A novel method of refining the performance of rail systems: an evaluation of system dynamics using discrete event simulation

Koorosh Gharehbaghi, Ken Farnes and Neville Hurst
RMIT University, Melbourne, Australia

Abstract

Purpose – This paper aims to trial a novel method of improving the performance of rail systems. Accordingly, an evaluation of rail system dynamics (SD) using discrete event simulation (DES) will be undertaken. Globally, cities and their transportation systems face ongoing challenges with many of these resulting from complicated rail SD. To evaluate these challenges, this study utilized DES as the basis of the analysis of Melbourne Metro Rail’s SD. The transportation SD processes including efficiency and reliability were also developed.

Design/methodology/approach – Using DES, this research examines and determines the Melbourne Metro Rail’s SD. Although the Melbourne Metro Rail is still in progress, the DES developed in this research examined the system requirements of functionality, performance and integration. As the basis of this examination, the Melbourne Metro Rail’s optimization was simulated using the developed DES. As the basis of the experiment, a total of 50 trials were simulated. This included 25 samples for each of efficiency and reliability. The simulation not only scrutinized the SD but also underlined some of its shortfalls.

Findings – This study found that information and communication technology (ICT) was the pinnacle of system application. The DES development highlighted that both efficiency and reliability rates are the essential SD and thus fundamental for Melbourne Metro Rail system functionality. Specifically, the three elements of SD, capacity, continuity and integration are considered critical in improving the system functionality of Melbourne Metro Rail.

Research limitations/implications – This particular mega rail infrastructure system was carefully analyzed, and subsequently, the DES was developed. However, since the DES is at its inception, the results are relatively limited without inclusive system calibration or validation process. Nonetheless, with some modifications, such as using different KPIs to evaluate additional systems variables and setting appropriate parameters to test the system reliability measures at different intensities, the developed DES can be modified to examine and evaluate other rail systems. However, if a broader system analysis is required, the DES model subsequently needs to be modified to specific system parameters.

Practical implications – Through evaluation of Melbourne’s Metro Rail in the manner described above, this research has shown the developed DES is a useful platform to understand and evaluate system efficiency and reliability. Such an evaluation is considered important when implementing new transport systems, particularly when they are being integrated into existing networks.

Social implications – Efficient rail networks are critical for modern cities and such systems, while inherently complex, aid local economies and societal cohesion through predictable and reliable movement of people. Through improved system functionality and greater efficiencies, plus improved passenger safety, security and comfort, the traveling public will benefit from the enhanced reliability of the transportation network that results from research as that provided in this paper.

Originality/value – This research paper is the first of its kind specifically focusing on the application of DES on the Melbourne Metro Rail System. The developed model aligns with the efficiency optimization framework, which is central to rail systems. The model shows the relationship between increased efficiency and optimizing system reliability. In comparison with more advanced mathematical modeling, the DES presented in this research provides robust, but yet rapid and uncomplicated system enhancements. These findings can better prepare rail professionals to adequately plan and devise appropriate system measures.

Keywords Discrete event simulation (DES), Melbourne metro rail, Transportation systems, System dynamics (SD), Information and communication technology (ICT)

Paper type Research paper

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1. Introduction

While systems generally can be categorized by inputs, processes and outputs, it is essentially their capability to be used for different purposes that is their advantage (May, 2015; Nehemia-Maletzky et al., 2018). Subsequently, their usage ranges from data warehouses to rail network administration (Zheng and Geroliminis, 2020). Although the discourse of traditional transportation systems considers various modes of transport, rail systems are seen as a method of mass patronage movements (Infrastructure Australia, 2017; Abenoza et al., 2017). Gharehbaghi and McManus (2019) noted that the primary apprehensions concerning rail transportation range from lack of efficiency to high expenditure. To investigate these concerns computer simulations are used to mathematically model the functionality and relationships of a target system together with logical analysis to reproduce an analog of the behavior of the target system (Kim, 2012; Rao et al., 2015; Gharehbaghi et al., 2020c; Ng et al., 2018; Odolinski and Boysen, 2019).

The discrete event simulation (DES) approach used for analysis models the operation of the system as a (discrete) sequence of events in time with each event occurring at a particular instant marking a change of state in the system. DES can be defined here as an event-based operation’s representation of the Melbourne Metro Rail’s system dynamics (SD) (Mattsson and Jenelius, 2015; Reggiani and Nijkamp, 2015). In other words, DES models a system based on specific events, which affect its outcome. Accordingly, DES techniques are effective in identifying, through prediction, the system shortfalls, and subsequent possible effects. Advantages of DES over other modeling techniques include allowing a dynamic approach to model unpredictable situations, that is, situations prone to change. This is due to DES’s flexible capability. It is worth noting; however, DES also has disadvantages such as potentially over or underestimating situations (Morgan, 2015; Kuo, 2017).

