interim and final. The contract specifies latest dates for adoption of interim and final targets.

Policies can be specified for the earliest times that new targets can be adopted, creating a time window for adoption. The model allows criteria for adoption to be specified in terms of the ability of the system to exceed the targets by a specified percent for a specified period of time. Since adopting a new target may require running a different number of trains (which can have a impact on metrics), the model uses arraying to calculate system capability for the current targets and for the next target. In this way the financial impacts of the current targets can be calculated as well as determining the ability to meet the next stage of targets.

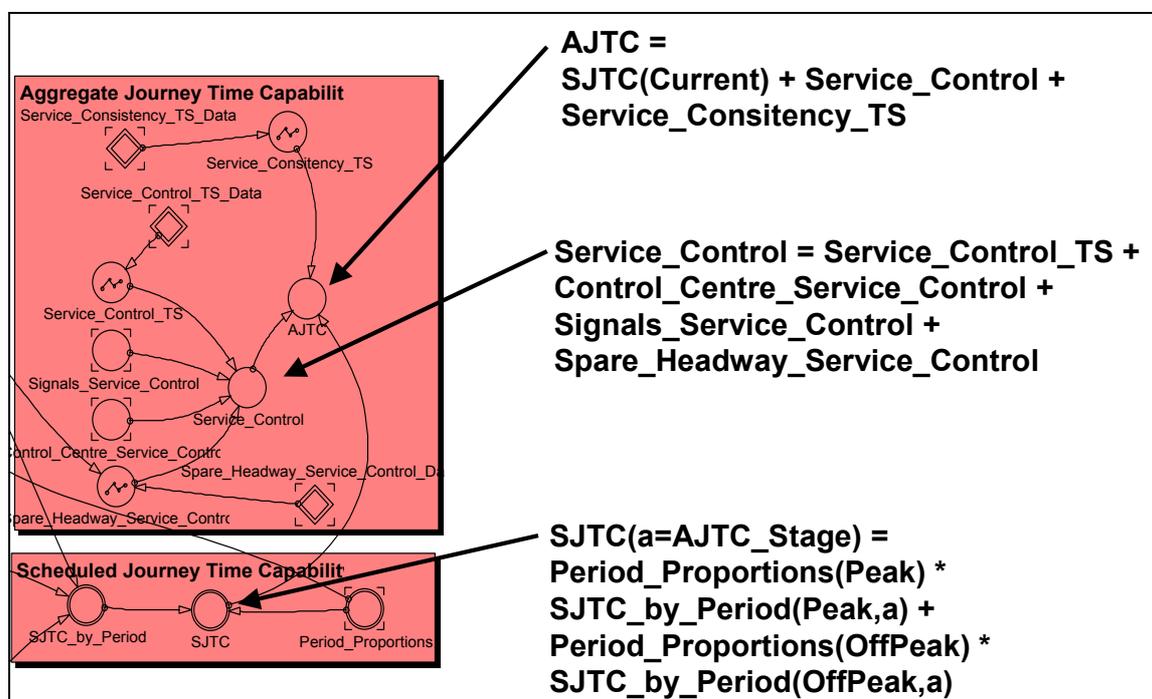


Figure 7: Capability Measures Including Arrays for Target Stage

Figure 7 shows an extract from the model showing key headline capability measures. Note the use of arraying for the current and next capability targets (AJTC\_Stage), and arraying for peak and off-peak operating periods.

## Financial

Activities and performance generate costs and revenues. These are applied as follows:

- Engineering work generates costs based on progress, and signalling can have a regular leasing cost;
- Train acquisition generates cost at time of acquisition and subsequently through life;
- Payments are based on meeting and exceeding targets;
- Abatements are based on failing to reach targets, service disruption due to failures, service disruption due to access required for engineering work.

## **Model Architecture**

The model architecture consists of the simulation model and an Excel spreadsheet. The spreadsheet is used for all data entry and collection of data outputs. Considerable use of formatting and hyperlinks is used to help navigation and data input.

Separate data files are used to store scenarios, which can be saved and loaded using the main spreadsheet. These data files capture input data, documentation in comments fields and cell notes, and output data. Since the data files do not contain formatting or graphs they are considerably smaller than the main spreadsheet.

