Agile Simulation: An approach for increasing optimisation in railway planning.

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Abstract
This paper defines agile simulation as embedding simulation experts into railway planning processes. It identifies five key advantages of agile simulation and recommends that railways use agile simulation to increase the effective use of simulation in all types of planning projects. The paper is based on the hypothesis that increasing the use of simulation would improve railway efficiency and service quality. The paper is based on experience operating London's Elizabeth line service since 2015.

Keywords
Simulation, Timetables, Strategic Planning, Elizabeth line, Agile Simulation

1 Introduction

This paper describes how MTREL (MTR Elizabeth line) used simulation during bidding for and operating London's Elizabeth line, one of the world's most complex and dense railway services. In a nutshell, MTREL embedded simulation experts into the planning team preparing the bid to operate service and has continued using this approach during operations.

The close collaboration between simulation experts and planners has helped MTREL maintain high reliability, punctuality, and customer satisfaction (Office of Rail and Roads, 15 September 2022) while integrating several existing services into a unified system and despite delays in opening the service's new central London tunnel. Integrating simulation planners into the bid preparation team is relatively common but maintaining and strengthening the relationship over time is rare.

Looking back, the authors realized that this close working relationship had many benefits including developing service improvements that might not otherwise have been recognised. This paper highlights these benefits and recommends that railways use this approach, which the authors call agile simulation, more frequently.

Many of the benefits directly address findings from a research project presented at the IAROR RailNorrköping 2019 conference which asked railway staff and simulation experts why optimisation projects were unsuccessful. Although the data set was small, the research identified decreases in management attention, insufficient staff time for validating data, outside constraints, cost, and the insufficient data quality to be the main reasons simulation

projects were unsuccessful (Liebchen and Schülldorf, 2019). We hypothesise that experience with unsuccessful projects leads railways to reduce their use of simulation.

More generally, innovation research shows that established organisations have difficulty obtaining the full benefits of new technologies because they apply these technologies to old processes rather than changing their existing processes to take full advantage of new technology (Nash et. al., 2020).

In the case of simulation, railways have long used simulation for large projects like annual timetables and long-term capital improvement plans. The process often consists of developing alternatives, sending them to a separate department/consultant for simulation, and then revising the alternative based on simulation results. In these cases, simulation is completed in a separate step by "outside" experts. This process has been satisfactory for large, long time horizon projects, but creates too many inefficiencies (among them the problems identified by Liebchen and Schülldorf) to be used effectively for smaller shorter-term projects.

Embedding simulation experts with the planning team changes the short-term planning process by supporting increased use of simulation. This is especially important because short term planning directly addresses many of today's key railway challenges including quickly increasing capacity though better timetabling and fast capital improvements, as well as maintenance and disruption planning. The authors recognise that this is not a new approach, but rather wish to call attention to it because they believe railways would benefit by using it more often.

The next section describes the concept of agile simulation in more detail. Section 3 presents a short summary of the Elizabeth line providing a context for Section 4 which presents a set of examples describing the benefits of agile simulation using examples from the Elizabeth line. Section 5 presents conclusions.

2 Agile simulation

Simulation is often done in a separate step completed by a different department. This creates friction and reduces the use of simulation despite the fact that today's simulation techniques and computing hardware are vastly improved, and simulation software is much easier to use.

Agile simulation addresses this problem by fully embedding simulation experts in the railway planning process. As members of the planning team these simulation experts can help improve alternative definition, smooth communications between planners and modellers, and clearly explain results as well as simply speeding-up the process. A key success factor in achieving these benefits are the personal relationships built by working together as a team.

The authors have named this approach "agile simulation" because it resembles agile software development: "a collaborative effort of self-organizing and cross-functional teams with their customer(s)/end user(s), adaptive planning, evolutionary development, early delivery, continual improvement, and flexible responses to changes in requirements, capacity, and understanding of the problems to be solved" (Beck, et al; 2001).

More specifically, the simulation expert becomes a member of the planning team, the planning team includes internal and external stakeholders, alternatives are developed and analysed quickly, the team is prepared to address rapid changes, and works together in a highly collaborative process. In a sense it might be better to call this agile planning because agile simulation implies changing the railway's planning process, but the key requirement driving this change is simulation.