This research aims to develop a rigorous optimization of rail systems through increased efficiency and reliability. Rail systems, like many other systems, are continuously the subject of efforts to increase efficiency. Generally, such an increase is achieved through optimizing system reliability. For rail systems, this is complex and time-consuming. Rail authorities spend significant time and effort trying to improve their system efficiencies (Gharehbaghi et al., 2022a). However, with continuous system outages, such reliability is ever eluding the rail administrator. Many complex mathematical models are used to increase system reliability. Such models require extensive knowledge and experience to be effectively used and applied. Accordingly, this research aims to develop a simpler, yet robust, method of optimizing rail systems through increased efficiency, which ultimately leads to improved reliability. The adaptation of DES in this research aims to achieve such an outcome.

For transportation infrastructure, DES is ideal since it evaluates specific system functionality, such as efficiency and reliability. Importantly for rail transportation, DES will be able to identify various system issues based on early determination (Ponti et al., 2013; Sáez et al., 2012). A careful investigation of the literature did not reveal any DES model(s) that dealt with rail SD processes, particularly those dealing with the aforementioned system functionalities. To fill such a void, this paper will use DES for the evaluation of the primary SD of the Melbourne Metro Rail which will facilitate better planning for mega rail infrastructure projects.

2. Research background: rail SD

With every increase in rail transportation usage, ongoing congruent high system performance is required. Generally, for all rail systems, innovative evaluation methods are sought to rapidly streamline high-system performance. As such, it is critical to systematically monitor the complex, yet essential rail networks. One key aspect of systematically monitoring rail networks is the inclusion of robust operational strategies. As He et al. (2016) highlighted,
such strategies deal with upgrading outdated systems to improve network-level operations. To undertake such a task, each rail network, their dynamics need to be carefully assessed (Gharehbaghi et al., 2022b). Typically, rail SD deals with the following:

1. Highly innovative network operating systems and mechanisms. System tests are conducted to certify precise recalibration of all risk variables such as emergency settings.
2. Increase in transport capacity via upgrading systems. Establishing high KPIs that are calibrated into system development.
3. Robust rail operations are based on different scenarios. Specific system configuration and simulation need to be meticulously recalibrated.
4. Up-to-date maintenance regimes. During the early system development, continuous improvement along with precision development are carefully recalibrated.
5. Utilizing innovative information systems. This includes the alignment of highly interactive intelligent transportation system (ITS) with the ever-increasing system functionality.

The inclusion of the above significantly improves the overall system operations. Particularly, the most significant element of improving network operations is through optimizing system reliability. For rail systems, optimization is essential since the network operates within many constraints, such as those discussed above. Overcoming these constraints not only improves the overall system quality but also leads to optimized system reliability.

3. Applying DES to boost SD
DES allows the construction of a mathematical model that represents the system under test in terms of logical and qualitative relationships that can be manipulated to investigate how the system may react. Simulation is one of the most widely accepted and utilized methods for system analysis. It enables the study of, and experimentation with, the internal interactions of a complex system, or subsystem within a complex system. It is appealing because it mimics what happens in a real system and can be used to experiment with new designs or policies before implementation. The knowledge gained during the designing of a simulation model and its operation is of great value in suggesting improvement in the system under investigation as the output data directly corresponds to the outputs from the real system (Banks et al., 2005).

The application of DES in the transport domain is vast ranging from the modeling of freeway merging behavior to the SD associated with the introduction of ITS into a rail network. Simulation-based models for transport are highly flexible and more suitable for reproducing correlated phenomena but may produce unstable results. However, this disadvantage may be alleviated with the introduction of sufficient repetitions to guarantee good performance concerning the simulation model, thereby enabling the differentiation of events (Gentile and Nökel, 2016). Discrete event simulation is widely used in the analysis of transportation. This is largely due to the complexity of resource allocation rules and the variety of stochastic processes involved that make it almost impossible to use analytical approaches (Parola and Sciomachen, 2005).

Computational tools such as Fuzzy logic and Boolean functions are useful tools to pinpoint infrastructure system performance indicators (Gharehbaghi et al., 2020b; McCahill et al., 2020). DES can be classified as a “gate-way” simulation process and is therefore also useful (Koziel and Yang, 2011). At its core, DES utilizes pseudo-random numbers as a way to differentiate dissimilar probability distributions. Although few systems in practice are
wholly discrete or continuous, the rail transport network can be classified as discrete since the variables under investigation change state at discrete intervals. Hence, for rail transportation, DES can be used as an effective tool to further evaluate system performance (Yang and Chao, 2017; Sáez et al., 2012; Saidi et al., 2017). Moreover, Xiao et al. (2018) argued the main steps of DES consist of a collection of appropriate discrete data as input, developing an appropriate process, and evaluation of the result.