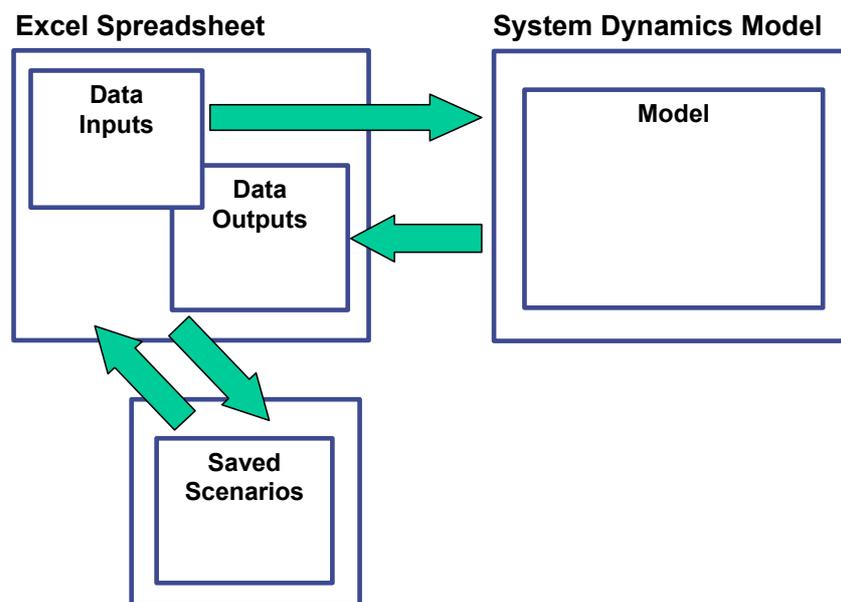


Figure 8: Model Architecture

## **Use of the Model**

The model was originally developed in order to examine a range of engineering and acquisition solutions for the upgrade process. As well as looking at the actual hardware solutions, the model allowed the issues of access and sequencing to be examined so as to factor in the programme, cost and revenue impacts of the migration issues during the upgrade.

Once the engineering solution had been selected, the model was subsequently updated to look at the scheduling and access issues in more detail. Work was also done to replicate the key parts of the contractual spreadsheet that represented the headline metric used to determine the

financial rewards and penalties. This involved adding some extra detail and some elements that were outside the scope of the original study.

A bench-marking process was undertaken to populate the model with the best estimates for the current stage of planning. At the same time, opinions were collected from the data providers as to the confidence in their estimates and where they thought risk and threats to the project lay. This provided the source for a set of scenarios to be used in what-if analysis so as to examine their potential impact on the project.

The graphs in Figure 9 use illustrative rather than actual data in order to demonstrate the use of the model to look at a scenario. In this case the scenario looked at the impact of a reduction in available access time due to other non-upgrade activities that may be required.