3 The Elizabeth line

The Elizabeth line is an ideal case study for investigating agile simulation because it operates dense services over a complex infrastructure shared by multiple operators. This makes it a microcosm for exploring the capacity and disruption challenges faced by all railways. Furthermore, the Elizabeth line's central London tunnel is one of the largest and most significant recent railway projects (Figure 1).

The Elizabeth line was named in honour of Queen Elizabeth II in 2016 (previously it had been called Crossrail). It consists of a tunnel through central London connected to surface lines on the east and west sides of the city. Existing railway service on these surface lines has been gradually transferred to MTREL, a private operator since it won the operating concession in 2015.

The Elizabeth line was built by Crossrail Limited, an agency created by (Transport for London (TfL) and the UK Department of Transport (Crossrail Ltd. 2022). Ground was broken in May 2009 and the tunnels were completed in 2015. Additional construction and testing were completed in the following years. The opening was delayed from December 2018 until May 2022 due partly to signalling system integration. Passenger service in the central tunnel started on 24 May 2022, full service is planned for May 2023.

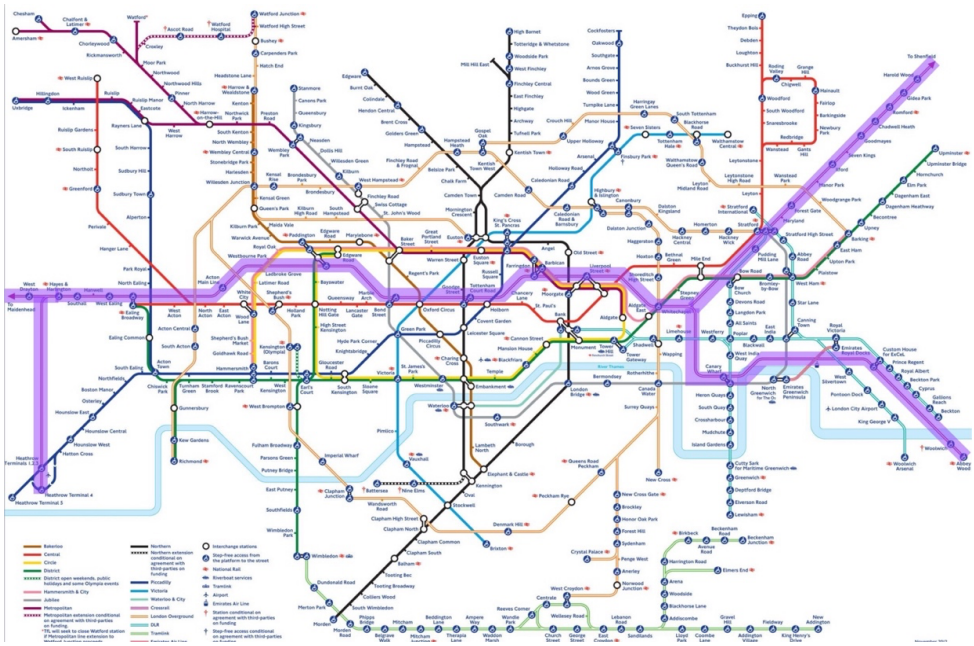

Figure 1 – Elizabeth line highlighted on London Railway Transport Map.

Railways in Britain were privatized in the 1990s. Today almost all railway service is operated by private companies on mostly government owned infrastructure. The Elizabeth line is operated as a concession (Medeossi, Nash 2020); in a concession the operator is paid a specified fee to provide a tightly defined service and does not take commercial risk. The Elizabeth line concession contract includes penalty clauses for failing to meet specified

quality requirements such as punctuality and reliability, as well as bonus clauses for exceeding the requirements. The operator's commercial success depends on meeting or exceeding these requirements.

The Elizabeth line concession was placed out to bid in 2015 by TfL. The successful bidder was to gradually take over operation of the surface lines and then operate the full service once the central tunnel was completed. The request for bids defined a staged implementation plan for service based on a planned schedule for construction, rolling stock acquisition, and service adjustments.

MTREL was one of the Elizabeth line bidders. MTREL is a subsidiary of the MTR Corporation, a privately-owned company that operates Hong Kong's rapid transit lines and service in several cities including Stockholm and London. They included Trenolab, a railway simulation company in the bid preparation team because simulation was necessary to develop and evaluate alternative timetables. Trenolab has continued working as part of the planning team since 2015, when MTREL won the concession.