For rail transportation systems, an input may include departure time, while the process could contain trip duration and the subsequent outcome may consist of efficiency rate (Thekdi and Lambert, 2012; Rao et al., 2015; Gharehbaghi et al., 2020a; Soteropoulos et al., 2020). While rail efficiency refers to performance over time, reliability indicates punctuality. They are both important aspects of system functionality and thus can be used as the basis of SD analysis. Further, to fully understand DES for rail infrastructure, transportation SD and processes need to be carefully examined. Gharehbaghi et al. (2022a, b) and Cordera et al. (2018) have all emphasized the complexities of rail transportation systems including their functionality and performance integration. Following this, Thekdi and Lambert (2012) highlighted that such systems would ultimately include complicated process simulation and modeling. Contrariwise, Gharehbaghi et al. (2019) argue that appropriate simulation of rail transportation intelligent systems could simplify such ambiguities. Figure 1 describes common incidents leading to efficiency and reliability changes, whether positive or negative.

The common causes of efficiency and reliability challenges range from actual physical assets such as aged rolling stock, through to the supporting information system functionality issues, such as the lack of real-time information. Sladkowski and Pamula (2016) noted that the main SD for rail transportation systems includes improving both efficiency and reliability thereby increasing safety. While generally, efficiency can be described as how well a system transforms its inputs to useful outputs, reliability is a measure of how long a system performs without failing (Sheu and Pan, 2014). Accordingly, efficiency is thus principally expressed in terms of the ratio of useful inputs into outputs (Gharehbaghi et al., 2023; Sheu and Pan, 2014; May, 2015). Further, via system redundancy, reliability can usually be improved (Kuo et al., 2017; Mattsson and Jenelius, 2015; Kumar and Rauba, 2021; Ghosh and Lee, 2010). There are many authors including Mattsson and Jenelius (2015), Rao et al. (2015) and Xiao et al. (2018) among others, who agree improved reliability is subsequently realized at the deterioration of efficiency.

The economic and rapid population growth of communities along rail transport patronage catchment corridors has resulted in increased rail passenger congestion. Congestion is recognized as a recurring problem which takes place in the same area and at the same times each day. This has become a significant problem placing great pressure on the efficient operation of rail transportation services while simultaneously generating a variety of social issues. Numerous studies, such as Chen et al., 2016, Xiao et al. (2018), Oberg et al. (2017) and Hassanin (2020), have highlighted congestion resulting from low capacity, disrupted

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**Figure 1.**
Common causes of efficiency and reliability challenges

**Source(s):** Authors
passenger flows and time delays as examples of the shortfalls of public transportation for large cities. Faced with the challenge of providing adequate transport services with limited resources, the Victorian state government has invested in ITS for the Melbourne Metro rail network. ITS contributes considerably to ensuring the expected efficiency and reliability of rail services while retaining the required traffic safety level.

With the aim of improving transport services, reducing congestion and easing social issues such as accidents and air pollution, Zhuhadar et al. (2017), Odolinski and Boysen (2019) and Kummitha and Trutzen (2017) highlighted the use of information and communication technology (ICT) for existing transport infrastructure. Investments in ITS are beginning to take place in the context of smart city initiatives and are contributors to the intricate and complex SD within the rail ITS. ITS improves the transportation network’s capacity, facilitates superior travel experiences and makes moving through the network more efficient, safer and secure. It does this through the utilization of smart sensors like Internet of Things (IoT) devices to provide data to advanced and powerful communication technologies (Muthuramalingam et al., 2019).

The inclusion of ITS technologies into existing facilities, such as the Melbourne metro rail, results in the increase of the effective capacity of the facility (Fageda, 2021; Abdujabbar et al., 2021). The benefits of ITS are numerous and can be quantified in terms of productivity or throughput increase and economic efficiencies via a reduction in maintenance and operations costs, such as a reduction in wheel flange wear (Benouar, 2001) through to the technologies managing the critical systems such as signaling, centralized control of traffic and vehicles, including speed control and telecommunications (Cruz and Cruz, 2021). Passenger safety, security and comfort, also called economic welfare, is improved through the use of ITS, as is the frequency of services and the timeliness of services. These translate to a direct and indirect economic benefit to passengers through increased leisure time.

Although ITS may refer to all modes of transport, the European Union defines ITS as systems “…in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users, and in traffic management and mobility management, as well as for interfaces with other modes of transport” (Directive 2010/40/EU, 2010, p. 4). In this study, the authors are referring to ITS within the rail transport network which represents critical enabling infrastructure for suburban and urban transit systems that are experiencing significant growth. Rail transportation system management and control is information intensive and brings together an array of technologies such as sensors, communications, computing and intelligent control to address various aspects of rail system management and control, such as customer service, planning and scheduling, dispatch, block control, interlock and speed control (Ning et al., 2006; Cruz and Cruz, 2021).

The term smart cities is a fuzzy concept and its use is not always consistent. It has come to describe different phenomena associated with new ways of organizing city functions and urban life based on the utilization of ICT’s potential to integrate the smart digital city into all walks of life. Over the past 20 years the term “smart city” has evolved from initially concerning sustainability issues to also including smart transport, that is, accessible and sustainable transport services utilizing ITS. Figure 2 represents the inclusion of ICT for ITS.