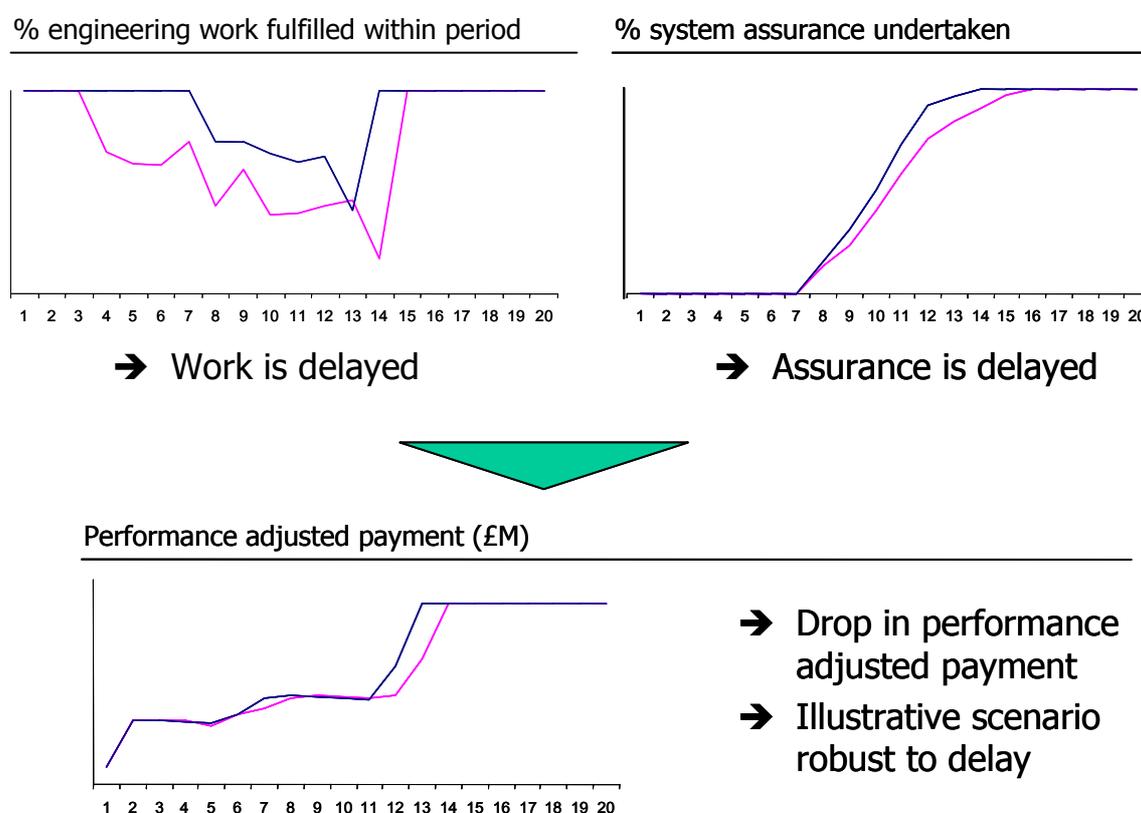


Figure 9: Illustrative Example of Use of Model to Examine Impact of a Scenario

In this example the access restriction creates delays in the engineering work being undertaken, with knock-on effects on the system assurance. The performance adjusted payment graph shows that revenue in relation to initial and interim targets are similar for both scenarios, however the adoption of the full targets is delayed with a subsequent impact on the revenue stream.

## Review of the Study

The model was developed in a number of stages, allowing high-level qualitative examination and feedback on the processes in the system, simulation analysis to support selection of the engineering solution, and further simulation analysis for the implementation strategy. In each case the model was developed to a degree of detail that was fit for purpose. In the latest iteration, data became more detailed to reflect the level of planning being undertaken, but more aspects of the solution had been fixed so that the solution space was more focused.

The model development process brought together a cross-functional team from different parts of the organisation. The model provided a common basis for discussion and acted as a repository for corporate knowledge. Ownership by client members of the team was such that they were keen to take on the task of talking through the stock-flow diagram with other members of the organisation.

The model encouraged a holistic view of the organisational activities and consequences of the upgrade, and highlighted the interdependence between activities. In particular it demonstrated that the solutions for each of the engineering problems could not be determined in isolation, and that sequencing of activities was important. In some cases, the ability of an activity to be appropriately sequenced or not ruled some solution in or out.

Other tools being used within the organisation allowed a snapshot view of the potential revenue and the interim and full upgrade stages. However, the system dynamics approach provided a time-based view that allowed examination of plans and revenue streams over the life of the project. This particularly highlighted the issues surrounding the migration process. The need to be able to continue the service during the upgrade process, with the revenue stream being associated with this has a significant impact on the plans compared with a green field development.

A key benefit of the model is that it provides a joined-up link between project activity decisions through to corporate cash-flow. Where risks or concerns are raised from an engineering perspective, the consequences can be gauged from a financial perspective. This can help raise the profile of concerns and allow the benefits of mitigation actions to be evaluated.

A key challenge to be faced was (and is) the ability and willingness of members of the organisation to provide data for the model, particularly during the early stages of the planning process. The model granularity has been designed to be fit for purpose, with an understanding that the interpretation of the results should be commensurate with the level of model detail and the confidence in the input data. The fear of some of the data providers is that by committing estimates to paper in the earlier stages of planning, those estimates will take on a significance beyond their worth.

An understanding needs to be developed that the process of planning is an iterative one, with increasing detail being added over time. This process must be demonstrated to the data providers such that they develop confidence that the model outputs will be treated in the appropriate manner.

A key development in meeting this challenge was the appointment of a project manager with a systems integration focus. His role is to collect data on activities, and to report and provide direction on integration issues. The model has become a key tool in undertaking this task and in communicating issues to the engineering and business functions.