4 Benefits of agile simulation

This section describes the benefits of agile simulation using examples from the Elizabeth line. These benefits are summarised in the paper's conclusions.

4.1 Agile simulation is fast and accurate – Bid preparation

Preparing a successful bid requires fast and accurate planning. Fast because of strict submission deadlines. Accurate because bidding low reduces profits and bidding high reduces the probability of being selected.

For the Elizabeth line these ordinary requirements were compounded by the concession contract's intricate penalty/bonus clauses and the line's operational complexity. More specifically, service is dense, it shares branches with other operators, and new services will be integrated in future years. Therefore, MTREL included simulation experts from Trenolab in the bid planning team. These simulation experts have remained part of MTREL's planning team because of the good working relationship developed over time and the benefits they have brought to MTREL's service and operations.

The first simulation task was to prepare the model. The original model was created with OpenTrack and used in bid preparation and during several years of operations (Nash, Huerlimann 2004). Trenissimo, a new railway micro-simulation model developed by Trenolab, has been used since 2018 (de Fabris et. al. 2018).

Once the model was built and calibrated it was used to test timetable alternatives. More specifically, although a reference timetable was specified in the concession tender, bidders were free to define an improved timetable if it met the specified service requirements.

By integrating simulation into the bid development process, it was possible not only to estimate the cost associated with a timetable alternative, but also to understand its sensitivity to changes such as traffic controller decisions, starting delays and extended dwell times. This was particularly important because the line did not exist and thus no real statistical data were available for developing the bid. Simulation was the only way to test the impact of increasing delays and dwell times on costs and identify an acceptable timetable.

Agile simulation increases the quality and speed of the planning process by enabling simulation experts to provide direct input into alternative development, ensuring that alternatives are clearly defined (e.g., reducing the need for clarification), and providing a more nuanced explanation of simulation results. As a team member the simulation expert understands the subtleties of the objective being sought and can help inform the team

discussion. The increased quality and speed of agile simulation proved crucial as the bid deadline neared and timetable alternatives needed to be very quickly defined and evaluated.

4.2 Agile simulation facilitates stakeholder consensus: Staged Operating Plan

The Elizabeth line's request for bids specified a staged plan for gradually taking-over a set of existing surface rail lines operating outside London and ultimately routing these lines through the central London tunnel (Crossrail Ltd. 2022). The ability to operate the service specified for each stage depended on completing a series of infrastructure improvements and rolling stock acquisitions. The stages are summarized in Table 1.

The process of transferring services from existing operators to MTREL can easily impact service quality and therefore revenues. In this case the process was further complicated because many services were operating on tracks controlled by different infrastructure owners on routes shared with other operators. This meant the new operating plan (timetable) for each stage needed to be approved by TfL, Network Rail, and other operators before it could be implemented.

Here agile simulation was especially helpful because the simulation experts were part of the stakeholder group (i.e., the planning team plus outside stakeholders) developing the new service plan. The accuracy and speed benefits outlined previously also helped build credibility among the stakeholders and helped increase their acceptance of the final plan.

In short, agile simulation helped move the stakeholder decision-making process forward quickly and efficiently. For example, since the embedded experts were participating in the alternative development process, they could ensure that the alternatives provided for modelling clearly defined the stakeholder goals, thus reducing back-and-forth between the modellers and client. The embedded experts also participated in the discussion of results, which ensured that stakeholders fully understood how these results affected their interests and encouraged them to suggest improvements that could be effectively modelled in the process of refining the alternative, ultimately leading to better timetables.