With advocacy from public transport associations, vendors and the community at large, the idea of a smart city has gained in popularity and Melbourne, like many other large cities has started to undertake a holistic approach to integrating technology with the view towards improving urban transport services as a component of the smart city initiative. Efficient public transport that responds to economic needs and connects labor with employment is considered a key feature of a smart city. ITS, which facilitates and supports efficient public transport, has become an essential application for a smart city initiative enabling the ability of passengers to travel with ease across the transport system (Lombardi et al., 2012).
The backbone of a successful rail ITS is an effective ICT. Liu and Peng (2013) observed that research into smart cities is focusing on ICT system miniaturization, wireless sensor network and intelligent wireless technologies, heterogeneous communication networks, the IoT and ubiquitous information distribution.

Advanced technologies like ITS are heavily dependent on the IoT for the interconnection of real-world physical objects to the virtual world enabling anytime, anywhere connectivity for radio frequency identification (RFID) sensors, ticketing gateways, traffic signaling and other objects that are providing data to the various information systems supporting the rail transportation network. As Figure 2 shows, the inclusion of ICT involves the integration of three primary elements namely, broadband communication, infrastructure and computing technologies. These three separate domains have their own unique specialties; however, they all aim to achieve a high standard of efficiency and reliability.

There is a need for the continuous modernization of Melbourne’s rail transport network through the introduction of innovative technologies, such as the ITS, to clarify and minimize transportation and congestion problems. Accordingly, prior to any rail system improvements, there needs to be careful consideration of which, the efficiency and reliability domain is the main deliberation. Subsequently, at times rail system priorities may change depending upon short-term ambitions (Gordon, 2015; Gharehbaghi et al., 2024; Saidi et al., 2017; Reggiani and Nijkamp, 2015), which is one of most intriguing predicaments facing rail transportation planners (Gudmundsson et al., 2016; Ponti, 2013; Morgan, 2015; Tang et al., 2022; Griskočič-Goričan and Burinskienė, 2012). However, from system engineering perspective, in many instances reliability is seen as the primary option (Gharehbaghi and McManus, 2019; Kim, 2012; Grilo et al., 2015). This is due to the need for of improving reliability and reducing failure. Nonetheless, optimization of a rail transportation system, although very complex, is subjective and/or predominately, a case-by-case scenario. For this reason, this research recommends DES modeling for Melbourne Metro Rail as a way to simplify its SD processes and capturing the dynamic nature of the environment.

4. Research methodology
Escalating transportation costs and reduced network efficiency has provided researchers and transport professionals with the impetus to identify new approaches to improve the
efficiency of transport operations and reduce operational costs. DES has become a popular tool for transport researchers and decision-makers to support their efforts in achieving these objectives. This research utilized DES as the basis of the predictive method to assess Melbourne Metro Rail’s SD. Initially, the primary data for this research was sourced from the Rail Projects Victoria, Australia. Rail Projects Victoria provided limited access to their database for the purpose of this research. The raw data were then prepared based on this research DES matrix and development process, please see Section 5 DES development. Once primary data were sorted and categorized, the simulation was then utilized to review and evaluate the Melbourne Metro Rail SD. Figure 3 outlines the overall research methodological design and approach. This approach was aided by using the Melbourne Metro Rail as the basis of experimental study.

The research commenced with a review of literature followed by site visits and the inspection of various project reports, plans and design schematics that were scrutinized to obtain additional data. This research first and foremost determined the current rail SD analysis gap within the literature. Once the gap was determined, then specific inefficiencies of rail transportation were also identified from inspection of the literature and the various reports and schematics. Further, initiation processes were carried out using the Koziel and Yang (2011) equation (discussed later in this article). This equation was used to separate the preliminary variables and determine specific functions. The subsequent results were then evaluated and presented.

The initial investigation of existing literature was conducted to identify extant gap. Then a cross sectional analysis was carried out to observe any relationships, together with evaluating the specific data through archival research. Using this information, the experimental study was then undertaken on Melbourne Metro rail. The data type consisted of real world – current train performance information, together with simulated performance and reliability modeling. Because of the discrete nature of the rail transport system, the simulation model also needs to be discrete. Therefore, a DES model was developed using MATLAB (R2019b) software. As the basis of simulation, MATLAB provided various probable outcomes, in particular, the foundation of SD, efficiency and reliability tests were simulated. The output of the simulation was then used to further optimize the DES model. This combined process allowed the researchers to identify SD, including system architecture, and therefore determine Melbourne Metro Rail SD. This is discussed in detail in the following sections.

**Source(s):** Authors
5. DES development

The Melbourne Metro Rail project is presently under construction in Melbourne, Victoria, Australia. This project is part of the greater Melbourne rail network, which is being progressively upgraded. Melbourne Metro Rail project consists of the creation of the twin Metro Tunnel connecting additional five underground stations and is estimated to be fully operational in 2025. Accordingly, this section includes the DES development for Melbourne Metro rail that includes the Metro tunnel.

5.1 Primary SD

The primary SD of Melbourne Metro Rail includes its advanced ITC. For Melbourne Metro Rail, its general ICT’s overview is shown in Table 1.

Specifically, the Melbourne Metro Rail’s ICT involves system interactions and interdependencies to enhance communication reliability performance. As a part of such system improvement, communication reliability is increased through decreased failures. Subsequently, to achieve the Melbourne Metro Rail’s ICT main objective, the following system developments are planned:

1. Develop an effective land-use and transport system integration (including communication systems) for Melbourne urban and rural areas. This is achieved via advanced transportation system analysis and planning within Victoria.

2. Increase communication accessibility via 4G and 5G network nodes and towers.

The above two dominant ICT plans are the initial setup arrangement for the Melbourne Metro Rail to improve its operations. DES is used to further evaluate Melbourne Metro Rail SD.

5.1.1 Setting the initial testing parameters.

As a part of initial system testing, parameters analysis was undertaken. This analysis was achieved mathematically using an Innoslate software and via the following “general system equations”:

Step 1: To set up “unit step function” as input:

\[ u(t) = \begin{cases} 
0 & t < 0 \\
1 & t \geq 0 
\end{cases} \]  \hspace{1cm} (1)

Step 2: To set up a general system description and process:

\[ y(t) = \int_{-\infty}^{\infty} g(t,r)x(r)dr \]  \hspace{1cm} (2)

<table>
<thead>
<tr>
<th>System dynamic</th>
<th>Main system objective</th>
<th>KPIs</th>
<th>Performance measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICT</td>
<td>Enhanced communication reliability performance</td>
<td>Rapid emergency response time, in case of accidents</td>
<td>Improve operation rate along with service safety optimization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Faster relaying of information</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Less communication downtime</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multi-platform for information sharing</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Long distance frequency</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Melbourne Metro Rail’s ICT overview  
Source(s): Authors
Step 3: Finally, to set up a general output equation:

\[ y(t) = Ce^{A(t-t_0)}x(t_0) + \int_{t_0}^{t} e^{A(t-\tau)}Bu(\tau)d\tau + Du(t) \]  

where \( y(t) \) is the actual system measurement, \( Ce^{A(t-t_0)}x(t_0) \) is a parameter, \( C \) is a specific factor of measurement, \( Bu(\tau)d\tau \) is condition one, and \( Du(t) \) is condition two of the system testing. Subsequently, for the three system equations, \( t \) was then converted to \( x \), \( y \) and \( z \) to represent the Melbourne Metro Rail system integration. These calculations would therefore evaluate the overall Melbourne Metro Rail SD based on three system integration factors: recalibration (\( x \)), nonlinear control (\( y \)) and precise systems (\( z \)). Based on such evaluation of system integration factors, a “system impact factor value” ranging from above average to extreme was then produced. The above system equations were carried out as a prelude to the DES process and to validate the two tested variables to increase efficiency and optimize system reliability. Once these two variables were endorsed, the DES process then commenced. The next sections present the actual DES system design and application.

5.2 System initiation: Melbourne Metro SD

For this research SD assessment was utilized for the following:

1. Converting the augmented causal graph to an SD flow graph (i.e. causal loop diagram)
2. Determining the relationship of the system parameters
3. Examining the variables and constants that vary over time
4. Finalization of verification and validation of system parameters

Thus, a causal loop diagram assists with understanding the causal influences which can be contained within a “closed system of feedback loops.” The causal loop diagram was ultimately used to initiate the modelling process (see Sections 5.3 DES process, and 5.4 Algorithm and simulation stage, for more information). Figure 4 represents the Causal loop diagrams for the Melbourne Metro Rail.

![Causal loop diagram](source: Authors)
Figure 4, which is a causal loop diagram, is a simple way of showing the parts of a Melbourne Metro Rail and its system along with how they interrelate. This diagram illustrates the relevant parts of the system using textual identifiers and their interrelationship. While "Balancing" feedback loops are positive; the [R] "Re-enforcing" feedback loops have negative implications. The reason why both system performance and system reliability have negative implications is that both of these areas are complicated, thus resulting in high costs and increased time consumption. For the Melbourne Metro Rail, both of these areas consider these key questions: What are the exact reliability measures? i.e. key functions; What are the exact efficiency measures? i.e. KPIs; How to monitor the overall quality of the system, and so on. Further, as it can be noticed these are central to the Melbourne Metro Rail's system (overall) performance. Therefore, effectively responding to such questions would possibly lead to overall system enhancement. Essentially this can be perceived as justification as to why both areas of system performance and reliability are examined in this research.