Table 1: Elizabeth line staged implementation plan

Stage	Summary Description	Date
1	MTREL takes over Shenfield-Liverpool Street Station service.	2015
2A	TfL Rail begins Paddington-Heathrow/Hayes & Harlington services	May 2018
5A	MTREL takes over Paddington – Reading Service (operates to Paddington Main station since central tunnel is delayed).	Dec 2019
2B	Increase from 7-car trains to 9-car trains on Paddington – Reading and introduce Class 345 rolling stock to Heathrow service.	July 2020
4A	Lengthen platforms at Liverpool Street Station to accommodate Class 345 cars and align timetable for future tunnel service.	April 2021
3	Open central tunnel to service (Abbey Road to Paddington)	24 May 22
5B	Through service from Reading/Heathrow to Abbey Wood	TBD
5B-	Though service from Reading/Heathrow to Abbey Wood/Shenfield (reduced timetable).	TBD
5C	Through service from Reading/Heathrow to Abbey Wood/Shenfield (full timetable).	Summer 2023

A good example was implementing Stage 5A in December 2019. Until mid-2018, it was expected that the central tunnels would be open for service in 2018. The delay in opening the tunnels meant service to/from Reading needed to be operated from the existing

Paddington Station (surface platforms). Modelling showed that operating from the surface platforms would create too many conflicting movements and make it difficult to achieve the required service quality. Therefore, MTREL developed alternative timetables and convinced stakeholders to adopt them by demonstrating that the proposed timetables would provide sufficiently high-quality service.

The good working relationship between planners and simulation specialists, together with the fact that the simulation results had been able to forecast the impacts of early stages accurately, built confidence among the stakeholders and helped smooth the process of obtaining the stakeholder buy-in needed to make key go/no-go decisions for later stages.

An ex-post analysis of operational data was carried out after each timetable change. These analyses demonstrated that the simulation results obtained during planning had captured the relevant trends, could identify the critical trains, and provided a reliable estimate of performance. In fact, the simulation results provided slightly conservative ex-ante estimates compared to actual operations. In this case conservative results were appreciated because they ensured that potentially critical operational factors were not underestimated and thereby reduced surprises when service went into operation.

4.3 Agile simulation supports efficient capital project construction: Liverpool Street Station platform lengthening

The Elizabeth line project included lengthening four platforms at the busy Liverpool Street station to accommodate the new Class 345 rolling stock. Stage 4A of the plan assumed that the project would be done after opening the central tunnel. Unfortunately, tunnel construction delays made it necessary to develop a new plan for the lengthening project.

In this case MTREL needed to develop a timetable that supported a high level of service while enabling the lengthening project to be completed as efficiently as possible. Performing construction on or near an operating railway line is always difficult, especially in the constrained environment of a busy station located in the middle of a dense city.

Simulation showed that operating the existing timetable during construction would reduce PPM (public performance measure, a measure that combines punctuality and reliability) (Network Rail, 2022). Therefore, the timetable planners, simulation specialists and construction contractors used agile simulation to help develop an integrated construction plan-timetable for lengthening the platforms while maintaining acceptable service.

An especially important part of this simulation was a stochastic analysis of disruptions based on real operating data from the Liverpool Street Station services. This was used to develop precisely defined recovery plans to prepare for similar disruptions occurring during construction. The simulation results helped convince stakeholders to proceed with the platform lengthening project and bring the benefits of the new rolling stock to passengers.

Construction was carried out in two 10-day periods during the Christmas 2020 and Easter 2021 holidays to further reduce impact on passengers (Figure 2). The interim service was operated without any major disruptions. Finally, MTR's management of the construction project led to a 20% savings compared to the original cost estimate. This highlights an important advantage of using agile simulation to carefully coordinate timetable and construction planning (MTR UK, 2022).

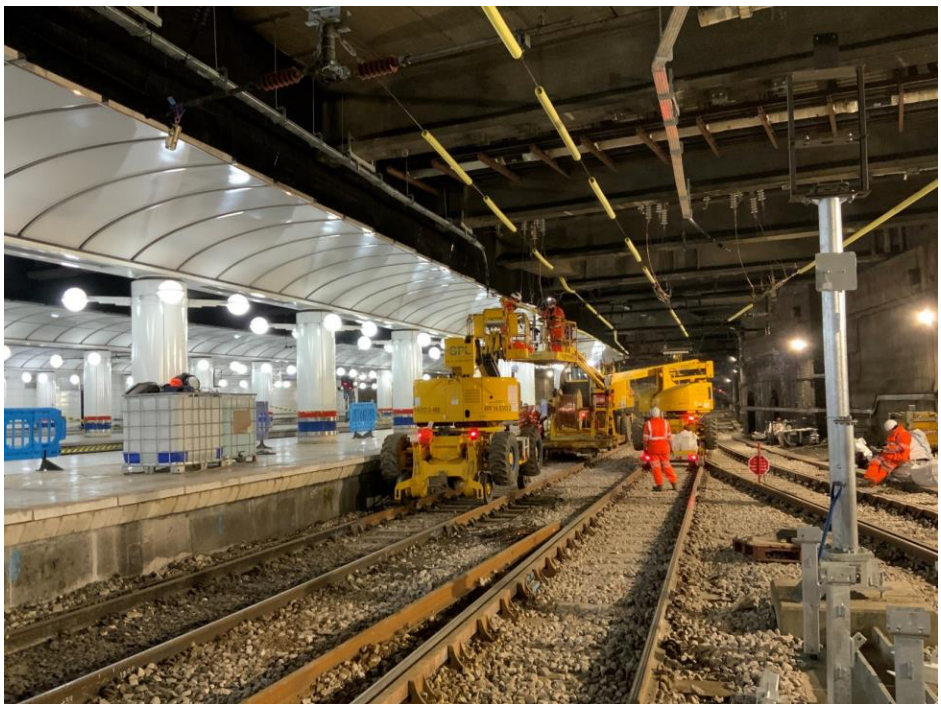

Figure 2 – Liverpool Street Station platform lengthening project construction.

4.4 Agile simulation inspires model improvements: Early start of End-to-End Service (Stage 5B-)

The original staged opening plan for the Elizabeth line consisted of first operating trains from Abbey Wood through the central tunnel to Paddington (Stage 3) while leaving the Shenfield – Liverpool Street and Reading/Heathrow – Paddington services on the surface. This service plan started on 24 May 2022. As shown in Figure 3, the service operates as three independent railways (Abbey Wood to Paddington through the central tunnel, Shenfield to Liverpool Street Mainline (surface) Station, and Paddington Mainline to Heathrow and Reading).

The Stage 3 service has been operating reliably (approximately 97% punctuality) since opening and is one of the country's best performing lines. Given these excellent results the stakeholders decided to examine advancing full end-to-end service by simultaneously implementing stages 5B and 5C. Given the negative public perception caused by the central tunnel's earlier delays, none of the stakeholders wanted to begin end-to-end operations with unreliable service.

Once again, MTREL used agile simulation to evaluate the full end-to-end service alternative. In this case the planners used stochastic simulation to test service reliability using data from the existing operations and input from TfL's Trail railway infrastructure model. The focus was assessing how delays on one of the three lines feeding the tunnel might propagate through the network when the services were integrated.

The simulation identified several weaknesses (e.g., inadequate sectional running times,

high dwell times, and too many trains terminating at Westbourne Park), which together would reduce punctuality and reliability. The planning team then worked closely with stakeholders to develop and test alternative timetables addressing these weaknesses. The result was a revised timetable (Stage 5B- (minus)) based on a simplified calling pattern to be implemented in autumn 2022 with full service (Stage 5C) now scheduled for implementation in 2023.

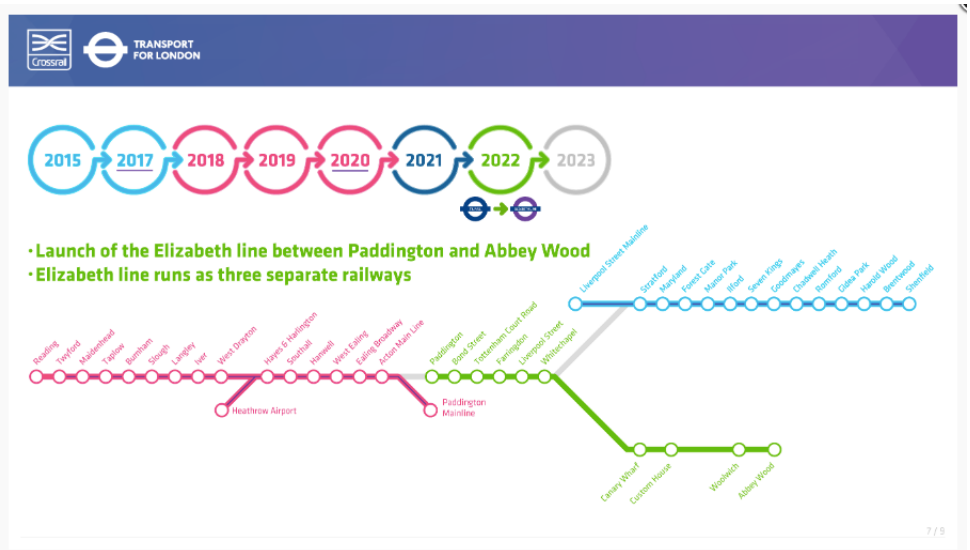

Figure 3 – Stage 3 Elizabeth line central tunnel initial operations.