5.3 DES process: pseudocode segment

The variables of DES are principally based on increased efficiency and optimized system reliability. As a preliminary variables and functions determination, specific Koziel and Yang (2011) equation was used:

$$\text{minimize } F_1(x) := [f_1(x), f_2(x), \ldots, f_k(x)]$$

$$\text{maximize } F_2(x) := [f'_1(x), f'_2(x), \ldots, f'_k(x)] \text{ Subject to: } g_i(x) \leq 0 \quad i = 1, 2, \ldots, m$$

where $x = [x_1, x_2, \ldots, x_n]^T$ is the vector of performance variables; $f_i : \mathbb{R}^n \rightarrow \mathbb{R}$ with $i = 1, 2, \ldots, k$ are the objective functions; $g_i$ and $h_j$ with $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, p$ are the constraints functions. Finally, based on the developed DES model and refinement processes, specific solutions were recommended that is, Solution$^1$, solution$^2$, \ldots solution$n$. Subsequently, the DES for Melbourne Metro Rail is determined on the following event based operational representation: reliability and efficiency functionalities which are presented in Table 2.

While the system parameters include both efficiency and reliability, necessary data needed to be collected to successfully optimize the developed DES. This included train arrival and departure rates, communication and other breakdown intervals and so on. The model was then verified to check if the program worked properly. Essentially, the overall DES setup involved the following processes:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Purpose</th>
<th>Performance measures</th>
<th>Simulation 1st pass</th>
<th>Simulation calibration</th>
<th>Simulation 2nd pass</th>
<th>Output evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase efficiency</td>
<td>Reliability specifications</td>
<td>&lt;5% system failure</td>
<td>Operation hours</td>
<td>decrease system failures</td>
<td>Improved service rate</td>
<td>Early determination of defective parts</td>
</tr>
<tr>
<td>Optimize system reliability</td>
<td>Efficiency rate</td>
<td>90–95% service delivery</td>
<td>Train departure and arrival rate</td>
<td>Train transit process</td>
<td>Improved transportation operation and safety</td>
<td>Reduction of delays</td>
</tr>
</tbody>
</table>

Table 2. DES system parameters settings

Source(s): Authors
(1) Determine the feasible range of input variables.
(2) Estimate efficiency and reliability rates for all feasible values of input variables using the model.
(3) Build a valid DES model.

The developed DES model is presented in Figure 5. The DES development for Melbourne Metro Rail was based on following model:

1. Events, i.e. operation hours etc.
2. Entities to determine the variable types, i.e. increase efficiency etc.
3. Simulation clock to determine simulation time, i.e. first iteration etc.
4. Control components to determine values generate random variants, i.e. 90–95% service delivery etc.
5. Random-number generators, i.e. experimentation or trails.
6. Carry-out simulation (SD evaluation) is based on the following steps:
   - Step 1: Define the purpose of the simulation, i.e. increase efficiency.
   - Step 2: Build a first pass simulation – i.e. multiply efficiency by for example 80% to get the efficiency percentage required, that is increase operation performance by approximately 5% – if achievable.
   - Step 3: Calibrate the simulation, i.e. compare the increased operation performance with the set benchmark.
   - Step 4: Analyze the results and provide multiple determine efficiency outcomes/outputs.

Once the DES was simulated, the succeeding “refinement process” was then staged into pre-processing, optimization and post-processing phases, which are now discussed.

![DES model](image-url)
5.4 Algorithm development and simulation stage

The algorithm development was based on the following two stages. First (Stage 1), two functions – efficiency ($X^1$) and reliability ($X^2$) – were selected and refined, as per the following three phases:

1. **Phase 1** (set performance variables)
   
   \[
   \text{else repeat.}
   \]
   
   If $X^2 = 80$ then continue,

   \[
   \text{else repeat.}
   \]

2. **Phase 2** (set objective functions)

   If $X^1 = 90$ then pass,

   \[
   \text{else repeat.}
   \]

3. **Phase 3** (revise constraints functions)

   If $X^2 = 92$ then continue,

   \[
   \text{else repeat.}
   \]

Then, (Stage 2) a programming process was undertaken to initiate the simulation process:

```matlab
refinmen opt = handel
   properties (GetAccess='current', SetAccess='current')
   methods
      function obj=opt
      function prepro=opt1 (output=80)
      function optim=opt2 (output=90)
      function postpro=opt3 (output=90)
      end
   end
end
```

The above loops are to enhance the overall performance of the Melbourne Metro Rail system. Such a process would improve the system’s application, thus leading to higher functioning output. Using MATLAB (R2019b) software, the simulation was then carried out. The results are presented in Figures 6 and 7.