In this case agile simulation led to the improvement of the simulation model software. More specifically the trenissimo model was modified to include a new rolling stock feature which allows trains to automatically reverse direction. This feature shortens turn-back times and helps solve the problem of too many trains terminating at Westbourne Park. Adding this feature to the model software enabled planners to better understand the benefits and impacts of auto reverse on key performance indicators such as punctuality and reliability. The agile simulation approach improved communication between software developers and planners helping to speed-up the process of adding a new software feature and, due to the trust developed in the close working relationship increased the credibility of model results.

4.5 Agile simulation encourages innovative ideas: Shenfield Line Project

A final example illustrating the benefits of agile simulation was a project carried out in 2016 to identify timetable adjustments to the high frequency Shenfield – Liverpool Street Station (Surface) Elizabeth line service. In this case the close working relationship between simulation specialists and timetable planners encouraged planners to attack a problem they might have "neglected" without easy access to powerful analysis tools they had learned to trust and understand.

In this project the planning team combined stochastic simulation and data from AFC systems (Oyster Card) with timetable planning experience to develop a set of small timetable adjustments designed to improve operations. These adjustments were implemented in May 2016 and led to a significant reduction in delays: punctuality at arrival

increased by 2.9% in the AM peak period and by 6.2% in the most critical hour (08:00-09:00) (Medeossi, Nash 2020).

The project is especially interesting because increasing punctuality (and capacity) is an important goal for many densely scheduled railway lines, and because it illustrates how combining railway simulation with other models and data can be used to quickly increase quality and/or capacity without building new infrastructure, an often-cited objective of railway policy and research. In this case it was once again helpful that the planning team's simulation experts were also the simulation developers because one key to success was adjusting the simulation model to use the new passenger arrival data.

Finally, this process of combining "traditional" railway simulation modelling with additional models and new data sources will certainly increase as software and hardware continue to improve. This is already happening as shown by new multi-objective simulations (e.g., Coviello et. al. 2022), the integration of additional models (e.g., power system efficiency: Longo et. al., 2020), and model integration platforms such as Nexus, which combines railway simulation, pedestrian simulation, and bus operations into a single user interface (Pu et. al. 2022).

5 Conclusions

This paper recommends that railways embed simulation experts into planning teams more frequently and in more types of projects. It describes examples of how this approach helped MTREL successfully implement the multi-phase operating plan for London's Elizabeth line, a dense and complex service.

The authors named this approach "agile simulation" because it resembles agile software development: the simulation expert becomes a member of the planning team, the planning team includes internal and external stakeholders, alternatives are developed and analysed quickly, the team is prepared to address rapid changes, and works together in a highly collaborative process. The paper identifies five key advantages of agile simulation for railway planning:

- **Speed and accuracy** – embedding experts in the planning process improves alternative definition, communications between planners and modellers, and model quality.
- **Stakeholder consensus** – embedding experts in the planning process with other stakeholders improves communications and builds credibility for model results.
- **Multi-disciplinary projects** – embedding experts in the planning process makes it easier to link simulation models with other models (e.g., power consumption) and processes (e.g., construction or maintenance projects).
- **Improve simulation software** – embedding experts in the planning process facilitates improving simulation software to make it more practical, functional, and comprehensive (e.g., adding new features).
- **Practical tool** – embedding experts in the planning process encourages planners to use simulation to explore ideas they may have neglected without positive experience using the simulation model and support from the expert.

These advantages address many of the problems that are holding back the more frequent use of simulation for smaller and shorter-term planning projects identified in previous research, innovation theory, and the sector's established opinion that all railways would benefit from greater use of simulation.

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