Computer simulation and modeling for this research were undertaken to carefully study and better understand the Melbourne Metro complex feedback systems. Both the performance and reliability simulations were based on the following metrics: (1) Throughput: to ensure the DES model could handle a large volume of data/requests, the evaluation of the transactions/operations was undertaken per unit of time, (2) Scalability: to ensure the DES Model could manage varying level of loads (data), the evaluation needed to cope with increased workload/user demand, (3) Reliability and Availability: to ensure the DES Model was reliable, the researchers needed to properly measure the system’s ability to perform consistently without failures. This also included observing any error rates to track the frequency of errors/failures in the system. Thus, the model produced low error rates which is indicative of a stable and reliable system.

As the basis of the experiment, a total of 50 trials were simulated. This included 25 samples for each of efficiency and reliability. Although 25 trials are seemingly small, it nonetheless provides a good opportunity to observe any correlations and specific patterns. Statistically, both Figures 6 and 7, represent a cumulative distribution function (CDF). Although Figure 6 (performance) is seemingly a quicker CDF, Figure 7 (reliability) is more gradual. This simulation output does have the following outcomes:
Melbourne Metro Rail’s system performance is achieved at a quicker rate.

While, Melbourne Metro Rail’s system reliability, shows a more traditional protracted progression.

To further examine the functioning of the developed DES Model, a comparative analysis was undertaken.

5.5 DES model evaluation: comparative analysis
The developed model whose output is shown in Figures 6 and 7 aligns with the efficiency optimization framework which is central to rail systems. The model shows the relationship
between increased efficiency and optimizing system reliability. In comparison with more advanced mathematical modeling, the DES presented in this research provides robust, but yet rapid and uncomplicated system enhancements. In terms of a determination of systems performance, the DES can rapidly determine such outcome. Further, it has the flexibility to be adapted and used for other rail systems. The key measure of any rail system evaluation tool is to determine the functions, parameters, etc., and provide a quick assessment of network condition. The DES developed in this research is thus explicitly meeting this requirement. Although the DES is only at its inception, nonetheless, its impact could be significant for the key rail stakeholders. For administrators who want a rapid system and network assessment of the rail infrastructure, the DES can be used for this purpose. Such an outcome will ultimately lead to more satisfied patronage by the broader communities. As a part of (the DES model) continuous improvement regimen and to improve the model’s efficiency, a comparative analysis was carried out. This is represented in Figure 8.

For this research, the comparative analysis involves evaluating and comparing two variables – performance and reliability – to identify patterns, similarities and differences. Comparative analysis helped in identifying particular patterns and trends by carefully examining similarities and differences among the two variables. Thus, this can be valuable for making predictions and understanding the DES model’s dynamics. The variables were compared based on samples and percentages. In Figure 8, while the X-axis for both variables is sample size, the Y-axis is percentage-based. Further, the comparison provides a suitable way of initial-checking the overall DES model performance.

As noticeable, the performance reached its peak (100%) rapidly thus indicating a swift efficiency increase. This is possibly due to the use of specific technological advancements. For Melbourne Metro, rapid technological advancements introduced were high-capacity signaling, high-capacity system integration, automated and integrated platform screen doors, among others. With such inclusion, Melbourne Metro is implementing cutting-edge technologies while aiming to maintain almost perfect efficiency. On the other hand, reliability took a while to reach its peak (not 100%). For Melbourne Metro and its systems, this is due to several factors. Factor one, due to uncertain operating conditions. Melbourne rail network and systems face a wide range of operating conditions some of which may be unpredictable, ie system shutdowns, system malfunctions, and so on. Adaption to such diverse and at times
extreme conditions poses challenges in maintaining very high (>90%) system reliability. Factor two, is cost constraints. For Melbourne Metro, balancing the very high reliability with cost constraints is somewhat difficult. The Victorian state government has already allocated approximately Aus$11 billion dollars for this project. To attain almost 100% reliability for a very large rail network like Melbourne requires ongoing investment in updated systems, constant expensive, rigorous, testing and rejuvenation regimes, as well as keeping the fares and cost minimum for the patronage.

Overall, the comparative analysis of the DES model further assessed the overall system performance of Melbourne Metro Rail. As noted, there are some difficulties when aiming to attain a very high (>90%) system performance – performance and reliability. Responding to such dilemmas requires a holistic approach which includes robust system design practices, thorough and ongoing system testing, ongoing system monitoring and maintenance particularly during and after peak/high demand periods, and a commitment to continuous (system) improvement.

6. Research findings
Using both DES together with appropriate simulation, this research experimented with particular efficiency and reliability tests, specifically for rail infrastructure. As a part of Melbourne Rail’s SD evaluation, this experiment was necessary. System efficiency and reliability simulation rates of >80% were observed. These high rates are a traditional “normalization” process specifically for rail ICT systems. In other words, globally a benchmark of >80% is expected for rail ICT systems.

Although the existing Melbourne rail network has been long established, the Melbourne Metro Rail including the Metro Tunnel is a new project. Since this section of the Melbourne rail network will be new, there may probably be some ICT issues with the rest of the network as a result of interconnecting the existing information systems with the ITS. Nonetheless, as the basis of SD evaluation, both efficiency and reliability are key parts of the Melbourne Metro Rail System framework, shown in Figure 9.

Various studies have shown some of the shortfalls of Australian rail transportation services (ATSB, 2013). ICT breakdown and interruption are part of the main reasons behind Australian rail transportation inadequacies. The most intriguing aspect of the Melbourne Metro Rail efficiency and reliability simulation is the variability of these two system measures (Figure 9). For Melburnians, rail operation and accessibility are among the most important factors. DES developed in this research highlights that specific SD of Melbourne Metro Rail covers improving system functionality through:

1. Improved capacity. Developing specific safety switches that provide early system failure warnings.

2. Improved continuity. For Melbourne’s large rail network this means being able to reduce congestion through gateways that allow for an increase/decrease in train numbers. This includes designated bus/tram terminals in the event of a rail network shortage.

3. Improved integration. This is the most complex function; yet the most important. As a part of the system integration, the Melbourne Metro Rail system will be carefully combined with the existing network. Besides, it is planned that Melbourne’s complete rail network can be integrated not only as a part of the state-wide system but also capable of operating nationally when feasible. For example, if the Australian High-Speed Rail long-distance hauling becomes operational, Melbourne’s rail network needs to have compatibility.
Essentially, this simulation provides the agenda for further research. Comparing Figures 6 and 7, the differing improvement gradients of performance and reliability show that the interaction of the input variables, being government-mandated performance standards (KPIs), is potentially affecting SD. Thus, further research is required to investigate the interaction of the independent variables to determine the optimal levels of SD. Such a metaheuristic approach will provide greater certainty towards desired outcomes and in turn, public confidence in the Metro Rail system.

7. Conclusion and recommendations
This research employed the Melbourne Metro Rail network as the platform for the experimental study. Like many other rail networks, it is subjected to the numerous challenges of including ITS to modernize the network which often results in complicated SD. This research used DES as the foundation of SD modeling. The modeling highlighted that both high efficiency and reliability rates are the essential SD and thus, are fundamental for the efficient and reliable operation of a rail network such as the Melbourne Metro. It was observed that the three key SD’s are capacity, continuity and integration.

In addition to improved system functionality and greater efficiencies plus improved passenger safety, security and comfort, the traveling public will benefit from the enhanced reliability of the transportation network that results from such improvements. This will have a flow-on effect on the general quality of life of patrons whether they be regular commuters or tourists, as they can have enhanced confidence in the rail services and in turn, may also result in a change in travel behaviors and higher levels of usage and trust in the public transport system.

Ultimately, these results can better prepare rail professionals to adequately plan and devise appropriate rail system measures. Nonetheless, to further review and assess the proposed DES model the following recommendations are suggested:
(1) A larger sample size is required for the simulation. This research used 50 samples as the basis of the initial trial. Thus, to further examine the DES model, a larger sample size, possibly in the range of a few hundred is necessary. A larger size would also show any outliers or abnormal outputs.

(2) The suggested larger samples could also be based on peak vs off-peak times to observe any differentiations once again during the normal and heavy usage times.

(3) Continuously check the revised DES model against the ongoing development of the Melbourne Metro Rail. This would assist in ensuring the practicality of the developed DES.

Through evaluation of Melbourne’s Metro Rail in the manner described above, this research has shown the developed DES is a useful platform to understand and evaluate system efficiency and reliability in rail networks. Such an evaluation is considered important when implementing new transport systems, particularly when they are being integrated into existing networks. In keeping with a sound academic inquiry, the researchers call for further research to be undertaken in this field to further enhance system efficiency, patronage safety and reliability.

7.1 Limitations of research
Generally, most rail networks and their systems have increased efficiency and optimize system reliability as their primary benchmarking requirements. For rail network testing such requirements needed to be constantly tested and validated. Due to the nature of the innovative DES testing for rail networks, the model presented in this research was initially tested on Melbourne Metro Rail. In other words, The Melbourne Metro is used as an exemplar (as a case study and example) to explore DES to identify the SD. The Melbourne Metro was selected since this mega infrastructure uses the most innovative ITS available. Subsequently, using the Melbourne Metro provided a good platform to test the developed DES. Accordingly, this particular mega rail infrastructure system was carefully analyzed and subsequently, the DES was developed. However, since the DES is at its inception, the results are relatively limited without inclusive system calibration or validation process. Nonetheless, with some modifications, such as using different KPIs to evaluate additional systems variables and setting appropriate parameters to test the system reliability measures at different intensities, the developed DES can be modified to examine and evaluate other rail systems. However, if a broader system analysis is required, the DES model subsequently needs to be modified to specific system parameters. Finally, for benchmarking, DES model performance needs to be compared against industry standards and similar systems. Doing so helps in identifying areas where improvements to the DES model can be made.

References


Further reading


Corresponding author

Neville Hurst can be contacted at: neville.hurst@rmit.edu.au

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